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# WINCLR: A Computer Code for Heat Transfer and Clearance Calculation in a Compressor - A Manual

T.K. Bose and S.N.B. Murthy

*Purdue University*
*West Lafayette, Indiana*



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T.K. Bose and S.N.B. Murthy

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One of the concerns during inclement weather operation of aircraft in rain and hail storm conditions is the nature and extent of changes in compressor casing clearance. An increase in clearance affects efficiency while a decrease may cause blade rubbing with the casing. The change in clearance is the result of geometrical dimensional changes in the blades, the casing and the rotor due to heat transfer between those parts and the two-phase working fluid. The heat transfer interacts nonlinearly with the performance of the compressor, and, therefore, the determination of clearance changes necessitates a simultaneous determination of change in performance of the compressor. A computer code the WINCLR has been designed for the determination of casing clearance, that is operated interactively with the PURDU-WINCOF I code designed previously for determining the performance of a compressor. A detailed description of the WINCLR code is provided in a companion report. The current report provides details of the code with an illustrative example of application to the case of a multistage compressor. It is found in the example case that under given ingestion and operational conditions, it is possible for a compressor to undergo changes in performance in the front stages and rubbing in the back stages.

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## EXECUTIVE SUMMARY

One of the concerns during flight operations in inclement weather involving rain and hail ingestion is the possibility of an appreciable change in compressor casing clearance. The compressor clearance is a design parameter selected on the basis of minimizing performance loss and the possibility of casing rubbing by the blades under various, normal operating conditions. In some engines an active control is incorporated to reduce the clearance change to a minimum. During ran and hail ingestion, there is heat transfer between the working fluid and the three parts of a compressor, namely the casing, the blades, and the rotor. Such heat transfer causes changes in the physical dimensions of the three parts and thus there can be either a positive or a negative change (an increase or a decrease) in clearance. In the current report, a computer code, WINCLR, is described, that has been established for determining the possible change in casing clearance under given conditions of compressor operation and water ingestion.

The details of the physical basis for setting up the WINCLR code are provided in a companion report entitled "WINCLR: A Computer Code for Heat Transfer and Clearance Calculation in a Compressor: A Detailed Description". The current report presents only a description of the code along with an illustrative case on application.

The determination of heat transfer between the working fluid and the metal parts of a compressor at any location in the compressor requires a knowledge of the state of the working fluid in the compressor at that location. However, the state of the working fluid depends on the initial conditions, the performance of the compressor up to that location, and also, significantly, the heat transfer between the working fluid and the metal parts. Thus there is a nonlinear interaction between the performance of the compressor and the heat transfer process. The PURDU-WINCOF I code has been suitably modified for taking into account heat exchange with the metal parts.

The WINCLR code and the modified WINCOF I code are set up to operate interactively. First the WINCOF I code is utilized to obtain the performance of the compressor neglecting the heat transfer to the metal parts. Next, the heat transfer to the metal parts is determined. The performance of the compressor is then determined accounting for the heat transfer using the

modified WINCOF-I code. Finally, the heat transfer and the performance calculations are repeated iteratively until the heat transfer is established to a desired accuracy.

The resulting casing clearance is obtained by determining the changes in the physical dimensions of the casing, the blades, and the rotor, and by summing the changes suitably.

An illustrative case is presented for the case of a generic high pressure ratio compressor operating under certain conditions of ingestion. it is of interest to note that the heat transfer calculations do not require more than one iteration, and that the clearance in the front stages of the multistage compressor is increased causing substantial changes in performance, while the clearance in the back stages is decreased leading to a possible contact and rubbing between the blades and the casing.

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# 1. INTRODUCTION

Compressor casing clearance is an important parameter in the operation of a flight engine. When the clearance becomes small there is the possibility of a contact between blades and the casing wall and, hence, rubbing. In rare cases the rubbing may be intense enough to cause melting, local welding and tear, causing severe damage to the blades involved, or burning, for example with titanium in the blades. When the clearance becomes large, there is a substantial increase in the losses in the performance of the compressor. An optimum value of clearance has largely remained a concept, especially in view of the variety of conditions in which an engine may be required to operate. However, a controlled clearance has become practical in recent times. Such developments require a knowledge of the manner in which the casing clearance in an engine of given materials of construction varies with given ambient atmospheric and operating conditions. The variation may be determined with respect to, for example, the value of the clearance under cold conditions as manufactured or under an operating condition such as the cruise condition. One method of undertaking the determination of casing clearance is through measurements under different conditions. Although attempts are underway to measure blade clearance even for individual blades in a multistage machine, it is obviously impractical to set up all possible environmental conditions. Therefore, there are extensive efforts to develop analytical-computational methods by means of which reasonable estimates can be made of the casing clearance under various conditions. The interest in the current report is in the development of such a computational method for an operating condition involving water ingestion into the engine the compressor of which is under consideration.

Water ingestion into an engine, such as during flight in a rain storm, causes the inlet and the compressor system to operate with an air-water mixture, some of the water being in liquid form. The air-water mixture passes through the annulus of the compressor and therefore causes heat exchange with the blades. In addition, the air-water mixture may enter the cooling passages of the rotor and thus the rotor temperature distribution could become different from what it would be during operation of the engine under normal circumstances when the cooling passages carry only air. Finally, during passage of the air-water mixture through the compressor annulus, water becomes centrifuged towards the casing wall and a film becomes formed at the casing wall. This gives rise to a change in the casing wall temperature.

The casing clearance is nothing but he difference in physical dimension of the casing and the rotor with the blade. Thus the clearance and its change can be determined if the dimensions of the casing, the rotor blade, and the rotor are known under different conditions. This is the method normally employed for establishing the clearance. In applying the method to an actual engine compressor, there are several complexities in the compressor and the engine, not necessarily related to the heat load and transfer of the three main parts of the compressor (the blades, the rotor and the casing), but nevertheless entering into the fluid flow dynamics and thermal balance of the system. Including such complexities is an extremely difficult task. In fact, while the basic methodology of determining the clearance is simple in principle, the detailed design of the engine is, in various respects, specific to the class of engine and, therefore, the method for a detailed estimation of clearance becomes specific at least to the class of the engine. The methodology developed and in the current report includes only the three basic components of the compressor and does not take any account of the complexities that are typical of a modern flight engine.

The main concern in determining the thermal load and the resulting physical dimension of the three main parts of a compressor during operation with an air-water mixture is that the working fluid is an air-water mixture. The two-phase nature of the fluid introduces a variety of complexities in flow and heat transfer processes. For example, in the case of the rotor it is not clear if the cooling flow passages operate with the same two-phase fluid mixture as in the annulus. The fluid dynamics of fine passages with two-phase flow is not understood in all aspects. The methodology for determining the clearance in the case of operation with air-water mixture is developed here under a series of assumptions and approximations. The methodology is suitable at best for obtaining estimates of clearance. The main outcome of the development of the methodology presented here is a framework for analyzing and calculating the clearance.

## 1.1. Description of the Methodology

Details of the methodology are presented in Ref. 1, along with the necessary background on various relevant aspects of compressor cooling schemes, analytical-computational methods for estimating loads, and the features of flow and heat transfer that need to be taken into account in the case of a two-phase working fluid. Here a brief outline of the methodology is presented as background to the discussion of the computational code developed for determining the clearance and its changes in different circumstances.

It may be useful to note that the performance of a compressor is affected by the heat transfer between the working fluid and the metal structure of the compressor. In order to establish the heat transfer in a stage of a compressor one needs to know the thermal state of the working fluid in the stage. However, the thermal state itself undergoes changes on account of heat transfer. In a multistage machine the changes in one location affect the performance everywhere downstream. It, therefore, becomes necessary to carry out the calculation of heat loads and thereby the clearance through an iterative procedure that includes the determination of the performance of the compressor in each iteration step.

In the methodology developed for the determination of clearance in the case of water ingestion, the procedure is the same as described above. A code has been developed for the determination of heat loads and clearance, the WINCLR code, that depends upon a knowledge of the performance of the compressor under a set of water ingestion and operating conditions.

The performance of a compressor operating with an air-water mixture can be determined utilizing the WINCOF-I code (Ref. 2). However, the WINCOF-I code, while it accounts for interphase heat and mass transfer, does not account for heat transfer between the working fluid and the metal structure of the compressor. In view of this, the WINCOF-I code has been modified to account for such heat transfer.

The WINCLR code is designed so as to work interactively with the modified WINCOF-I code. The procedure is shown schematically in Fig. 1. The application of the procedure is illustrated in the following first to a single stage unit and then to a multi-stage unit.

### 1.1.1. Application to a Single-Stage Unit

It may be recalled that the WINCOF-I code is written for a single-stage unit. In the case of a multi-stage unit, the WINCOF-I code is utilized adopting the so-called stage-stacking procedure. The modified WINCOF-I code, that incorporates heat transfer to the metal parts of the unit, is also written for a single-stage unit and a stage-stacking procedure for use in the case of a multi-stage unit.

The methodology for the determination of clearance changes in the case of a single-stage machine may be summarized as follows with reference to the scheme shown in Fig. 1:

(i) The modified WINCOF-I code is utilized to determine the performance of the compressor stage under given conditions of air-water mixture at entry and operation, without including heat transfer to the metal parts.

(ii) The WINCLR code is utilized to establish the heat transfer to the metal parts and the resulting value of casing clearance utilizing the stage performance values generated under (i).

(iii) The modified WINCOF-I code is exercised next to determine the performance of the stage taking into account the heat transfer to the metal parts established under (ii).

(iv) The WINCLR code is next exercised utilizing the compressor performance established under (iii).

Such an iteration procedure can be continued until the change in clearance is successive iterations is small enough to ensure convergence. In general it is also desirable to establish the trend in convergence of compressor performance.

### 1.1.2. Application to a Multi-Stage Unit

The procedure is in general identical to that adopted in the case of a single-stage unit. The main difference is that in each step, (i) through (iv), it is necessary to undertake the calculation over the entire multi-stage compressor, while storing performance and heat transfer calculations for each stage in each step so as to be able to recall them in the next step. The main reason for adopting this method of dealing with a multistage machine is that the rotor as well as the casing are single units, and heat transfer calculations for those parts may only be undertaken with respect to the total unit. In other words while stage-stacking is feasible, within its own limitations, for the calculation of compressor performance, heat transfer calculations for the rotor and the casing require a consideration of the total unit. Accordingly, for a multi-stage unit, the performance is calculated using the stage-stacking procedure of the WINCOF-I code and then, the corresponding heat transfer calculations undertaken for the total unit using the WINCLR code. All of the succeeding iterations are carried out in the same fashion.

## 1.2. Architecture of the WINCLR Code

The WINCLR code may be utilized for heat transfer calculations in the cases of operation with (i) air flow and (ii) air-water mixture flow. Case (i) is sometimes referred to as the dry case. The WINCLR code may be utilized in itself as in combination with the compressor performance code, the WINCOF-I. As stated earlier, the WINCOF-I code is available for use in both the original form, and with inclusion of heat transfer to the metal structure, the later code referred to as the modified WINCOF-I code. The WINCLR code in combination with the modified WINCOF-I code can be utilized to establish the casing clearance in a multi-stage compressor.

The modified WINCOF-I code consists of the original WINCOF-I code with various added routines for the calculation of heat transfer to the metal structure of the compressor and the resulting changes in the performance of the compressor. The input data for the two parts, namely the original WINCOF-I code and the added routines in the modified WINCOF-I code, have been organized separately. The input data for the original WINCOF-I code are provided in files, for example, listed as "case 1-inp". The input data for the modified WINCOF-I code are provided in files, for example listed as "case 2-inp". The input data may, thus, be used without entering the thermal load and casing clearance programs, when necessary. The input data may also be used along with the thermal load and casing clearance programs.

In Fig. 2 a two-stage compressor is shown schematically with a rotor, a casing, and two stages of blading with an IGV row ahead of the first stage. The figure also illustrates the representation of the unit with 19 nodes each encompassing a distinct part or zone of the compressor unit.

Among the three parts of the compressor, the rotor is the most complicated considering the manner in which its cooling is designed in practice. The complexity becomes considerably greater in the case in which the working fluid is a mixture of two phases, such as the air-water mixture. The manner of entry and flow of such a mixture in the cooling passages of the rotor present several ambiguities. In order to proceed, the rotor or disk cooling has been considered in the WINCLR code in terms of four, reasonably well-defined cases, namely: (i) The rotor disk is not internally cooled; (ii) the rotor disk is internally cooled with dry air; (iii) the rotor disk is internally cooled with air-water mixture of the same type as at entry; and (iv) the rotor disk is cooled with a stagnant body of air-water mixture, which may become replenished in total periodically. The input data for the four cases are given as "blheat l-inp", "blheat 2-inp", "blheat 3-inp", and "blheat 4-inp", respectively. In each case, a different type of thermal node structure is required. For example, the node-distribution given in Fig. 2 and also, Table I, applies to case (i). In case (iv), the number of nodes remains the same as in case (i) when the cooling fluid is not replenished; however, when there is a replenishment of the fluid, the temperature of the cooling fluid periodically changes and hence, an additional node is required per stage of the compressor unit. Thus a total of 21 nodes becomes necessary, as shown in Fig. 3 for the case of the two-stage compressor. In general, the number of thermal nodes needed for a compressor with N stages is [(N X 7) + 5] for all cases, except in the case (iv) where the cooling fluid may be undergoing replenishment when the number of thermal nodes required becomes [(N X 8) +5]. An integer, called "NROTICS" has been introduced in the program to identify the various cases.

## 1.3. Outline of the Report

Section 2 deals with a brief description of the WINCLR code. The next section, 3, provides a test case, and finally in the last section a brief discussion is presented.

Table 1. List of various elements

| Type of element | Where the type is used | No. of adj. nodes (mm,mf) |
|---|---|---|
| 1 | disk | 3(1,2) |
| 2 | rotating tube or shaft | 4(2,2) |
| 2 | rotor rim (extern+intern. cooling) | 4(2,2) |
| 3 | rotating tube or shaft | 4(3,1) |
| 4 | rotating tube or shaft | 3(2,1) |
| 5 | rotating tube or shaft | 3(3,0) |
| 6 | vane or rotor blade (no intern.cool.) | 2(1,1) |
| 7 | vane or rotor blade (with intern.cool.) | 3(1,2) |
| 8 | bore node | 1(1,0) |
| 9 | metal/rim/casing node(4 adj.metal nodes) | 4(4,0) |
| 10 | rim node(extern.fluid,intern.metal node) | 4(3,1) |
| 11 | rim node(extern.metal,intern.fluid node) | 4(3,1) |
| 12 | casing(extern+intern.fluid) | 4(2,2) |
| 13 | casing(extern.fluid+intern.solid) | 4(3,1) |
| 14 | casing(extern.solid+intern.fluid) | 4(3,1) |
| 15 | rotor disk (without intern.cooling) | 2(1,1) |
| 16 | rotor disk (with intern.fluid node) | 3(1,2) |

## 2. DETAILS OF THE WINCLR CODE

The WINCLR code is written in Fortran 77. A description of the code is given in this section, while the details are given in Appendices I through VI to this report.

### 2.1. List of Subroutines

The list of subroutines is given in Appendix A to this report.

### 2.2. Detailed Description of Subroutines and External Functions

A detailed description of the subroutines and external functions is given in Appendix AI to this report.

### 2.3. Program Source Listing for Modified WINCOF-I Code

The program source listing for the modifications made to the original WINCOF-I code is given in Appendix AII to this report.

### 2.7. Input And Output Files

As mentioned in section I, the input data are organized in two groups as follows:

A. Compressor performance data (original WINCOF-I code); and
B. Nodal temperature and blade clearance.

In group A, the following input files are available:

A1: case1.inp - for dry air; and
A2: case2.inp - for air with 4 percent water in droplet form.

In group B, the available input files are as follows:

B1: blheat1.inp - for solid rotor disk;

B2: blheat2.inp - for rotor disk internally cooled with dry air in bore channel;

B3: blheat3.inp - for rotor disk internally cooled in bore channel with air-water mixture; and

B4: blheat4.inp - for rotor disk internally cooled with intermittently renewed air-water mixture.

In addition one can have additional options from keyboard:

O1: water film/no water film outside the casing; and

O2: the state variables of the fluid (air or air-water mixture) in the compressor blade channel is affected/not affected due to heat transfer from hot metal components in the neighborhood of the blade channel fluid.

## 3 UTILIZATION OF WINCLR CODE

The WINCLR code consists of two parts: (i) related to the modified WINCOF-I code, and (ii) the thermal load and clearance calculation part. In order to illustrate the use of the code, a test case is provided consisting of a two-stage compressor with a row of IGV. It may be recalled that the original WINCOF-I code includes calculations of performance at the design point of the compressor under consideration and, also, the calculation scheme for the off-design performance at desired off-design conditions. When calculations of performance are desired at off-design conditions, they are done for each set of off-design conditions following calculation at the design point. This procedure is left unaltered in the modified WINCOF-I code.

In this section, the utilization of the WINCLR code is given with data preparation, and compilation, linking and running of the code. The utilization of the code may be for a compressor under consideration, or for establishing the operation of the code using the given test case.

The listing of input data files for the test case, consisting of 6 files for different options, is given in Appendix A through D to this report. The listing of output data files for the test case, consisting of 6 files for different options, is given in Appendix E to this report. Finally, the sample data for the thermal load and clearance part of the program are given in Appendix F to this report.

### 3.1 Test Case

The test case included to illustrate the use of the code is that of a 2-stage compressor with a row of IGV. The details of the compressor are the same as provided in Ref. 2.

It is assumed that the outside surface of the compressor casing remains dry even when considering air-water mixture flow through the compressor.

The input and output files for the test case are given below.

| Input files | Output files |
|---|---|
| A1 + B1 | case1.out+blheat1.out |
| A2 + B1 | case2.out+blheat2.out |
| A2 + B2 | case3.out+blheat3.out |

## 3.2. Data Preparation

For both WINCOF-I data and for thermal load and blade clearance data subroutines have been provided for interactive data input. For the latter the thermal model of a nodal element consists of a centroid mass node, for which one needs the product of the mass and the specific heat. The mass mode has heat paths to adjacent element nodes. In the present study one to four adjacent nodes have been used. In some cases, where, because of the geometry, there is no heat flux in a particular direction, one has to take a decision about placement of the centroid mass node. For example for flow within a cylindrical tube the dominant heat flow is in the radial direction, for which the heating surface is obtained from an arbitrarily considered axial length and azimuthal angle (unit axial length, unit radian of azimuthal angle), and the heat flux path length is half of the hollow cylinder (tube) thickness; the mass can be calculated from the volume, which, in turn, is obtained from the axial length, azimuthal angle and thickness. At the same time the external surface area of a blade or the rotor disk may be evaluated as the total external surface, but the centroid node can be placed at the center of gravity determined from the area distribution in the axial direction.

The casing is considered here as a cylinder of given thickness distribution. It is assumed to be subject to heat transfer relative to the fluids both on the inner and the outer surfaces.

In the case of blades, it is assumed that there is no internal cooling. The main concern is with the area exposed to the air-water mixture. This can be determined based on the blockage.

In the case of the rotor, cooling may often be arranged in repetitive sectors over the disk area. In other words, the cooling scheme for a rotor may be repetitive over a certain azimuthal angle. For example, there may be a single passage of fluid covering a sector of 5 blades. Care is then required in determining the centroid node in the rotor.

For the case of the 2-stage compressor considered as the example case, the relevant heat capacity, interface surface area, and heat flux specific path length have been compiled and are given in Tables 2.1 to 2.4 for case (i), that is rotor without internal cooling, and Tables 3.1 to 3.3 for cases (ii), (iii) and (iv), except in case (iv) with replenishment of coolant fluid (or, equivalently, intermittent supply of new coolant fluid); for the latter case the data are given in Tables 4.1 to 4.3.

Table 2.1

Example of a Nodal Topology Matrix

for a two-stage compressor without internal cooling of the rotor

| Stage No. | Element No. | Element Type | No. of adj. nodes | Adjacent Node Nos. |
|---|---|---|---|---|
| IGV | 1 | 2 | 4 | -75,6,-72,-76 |
| | 2 | 12 | 4 | -75,3,-73/-74,-72 |
| | 3 | 14 | 4 | 2,9,-73/-74,4 |
| | 4 | 6 | 2 | 3,-72 |
| 1 | 5 | 6 | 2 | 6,-71 |
| | 6 | 11 | 4 | 1,8,5,7 |
| | 7 | 15 | 2 | 6,-76 |
| | 8 | 2 | 4 | 6,13,-72,-76 |
| | 9 | 12 | 4 | 3,10,-73/-74,-71 |
| | 10 | 14 | 4 | 9,16,-73/-74,11 |
| | 11 | 6 | 3 | 10,-72 |
| 2 | 12 | 6 | 2 | 13,-71 |
| | 13 | 11 | 4 | 8,15,12,14 |
| | 14 | 15 | 2 | 13,-76 |
| | 15 | 2 | 4 | 12,-75,-72,-76 |
| | 16 | 12 | 4 | 10,17,-73/-74,-71 |
| | 17 | 14 | 4 | 16,19,-73/-74,18 |
| | 18 | 6 | 2 | 17,-72 |
| Post | 19 | 12 | 4 | 17,-75,-73/-74,-72 |

Meaning of negative nodes:

-71: external flow past rotor blades

-72: external flow past stator blades.

-73: flow outside casing.

-74: effective heat transfer coefficient very large (for example, $10^8$).

-75: gradient = 0 (effective heat transfer coefficient = 0).

-76: flow external to the rotor disk.

Table 2.2
Example of a Nodal Topology Matrix for a two-stage compressor
with internal cooling of the rotor by dry air or air-water mixture

| Stage No. | Element No. | Element Type | No. of adj. nodes | Adjacent Node Nos. |
|---|---|---|---|---|
| IGV | 1 | 2 | 4 | -75,6,-72,-76 |
| | 2 | 12 | 4 | -75,3,-73/-74,-72 |
| | 3 | 14 | 4 | 2,9,-73/-74,4 |
| | 4 | 6 | 2 | 3,-72 |
| 1 | 5 | 6 | 2 | 6,-71 |
| | 6 | 11 | 4 | 1,8,5,7 |
| | 7 | 16 | 3 | 6,-76,-77 |
| | 8 | 2 | 4 | 6,13,-72,-76 |
| | 9 | 12 | 4 | 3,10,-73/-74,-71 |
| | 10 | 14 | 4 | 9,16,-73/-74,11 |
| | 11 | 6 | 2 | 10,-72 |
| 2 | 12 | 6 | 2 | 13,-71 |
| | 13 | 11 | 4 | 8,15,12,14 |
| | 14 | 16 | 3 | 13,-76,-77 |
| | 15 | 2 | 4 | 12,-75,-72,-76 |
| | 16 | 12 | 4 | 10,17,-73/-74,-71 |
| | 17 | 14 | 4 | 16,19,-73/-74,18 |
| | 18 | 6 | 2 | 17,-72 |
| Post | 19 | 12 | 4 | 17,-75,-73/-74,-72 |

Meaning of negative nodes:

-71: external flow past rotor blades

-72: external flow past stator blades.

-73: flow outside casing.

-74: effective heat transfer coefficient very large (for example, $10^8$).

-75: gradient = 0 (effective heat transfer coefficient = 0).

-76: flow external to the rotor disk.

Table 2.3

Example of a Nodal Topology Matrix for a two-stage compressor with internal cooling of the rotor by intermittent stagnant air-water mixture.

| Stage No. | Element No. | Element Type | No. of adj. nodes | Adjacent Node Nos. |
|---|---|---|---|---|
| IGV | 1 | 2 | 4 | -75,6,-72,-76 |
| | 2 | 12 | 4 | -75,3,-73/-74,-72 |
| | 3 | 14 | 4 | 2,9,-73/-74,4 |
| | 4 | 6 | 2 | 3,-72 |
| 1 | 5 | 6 | 2 | 6,-71 |
| | 6 | 11 | 4 | 1,8,5,7 |
| | 7 | 17 | 3 | 6,-76,-77(12) |
| | 8 | 2 | 4 | 6,14,-72,-76 |
| | 9 | 12 | 4 | 3,10,-73/-74,-71 |
| | 10 | 14 | 4 | 9,17,-73/-74,11 |
| | 11 | 6 | 2 | 10,-72 |
| | 12 | 8 | 1 | -77(7) |
| 2 | 13 | 6 | 2 | 14,-71 |
| | 14 | 11 | 4 | 8,16,13,15 |
| | 15 | 17 | 2 | 14,-76,-77(20) |
| | 16 | 2 | 4 | 14,-75,-72,-76 |
| | 17 | 12 | 4 | 10,18,-73/-74,-71 |
| | 18 | 14 | 4 | 17,21,-73/-74,19 |
| | 19 | 6 | 2 | 18,-72 |
| | 20 | 8 | 1 | -77(15) |
| Post | 21 | 12 | 4 | 17,-75,-73/-74,-72 |

<u>Meaning of negative nodes:</u>

-71: external flow past rotor blades

-72: external flow past stator blades.

-73: flow outside casing.

-74: effective heat transfer coefficient very large (for example, $10^8$).

-75: gradient = 0 (effective heat transfer coefficient = 0).

-76: flow external to the rotor disk.

-77: internal cooling of rotor disk.

Table 3.1

Heat capacity and interface surface area

| Stage No. | Elem. No. | No. of adj. nodes | $M_i$ [kg] | $M_i c_i$ [J/K] | $S^{ij}$ $\left[m^2\right]$ |
|---|---|---|---|---|---|
| IGV | 1 | 4 | 0.5249 | 241.45 | 9.252e-4,9.252e-4,2.786e-3,2.4663-3 |
| | 2 | 4 | 0.1802 | 162.19 | 2.628e-3,2.628e-3,1.402e-3,1.226e-3 |
| | 3 | 4 | 0.2272 | 204.53 | 2.628e-3,2.628e-3,1.768e-3,1.546e-3 |
| | 4 | 2 | 0.0264 | 13.70 | 1.546e-3,1.035e-2 |
| 1 | 5 | 2 | 0.0658 | 34.17 | 1.352e-3,2.119e-2 |
| | 6 | 4 | 0.2510 | 115.40 | 9.252e-4,9.252e-4,1.352e-3,1.158e-3 |
| | 7 | 2 | 0.2596 | 119.43 | 1.158e-3,3.129e-3 |
| | 8 | 4 | 0.6091 | 280.21 | 9.252e-4,1.182e-3,3.047e-3,2.632e-3 |
| | 9 | 4 | 0.6500 | 585.08 | 2.628e-3,3.461e-3,4.939e-3,4.327e-3 |
| | 10 | 4 | 0.3940 | 354.65 | 5.346e-3,5.346e-3,3.060e-3,2.686e-2 |
| | 11 | 2 | 0.0566 | 29.36 | 2.686e-3,1.1751e-2 |
| 2 | 12 | 2 | 0.0732 | 37.99 | 2.607e-3,2.098e-2 |
| | 13 | 4 | 0.4870 | 224.07 | 1.182e-3,1.182e-3,2.607e-3,2.266e-3 |
| | 14 | 2 | 0.5260 | 241.96 | 2.266e-3,5.118e-3 |
| | 15 | 4 | 0.7770 | 357.65 | 1.182e-3,1.182e-3,4.145e-2,3.632e-3 |
| | 16 | 4 | 0.8431 | 758.84 | 3.461e-3,3.064e-3,6.545e-3,5.739e-3 |
| | 17 | 4 | 0.3003 | 270.30 | 3.064e-3,3.064e-3,2.334e-3,2.045e-3 |
| | 18 | 2 | 0.0383 | 19.88 | 2.045e-3,1.339e-2 |
| Post | 19 | 4 | 0.2100 | 189.15 | 3.064e-3,3.064e-3,1.634e-3,1.431e-3 |

Table 3.2

Heat capacity and interface surface area for rotor disk with internal cooling by air or air-water mixture flow

| Stage No. | Elem. No. | No. of adj. nodes | $M_i$ [kg] | $M_i c_i$ [J/K] | $S^{ij}$ $\left[m^2\right]$ |
|---|---|---|---|---|---|
| IGV | 1 | 4 | 0.5249 | 241.45 | 9.252e-4,9.252e-4,2.786e-3,2.4663-3 |
| | 2 | 4 | 0.1802 | 162.19 | 2.628e-3,2.628e-3,1.402e-3,1.226e-3 |
| | 3 | 4 | 0.2272 | 204.53 | 2.628e-3,2.628e-3,1.768e-3,1.546e-3 |
| | 4 | 2 | 0.0264 | 13.70 | 1.546e-3,1.035e-2 |
| 1 | 5 | 2 | 0.0658 | 34.17 | 1.352e-3,2.119e-2 |
| | 6 | 4 | 0.2510 | 115.40 | 9.252e-4,9.252e-4,1.352e-3,1.158e-3 |
| | 7 | 3 | 1.4260 | 655.91 | 6.946e-3,1877e-2,1.340e-3 |
| | 8 | 4 | 0.6091 | 280.21 | 9.252e-4,1.182e-3,3.047e-3,2.632e-3 |
| | 9 | 4 | 0.6500 | 585.08 | 2.628e-3,3.461e-3,4.939e-3,4.327e-3 |
| | 10 | 4 | 0.3940 | 354.65 | 5.346e-3,5.346e-3,3.060e-3,2.686e-2 |
| | 11 | 2 | 0.0566 | 29.36 | 2.686e-3,1.1751e-2 |
| 2 | 12 | 2 | 0.0732 | 37.99 | 2.607e-3,2.098e-2 |
| | 13 | 4 | 0.4870 | 224.07 | 1.182e-3,1.182e-3,2.607e-3,2.266e-3 |
| | 14 | 3 | 2.6030 | 1197.5 | 1.180e-3,2.661e-2,1.340e-3 |
| | 15 | 4 | 0.7770 | 357.65 | 1.182e-3,1.182e-3,4.145e-2,3.632e-3 |
| | 16 | 4 | 0.8431 | 758.84 | 3.461e-3,3.064e-3,6.545e-3,5.739e-3 |
| | 17 | 4 | 0.3003 | 270.30 | 3.064e-3,3.064e-3,2.334e-3,2.045e-3 |
| | 18 | 2 | 0.0383 | 19.88 | 2.045e-3,1.339e-2 |
| Post | 19 | 4 | 0.2100 | 189.15 | 3.064e-3,3.064e-3,1.634e-3,1.431e-3 |

Table 3.3

Heat capacity and interface surface area for rotor disk with internal cooling by intermittently stagnant air-water mixture

| Stage No. | Elem. No. | No. of adj. nodes | $M_i$ [kg] | $M_i c_i$ [J/K] | $S^{ij}$ $\left[m^2\right]$ |
|---|---|---|---|---|---|
| IGV | 1 | 4 | 0.5249 | 241.45 | 9.252e-4,9.252e-4,2.786e-3,2.4663-3 |
| | 2 | 4 | 0.1802 | 162.19 | 2.628e-3,2.628e-3,1.402e-3,1.226e-3 |
| | 3 | 4 | 0.2272 | 204.53 | 2.628e-3,2.628e-3,1.768e-3,1.546e-3 |
| | 4 | 2 | 0.0264 | 13.70 | 1.546e-3,1.035e-2 |
| 1 | 5 | 2 | 0.0658 | 34.17 | 1.352e-3,2.119e-2 |
| | 6 | 4 | 0.2510 | 115.40 | 9.252e-4,9.252e-4,1.352e-3,1.158e-3 |
| | 7 | 2 | 1.4260 | 655.9 | 6.946e-3,1.877e-2,1.340e-3 |
| | 8 | 4 | 0.6091 | 280.21 | 9.252e-4,1.182e-3,3.047e-3,2.632e-3 |
| | 9 | 4 | 0.6500 | 585.08 | 2.628e-3,3.461e-3,4.939e-3,4.327e-3 |
| | 10 | 4 | 0.3940 | 354.65 | 5.346e-3,5.346e-3,3.060e-3,2.686e-2 |
| | 11 | 2 | 0.0566 | 29.36 | 2.686e-3,1.1751e-2 |
| | 12 | 1 | 0.0000 | 00.00 | 1.340e-3 |
| 2 | 13 | 2 | 0.0732 | 37.99 | 2.607e-3,2.098e-3 |
| | 14 | 4 | 0.4870 | 224.07 | 1.182e-3,1.182e-3,2.607e-3,2.266e-3 |
| | 15 | 3 | 0.52.60 | 241.96 | 1.180e-3,2.661e-2,1.340e-3 |
| | 16 | 4 | 0.7770 | 357.65 | 1.182e-3,1.182e-3,4.145e-2,3.632e-3 |
| | 17 | 4 | 0.8431 | 758.84 | 3.461e-3,3.064e-3,6.545e-3,5.739e-3 |
| | 18 | 4 | 0.3003 | 270.30 | 3.064e-3,3.064e-3,2.334e-3,2.045e-3 |
| | 19 | 2 | 0.0383 | 19.88 | 2.045e-3,1.339e-2 |
| | 20 | 1 | 0.0000 | 00.00 | 1.340e-3 |
| Post | 21 | 4 | 0.2100 | 189.15 | 3.064e-3,3.064e-3,1.634e-3,1431e-3 |

## 3.3. Compilation, Linking, and Running of the Code

As the code is written in FORTRAN-77, compilation and linking can be done with the help of any suitable Fortran-77 compiler, and the executable file operated. The typical sequential steps in running the code are as follows, noting that the code may be in use for examining the test case, or for establishing the casing clearance for a given compressor:

Step 1: The computer writes the following messages:

WINCOF program
updated data input and compressor clearance
Input data to be generated?

If a response is made with "Y" or "y" and <CR> is pressed, the code performs in the interactive data mode. A file name is requested where all of the data are to be stored, as well as the relevant data to be entered. Step 2 is then skipped and one can proceed to step 3. When, however, it is intended to use a data set stored earlier or the data set for the test case, it is sufficient to press <CR>, and proceed to the next step.

Step 2: The computer writes the following:

WINCOF-I Input data file:

One may then write the name of the data file generated earlier, or one of the data files such as "case1, inp", "case2, inp", or "case2b, inp", and press <CR>. The computer then writes

Output data file:

The output data file name is entered, and on pressing <CR>, the WINCOF-I part of the code is exercised.

Step 3: The computer then writes the following:

total number of sweeps:

Table 4.1

Specific length of the elements for rotor disk without internal cooling

| Stage No. | Elem. No. | No. of adj. nodes | $l_S$ $\left[m^2K/W\right]$ |
|---|---|---|---|
| IGV | 1 | 4 | 4.780e-4,7.691e-4,2.771e-4,2.771e-4 |
| | 2 | 4 | 1.246e-4,2.817e-4,2.493e-4,2.493e-4 |
| | 3 | 4 | 2.817e-4,5.430e-4,2.493e-4.3.538e-3 |
| | 4 | 2 | 3.538e-3,5.654e-4 |
| 1 | 5 | 2 | 5.052e-3,6.890e-5 |
| | 6 | 4 | 7.691e-4,8.263e-4,5.052e-3,2.771e-4 |
| | 7 | 2 | 5.053e-4,1.940e-4 |
| | 8 | 4 | 8.263e-4,9.038e-4,2.771e-4,2.771e-4 |
| | 9 | 4 | 5.430e-4,5.726e-4,2.493e-4,2.493e-4 |
| | 10 | 4 | 5.926e-4,6.176e-4,2.493e-4,4.707e-3 |
| | 11 | 2 | 4.707e-3,7.163e-5 |
| 1 | 12 | 2 | 4.468e-3,7.734e-5 |
| | 13 | 3 | 9.038e-4,9.227e-4,4.468e-3,2.771e-4 |
| | 14 | 2 | 5.053e-4,2.458e-4 |
| | 15 | 4 | 9.227e-4,5.541e-4,2.771e-4,2.771e-4 |
| | 16 | 4 | 6.176e-4,6.489e-4,2.493e-4,2.493e-4 |
| | 17 | 4 | 6.489e-4,3.026e-4,2.493e-4,4.072e-3 |
| | 18 | 2 | 4.072e-3,6.344e-5 |
| Post | 19 | 4 | 3.026e-4,1.246e-4,2.493e-4,2.493e-4 |

Table 4.2
Specific length of the elements for rotor disk
with internal cooling by air or air-water mixture

| Stage No. | Elem. No. | No. of adj. nodes | $l_S$ $[m^2K/W]$ |
|---|---|---|---|
| IGV | 1 | 4 | 4.780e-4,7.691e-4,2.771e-4,2.771e-4 |
| | 2 | 4 | 1.246e-4,2.817e-4,2.493e-4,2.493e-4 |
| | 3 | 4 | 2.817e-4,5.430e-4,2.493e-4.3.538e-3 |
| | 4 | 2 | 3.538e-3,5.654e-4 |
| 1 | 5 | 2 | 5.052e-3,6.890e-5 |
| | 6 | 4 | 7.691e-4,8.263e-4,5.052e-3,2.771e-4 |
| | 7 | 3 | 5.053e-4,1.940e-4,6.541e-5 |
| | 8 | 4 | 8.263e-4,9.038e-4,2.771e-4,2.771e-4 |
| | 9 | 4 | 5.430e-4,5.726e-4,2.493e-4,2.493e-4 |
| | 10 | 4 | 5.926e-4,6.176e-4,2.493e-4,4.707e-3 |
| | 11 | 2 | 4.707e-3,7.163e-5 |
| 2 | 12 | 2 | 4.468e-3,7.734e-5 |
| | 13 | 4 | 9.038e-4,9.227e-4,4.468e-3,2.771e-4 |
| | 14 | 3 | 5.053e-4,2.458e-4,7.555e-5 |
| | 15 | 4 | 9.227e-4,5.541e-4,2.771e-4,2.771e-4 |
| | 16 | 4 | 6.176e-4,6.489e-4,2.493e-4,2.493e-4 |
| | 17 | 4 | 6.489e-4,3.026e-4,2.493e-4,4.072e-3 |
| | 18 | 2 | 4.072e-3,6.344e-5 |
| Post | 19 | 4 | 3.026e-4,1.246e-4,2.493e-4,2.493e-4 |

Table 4.3

Specific length of the elements for rotor disk

with internal cooling by intermittently stagnant air-water mixture

| Stage No. | Elem. No. | No. of adj. nodes | $l_S$ $[m^2K/W]$ |
|---|---|---|---|
| IGV | 1 | 4 | 4.780e-4,7.691e-4,2.771e-4,2.771e-4 |
| | 2 | | 1.246e-4,2.817e-4,2.493e-4,2.493e-4 |
| | 3 | | 2.817e-4,5.430e-4,2.493e-4.3.538e-3 |
| | 4 | | 3.538e-3,5.654e-4 |
| 1 | 5 | | 5.052e-3,6.890e-5 |
| | 6 | | 7.691e-4,8.263e-4,5.052e-3,2.771e-4 |
| | 7 | | 5.053e-4,1.940e-4,6.541e-5 |
| | 8 | | 8.263e-4,9.038e-4,2.771e-4,2.771e-4 |
| | 9 | | 5.430e-4,5.726e-4,2.493e-4,2.493e-4 |
| | 10 | | 5.926e-4,6.176e-4,2.493e-4,4.707e-3 |
| | 11 | | 4.707e-3,7.163e-5 |
| | 12 | | 6.541e-5 |
| 2 | 13 | | 4.468e-3,7.734e-5 |
| | 14 | | 9.038e-4,9.227e-4,4.468e-3,2.771e-4 |
| | 15 | | 5.053e-4,2.458e-4,7.555e-5 |
| | 16 | | 9.227e-4,5.541e-4,2.771e-4,2.771e-4 |
| | 17 | | 6.176e-4,6.489e-4,2.493e-4,2.493e-4 |
| | 18 | | 6.489e-4,3.026e-4,2.493e-4,4.072e-3 |
| | 19 | | 4.072e-3,6.344e-5 |
| | 20 | 1 | 7.555e-5 |
| Post | 21 | 4 | 3.026e-4,1.246e-4,2.493e-4,2.493e-4 |

The number of sweeps desired is entered, noting that the minimum is one sweep. On pressing <CR>, the computer writes the following:

thermal node distribution?

When it is intended to bypass it, one needs to press <CR>, and then, the WINCOF-I part of the code alone is exercised, and calculations proceed till the execution is completed. When it is desired to exercise the thermal load and clearance part of the code, one may write "Y" or "y", and press <CR> to proceed to the next step.

Step 4: The computer then writes the following:

metal temp.calculations done after every no. of sweeps=

The desired number of sweeps is entered and <CR> pressed.

A sweep here is the same as the sweep in the original WINCOF-I code, namely the calculation of aerodynamic performance of the compressor over the entire compressor, for example from entry to the compressor to the exit of the last stage of a multi-stage compressor.

When it is desired to account for heat transfer to the metal structure of the compressor, the code performs as follows for a chosen number of sweeps:

(i) The performance of the compressor is determined in the first sweep. The performance of each stage of the compressor is stored.

(ii) Heat transfer to the metal structure is determined, over a chosen period of time such as, for example, 0.15 to 0.25, with reference to the temperature of the working fluid as determined in (i) and a value of temperature for the metal structure. Regarding the latter, the metal temperature may be assumed, in the first instance, as the given ambient conditions.

(iii) Entering an inner loop in a sweep, the metal temperature is updated in a series of iterations, each time assuming the working fluid parameters to remain unaltered at the values stored for each stage and accounting for the modified heat transfer. At the end of a certain number of iterations, such as 30 to 50 over a period of time equal to [(0.1 to 0.2) s X (30 to 50)], it can be expected that an equilibrium is reached between the working fluid and the metal structure, and the temperature of the metal does not undergo appreciable changes.

(iv) Then, the performance of the compressor is determined accounting in each stage of the compressor for heat transfer to the metal. The updated data on performance is stored for each stage.

(v) The calculations in step (iii) are repeated, and using the heat transfer data so determined, the performance calculation of (iv) is repeated. The changes in the performance of the compressor may generally be small in such an iteration, and thus it may not be necessary to repeat the calculations over more than 2 to 5 sets of sweeps.

The computer writes, at the end of this calculation, as follows:

This subroutine helps for use in nodal temperature and clearance package

1. to generate data, and
2. to retrieve data for calculation.

- choice:

Writing 1 and pressing <CR> leads to step 5, and writing 2 and pressing <CR> to step 6.

<u>Step 5:</u> The computer now writes as follows:

generated data to be stored in file:

Giving the file name and pressing <CR> leads the code to ask for data in the interactive mode, and then one can proceed to step 7.

<u>Step 6:</u> The computer writes as follows:

data retrieved from file:

The name of the data file for temperature distribution and blade clearance may be given, or one may write the name of one of the data files such as "blheat1.inp" supplied.

Step 7: The computer writes as follows:

Type in the following data:
casing air density(kg/m**3);
casing air temp.(K);
airspeed outside casing(m/s);
stagn.temp. of air outside casing(K);
airflow temp.inside rotor(K);
airflow density inside rotor(K);
airflow speed inside rotor(m/s);
delta_temp.(K) needed to compute Grashof number in rotor disk(20); and
water film surface temp.relax.factor(0. to 1.)

The desired data is typed in and <CR> pressed.

The computer then asks as follows:

water film outside casing?

If <CR> is pressed, the code proceeds further till execution is completed. If "Y" or "y" and <CR> are pressed, the temperature of the film outside the casing is requested. When the temperature is given and <CR> pressed, the code proceeds to completion of execution.

## 4. DISCUSSION

The WINCLR includes two major parts: (i) the modified WINCOF-I code for obtaining the performance of a multi-stage compressor, taking into account heat transfer to the metal structure, and (ii) the thermal load and clearance part.

The WINCLR code can be utilized to determine the performance and the blade clearance in two major options: (i) adiabatic, with no heat exchange between the working fluid and the metal structure of a compressor, and (ii) non-adiabatic, allowing for such heat exchange.

In option (ii), there are several internal options depending upon the manner in which the casing wall and the rotor are required to be taken into account. For the casing wall, the outer surface may be assumed to be covered with air or air-water mixture when the compressor is ingesting an air-water mixture. For the rotor, the rotor build-up and cooling scheme provide various options.

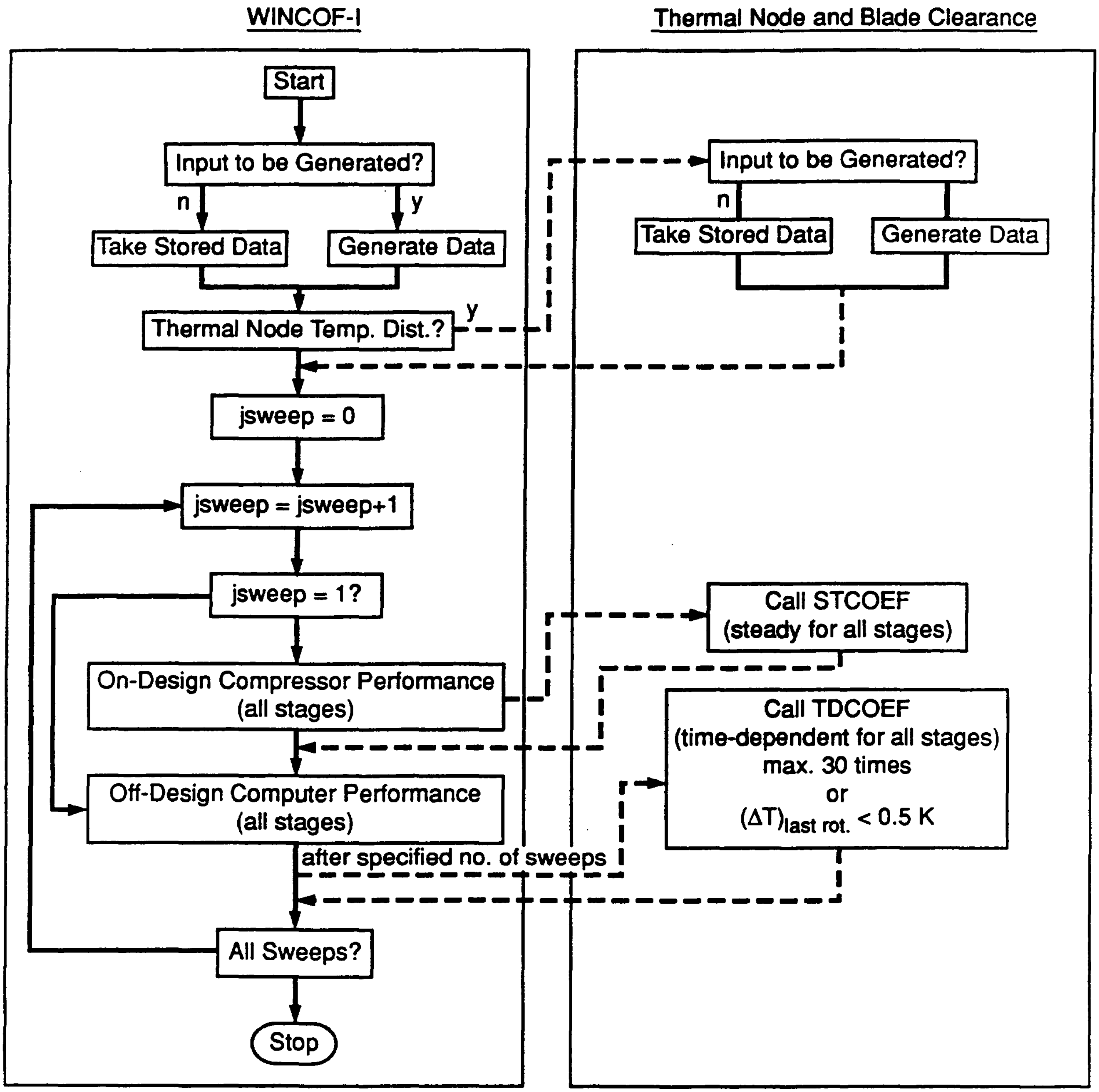
Accounting for heat transfer, as in the non-adiabatic case, it is important to recognize that changes occur both in compressor performance and in clearance. It is shown in Refs. 1 and 3 that, in the case of a multi-stage compressor with a large number of sages, changes in performance are the most dominant in the initial stages, and changes in clearance occur, generally tending to cause rubbing in the later stages.

## REFERENCES


1. Bose, T.K., and Murthy, S.N.B., WINCLR: A Computer Code for Heat Transfer and Clearance Calculation in a Compressor: A Detailed Description, Report to be published by NASA Lewis Research Center, 1994.

2. Murthy, S.N.B., and Mullican, A., The WINCOF-I Code: Detailed Description, NASA Contractor Report NASA CR 190779, April 1993.

3. Bose, T.K., and Murthy, S.N.B., Blade Clearance Estimation in a Generic Compressor with Air-Water Mixture Operation, AIAA Paper No. 94-2693, June, 1994.




≡ Alternate Path if Thermal Node and Blade Clearance Programmes are Required.

Figure 1. Structure of WINCLR Code.

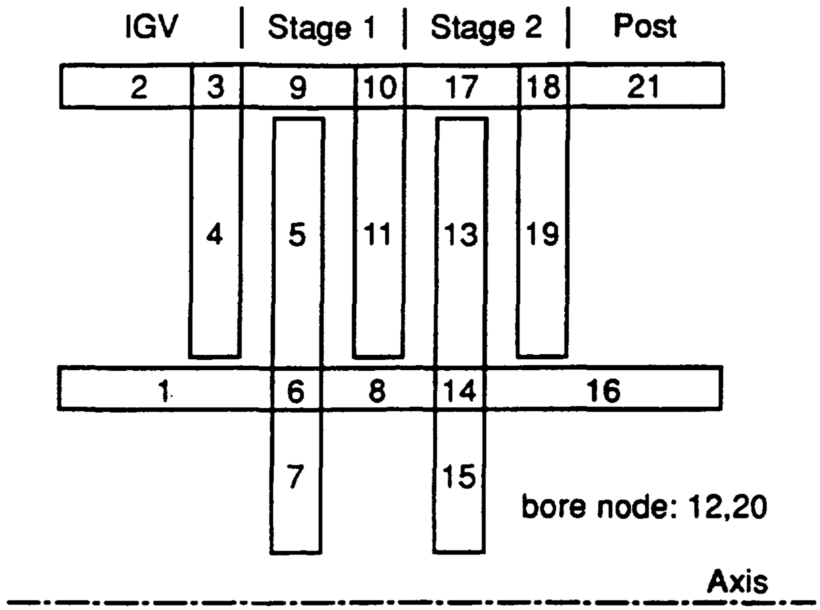



Figure 2. Schematic sketch of a two-stage compressor with rotor disk internal node.

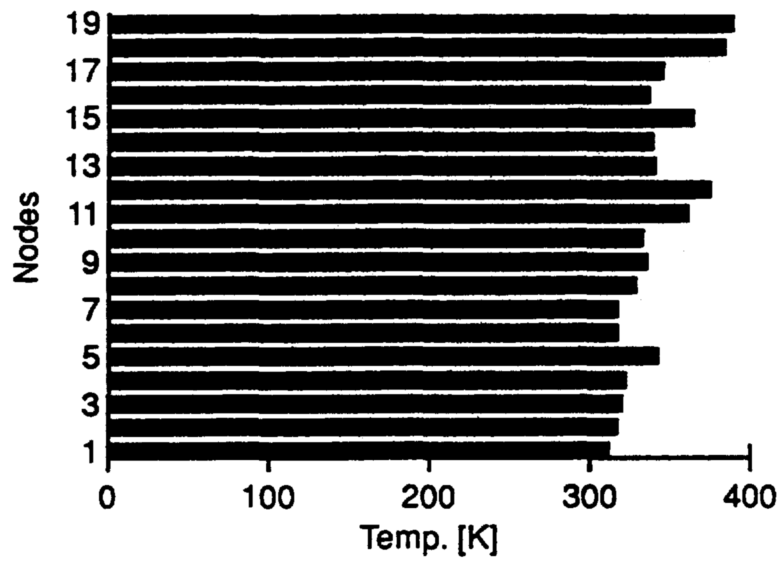



Figure 3. Temperature distribution of various nodes.

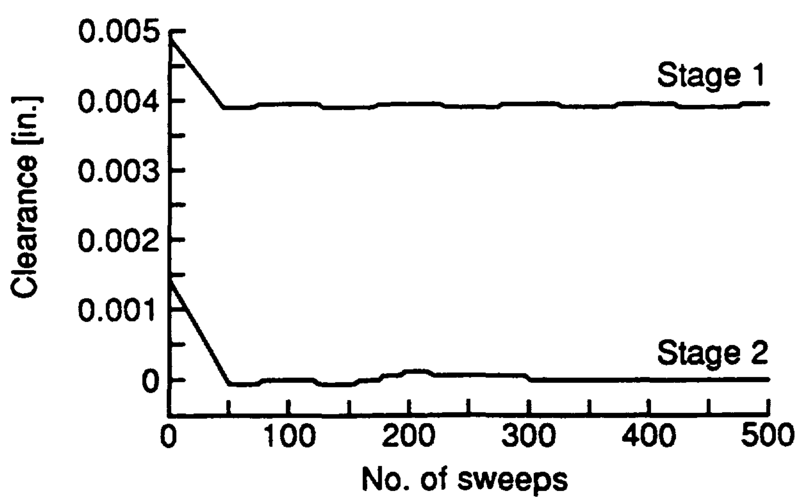



Figure 4. Change in rotor blade clearance due to water ingestion.

## Appendix A: List of Subroutines

This list contains the following: names of subroutines and functions of original WINCOF-I; two subroutines to help data-input in interactive mode (designated with superscript $) for the original WINCOF-I; functions and subroutines for the nodal temperature and rotor blade clearnce calculations (designated with superscript #); and a description of what each of these functions and subroutines do.

wicinp$^{\$}$: data input for WINCOF-I in non-interactive mode
wicspb: stage performance (off-design) for small droplet
wcspbs: part of original wicspb, but only for stator calculations
prince: printing part of original wicspb
wicspc: stage performance (off-design) for large droplet
wicmac: part of original wicspc to compute for stator
wicasd: acoustic speed in two-phase flow
wiced: calculation of equivalent diffusion
wicmtk: calculation of dimensionless momentum thickness
wiclos: total pressure loss coefficient
wicirs: small droplet impingement and rebound in rotor blades
wicirl: large droplet impingement and rebound in rotor blades
wiciss: small droplet impingement and rebound in stator blades
wicisl: large droplet impingement and rebound in stator blades
wicwak: water ingestion into wake of blades
wichet: heat transfer between gaseous phase and droplets
wicmas: mass transfer between gaseous phase and droplets
wicmtr: calculation of mass transfer rate
wicpwb: calculation of vapor pressure
wicnew: to seek new trial value in an iterative procedure
wicbpt: calculation of boiling point
wicsh: calculation of specific humidity
wictan: tangent function
wiccen: spanwise replacement of droplets due to centrifugal action
wicrgv: quantity of vapor centrifuged
wicdmv: compute area that vapor occupies (used by "wicdml" called by "wicrgv")
wicdms: (not called by any routine at present)
wicdml: quantity of large droplets centrifuged (called by "wicrgn")
wicflm: (not called by any routine at present)
wicrgn: water distribution routine
wicdrg: drag force on droplet
wicsiz: calculation of droplet size (by considering "Stability number")
wicprp: flow properties for gaseous phase
wiccpa: specific heat of air at constant pressure
wiccph: specific heat of vapor at constant pressure
wiccpc: specific heat of methane at constant pressure
wicgsl: single phase (gas) flow loss
wicsdl: loss due to small droplets to change boundary layer momentum thickness
wicstl: loss due to Stokesian drag in free-stream
wicfml: loss due to film formed on blade surface when large droplets are present
wicrsl: loss due to surface roughness modelling of large droplets
wicspd: design point performance

pldatv: plotting routine (not being used at present)
wicbet: applies normal stator setting to IGV
wicvap: to get correct droplet temperature at very high evaporation rate
msec: help routine to compute gemax by secant method
fpm: auxilliary function for msec
fppm: (not called by any routine)
wicrng: creates a range of flow coefficients
getnm: gets upto 19 strings of 4 characters till "do"
plotit: does scaling, etc. for the plotter (not being used at present)
phimx: maximum value of flow coefficient, depending on rpm fraction
datinp$: data input for WINCOF-I in interactive mode
htdgen#: data creation/input interactively for node temperature and blade clearance
htexin#: data input non-interactively for node temperature and blade clearance
therex#: blade clearance thermal expansion function
spear#: to extract/add/remove/replace in a sparse matrix
spcrp#: sparse matrix counting and row parameters
spmsol#: general sparse matrix solution
stcoef#: steady state influence cefficients calculation
tdcoef#: time-dependent case to calculate influence coefficients
mixprp#: properties of air+vapor+water (homogeneous mix.)

## APPENDIX B: Detailed Description of Subroutines and External Functions

In the following a description is provided of the subroutines and external function generated in connection with the nodal temperature distribution and blade clearance. Each of the subroutines and external functions is presented as follows: (1) Description, (2) Input variables, (3) Output variables , and (4) Usage.

SUBROUTINE DATINP:
(1) Description: The subroutine allows data generation and output it to a file to store away in interactive manner, or if the data has already been generated in another occasion, then to recover it.
(2) and (3) Input and Output variables:

ns      number of stages (total)
nsf      number of stages (fan)
nslpc      number of stage (low pressure compressur)
nshpc      number of stage (high pressure compressor)
rrhub(i)   rotor inlet radius at hub for i-th stage in inch
rc(i)      rotor chord for i-th stage in inch
rblade(i)   number of rotor blade for i-th stage
stager(i)   rotor stager angle for i-th stage in degree
srhub(i)   stator inlet radius at hub for i-th stage in inch
sc(i)      stator chord for i-th stage in inch
sblade(i)   number of stator blade for i-th stage
stages(i)   stator stager angle for i-th stage in degree (i=ns+1 for igv)
sigumr(i)   solidity of rotor for i-th stage
sigums(i)   solidity of stator for i-th stage
bet2ss(i)   stator outlet absolute flow angle at design point for i-th stage in degree
fnf      fraction of design corrected rotor speed for a particular speed
xdin      initial water content (mass fraction) of small droplet
xddin      initial water content (mass fraction) of darge droplet
icent      index for centrifugal calculation (icent=1 when xdin=0 otherwise icent=2)
iicent      same as icent
        icent=3,iicent=3: no heat and mass transfer
        icent=4,iicent=4: no centrifugal action
        icent=5,iicent=5: no heat and mass transfer;and no centrifugal action
        icent=6,iicent=6: no mass transfer
        icent=7,iicent=7: no mass transfer;and no centrifugal action
icentv      index for centrifugal action of vapor
        icentv=0: vapor is centrifuged
        icentv=1: vapor is not centrifuged
t0g      total temperature at compressr inlet in rankin
t0w      water droplet temperature at compressor inlet in rankin
p0      total pressure at compressor inlet in lb/ft**2
din      initial water droplet diameter in micron(small drollet)
ddin      initial water droplet diameter in micron(large droplet)
fnd      rotor rotational speed at design speed in rpm

(fan and low pressure compressor )
fndlpc rotor rotational speed at design speed in rpm
( low pressure compressor )
fndhpc rotor rotational speed at design speed in rpm
( high pressure compressor )
t01d design value for compressor inlet total temperature
p01d design value for compressor inlet total pressure
xch4 initial methane content
rhumid initial relative humidity
fmwa molecular weight of air (28.964)
fmwv molecular weight of water vapor (18.016)
fmwc molecular weight of methane (16.043)
preb percent of water that rebound after impingement
dlimit max. diameter for small droplet
gapr(i) gap between i th stage rotor and i-1 th stage stator
gaps(i) gap between i th stage stator and i-1 th stage rotor
rrtip(i) rotor inlet tip radius for i-th stage
srtip(i) stator inlet tip radius for i-th stage
irad index for radius at which calculation is carried out
irad=1: tip
irad=2: mean
irad=3: hub
irad=4: mean for fan and tip for lpc,hpc
rt(i) rotor inlet radius at which tip performance calculation
is carried out.
rm(i) rotor inlet radius at which mean line performance
calculation is carried out.
rh(i) rotor inlet radius at which hub performance calculation
is carried out.
st(i) stator inlet radius at which tip performance calculation
is carried out
sm(i) stator inlet radius at which mean line performance calcu-
lation is carried out
sh(i) stator inlet radius at which hub peformance calculation is
carried out
block(i) blockage factor for i-th stage rotor
blocks(i) blockage factor for i-th stage stator
idesin index for output
idesin=1:both stage and overall performance may be printed out
idesin=2:only overall performance may be printed out
jcent index for centrifugal calculation of large droplet
jcent=0:large droplets in rotor free streamm are not
centrifuged
jcent=1:large droplets in rotor free-stream are centrifuged
bet1mr(i) blade metal angle at rotor inlet for i-th stage
bet2mr(i) blade metal angle at rotor outlet for i-th stage
bet1ms(i) blade metal angle at stator inlet for i-th stage
bet2ms(i) blade metal angle at stator outlet for i-th stage
dsmass design mass flow rate for fan part (streamtube)
bypass bypass ratio
pr12d(i) design total pressure ratio for i-th stage rotor

pr13d(i) design total pressure ratio for i-th stage
etard(i) design adiabatic efficiency for i-th stage rotor
sarea(i) flow area at i-th stage rotor inlet (streamtube)
sareas(i) flow area at i-th stage stator inlet (streamtube)

(4) Usage: CALL DATINP

SUBROUTINE HTDGEN
(1) Description : it is the counterpart of the subroutine DATINP for the nodal tempertature distribution and blade clearance part.

(2) and (3) Input and Output Variables:
arnod surface area of a nodal element
casrad radius of the casing
dwat water film thickness inside rotor bore [m]
excfcs coeff. of expansion for casing
excfr thermal expansion coefficient for casing
htcap heat capacity of nodal element
ifan number of fan stages
imax number of stages
jmax maximum number of elements per stage
kmax maximum number of adjacent nodes per stage
ndmax array of number of nodes in each stage
ndtop nodal type and topology matrix
nexcas casing thermal expansion node number
nexnod thermal expansion node numbers in each stage
nexpr no.of nodes considered for thermal expansion in each stage
nrotcs index for rotor disk cooling
ntex no.of thermal expansion nodes in rotor stage
permax cooling channel pressure increase in percent of maximum
radex radial length to be considered for thermal expansion
splen heat flow path length divided by heat cond.coefficient
tpawm rotor disk bore fluid pressure [bar]
trchi rotor disk bore inside radius [in]
trcho rotor disk bore outside radius [in]
ttawm temperature of cooling fluid of rotor disk [K]
tvol rotor disk bore cooling fluid volume per sector [m3]
txw0 rotor disk bore cooling fluid water content
xlcso axial length of elements on casing
xlro axial length of nodal elements on rotor rim

(4)Usage: CALL HTDGEN

SUBROUTINE HTEXIN
(1) Description: Same as subroutine HTDGEN, except that it is for input of variables only.
(2) and (3):Input and Output variables: Same as in subroutine HTDGEN
(4)Usage: CALL HTEXIN

SUBROUTINE MIXPRP:
(1) Description: mixture properties of air+water+vapor (homogeneous fluid model)

(2) Input variables: tkin(oK)=temp.in degrees Kelvin,pbar = pressure in bar, xv = kg_vapor/kg_air,xw=kg_water/kg_air
(3) Output variables: cpm(J/kg-K)=spec.heat,rhom(kg/m**3)=density; xmum(kg/m-s)=dyn.viscosity,xkm(W/m-K)=heat conductivity.
(4) Usage: CALL MIXPRP (tkin,pbar,xv,xw,cpm,rhom,xmum,xkm,xkw)

SUBROUTINE SPCRP
(1) Description: Subroutine to find pointers for minimum, maximum and diagonal elements in a row.
(2) Input variables:
i index for row
n order of matrix
lmax maximum value of the location pointer
n order of matrix
nemax maximum locations in inl(nemax)
(3) Output variables:
l1 minimum pointer value (Ccolumn no.) in a row
l2 maximum pointer value (column no.) in a row
ld pointer value on the diagonal element in a row
ni no.of data in a row
(4) Usage:

```
    CALL SPCRP(i,n,lmax,nemax,inl,l1,l2,ld,ni)

    subroutine spmsol(n,lmax,nemax,inl,vl,rv,c)
c   subroutine for general sparse matrix solution
c   n=order of matrix, lmax=max.value of pointer, nemax=size
c   of two vectors inl(nemax) and vl(nemax), rv(n)=right
c   hand side vector,c=working place
```

SUBROUTINE SPMSOL:
(1) Description: Solver for sparse matrix solution
(2) Input variables:
inl vector of locations of coefficient array
lmax maximum value of locations of coefficient matrix
n order of the coefficient matrix
nemax maximum locations in inl(nemax),vl(nemax)
rv right hand side vector
vl coefficient matrix (destroyed in subroutine)
(3) Output variables:
rv solved vector
(4) Usage:

```
    CALL SPMSOL(n,lmax,nemax,inl,vl,rv,c)
```

SUBROUTINE SPEAR:
(1) Description: Subroutine to extract/add/remove/replace in a sparse matrix
(2) Input variables:
nemax max.length of inl(nemax),vl(nemax) arrays
i row index for matrix
iflag computation option flag (1-4) for extract/add/remove/replace
inl array of index of values
j column index for the matrix

lcur current pointer position
lmax maximum pointer position
n order of the matrix
vl array of values
x external value for manipulation in subroutine
(3) Output variables:
ier error code
lcur current pointer position
lmax maximum pointer position
vl array of values
x external value for manipulation in subroutine

(4) Usage:
CALL SPEAR(nemax,i,j,n,lcur,lmax,inl,x,vl,iflag,ier)

SUBROUTINE STCOEF:
(1) Description: Computing coefficients for steady solution of heat conduction.
(2) and (3) Input and Output variables:
They are the same as in HTDGEN through COMMON statement. On exit from the subroutine the results are in rrv().
(4) Usage: CALL STCOEF

SUBROUTINE TDCOEF:
(1) Description: Computing coefficients for unsteady solution of heat conduction.
(2) and (3) Input and Output variables:
They are the same as in HTDGEN through COMMON statement. At the time of entry to the subroutine the old temperature values are in rrv() and on exit from the subroutine the results are in rrv().
(4) Usage: CALL TDCOEF

FUNCTION THEREX:
(1) Description: function to calculate rotor-casing clearance in a stage.
(2) Input variable:
istage index for a stage
(3) Output variable:
therex output result
(4)Usage: THEREX(istage)

SUBROUTINE WICINP
(1) Description: Same as subroutine DATINP, except that it is for input of variables only.
(2) and (3):Input and Output variables: Same as in subroutine DATINP
(4)Usage: CALL WICINP

## APPENDIX C: Program Source Listing

The following source listing presents only the additions made to the WINCOF-I code to obtain the modified WINCOF-I code.

```
      subroutine wicinp
c input data
c ns        number of stages (total)
c nsf       number of stages (fan)
c nslpc     number of stage (low pressure compressur)
c nshpc     number of stage (high pressure compressor)
c rrhub(i)  rotor inlet radius at hub for i-th stage in inch
c rc(i)     rotor chord for i-th stage in inch
c rblade(i) number of rotor blade for i-th stage
c stager(i) rotor stager angle for i-th stage in degree
c srhub(i)  stator inlet radius at hub for i-th stage in inch
c sc(i)     stator chord for i-th stage in inch
c sblade(i) number of stator blade for i-th stage
c stages(i) stator stager angle for i-th stage in degree (i=ns+1 for igv)
c sigumr(i) solidity of rotor for i-th stage
c sigums(i) solidity of stator for i-th stage
c bet2ss(i) stator outlet absolute flow angle at design point for i-th
c           stage in degree
c fnf       fraction of design corrected rotor speed for a particular
c           speed
c xdin      initial water content (mass fraction) of small droplet
c xddin     initial water content (mass fraction)  of darge droplet
c icent     index for centrifugal calculation (icent=1 when xdin=0
c           otherwise icent=2)
c iicent    same as icent
c           icent=3,iicent=3: no heat and mass transfer
c           icent=4,iicent=4: no centrifugal action
c           icent=5,iicent=5: no heat and mass transfer;and
c                     no centrifugal action
c            icent=6,iicent=6: no mass transfer
c            icent=7,iicent=7: no mass transfer;and
c                     no centrifugal action
c icentv    index for centrifugal action of vapor
c           icentv=0: vapor is centrifuged
c           icentv=1: vapor is not centrifuged
c t0g       total temperature at compressr inlet in rankin
c t0w       water droplet temperature at compressor inlet in rankin
c p0        total pressure at compressor inlet in lb/ft**2
c din       initial water droplet diameter in micron(small drollet)
c ddin      initial water droplet diameter in micron(large droplet)
c fnd       rotor rotational speed at design speed in rpm
c           (fan and low pressure compressor )
c fndlpc    rotor rotational speed at design speed in rpm
c           ( low pressure compressor )
c fndhpc    rotor rotational speed at design speed in rpm
```

```
c           ( high pressure compressor )
c t01d      design value for compressor inlet total temperature
c p01d      design value for compressor inlet total pressure
c xch4      initial methane content
c rhumid    initial relative humidity
c fmwa      molecular weight of air (28.964)
c fmwv      molecular weight of water vapor (18.016)
c fmwc      molecular weight of methane (16.043)
c preb      percent of water that rebound after impingement
c dlimit    max. diameter for small droplet
c gapr(i)   gap between i th stage rotor and i-1 th stage stator
c gaps(i)   gap between i th stage stator and i-1 th stage rotor
c rrtip(i)  rotor inlet tip radius for i-th stage
c srtip(i)  stator inlet tip radius for i-th stage
c irad      index for radius at which calculation is carried out
c           irad=1: tip
c           irad=2: mean
c           irad=3: hub
c           irad=4: mean for fan and tip for lpc,hpc
c rt(i)     rotor inlet radius at which tip performance calculation
c           is carried out.
c rm(i)     rotor inlet radius at which mean line performance
c           calculation is carried out.
c rh(i)     rotor inlet radius at which hub performance calculation
c           is carried out.
c st(i)     stator inlet radius at which tip performance calculation
c           is carried out
c sm(i)     stator inlet radius at which mean line performance calcu-
c           lation is carried out
c sh(i)     stator inlet radius at which hub peformance calculation is
c           carried out
c block(i)  blockage factor for i-th stage rotor
c blocks(i) blockage factor for i-th stage stator
c idesin    index for output
c           idesin=1:both stage and overall performance may be printed out
c           idesin=2:only overall performance may be printed out
c jcent     index for centrifugal calculation of large droplet
c           jcent=0:large droplets in rotor free streamm are not
c               centrifuged
c           jcent=1:large droplets in rotor free-stream are centrifuged
c bet1mr(i) blade metal angle at rotor inlet for i-th stage
c bet2mr(i) blade metal angle at rotor outlet for i-th stage
c bet1ms(i) blade metal angle at stator inlet for i-th stage
c bet2ms(i) blade metal angle at stator outlet for i-th stage
c dsmass    design mass flow rate for fan part (streamtube)
c bypass    bypass ratio
c pr12d(i)  design total pressure ratio for i-th stage rotor
c pr13d(i)  design total pressure ratio for i-th stage
c etard(i)  design adiabatic efficiency for i-th stage rotor
c sarea(i)  flow area at i-th stage rotor inlet (streamtube)
c sareas(i) flow area at i-th stage stator inlet (streamtube)
```

```
c
c ---------------------------------------------------------------------
     character*60 title
c ---------------------------------------------------------------------
c--- pgb 11-21-84. added for doing 6 streamlines. top.
     common /cdat2/ rfc(20),sfc(20),bt2ssa(6,20),bt1mra(6,20),bt2mra
    &(6,20),bt1msa(6,20),bt2msa(6,20),stagra(6,20),stagsa(6,20),
    &etarda(6,20),pr12da(6,20),pr13da(6,20),rca(6,20),sca(6,20),
    &sigmra(6,20),sigmsa(6,20),xsarea(6,20),xareas(6,20)
c--- pgb 11-21-84. added for doing 6 streamlines. bottom.
c
     common /cdat3/jperfm,rhog(3),rerup,rerlow,resup,reslow
    &,preb,rrtip(20),srtip(20),aaa1,aaa2,aaa3,sarea(20),sareas(20)
    &,p(3),tg(3),xa,xv(3),xch4,xw(3),xww(3),xwt(3),tw(3),tww(3)
    &,omegs(20),omegr(20),gapr(20),gaps(20),tsg(3),psg(3)
    &,rrhub(20) , rc(20) , rblade(20) , stager(20)
    &,srhub(20) , sc(20) , sblade(20),stages(20)
    &,sigumr(20) , bet1sr(20) , bet2sr(20) , aincsr(20) , adevsr(20)
    &,sigums(20) , bet1ss(20) , bet2ss(20) , aincss(20) , adevss(20)
    &,utipg(20),utip(20),utipd(20),uou(20),umean(20),uhub(20),u(20),fai
    &,area(20),areas(20),uu2(20),utip2(20),umean2(20),uhub2(20),iprint
    &,icent,iicent,fmr1(20),fma2(20),idesin,faid
    &,ns,nsf,nslpc,bypass,ns1,rt(20),rm(20),rh(20),st(20),sm(20),sh(20)
    &,dsmass,aarea(20),aareas(20),pr12d(20),pr13d(20),etard(20)
    &,dr(20),ds(20),deqr(20),deqs(20),block(20),blocks(20)
    &,bet1mr(20),bet2mr(20),bet1ms(20),bet2ms(20),radi1(20),radi2(20)
    &,fairin(20),faiout(20),etasg(20),psid(20),taud(20),sitadr(20)
    &,sitads(20),wwd(20),vvd(20)
c
     common/step/ichord
     common/step1/title,nvinam(13,4),nshpc,jend,nwater,icase,irad,jrad,
    $idespt,jcent,icentv,xdin,xddin,vairwa,fnf,
    $xphi,t0g,t0w,p0,fnd,t01d,p01d,fndlpc,fndhpc,rhumid,fmwa,fmwv,fmws,
    $dlimit,predes,temdes,din,ddin
c
     common /cdat4/ dvz1(3,20),dvz2(3,20),dvz3(3,20),arout(20),asout
    &(20),arin(20),arine(20),aroute(20),asoute(20),ws(3),wmass(3),
    $vmass(3),rhoa(3),rhom(3),tb(3),delz(20),etaa(20),dave(20),tdew
    $(3),ddave(40),wwmass(3),wtmass(3),tmass(3),gmass(3),xair(3),
    $xmetan(3),xgas(3),ak1(20),ak2(20),ak3(20),zdis(20),clear(20),
    $cstara(20),fmmass(3),xf(3),watrgn(20),vaprgn(20),rcase(20),xws
    $(20),watrgx(20),uis(20),jflag(20),hhcs(20)
c     *=*=*=*=* added by tdh to compute the necessary values
     rewind(15)
c     ------------------------------------------------------------
c     xphi=inlet flow coefficient is selected
c     ------------------------------------------------------------
1     format(a)
     read(15,1)title
     if(jsweep.eq.1)write(16,1)title
     read(15,*)xphi
```

```
c    ---------------------------------------------------------------
c    ichord=number of steps per chord used for centrifuging in wicrgn
c    ---------------------------------------------------------------
     read(15,*)ichord
c    ---------------------------------------------------------------
c    jend=max.number of allowed sweeps (1 for dry air)
c    ---------------------------------------------------------------
     read(15,*)jend
c    ---------------------------------------------------------------
c    nwater=counter for water cases (=1, dry; =2, wet)
c    ---------------------------------------------------------------
     read(15,*)nwater
c    ---------------------------------------------------------------
c    icase allows the initial distribution of water to be selected, as
c    different cases
c    2-2%, 4-4% (GE case1), 5-GE case 2, 7-GE case 3
c    ---------------------------------------------------------------
     read(15,*)icase
c      for making the engsim compatable performance maps
c      and to plot the results using the pucc calcomp
     read(15,*)ns,nsf,nslpc,nshpc
     ns1=ns+1
     read(15,*)(rrhub(i),i=1,ns)
     do11i=1,3
     read(15,*)(rca(i,j),j=1,ns)
11   continue
     read(15,*)(rblade(i),i=1,ns)
     do13i=1,3
     read(15,*)(stagra(i,j),j=1,ns)
13   continue
     read(15,*)(srhub(i),i=1,ns1)
     do14i=1,3
     read(15,*)(sca(i,j),j=1,ns1)
14   continue
     read(15,*)(sblade(i),i=1,ns1)
     do15i=1,3
     read(15,*)(stagsa(i,j),j=1,ns1)
15   continue
     do17i=1,3
     read(15,*)(sigmra(i,j),j=1,ns)
17   continue
     do22i=1,3
     read(15,*)(sigmsa(i,j),j=1,ns1)
22   continue
     do1151i=1,3
     read(15,*)(bt2ssa(i,j),j=1,ns1)
1151 continue
c -- pgb 11-21-84. change so can read in 6 stream lines worth. bottom.
c
     read(15,*)fnf
     read(15,*)xdin,icent,xddin,iicent,icentv
```

```
      read(15,*)t0g,t0w,p0
      read(15,*)din,ddin
      read(15,*)fnd,t01d,p01d,fndlpc,fndhpc
      read(15,*)xch4,rhumid
      read(15,*)fmwa,fmwb,fmwc
      read(15,*)preb,dlimit
      read(15,*)(gapr(i),i=1,ns)
      read(15,*)(gaps(i),i=1,ns)
      read(15,*)(rrtip(i),i=1,ns)
      read(15,*)(srtip(i),i=1,ns1)
      read(15,*)irad
      read(15,*)(rt(i),i=1,ns)
      read(15,*)(rm(i),i=1,ns)
      read(15,*)(rh(i),i=1,ns)
c --- pgb 11-21-84. change so can read 6 streamlines worth. top
      read(15,*)(rfc(i),i=1,ns)
c --  pgb 11-21-84. change so can read 6 stream tubes worth. bottom
      read(15,*)(st(i),i=1,ns)
      read(15,*)(sm(i),i=1,ns)
      read(15,*)(sh(i),i=1,ns)
      read(15,*)(sfc(i),i=1,ns)
c --  pgb 11-21-84. change so can read in 6 stream lines worth. bottom
      read(15,*)(block(i),i=1,ns)
      read(15,*)(blocks(i),i=1,ns1)
      read(15,*)idesin,idespt,jcent
c --  pgb 11-21-84. change so can read in 6 stream lines worth. top
      do1152i=1,3
      read(15,*)(bt1mra(i,j),j=1,ns)
1152  continue
      do1153i=1,3
      read(15,*)(bt2mra(i,j),j=1,ns)
1153  continue
      do1154i=1,3
      read(15,*)(bt1msa(i,j),j=1,ns1)
1154  continue
      do1155i=1,3
      read(15,*)(bt2msa(i,j),j=1,ns1)
1155  continue
      read(15,*)dsmass,bypass
      do57i=1,3
      read(15,*)(pr12da(i,j),j=1,ns)
57    continue
      do58i=1,3
      read(15,*)(pr13da(i,j),j=1,ns)
58    continue
      do59i=1,3
      read(15,*)(etarda(i,j),j=1,ns)
59    continue
      do60i=1,3
      read(15,*)(xsarea(i,j),j=1,ns)
60    continue
```

```
      do61i=1,3
      read(15,*)(xareas(i,j),j=1,ns1)
61    continue
c     ------------------------------------------------------------
c     nhg         the variable vairwa refers to the ratio of
c       the velocity of air to the velocity of some other phase
c       such as droplet (large or small) or film.  the phase
c       with the smallest velocity should be used because, vairwa
c       is used to calculate residence time for centrifugal
c       calculations.
c
c*****************************************************************
      read(15,*)vairwa
c*****************************************************************
c
c     nhg         the variable clear(i) refers to the clearance
c       of the rotor.
c
c******************************************************************
      read(15,*)(clear(i),i=1,ns)
      read(15,*)(zdis(i),i=1,ns)
      do 1523 i=1,ns
      zdis(i) = zdis(i)/12.0
 1523 continue
c     ************************************************************
c     * nhg       the variable jrad is being used because the
c     *     variable irad is always set to a value of 2.. jrad
c     *     represents the the stream line where the calculations
c     *     are being done :
c     *                    1 = tip
c     *                    2 = mean
c     *                    3 = hub
c     ************************************************************
      read(15,*)jrad
5557  continue
c ajm
      read(15,*)predes,temdes
c     ************************************************************
c     * changed program to read different values of the constants    *
c     * ak1, ak2 and ak3 for each stage of the compressor.-skm.       *
c     *  nhg  changed format from f5.3 to f6.4     *****************
      read(15,*) (ak1(i), i=1,ns)
      read(15,*) (ak2(i), i=1,ns)
      read(15,*) (ak3(i), i=1,ns)
c *+*+*+*+*+*+*+*+*+*+*+*+*+*++*+*+*+*+*+*+*+*+*+*+*+*++*+*+*+*+*
c   the variables dvz1, dvz2, and dvz3 are  the axial
c   velocity of the gaseous working fluid at rotor inlet,
c   rotor outlet, and stator outlet, respectively, for the
c   design case.
c
c *+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+
```

```
      do 62 i=1,3
      read(15,*)(dvz1(i,j),j=1,ns1)
 62   continue
      do 64 i=1,3
      read(15,*)(dvz2(i,j),j=1,ns1)
 64   continue
      do 66 i=1,3
      read(15,*)(dvz3(i,j),j=1,ns)
 66   continue
c *+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*++*+*+*+*+*+*+*++*+*+*+*
c  the variables arine, aroute, and asoute are the effective
c  streamtube areas corresponding to the design point case
c  for rotor inlet, rotor outlet, and stator outlet,
c  respectively.  currently, the program does not use these
c  values; instead the stremtube areas are calculated in the
c  design point case such that the correct axial velocity
c  is obtained at design.  approximate values may inserted.
c  if the axial velocity data is not available for a machine
c  then to obtain correct overall performance at design, the
c  effective streamtube areas may be used.
c
c *+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+*+
       read(15,*)(arine(i),i=1,ns)
       read(15,*)(aroute(i),i=1,ns)
       read(15,*)(asoute(i),i=1,ns)
c...added for plotting by pgb 7/5/84 top....
      call getnm(nvinam)
c...added for plotting by pgb 7/5/84 bottom....
      return
      end
c ++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
      subroutine datinp
c     developed to generate data and storeaway automatically.
c
      character viname(13,4)
      common /cdat3/jperfm,rhog(3),rerup,rerlow,resup,reslow
     &,preb,rrtip(20),srtip(20),aaa1,aaa2,aaa3,sarea(20),sareas(20)
     &,p(3),tg(3),xa,xv(3),xch4,xw(3),xww(3),xwt(3),tw(3),tww(3)
     &,omegs(20),omegr(20),gapr(20),gaps(20),tsg(3),psg(3)
     &,rrhub(20) , rc(20) , rblade(20) , stager(20)
     &,srhub(20) , sc(20) , sblade(20),stages(20)
     &,sigumr(20) , bet1sr(20) , bet2sr(20) , aincsr(20) , adevsr(20)
     &,sigums(20) , bet1ss(20) , bet2ss(20) , aincss(20) , adevss(20)
     &,utipg(20),utip(20),utipd(20),uou(20),umean(20),uhub(20),u(20),fai
     &,area(20),areas(20),uu2(20),utip2(20),umean2(20),uhub2(20),iprint
     &,icent,iicent,fmr1(20),fma2(20),idesin,faid
     &,ns,nsf,nslpc,bypass,ns1,rt(20),rm(20),rh(20),st(20),sm(20),sh(20)
     &,dsmass,aarea(20),aareas(20),pr12d(20),pr13d(20),etard(20)
     &,dr(20),ds(20),deqr(20),deqs(20),block(20),blocks(20)
     &,bet1mr(20),bet2mr(20),bet1ms(20),bet2ms(20),radi1(20),radi2(20)
     &,fairin(20),faiout(20),etasg(20),psid(20),taud(20),sitadr(20)
```

```
      &,sitads(20),wwd(20),vvd(20)
c
      common /cdat2/ rfc(20),sfc(20),bt2ssa(6,20),bt1mra(6,20),bt2mra
     &(6,20),bt1msa(6,20),bt2msa(6,20),stagra(6,20),stagsa(6,20),
     &etarda(6,20),pr12da(6,20),pr13da(6,20),rca(6,20),sca(6,20),
     &sigmra(6,20),sigmsa(6,20),xsarea(6,20),xareas(6,20)
c
      common /cdat4/ dvz1(3,20),dvz2(3,20),dvz3(3,20),arout(20),asout
     &(20),arin(20),arine(20),aroute(20),asoute(20),ws(3),wmass(3),
     $vmass(3),rhoa(3),rhom(3),tb(3),delz(20),etaa(20),dave(20),tdew
     $(3),ddave(40),wwmass(3),wtmass(3),tmass(3),gmass(3),xair(3),
     $xmetan(3),xgas(3),ak1(20),ak2(20),ak3(20),zdis(20),clear(20),
     $cstara(20),fmmass(3),xf(3),watrgn(20),vaprgn(20),rcase(20),xws
     $(20),watrgx(20),uis(20),jflag(20),hhcs(20)
c
      write(*,*)'no.of fan stages= '
      read(*,*)nsf
      write(*,*)'no.of low pressure compressor stages= '
      read(*,*)nslpc
      write(*,*)'no.of high pressure compressor stages= '
      read(*,*)nshpc
      ns=nsf+nslpc+nshpc
      ns1=ns+1
      write(*,*)' data may be given at mean radius or three radii[1,3]:'
      read(*,*)nset
      write(*,*)'geom.data is read first for inlet guide vane [IGV] '
      write(*,*)'followed by data for all stages (stator/rotor)',
     $' (separated by comma)'
      write(*,*)'For IGV:no.of blades,Rhub[in],Rtip[in],block factor '
      read(*,*)nblad,srhub(ns1),srtip(ns1),blocks(ns1)
      sblade(ns1)=float(nblad)
      if(nset.eq.3)goto 2
      write(*,*)'For IGV:mid-chord[in],mid_metal_angle[deg](entry,',
     $'exit),solidity,'
      write(*,*)'      abs. outlet flow angle [deg],stager_angle: '
      read(*,*)sc(ns1),bet1ms(ns1),bet2ms(ns1),sigums(ns1),bet2ss(ns1)
     $,stages(ns1)
      do1i=1,3
      sca(i,ns1)=sc(ns1)
      bt1msa(i,ns1)=bet1ms(ns1)
      bt2msa(i,ns1)=bet2ms(ns1)
      bt2ssa(i,ns1)=bet2ss(ns1)
      stagsa(i,ns1)=stages(ns1)
1     sigmsa(i,ns1)=sigums(ns1)
      goto4
2     continue
      do3i=1,3
      write(*,*)'For IGV,set ',i,':chord[in],metal_angle[deg](entry,',
     $'exit),solidity '
      write(*,*)'      abs_outlet_flow_angle [deg],stager_angle: '
3     read(*,*)sca(i,ns1),bt1msa(i,ns1),bt2msa(i,ns1),sigmsa(i,ns1),
```

```
     $bt2ssa(i,ns1),stagsa(i,ns1)
4     continue
      do30ist=1,ns
      write(*,*)' Stage',ist,' rotor:no.of blades,Rhub[in],Rtip[in],bl'
     $,'ockage factor,gapS_R[in]: '
      read(*,*)nblad,rrhub(ist),rrtip(ist),block(ist),gapr(ist)
      rblade(ist)=float(nblad)
      if(nset.eq.3)goto16
      write(*,*)' Stage',ist,' rotor:chord[in],stager angle[deg],solidi'
     *,'ty,'
      write(*,*)'metal entry angle[deg],metal exit angle[deg]:'
      read(*,*)rc(ist),stager(ist),sigumr(ist),bet1mr(ist),
     $bet2mr(ist)
      do15i=1,3
      rca(i,ist)=rc(ist)
      stagra(i,ist)=stager(ist)
      sigmra(i,ist)=sigumr(ist)
      bt1mra(i,ist)=bet1mr(ist)
      bt2mra(i,ist)=bet2mr(ist)
15    continue
      goto19
16    do17i=1,3
      write(*,*)' For rotor stage ',ist,' set ',i
      write(*,*)'chord[in],stager angle[deg],solidity,metal entry ',
     $'angle[deg],exit angle[deg]'
      read(*,*)rca(i,ist),stagra(i,ist),sigmra(i,ist),bt1mra(i,ist),
     $bt2mra(i,ist)
17    continue
19    continue
      write(*,*)' Stage',ist,' stator:no.of blades,Rhub[in],Rtip[in]',
     $',blockage factor,gapR_S[in]: '
      read(*,*)nblad,srhub(ist),srtip(ist),blocks(ist),gaps(ist)
      sblade(ist)=float(nblad)
      if(nset.eq.3)goto26
      write(*,*)' Stage',ist,' stator:chord[in],stager angle[deg],'
     *,'solidity,'
      write(*,*)'metal entry angle[deg],metal exit angle[deg],'
      write(*,*)'absolute outlet flow angle[deg]: '
      read(*,*)sc(ist),stages(ist),sigums(ist),bet1ms(ist),bet2ms
     $(ist),bet2ss(ist)
      do25i=1,3
      sca(i,ist)=sc(ist)
      stagsa(i,ist)=stages(ist)
      sigmsa(i,ist)=sigums(ist)
      bt1msa(i,ist)=bet1ms(ist)
      bt2msa(i,ist)=bet2ms(ist)
      bt2ssa(i,ist)=bet2ss(ist)
25    continue
      goto30
26    do27i=1,3
      write(*,*)' For stator stage ',ist,' set ',i
```

```
      write(*,*)'chord[in],stager angle[deg],solidity,metal entry angle'
     $,'[deg],exit angle[deg],'
      write(*,*)'absolute outlet flow angle [deg]: '
      read(*,*)sca(i,ist),stagsa(i,ist),sigmsa(i,ist),bt1msa(i,ist),
     $bt2msa(i,ist),bt2ssa(i,ist)
27    continue
30    continue
      write(*,*)'Should rotor clearance be standard? '
      read(*,31)rkey
31    format(a)
      ncle=0
      if(rkey.ne.'y'.and.rkey.ne.'Y')ncle=1
      do50ist=1,ns
      write(*,*)'For stage ',ist,' rotor: radii [in] - rt,rm,rh,rfc'
     $,'(casing): '
      read(*,*)rt(ist),rm(ist),rh(ist),rfc(ist)
      write(*,*)'For stage ',ist,' stator: radii [in] - st,sm,sh,sfc'
     $,'(casing): '
      read(*,*)st(ist),sm(ist),sh(ist),sfc(ist)
50    continue
      if(ncle.eq.0)goto52
      write(*,*)'Rotor clearance [in] for ',ns,' rotors(sep.by comma):'
      read(*,*)(clear(ist),ist=1,ns)
      goto 55
52    continue
      write(*,*)'rotor clearance[in]:'
      write(*,*)'stage no.  clearance[in]'
      do53ist=1,ns
      clear(ist)=(rt(ist)-rrhub(ist))*0.0025
      if(clear(ist).lt.0.01)clear(ist)=0.01
      write(*,*)ist,clear(ist)
53    continue
55    continue
      write(*,*)'Axial stage length for ',ns,' stages(sep.by comma)',
     $'(zdis)[in]:'
      read(*,*)(zdis(ist),ist=1,ns)
      write(*,*)'Geometrical data completed'
      write(*,*)' '
      write(*,*)'inlet flow coefficient(xphi)= '
      read(*,*)xphi
      write(*,*)'no.of steps per chord needed for centrifuging(ichord)'
      read(*,*)ichord
      write(*,*)'max.no.of sweeps(jend)= '
      read(*,*)jend
      write(*,*)'Wet case? '
      read(*,31)rkey
      nwater=1
      if(rkey.eq.'Y'.or.rkey.eq.'y')nwater=2
      irad=2
      write(*,*)'jrad = 1/2/3 for tip/mean/hub: '
      read(*,*)jrad
```

```
      write(*,*)'idesin = 1/2 for output stage+overall/overall: '
      read(*,*)idesin
      write(*,*)'idespt=0/1 for no_print/print of design point: '
      read(*,*)idespt
      write(*,58)
58    format('Design point data:'/,1x,'fan_rpm,inlet_stag_temp',
     $'(R),inlet-stag-pressure(lb/sq.ft)'/,1x,'rpm_lpc,rpm_hpc'
     $)
      read(*,*)fnd,T01d,p01d,fndlpc,fndhpc
      write(*,*)'standard day pressure(lbf/sq.ft),temp(oR):'
      read(*,*)predes,temdes
      write(*,*)'Overall mass flow rate (lbm/s), bypass ratio: '
      read(*,*)Ovmass,bypass
      dsmass=Ovmass*.1
59    format('For stage ',i2,'values for (p02/p01),(p03/p01),stage',
     $' efficiency')
      do65ist=1,ns
      if(nset.eq.3)goto62
      write(*,59)ist
      read(*,*)pr12d(ist),pr13d(ist),etard(ist)
      do60i=1,3
      pr12da(i,ist)=pr12d(ist)
      pr13da(i,ist)=pr13d(ist)
60    etarda(i,ist)=etard(ist)
      goto65
61    format('For stage ',i2,' set ',i1,' values for (p02/p01),(p03/',
     1'p01),stage efficiency: ')
62    do63i=1,3
      write(*,61)ist,i
      read(*,*)pr12da(i,ist),pr13da(i,ist),etarda(i,ist)
63    continue
65    continue
69    format('For stage ',i2,' axial speeds (ft/s) at rotorin,rotor',
     $'exit,statorexit')
      do75ist=1,ns
      if(nset.eq.3)goto72
      write(*,69)ist
      read(*,*)vrin,vrout,vsout
      do70i=1,3
      dvz1(i,ist)=vrin
      dvz2(i,ist)=vrout
70    dvz3(i,ist)=vsout
      goto75
71    format('For stage ',i2,' set ',i1,' axial speeds (ft/s) at',
     1'rotorin,rotorexit,statorexit: ')
72    do73i=1,3
      write(*,71)ist,i
      read(*,*)dvz1(i,ist),dvz2(i,ist),dvz3(i,ist)
73    continue
75    continue
      if(nset.eq.3)goto77
```

```
      write(*,*)'For IGV axial speeds (ft/s) at inlet and outlet:'
      read(*,*)vrout,vsout
      do76i=1,3
      dvz1(i,ns1)=vrout
 76   dvz2(i,ns1)=vsout
      goto79
 77   do78i=1,3
      write(*,*)'For IGV, set ',i,' axial speeds (ft/s) at inlet and '
     $,'outlet'
 78   read(*,*)dvz1(i,ns1),dvz2(i,ns1)
 79   continue
      write(*,*)'stream tube areas to be read ?'
      read(*,31)rkey
      if(rkey.eq.'Y'.or.rkey.eq.'y')goto90
      dsm=dsmass/2.204623
      nsf1=nsf+1
c     1 ft=0.3048 m; 1 sq.ft=0.092903 sq.m; 1 bar=2088.5 lbf/sq.ft
c     1 kg= 2.204623 lbm
      do81i=1,3
      T01K=T01d/1.8
      p01bar=p01d/2088.5
      do80ist=1,ns
      if(ist.ne.nsf1)goto380
      vzin=dvz1(i,ns1)*0.3048
      TK=T01K-(vzin**2/2010.)
      pbar=p01bar*(TK/T01K)**3.5
      ro=pbar/(TK*0.002875)
        xareas(i,ns1)=dsm/(ro*vzin*0.092903)
 380  continue
      vzin=dvz1(i,ist)*0.3048
      TK=T01K-(vzin**2/2010.)
      pbar=p01bar*(TK/T01K)**3.5
      ro=pbar/(TK*0.002875)
      xsarea(i,ist)=dsm/(ro*vzin*0.092903)
      T02K=T01K*(1.+((pr12da(i,ist)**0.286-1.)/etarda(i,ist)))
      p02bar=p01bar*pr12da(i,ist)
      vzin=dvz2(i,ist)*0.3048
      TK=T02K-(vzin**2/2010.)
      pbar=p02bar*(TK/T02K)**3.5
      ro=pbar/(TK*0.002875)
      xareas(i,ist)=dsm/(ro*vzin*0.092903)
      if(ist.eq.ns)goto80
      T01K=T02K
      p01bar=p01bar*pr13da(i,ist)
 80   continue
 81   continue
      goto100
 90   continue
      if(nset.eq.3)goto95
 91   format('rotor inlet stream tube area (sq.ft)(all stages): ')
      write(*,91)
```

```
      read(*,*)(area(ist),ist=1,ns)
92    format('stator inlet stream tube area (sq.ft)(all stages + last '
     $,'value for IGV')
      write(*,92)
      read(*,*)(areas(ist),ist=1,ns1)
      do94i=1,3
      do93ist=1,ns
93    xsarea(i,ist)=area(ist)
      do94ist=1,ns1
      xareas(i,ist)=areas(ist)
94    continue
      goto100
95    continue
      do96i=1,3
      write(*,*)'For set ',i
      write(*,91)
      read(*,*)(xsarea(i,ist),ist=1,ns)
      write(*,92)(xareas(i,ist),ist=1,ns1)
96    continue
100   continue
c     put approximate streamtube data in arine, aroute,asoute
      do194ist=1,ns
      arine(ist)=xsarea(2,ist)
      aroute(ist)=xareas(2,ist)
      if(ist.lt.ns)asoute(ist)=xsarea(2,ist+1)
      if(ist.eq.ns)asoute(ist)=xareas(2,ist)
194   continue
      write(*,*)'Off-design data'
      write(*,*)'fraction of design corrected rotor speed for ',
     $'off-design(1.0): '
      read(*,*)fnf
      fmwa=28.964
      fmwv=18.016
      fmch=16.043
      xdin=0.
      xddin=0.
      din=20.
      ddin=600.
      rhumid=0.
      icent=1
      iicent=1
      icentv=0
      jcent=0
      icase=0
      T0w=597.
      preb=1.
      dlimit=10.
      vairwa=80.
      if(nwater.eq.1)goto110
      write(*,*)'initial water percentage distribution cases - '
      write(*,*)'2 for 2%, 4 for 4%, 5 for GE2, 7 for GE3: '
```

```
      read(*,*)icase
      write(*,*)'jcent=0/1 for large droplets in rotor not_centr'
     $,'ifuged/centrif.'
      read(*,*)jcent
101   format('icent,iicnet= 2, no restriction',/,14x,
     $'3, no heat and mass transfer;',/,14x,
     $'4, no centrifugal action;',/,14x,'5, no heat/mass transfer',
     $'/centrifugal action;',/,14x,'6, no mass transfer;',/,14x,
     $'7, no mass transfer/centrifubal action.',/,'icent,iicent =')
      write(*,101)
      read(*,*)icent,iicent
      write(*,*)'inital mass content of small/large droplet(xdin'
     $,',xddin)= '
      read(*,*)xdin,xddin
      write(*,*)'initial small/large droplet dia(in micro-meter)',
     $'(din,ddin)= '
      read(*,*)din,ddin
      write(*,*)'initial water droplet temp. (in degr. R)= '
      read(*,*)T0w
      write(*,*)'initial water vapor content in air (kgv/kgair)',
     $'(rhumid)='
      read(*,*)rhumid
      write(*,*)'percent of water that rebound from wall(preb)= '
      read(*,*)preb
      write(*,*)'max.dia (in micrometer) to be considered as small '
     $,'droplet(dlimit)= '
      read(*,*)dlimit
      write(*,*)'speed ratio air to condensed phase(vairwa)[%]= '
      read(*,*)vairwa
      write(*,*)'vapor is centrifuged?'
      read(*,31)rkey
      if(rkey.ne.'Y'.and.rkey.ne.'y')icentv=1
110   continue
      write(*,*)'off design inlet temp(R),pressure(lbf/sq.ft)= '
      read(*,*)T0g,p0
      write(*,*)'Methane fraction= '
      read(*,*)xch4
      write(*,*)'ak1,ak2 and ak3 are 3 correction factors [1.]'
      write(*,*)'use default values?<CR>'
      read(*,31)rkey
      ncor=0
      if(rkey.eq.'N'.or.rkey.eq.'n')ncor=1
      do411ist=1,ns
      if(ncor.eq.0) then
      ak1(ist)=1.
      ak2(ist)=1.
      ak3(ist)=1.
      endif
      if(ncor.ne.0) then
      write(*,*)'for stage',ist,' type ak1,ak2,ak3: '
      read(*,*)ak1(ist),ak2(ist),ak3(ist)
```

```
      endif
411   continue
      write(*,*)'input data being stored away -wait!'
157   format(4(i2,1x))
158   format(16(f5.2,1x))
159   format(16(f5.3,1x))
160   format(16(f7.5,1x))
161   format(16(f6.4,1x))
162   format(f7.1,2(1x,f7.2),2(1x,f7.1))
163   format(3(f6.3,1x))
      write(15,'(f4.2)')xphi
      write(15,157)ichord,jend,nwater,icase
      write(15,157)ns,nsf,nslpc,nshpc
      write(15,158)(rrhub(ist),ist=1,ns)
      do257i=1,3
      write(15,159)(rca(i,ist),ist=1,ns)
257   continue
      write(15,158)(rblade(ist),ist=1,ns)
      do258i=1,3
      write(15,158)(stagra(i,ist),ist=1,ns)
258   continue
      write(15,158)(srhub(ist),ist=1,ns1)
      do259i=1,3
      write(15,159)(sca(i,ist),ist=1,ns1)
259   continue
      write(15,158)(sblade(ist),ist=1,ns1)
      do260i=1,3
      write(15,158)(stagsa(i,ist),ist=1,ns1)
260   continue
      do261i=1,3
      write(15,159)(sigmra(i,ist),ist=1,ns)
261   continue
      do262i=1,3
      write(15,159)(sigmsa(i,ist),ist=1,ns1)
262   continue
      do263i=1,3
      write(15,158)(bt2ssa(i,ist),ist=1,ns1)
263   continue
      write(15,*)fnf
164   format(f5.3,1x,i1,1x,f5.3,1x,i1,1x,i1)
      write(15,*)xdin,icent,xddin,iicent,icentv
165   format(3(f7.2,1x))
      write(15,165)T0g,T0w,p0
166   format(2(f6.1,1x))
      write(15,166)din,ddin
      write(15,162)fnd,T01d,p01d,fndlpc,fndhpc
167   format(f5.3,1x,f10.5)
      write(15,167)xch4,rhumid
      write(15,163)fmwa,fmwv,fmch
168   format(f5.1,1x,f7.1)
      write(15,168)preb,dlimit
```

```
      write(15,160)(gapr(ist),ist=1,ns)
      write(15,160)(gaps(ist),ist=1,ns)
      write(15,159)(rrtip(ist),ist=1,ns)
      write(15,159)(srtip(ist),ist=1,ns1)
      write(15,*)irad
      write(15,159)(rt(ist),ist=1,ns)
      write(15,159)(rm(ist),ist=1,ns)
      write(15,159)(rh(ist),ist=1,ns)
      write(15,159)(rfc(ist),ist=1,ns)
      write(15,159)(st(ist),ist=1,ns)
      write(15,159)(sm(ist),ist=1,ns)
      write(15,159)(sh(ist),ist=1,ns)
      write(15,159)(sfc(ist),ist=1,ns)
      write(15,159)(block(ist),ist=1,ns)
      write(15,159)(blocks(ist),ist=1,ns1)
      write(15,157)idesin,idespt,jcent
      do264i=1,3
      write(15,158)(bt1mra(i,ist),ist=1,ns)
264   continue
      do265i=1,3
      write(15,158)(bt2mra(i,ist),ist=1,ns)
265   continue
      do266i=1,3
      write(15,158)(bt1msa(i,ist),ist=1,ns1)
266   continue
      do267i=1,3
      write(15,158)(bt2msa(i,ist),ist=1,ns1)
267   continue
      write(15,163)dsmass,bypass
      do268i=1,3
      write(15,159)(pr12da(i,ist),ist=1,ns)
268   continue
      do269i=1,3
      write(15,159)(pr13da(i,ist),ist=1,ns)
269   continue
      do270i=1,3
      write(15,159)(etarda(i,ist),ist=1,ns)
270   continue
170   format(8(f10.7,1x))
      do271i=1,3
      write(15,170)(xsarea(i,ist),ist=1,ns)
271   continue
      do272i=1,3
      write(15,170)(xareas(i,ist),ist=1,ns1)
272   continue
      write(15,'(f6.2)')vairwa
      write(15,161)(clear(ist),ist=1,ns)
      write(15,159)(zdis(ist),ist=1,ns)
      write(15,*)jrad
      write(15,'(2f7.1)')predes,temdes
      write(15,161)(ak1(ist),ist=1,ns)
```

```
      write(15,161)(ak2(ist),ist=1,ns)
      write(15,161)(ak3(ist),ist=1,ns)
171   format(16(f5.1,1x))
      do1271i=1,3
      write(15,171)(dvz1(i,ist),ist=1,ns1)
1271  continue
      do1272i=1,3
      write(15,171)(dvz2(i,ist),ist=1,ns1)
1272  continue
      do273i=1,3
      write(15,171)(dvz3(i,ist),ist=1,ns)
273   continue
172   format(13(f6.4,1x))
      write(15,172)(arine(ist),ist=1,ns)
      write(15,172)(aroute(ist),ist=1,ns)
      write(15,172)(asoute(ist),ist=1,ns)
      write(*,*)'type upto twelve 4 byte words used by sub getnm'
      do275i=1,13
      read(*,'(4a1)')(viname(i,ist),ist=1,4)
      write(15,'(4a1)')(viname(i,ist),ist=1,4)
      if(viname(i,1).eq.'d'.and.viname(i,2).eq.'o')goto300
275   continue
300   continue
      write(*,*)'input data storage complete'
      return
      end
      subroutine htdgen
      character rkey
      character*20 filout,fildat
c     data generation interactively and storing away for later use
c     or to retrieve data from file for further calculation.
      common /htd1/filout,ndtop(20,8,6),ndmax(20),splen(20,8,4),
     $arnod(20,8,4),htcap(20,8),casrad(20),excfcs,nexpr(20),excfr
     $(20,4),radex(20,4),tradd(145),xlcso(2,170),xlro(2,170),rotdis(20)
     $,dtimcl,rrv(145),cwork(300),rrvp(145),nexnod(4,20),
     $nexcas(20),t0cas,tcas,rocas,ucas,trotor,rpm,rorot,urot,deltem
     $,nboht,twcas,nemax,wfstrf,nrotcs,trchi(20),trcho(20),txw0(20),
     $ttawm(20),tpawm(20),tvol(20),permax,txwc(20),ttawc(20),tpawc(20)
     $,tmasa(20),dwat
c     -----------------------------------------------------------
c     meaning of variables in common block /htd1/ used here:
c     ndtop(i1,i2,i3), where i1=stage no.,i2=elem. no in stage,
c     i3=1:type no.,i3=2: no.of adj.nodes,i3>2:adj.node numbers)
c     ndmax=number of nodes in "ndtop" in each stage
c     splen=array for specific length (m**2-K/W) for each node
c     arnod=array for interface surface area (m**2)
c     htcap=heat capacity(J/K) for each nodal element
c     excfcs=thermal expansion coefficient of casing material(K**-1)
c     nexpr=no.of nodes considered for thermal expansion of rotor in
c          each stage
c     excfr=thermal expansion coefficient for rotor nodes material (K**-1)
```

```
c    ----------------------------------------------------------------
c
      write(*,*)' This subroutine helps for use in nodal temperature'
     $,' and clearance package '
      write(*,*)' 1. to generate data, and'
      write(*,*)' 2. to retrieve data for calculation.'
      write(*,*)' --- choice: '
      read(*,*)nchoic
      if(nchoic.eq.1)write(*,*)' generated data to be stored in file: '
      if(nchoic.eq.2)write(*,*)' data retreaval from file: '
1     format(a)
      read(*,1)filout
      open(17,file=filout)
      goto(601,602),nchoic
      write(*,*)'err STOP in sub htdgen'
      Stop
601   continue
      write(*,1602)
      read(*,*)nrotcs
      nelst=7
      if(nrotcs.eq.3)nelst=8
      write(*,*)'number of stages='
      read(*,*)imax
      write(*,*)'number of fan stages= '
      read(*,*)ifan
      write(*,*)'max.number of elements per stage (',nelst,')='
      read(*,*)jmax
      write(*,*)'max.number of adj. nodes for each centroid node (4)='
      read(*,*)kmax
      if(imax.le.20.and.jmax.le.nelst.and.(kmax+2).le.6)goto5
      write(*,*)'err stop in sub htdgen since array specified too ',
     $'small'
      close(17)
      stop
5     continue
500   format(5(1x,i2))
1602  format(1x,'rotor internal cooling:',/,1x,'1. none;',/,1x,
     $'2. cooled by air(with or without water) flow; and',
     $/,1x,'3. cooled by intermittently stagnant air-water mix.'
     $,/,2x,' --- choice: ')
      write(17,500)imax,ifan,jmax,kmax,nrotcs
c     preparing nodal topology matrix
      ic=0
      do200i=1,imax
      if(ic.ne.ifan)goto10
      write(*,*)'nodal information for igv: 4 nodes'
      jp=4
      ndmax(ic+1)=jp
      do4j=1,jp
      write(*,*)'igv,for elem. ',j,' type no.(1-15):'
      read(*,*)ntyp
```

```
      nnd=4
      if(ntyp.eq.1.or.ntyp.eq.4.or.ntyp.eq.5.or.ntyp.eq.7)nnd=3
      if(ntyp.eq.6.or.ntyp.eq.15)nnd=2
      if(ntyp.eq.8)nnd=1
      ndtop(ic+1,j,1)=ntyp
      ndtop(ic+1,j,2)=nnd
      write(*,*)'heat capacity [J/K] for igv elem. ',j,':'
      read(*,*)htcap(ic+1,j)
      write(*,*)'node numbers for igv elem. ',j,',',nnd,' adj.nodes:'
      read(*,*)(ndtop(ic+1,j,k+2),k=1,nnd)
      write(*,*)'Sij[m2] for igv elem. ',j,',',nnd,' adj.nodes:'
      read(*,*)(arnod(ic+1,j,k),k=1,nnd)
      write(*,*)'ls[m2K/W] for igv elem. ',j,',',nnd,' adj.nodes:'
      read(*,*)(splen(ic+1,j,k),k=1,nnd)
      write(17,501)ntyp,nnd,htcap(ic+1,j)
      write(17,502)(ndtop(ic+1,j,k+2),k=1,nnd)
      write(17,503)(arnod(ic+1,j,k),k=1,nnd)
      write(17,503)(splen(ic+1,j,k),k=1,nnd)
501   format(2(1x,i3),10(1x,1pe11.4))
502   format(10(i3,1x))
503   format(10(1x,1pe11.4))
4     continue
      ic=ic+1
10    continue
      jp=nelst
      write(*,*)'nodal information for stage ',i,' rotor',
     $' followed by stator'
      ndmax(ic+1)=jp
      write(17,500)jp
      do14j=1,jp
      write(*,*)'for elem. ',j,'type no.(1-16):'
      read(*,*)ntyp
      nnd=4
      if(ntyp.eq.1.or.ntyp.eq.4.or.ntyp.eq.5.or.ntyp.eq.7.or.
     $ntyp.eq.16)nnd=3
      if(ntyp.eq.8)nnd=1
      if(ntyp.eq.6.or.ntyp.eq.15)nnd=2
      ndtop(ic+1,j,1)=ntyp
      ndtop(ic+1,j,2)=nnd
      write(*,*)'heat capacity [J/K] for elem. ',j,':'
      read(*,*)htcap(ic+1,j)
      write(*,*)'node numbers for elem. ',j,',',nnd,' adj.nodes:'
      read(*,*)(ndtop(ic+1,j,k+2),k=1,nnd)
      write(*,*)'Sij[m2] for elem. ',j,',',nnd,' adj.nodes:'
      read(*,*)(arnod(ic+1,j,k),k=1,nnd)
      write(*,*)'ls[m2K/W] for elem. ',j,',',nnd,' adj.nodes:'
      read(*,*)(splen(ic+1,j,k),k=1,nnd)
      write(17,501)ntyp,nnd,htcap(ic+1,j)
      write(17,502)(ndtop(ic+1,j,k+2),k=1,nnd)
      write(17,503)(arnod(ic+1,j,k),k=1,nnd)
      write(17,503)(splen(ic+1,j,k),k=1,nnd)
```

```
14   continue
     ic=ic+1
200  continue
     write(*,*)'nodal information for 1 post node with 4 adj.nodes:'
     nnd=4
     ntyp=12
     ndmax(ic+1)=1
     ndtop(ic+1,1,1)=12
     ndtop(ic+1,1,2)=4
     write(*,*)'heat capacity [J/K] for post node:'
     read(*,*)htcap(ic+1,1)
     write(*,*)'node numbers for ',nnd,' adj.nodes of post node:'
     read(*,*)(ndtop(ic+1,1,k+2),k=1,nnd)
     write(*,*)'Sij[m2] for ',nnd,' adj.nodes of post node:'
     read(*,*)(arnod(ic+1,1,k),k=1,nnd)
     write(*,*)'ls[m2K/W] for ',nnd,' adj.nodes of post node:'
     read(*,*)(splen(ic+1,1,k),k=1,nnd)
     write(17,501)ntyp,nnd,htcap(ic+1,1)
     write(17,502)(ndtop(ic+1,1,k+2),k=1,nnd)
     write(17,503)(arnod(ic+1,1,k),k=1,nnd)
     write(17,503)(splen(ic+1,1,k),k=1,nnd)
     nnd=(imax*nelst)+5
     write(*,*)'no.of elements = ',nnd
     write(*,*)' axial coord.[in] for all elem.(put 0.,if irrelevant)'
     do201i=1,nnd
     write(*,*)'For elem. ',i,' case[in](upstr.),case(dnstr.):'
     read(*,*)xlcso(1,i),xlcso(2,i)
     write(17,202)xlcso(1,i),xlcso(2,i)
     write(*,*)'For elem. ',i,' rotor[in](upstr.),rotor(dnstr.):'
     read(*,*)xlro(1,i),xlro(2,i)
     write(17,202)xlro(1,i),xlro(2,i)
201  continue
202  format(2(1pe11.4,1x))
c
     write(*,*)'thermal expansion data'
     write(*,*)'coeff.of thermal exp.for casing(1/K): '
     read(*,*)excfcs
     write(17,*)excfcs
     do20i=1,imax
     write(*,*)'rotor stage no.= ',i
     write(*,*)
    $'casing thermal node no.,casing radius,rotor disk intern.radius'
    $,'[in]= '
     read(*,*)nexcas(i),casrad(i),rotdis(i)
     write(*,*)'no.of thermal expansion nodes in rotor stage ',i
     read(*,*)ntex
     nexpr(i)=ntex
     if(ntex.le.4)goto 11
     write(*,*)'err stop since size array excfr(,) insuff.'
     stop
11   continue
```

```
      write(*,*)'thermal expansion nodes (',ntex,') in stage',i
      read(*,*)(nexnod(itex,i),itex=1,ntex)
      write(*,*)'coeff.of thermal expansion of ',ntex,' nodes in'
     $,' stage ',i,':'
      read(*,*)(excfr(i,k),k=1,ntex)
      write(*,*)'thermal expansion node length of ',ntex,' nodes in'
     $,' stage ',i,':'
      read(*,*)(radex(i,k),k=1,ntex)
      write(17,*)ntex,nexcas(i),casrad(i),rotdis(i)
      write(17,504)(nexnod(itex,i),itex=1,ntex)
      write(17,503)(excfr(i,k),k=1,ntex)
      write(17,503)(radex(i,k),k=1,ntex)
20    continue
      if(nrotcs.gt.1) then
      write(*,*)' '
      write(*,*)' rotor disk is cooled by fluid flowing in channel'
      write(*,*)' Data required for each cooled rotor disk are: '
      write(*,*)' cooling channel min. and max. radius[in],'
      write(*,*)' total volume of the cooling channel fluid[m**3],'
      write(*,*)' cooling channel water content,temp.and pressure'
      write(*,*)' '
      do21i=1,imax
      write(*,*)
     $'for stage ',i,':Ri[in],Ro[in],vol[m**3],xw,T[K],p[bar]'
      read(*,*)trchi(i),trcho(i),tvol(i),txw0(i),ttawm(i),tpawm(i)
      write(17,22)trchi(i),trcho(i),tvol(i),txw0(i),ttawm(i),tpawm(i)
21    continue
      write(*,*)'water film thick. in rotor bore if water present[m]:'
      read(*,*)dwat
      write(17,*)dwat
22    format(1p6e12.5)
      endif
      if(nrotcs.eq.3) then
      write(*,*)
     $'cooling channel pressure incr. in percent of max.incr.possible'
      read(*,*)permax
      write(17,*)permax
      endif
504   format(20(i2,1x))
      close(17)
      goto 603
602   continue
      read(17,*)imax,ifan,jmax,kmax,nrotcs
      nelst=7
      if(nrotcs.eq.3)nelst=8
      ic=0
      do250i=1,imax
      if(ic.ne.ifan)goto240
      ndmax(ic+1)=4
      do235j=1,4
      read(17,*)ntyp,nnd,htcap(ic+1,j)
```

```
      ndtop(ic+1,j,1)=ntyp
      ndtop(ic+1,j,2)=nnd
      read(17,*)(ndtop(ic+1,j,k+2),k=1,nnd)
      read(17,*)(arnod(ic+1,j,k),k=1,nnd)
      read(17,*)(splen(ic+1,j,k),k=1,nnd)
 235  continue
      ic=ic+1
 240  continue
      read(17,*)jp
      ndmax(ic+1)=jp
      do245j=1,jp
      read(17,*)ntyp,nnd,htcap(ic+1,j)
      ndtop(ic+1,j,1)=ntyp
      ndtop(ic+1,j,2)=nnd
      read(17,*)(ndtop(ic+1,j,k+2),k=1,nnd)
      read(17,*)(arnod(ic+1,j,k),k=1,nnd)
      read(17,*)(splen(ic+1,j,k),k=1,nnd)
 245  continue
      ic=ic+1
 250  continue
      ndmax(ic+1)=1
      read(17,*)ntyp,nnd,htcap(ic+1,1)
      ndtop(ic+1,1,1)=ntyp
      ndtop(ic+1,1,2)=nnd
      read(17,*)(ndtop(ic+1,1,k+2),k=1,nnd)
      read(17,*)(arnod(ic+1,1,k),k=1,nnd)
      read(17,*)(splen(ic+1,1,k),k=1,nnd)
      nnd=(imax*nelst)+5
      do252i=1,nnd
      read(17,*)xlcso(1,i),xlcso(2,i)
      read(17,*)xlro(1,i),xlro(2,i)
 252  continue
      read(17,*)excfcs
      do260i=1,imax
      read(17,*)ntex,nexcas(i),casrad(i),rotdis(i)
      nexpr(i)=ntex
      read(17,*)(nexnod(itex,i),itex=1,ntex)
      read(17,*)(excfr(i,k),k=1,ntex)
      read(17,*)(radex(i,k),k=1,ntex)
 260  continue
      if(nrotcs.gt.1) then
      do421i=1,imax
      read(17,*)trchi(i),trcho(i),tvol(i),txw0(i),ttawm(i),tpawm(i)
 421  continue
      read(17,*)dwat
      endif
      if(nrotcs.eq.3)read(17,*)permax
      close(17)
 603  continue
      write(*,*)'Nodal temp.and clearance output file: '
      read(*,1)fildat
```

```
      open(21,file=fildat)
604   format(1x,'Type in the following data:',/,1x,'casing air '
     $,'density(kg/m**3);',/,1x,'casing air temp.(K);',/,1x
     $,'air speed outside casing(m/s);',/,1x,'stagn.temp. of air '
     $,'outside casing(K);',/,1x,'airflow temp.inside rotor(K);',/
     $,1x,'airflow density inside rotor(K);',/,1x,'airflow speed'
     $,' inside rotor(m/s); ',/,1x,'delta_temp.(K) needed to '
     $,'compute Grashof number in rotor disk(20.); and',/,1x,
     $'water film surface temp.relax.factor(0. to 1.)',/)
      write(*,604)
      read(*,*)rocas,tcas,ucas,t0cas,trotor,rorot,urot,deltem
     $,wfstrf
      twcas=0.
      write(*,*)'water film outside casing? '
      read(*,1)rkey
      if(rkey.eq.'Y'.or.rkey.eq.'y') then
      write(*,*)'temp.of water film outside casing(K): '
      read(*,*)twcas
      endif
c       write(*,*)'Output file for nodal temp. and clearance: '
c       read(*,1)filout
c       open(21,file=filout)
      nemax=600
      return
      end
      subroutine htexin
c     reading of heat transfer data without asking
      character*20 filin
      common /htd1/filin,ndtop(20,8,6),ndmax(20),splen(20,8,4),
     $arnod(20,8,4),htcap(20,8),casrad(20),excfcs,nexpr(20),excfr
     $(20,4),radex(20,4),tradd(145),xlcso(2,170),xlro(2,170),rotdis(20)
     $,dtimcl,rrv(145),cwork(300),rrvp(145),nexnod(4,20),
     $nexcas(20),t0cas,tcas,rocas,ucas,trotor,rpm,rorot,urot,deltem
     $,nboht,twcas,nemax,wfstrf,nrotcs,trchi(20),trcho(20),txw0(20),
     $ttawm(20),tpawm(20),tvol(20),permax,txwc(20),ttawc(20),tpawc(20)
     $,tmasa(20),dwat
      open(17,file=filin)
      read(17,*)imax,ifan,jmax,kmax,nrotcs
      nelst=7
      if(nrotcs.eq.3)nelst=8
      ic=0
      do250i=1,imax
      if(ic.ne.ifan)goto240
      ndmax(ic+1)=4
      do235j=1,4
      read(17,*)ntyp,nnd,htcap(ic+1,j)
      read(17,*)(ndtop(ic+1,j,k+2),k=1,nnd)
      read(17,*)(arnod(ic+1,j,k),k=1,nnd)
      read(17,*)(splen(ic+1,j,k),k=1,nnd)
235   continue
      ic=ic+1
```

```
240  continue
     read(17,*)jp
     ndmax(ic+1)=jp
     do245j=1,jp
     read(17,*)ntyp,nnd,htcap(ic+1,j)
     read(17,*)(ndtop(ic+1,j,k+2),k=1,nnd)
     read(17,*)(arnod(ic+1,j,k),k=1,nnd)
     read(17,*)(splen(ic+1,j,k),k=1,nnd)
245  continue
     ic=ic+1
250  continue
     ndmax(ic+1)=1
     read(17,*)ntyp,nnd,htcap(ic+1,j)
     read(17,*)(ndtop(ic+1,j,k+2),k=1,nnd)
     read(17,*)(arnod(ic+1,j,k),k=1,nnd)
     read(17,*)(splen(ic+1,j,k),k=1,nnd)
     nnd=(imax*nelst)+5
     do252i=1,nnd
     read(17,*)xlcso(1,i),xlcso(2,i)
     read(17,*)xlro(1,i),xlro(2,i)
252  continue
     read(17,*)excfcs
     do260i=1,imax
     read(17,*)ntex,nexcas(i),casrad(i),rotdis(i)
     nexpr(i)=ntex
     read(17,*)(nexnod(itex,i),itex=1,ntex)
     read(17,*)(excfr(i,k),k=1,ntex)
     read(17,*)(radex(i,k),k=1,ntex)
260  continue
     if(nrotcs.gt.1) then
     do21i=1,imax
     read(17,*)trchi(i),trcho(i),tvol(i),txw0(i),ttawm(i),tpawm(i)
21   continue
     read(17,*)dwat
     endif
     if(nrotcs.eq.3)read(17,*)permax
     close(17)
     return
     end
     function therex(istage)
c    calculation of rotor-casing clearance due to clearance gap
c    ---------------------------------------------------------------
     common /htd1/ndum(5),ndtop(20,8,6),ndmax(20),splen(20,8,4),
    $arnod(20,8,4),htcap(20,8),casrad(20),excfcs,nexpr(20),excfr
    $(20,4),radex(20,4),tradd(145),xlcso(2,170),xlro(2,170),rotdis(20)
    $,dtimcl,rrv(145),cwork(300),rrvp(145),nexnod(4,20),
    $nexcas(20),t0cas,tcas,rocas,ucas,trotor,rpm,rorot,urot,deltem
    $,nboht,twcas,nemax,wfstrf,nrotcs,trchi(20),trcho(20),txw0(20),
    $ttawm(20),tpawm(20),tvol(20),permax,txwc(20),ttawc(20),tpawc(20)
    $,tmasa(20),dwat
c    meaning of variables in common block /htd1/:
```

```
c    casrad=corresponding casing internal radius(not read in this
c         subroutine)
c    excfcs=thermal expansion coefficient of casing material(K**-1)
c    nexpr=no.of nodes considered for thermal expansion of rotor in
c        each stage
c    ndexp=nodal array for thermal expansion of rotor
c    excfr=thermal expansion coefficient for rotor nodes material (K**-1)
c    radex=corresponding original radial length(not read in this subroutine)
c    tradd(145)=temp.diff.(from orig.temp)(K) at all thermal nodes (input)
c    ------------------------------------------------------------------
c
      ndcas=nexcas(istage)
      tdiff=tradd(ndcas)
      casr=casrad(istage)*(1.+(excfcs*tdiff))
      ndd=nexpr(istage)
      rotl=0.
      do10i=1,ndd
      nod=nexnod(i,istage)
      rotl=rotl+(radex(istage,i)*(1.+(excfr(istage,i)*tradd(nod))))
10    continue
      therex=casr-rotl
100   format(a)
      return
      end
      subroutine spear(nemax,i,j,n,lcur,lmax,inl,x,vl,iflag,ier)
c    ------------------------------------------------------------------
c    subroutine to extract/add/remove/replace in a sparse matrix(vers 8/93)
c    nemax=max.length of 1-D array of inl(nemax),vl(nemax)
c    i,j,n = (row,col.,order) of matrix
c    index value manipulated in inl = ((i-1)*n)+j and correspond.value in vl.
c    lcur,lmax = current,maximum location of pointer (initiate with lcur=0)
c    x = external value for manipulation in the subroutine
c    iflag = 1 to 4 for extract/add/remove/replace
c    ier = error code on exit from the subroutine
c       = 0 (no error)
c       = 1 iflag,i,j,n not compatible
c       = 2 value to extract/remove not available
c       = 3 no space available to add
c       = 4 miscelleneous error
c    ------------------------------------------------------------------
      dimension inl(nemax),vl(nemax)
      ier=0
      k=j+((i-1)*n)
      if(iflag.eq.2.and.lcur.eq.0)goto26
      if(iflag.ne.2.and.lcur.eq.0)ier=4
      if(ier.eq.4)goto 100
      if(lcur.gt.lmax)lcur=lmax
      ier=0
      if(iflag.gt.0.and.iflag.lt.5.and.i.gt.0.and.i.le.n.and.j.gt.0
     $.and.j.le.n.and.lcur.ge.0.and.lcur.le.lmax)goto 2
      ier=1
```

```
      goto100
2     continue
c     examine movement forward or backward
      kd=k-inl(lcur)
      nd=0
      if(kd.ne.0)nd=kd/iabs(kd)
      ni=0
      lc=lcur
      if(nd.eq.0)ni=-1
      if(ni.lt.0)goto 11
      if(nd.gt.0.and.lcur.eq.lmax.and.iflag.eq.2)goto26
c     ni=0,-1,+1 for out of range,exact,intermediate
      li=lcur
      lf=lmax
      lc=lcur
      if(nd.gt.0)goto3
      li=1
      lf=lcur
3     continue
      do10lin=li,lf
      if(((k-inl(lc))*nd).eq.0)ni=-1
      if(((k-inl(lc))*nd).lt.0)ni=1
      if(ni.ne.0)goto11
10    lc=lc+nd
11    continue
      if(ni.ge.0.and.iflag.ne.2)ier=2
      if(ier.ne.0)goto 100
      lcur=lc
      if(ni.eq.0.and.nd.gt.0.and.iflag.eq.2)goto28
      if(ni.eq.0.and.nd.lt.0.and.iflag.eq.2)goto27
      if(ni.lt.0.and.iflag.eq.4)then
      vl(lc)=x
      return
      endif
      if(iflag.eq.2.and.ni.ge.0.and.(lmax+1).gt.nemax)ier=3
      if(ier.ne.0)goto100
      if(iflag.eq.2.and.ni.lt.0)vl(lc)=vl(lc)+x
      if(iflag.eq.1.and.ni.lt.0)x=vl(lc)
      if(iflag.ne.3.and.ni.lt.0)return
      if(iflag.eq.2)goto15
      lmax=lmax-1
      if(lmax.le.0)ier=4
      if(ier.ne.0)goto100
      ntk=0
      if(lcur.gt.lmax)ntk=1
      if(ntk.eq.0)goto13
      x=vl(lcur)
      lcur=lmax
      return
13    x=vl(lc)
      do12ia=lcur,lmax
```

```
      inl(ia)=inl(ia+1)
12    vl(ia)=vl(ia+1)
      return
15    lmax=lmax+1
      if(ni.eq.1.and.nd.lt.0)lc=lc+1
      ka=k
      xa=x
      do20ia=lc,lmax
      xb=vl(ia)
      vl(ia)=xa
      kb=inl(ia)
      inl(ia)=ka
      ka=kb
20    xa=xb
25    lcur=lmax
      return
27    lc=1
      goto 15
28    lcur=lmax
26    lcur=lcur+1
      lmax=lcur
      if(lmax.gt.nemax)ier=3
      if(ier.eq.3)goto100
      inl(lcur)=k
      vl(lcur)=x
      return
100   write(*,*)'err return from sub spear'
      return
      end
c     ----------------------------------------------------------
      subroutine spcrp(i,n,lmax,nemax,inl,l1,l2,ld,ni)
c     subroutine to find pointers on inl(nemax) for initial data l1,
c     final data l2, and diagonal element ld for a given row no., i
c     on exit,ni=no.of data in the row
c     if ld=0: no diagonal element, ni=0:no data for the row
c     i=row no.sought,n=order of matrix,lmax=pointer for furthest
c     pointer for data in inl(nemax)
      dimension inl(nemax)
      l1=0
      l2=0
      ld=0
      ni=0
      k1=((i-1)*n)+1
      k2=k1+i-1
      k3=k1+n-1
      if(inl(1).gt.k3.or.inl(lmax).lt.k1)return
      do50l=1,lmax
      k=inl(l)
      if(k1.le.k.and.k.le.k3)goto 10
      goto 20
10    if(ni.eq.0)l1=l
```

```
      ni=ni+1
      if(k.eq.k2)ld=l
      l2=l
      goto 50
20    if(k.lt.k3)goto50
      goto 60
50    continue
60    return
      end
c     ----------------------------------------------------------
      subroutine spmsol(n,lmax,nemax,inl,vl,rv,c)
c     subroutine for general sparse matrix solution
c     n=order of matrix, lmax=max.value of pointer, nemax=size
c     of two vectors inl(nemax) and vl(nemax), rv(n)=right
c     hand side vector,c=working place
c
      dimension vl(nemax),inl(nemax),rv(n),c(2,n),r(2)
      ier=0
      lcur=1
      np=n-1
      do1j=1,n
      do1i=1,2
      c(i,j)=0.
1     continue
      do10i1=1,np
      i=i1
      call spcrp(i,n,lmax,nemax,inl,l11,l21,ld1,ni1)
      if(ni1.eq.0)goto10
      do2j=i1,n
2     c(1,j)=0.
      do3i=l11,l21
      k=inl(i)
      j=k-((i1-1)*n)
      if(j.lt.i1)goto 3
      c(1,j)=vl(i)
3     continue
      r(1)=rv(i1)
c     addition of rows, if diagonal = 0
      if(c(1,i1).ne.0.)goto36
      l22=l21+1
      do31i2=l22,lmax
      k=inl(i2)
      i=((k-1)/n)+1
      j=k-((i-1)*n)
      if(j.eq.i1.and.vl(i2).ne.0.)goto32
31    continue
      lab=31
      goto 20
32    call spcrp(i,n,lmax,nemax,inl,l12,l22,ld2,ni2)
      lab=32
      do33i2=l12,l22
```

```
      k=inl(i2)
      j=k-((i-1)*n)
      if(j.lt.i1)goto 33
      x=vl(i2)
      k=i1
      call spear(nemax,k,j,n,lcur,lmax,inl,x,vl,2,ier)
      if(ier.ne.0) GOTO 20
33    continue
      rv(i1)=rv(i1)+rv(i)
      call spcrp(k,n,lmax,nemax,inl,l11,l21,ld1,ni1)
      do34j=1,n
34    c(1,j)=0.
      do35i=l11,l21
      k=inl(i)
      j=k-((i1-1)*n)
      if(j.lt.i1)goto35
      c(1,j)=vl(i)
35    continue
      r(1)=rv(i1)
36    na=i1+1
      do8i2=na,n
      i=i2
      call spcrp(i,n,lmax,nemax,inl,l12,l22,ld2,ni2)
      if(ni2.eq.0)goto 8
      do4j=i1,n
4     c(2,j)=0.
      do5i=l12,l22
      k=inl(i)
      j=k-((i2-1)*n)
      if(j.lt.i1)goto 5
      c(2,j)=vl(i)
5     continue
      r(2)=rv(i2)
      xa=c(2,i1)/c(1,i1)
      rv(i2)=r(2)-(r(1)*xa)
      i=i2
      lab=6
      do6j1=i1,n
      j=j1
      x=0.
      if(j.ne.i1)x=c(2,j)-(c(1,j)*xa)
      nsp=0
      if(c(2,j).eq.0..and.x.ne.0.)nsp=2
      if(c(2,j).ne.0..and.x.eq.0.)nsp=3
      if(c(2,j).ne.0..and.x.ne.0.)nsp=4
      if(nsp.ne.0)call spear(nemax,i,j,n,lcur,lmax,inl,x,vl,nsp,ier)
      if(ier.ne.0) goto 20
6     continue
8     continue
10    continue
      k1=inl(1)
```

```
      k2=inl(lmax)
      i1=((k1-1)/n)+1
      i2=((k2-1)/n)+1
      if((((i1-1)*n)+i1).ne.k1.or.(((i2-1)*n)+i2).ne.k2)goto20
      imin=n-i2+2
      imax=n-i1+1
      rv(i2)=rv(i2)/vl(lmax)
      lab=15
      do15is=imin,imax
      i1=n-is+1
      i=i1
      call spcrp(i,n,lmax,nemax,inl,l11,l21,ld1,ni1)
      if(ni1.eq.0)rv(i1)=0.
      if(ni1.eq.0)goto15
      if(ld1.eq.0)goto20
      if(ld1.ne.0) then
      if(vl(ld1).eq.0.)goto20
      endif
      l12=ld1+1
      if(i1.eq.n)goto14
      do12j=l12,l21
      k1=inl(j)
      j1=k1-((i1-1)*n)
12    rv(i1)=rv(i1)-(vl(j)*rv(j1))
14    rv(i1)=rv(i1)/vl(ld1)
15    continue
      return
20    write(*,*)'err stop in sub spmsol at label= ',lab
      stop
      end
      subroutine stcoef
c     character rkey
c    computing coefficients for steady solution of heat conduction
c    --------------------------------------------------------------
c    ns=number of stages, nsf=number of fan stages
c
      common /htd1/ndum(5),ndtop(20,8,6),ndmax(20),splen(20,8,4),
     $arnod(20,8,4),htcap(20,8),casrad(20),excfcs,nexpr(20),excfr
     $(20,4),radex(20,4),tradd(145),xlcso(2,170),xlro(2,170),rotdis(20)
     $,dtimcl,rrv(145),cwork(300),rrvp(145),nexnod(4,20),
     $nexcas(20),t0cas,tcas,rocas,ucas,trotor,rpm,rorot,urot,deltem
     $,nboht,twcas,nemax,wfstrf,nrotcs,trchi(20),trcho(20),txw0(20),
     $ttawm(20),tpawm(20),tvol(20),permax,txwc(20),ttawc(20),tpawc(20)
     $,tmasa(20),dwat
c    xlcso=(begin,end) coordinates [in] in axial direction
c              outside/inside casing for specified nodes
c    xlro=(begin,end) coordinates [in] in axial direction
c            at outer/inner rotor radius for specified nodes
c    t0cas[K],tcas[K],rocas[kg/m3],ucas[m/s] are gas-states outside
c    casing
c
```

```
      common /hdat/tt1c(20),tt2c(20),tt3c(20),tro1c(20),tro2c(20),
     $tro3c(20),tcm1c(20),tcm2c(20),tcm3c(20),tw1c(20),tw2c(20),tc1c
     $(20),tc2c(20),tc3c(20),inl(600),vl(600),twcasr(20),twbr(20),
     $twbs(20),trpmc(20)
c
      common /cdat3/jperfm,rhog(3),rerup,rerlow,resup,reslow
     &,preb,rrtip(20),srtip(20),aaa1,aaa2,aaa3,sarea(20),sareas(20)
     &,p(3),tg(3),xa,xv(3),xch4,xw(3),xww(3),xwt(3),tw(3),tww(3)
     &,omegs(20),omegr(20),gapr(20),gaps(20),tsg(3),psg(3)
     &,rrhub(20) , rc(20) , rblade(20) , stager(20)
     &,srhub(20) , sc(20) , sblade(20),stages(20)
     &,sigumr(20) , bet1sr(20) , bet2sr(20) , aincsr(20) , adevsr(20)
     &,sigums(20) , bet1ss(20) , bet2ss(20) , aincss(20) , adevss(20)
     &,utipg(20),utip(20),utipd(20),uou(20),umean(20),uhub(20),u(20),fai
     &,area(20),areas(20),uu2(20),utip2(20),umean2(20),uhub2(20),iprint
     &,icent,iicent,fmr1(20),fma2(20),idesin,faid
     &,ns,nsf,nslpc,bypass,ns1,rt(20),rm(20),rh(20),st(20),sm(20),sh(20)
     &,dsmass,aarea(20),aareas(20),pr12d(20),pr13d(20),etard(20)
     &,dr(20),ds(20),deqr(20),deqs(20),block(20),blocks(20)
     &,bet1mr(20),bet2mr(20),bet1ms(20),bet2ms(20),radi1(20),radi2(20)
     &,fairin(20),faiout(20),etasg(20),psid(20),taud(20),sitadr(20)
     &,sitads(20),wwd(20),vvd(20)
c
c     dummy arrays
      dimension nnv(4),vtmp(4)
      real nu
      ns1=ns+1
      nele=(ns*7)+5
      if(nrotcs.eq.3)nele=(ns*8)+5
c
      pi=atan(1.)*4.
c
c     clear space in inl,vl,rrv
c
      do1i=1,nemax
      inl(i)=0
1     vl(i)=0.
      do2i=1,nele
2     rrv(i)=0.
3     format(a)
c
c     calculate coefficient matrix, ipst=pointer on stages
c     ipel = pointer on element = pointer on row
      jpc = pointer on column
c
      ipst=1
      ipel=1
      lcur=0
      lmax=0
      do1000ist=1,ns
      if((ipst-1).ne.nsf)goto100
```

```
c    for IGV: nerow= no.of elements in IGV,nadj=no.of adjacent nodes
      nerow=ndmax(ipst)
      tblad=(tt2c(ns1)+tt3c(ns1))*.5
      ub=(tc2c(ns1)+tc3c(ns1))*.5
      rhob=(tro2c(ns1)+tro3c(ns1))*.5
      do80i1=1,nerow
      nadj=ndtop(ipst,i1,2)
      do10i2=1,nadj
      vtmp(i2)=0.
      n3=ndtop(ipst,i1,i2+2)
      nnv(i2)=n3
      if(n3.gt.0.or.n3.eq.-74)vtmp(i2)=arnod(ipst,i1,i2)
     $/splen(ipst,i1,i2)
      if(n3.eq.-72) then
      if(i1.eq.1.or.i1.eq.2) then
      if(i1.eq.1) then
      x1=xlro(1,i1)
      x2=xlro(2,i1)
      endif
      if(i1.eq.2) then
      x1=xlcso(1,i1)
      x2=xlcso(2,i1)
      endif
      x1=x1*0.0254
      x2=x2*0.0254
      tc=tt2c(ns1)
      xmu=1.8366e-5*(tc/300.)**.6
      ro=tro2c(ns1)
      uz=tcm2c(ns1)
      re1=ro*uz*x1/xmu
      re2=ro*uz*x2/xmu
      nu=0.02063*abs(re2**0.8-re1**0.8)/0.8
      xl=abs(x2-x1)
      xk=xmu*1415.493
      vtmp(i2)=arnod(ipst,i1,i2)/((xl/(nu*xk))+splen(ipst,i1,i2))
      endif
      if(i1.eq.4) then
      xl=sc(ns1)*.0254
      xmu=1.8366e-5*(tblad/300.)**0.6
      re=rhob*ub*xl/xmu
      nu=0.02063*re**0.8
      xk=xmu*1415.493
      vtmp(i2)=arnod(ipst,i1,i2)/((xl/(nu*xk))+splen(ipst,i1,i2))
      endif
      endif
      if(n3.eq.-73) then
      x1=xlcso(1,i1)*0.0254
      x2=xlcso(2,i1)*0.0254
      xmu=1.8366e-5*(tcas/300.)**0.6
      xk=xmu*1415.493
      re1=rocas*ucas*x1/xmu
```

```
      re2=rocas*ucas*x2/xmu
      nu=0.02063*abs(re2**0.8-re1**0.8)/0.8
      vtmp(i2)=arnod(ipst,i1,i2)/((abs(x2-x1)/(nu*xk))+splen(ipst,i1
     $,i2))
      endif
      if(n3.eq.-76) then
      x1=xlro(1,i1)*.0254
      x2=xlro(2,i1)*.0254
      xmu=1.8366e-5*(trotor/300.)**.6
      re1=rorot*urot*x1/xmu
      re2=rorot*urot*x2/xmu
      nu=0.02063*abs(re2**0.8-re1**0.8)/0.8
      xl=abs(x2-x1)
      xk=xmu*1415.493
      vtmp(i2)=arnod(ipst,i1,i2)/((xl/(nu*xk))+splen(ipst,i1,i2))
      endif
c     write(*,*)'10:i1,i2,nadj,n3,vtmp(i2):',i1,i2,nadj,n3,vtmp(i2)
10    continue
      sum=0.
      do12i2=1,nadj
12    sum=sum+vtmp(i2)
      do13i2=1,nadj
13    vtmp(i2)=vtmp(i2)/sum
      call spear(nemax,ipel,ipel,nele,lcur,lmax,inl,-1.,vl,2,ier)
      ichk=14
      if(ier.ne.0)goto1005
      do20i2=1,nadj
      n3=nnv(i2)
      if(n3.eq.-75)vtmp(i2)=0.
      if(n3.lt.0.and.n3.ne.-75) then
      if((i1.eq.2.or.i1.eq.3).and.(n3.eq.-73.or.n3.eq.-74)) then
      tc=t0cas
      rrv(ipel)=rrv(ipel)-(vtmp(i2)*tc)
      vtmp(i2)=0.
      endif
      if(i1.eq.1) then
      if(n3.eq.-74.or.n3.eq.-76)tc=trotor
      if(n3.eq.-72)tc=(tt2c(ns1)+tt2c(ns1))*.5
      rrv(ipel)=rrv(ipel)-(vtmp(i2)*tc)
      vtmp(i2)=0.
      endif
      if(i1.eq.2.and.n3.eq.-72) then
      tc=tt2c(ns1)
      rrv(ipel)=rrv(ipel)-(vtmp(i2)*tc)
      vtmp(i2)=0.
      endif
      if(i1.eq.4.and.n3.eq.-72)then
      tc=(tt2c(ns1)+tt2c(ns1))*.5
      rrv(ipel)=rrv(ipel)-(vtmp(i2)*tc)
      vtmp(i2)=0.
      endif
```

```
      endif
      if(n3.gt.0.and.vtmp(i2).ne.0.) then
      jpc=n3
      val=vtmp(i2)
      call spear(nemax,ipel,jpc,nele,lcur,lmax,inl,val,vl,2,ier)
      ichk=20
      if(ier.ne.0)goto1005
      endif
20    continue
c     write(*,*)'20:ipel,ipst,nele,lmax:',ipel,ipst,nele,lmax
c     read(*,3)rkey
      ipel=ipel+1
80    continue
      ipst=ipst+1
100   continue
c    for stage nerow= no.of elements,nadj=no.of adjacent nodes
      nerow=ndmax(ipst)
      tbladr=(tt1c(ist)+tt2c(ist))*.5
      ubr=(tw1c(ist)+tw2c(ist))*.5
      ubmr=(tcm1c(ist)+tcm2c(ist))*.5
      xmur=1.8366e-5*(tbladr/300.)**.6
      xkr=xmur*1415.493
      rhobr=(tro1c(ist)+tro2c(ist))*.5
      tblads=(tt3c(ist)+tt2c(ist))*.5
      ubs=(tc3c(ist)+tc2c(ist))*.5
      ubms=(tcm3c(ist)+tcm2c(ist))*.5
      xmus=1.8366e-5*(tblads/300.)**.6
      xks=xmus*1415.493
      rhobs=(tro2c(ist)+tro3c(ist))*.5
      do180i1=1,nerow
      nadj=ndtop(ipst,i1,2)
      do110i2=1,nadj
      vtmp(i2)=0.
      n3=ndtop(ipst,i1,i2+2)
      nnv(i2)=n3
      if(n3.gt.0.or.n3.eq.-74)vtmp(i2)=arnod(ipst,i1,i2)
     $/splen(ipst,i1,i2)
      if(n3.eq.-71) then
      if(i1.eq.1)xl=rc(ist)*0.0254
      if(i1.eq.5)xl=abs(xlcso(2,ipel)-xlcso(1,ipel))*0.0254
      re=rhobr*ubr*xl/xmur
      nu=0.02063*re**0.8
      vtmp(i2)=arnod(ipst,i1,i2)/((xl/(nu*xk))+splen(ipst,i1,i2))
      endif
      if(n3.eq.-72) then
      if(i1.eq.7)xl=sc(ist)*0.0254
      if(i1.eq.4)xl=abs(xlro(2,ipel)-xlro(1,ipel))*0.0254
      re=rhobs*ubs*xl/xmur
      nu=0.02063*re**0.8
      vtmp(i2)=arnod(ipst,i1,i2)/((xl/(nu*xk))+splen(ipst,i1,i2))
      endif
```

```
      if(n3.eq.-73.and.i2.eq.3) then
      x1=xlcso(1,ipel)*0.0254
      x2=xlcso(2,ipel)*0.0254
      xmu=1.8366e-5*(tcas/300.)*0.6
      xk=xmu*1415.493
      re1=rocas*ucas*x1/xmu
      re2=rocas*ucas*x2/xmu
      nu=0.02063*abs(re2**0.8-re1**0.8)/0.8
      vtmp(i2)=arnod(ipst,i1,i2)/((abs(x2-x1)/(nu*xk))+splen(ipst,i1,
     $i2))
      endif
      if(n3.eq.-76) then
      if(i1.eq.4) then
      x1=xlro(1,ipel)*.0254
      x2=xlro(2,ipel)*.0254
      xmu=1.8366e-5*(trotor/300.)**.6
      re1=rorot*urot*x1/xmu
      re2=rorot*urot*x2/xmu
      nu=0.02063*abs(re2**0.8-re1**0.8)/0.8
      xl=abs(x2-x1)
      xk=xmu*1415.493
      vtmp(i2)=arnod(ipst,i1,i2)/((xl/(nu*xk))+splen(ipst,i1,i2))
      endif
      if(i1.eq.3) then
      rroti=rotdis(ist)*.0254
      omega=pi*rpm/30.
      betdt=deltem/trotor
      xmu=1.8366e-5*(trotor/300.)**.6
      xk=xmu*1415.493
      nu=0.0054*(rorot*2.*urot*rroti/xmu)**0.3*((rorot*omega/xmu)**2*
     $betdt)**0.25
      vtmp(i2)=arnod(ipst,i1,i2)/((1./(nu*xk))+splen(ipst,i1,i2))
      endif
      endif
      if(n3.eq.-77) then
      if(nrotcs.eq.2.or.(nrotcs.eq.3.and.i1.eq.3)) then
      xwc=txw0(ist)
      tc=ttawm(ist)
      trotin=tc
      xvc=0.
      pb=tpawm(ist)
      rmc=(trchi(ist)+trcho(ist))*.0127
      xl=abs(trcho(ist)-trchi(ist))*.0254
      call mixprp(tc,pb,xvc,xwc,cpm,rhom,xmum,xkm,xkwat)
      omega=pi*rpm/30.
      gr=rmc*(omega*rhom/xmum)**2*deltem*xl**3/tc
      pran=xmum*cpm/xkm
      if(gr.le.1.e9)nu=0.508*(pran*gr/(pran+0.952))**0.25
      if(gr.gt.1.e9)nu=0.024*(pran**1.17*gr/(1.+(pran**.666667*.494)
     $))**.4
c     if water present water thickness taken as 5 micron
```

```
      dw=0.
      if(xwc.gt.0.)dw=dwat
      vtmp(i2)=
     $arnod(ipst,i1,i2)/((xl/(xkm*nu))+(dw/xkwat)+splen(ipst,i1,i2))
      vtmps=vtmp(i2)
      endif
      if(nrotcs.eq.3)vtmp(i2)=vtmps
      endif
c     write(*,*)'110:i1,i2,nadj,n3,vtmp(i2):',i1,i2,nadj,n3,vtmp(i2)
110   continue
      sum=0.
      do112i2=1,nadj
112   sum=sum+vtmp(i2)
      do113i2=1,nadj
113   vtmp(i2)=vtmp(i2)/sum
      call spear(nemax,ipel,ipel,nele,lcur,lmax,inl,-1.,vl,2,ier)
      ichk=114
      if(ier.ne.0)goto1005
      do120i2=1,nadj
      n3=nnv(i2)
      if(n3.eq.-75)vtmp(i2)=0.
      if((n3.lt.0.and.n3.ne.-75.and.n3.ne.-77).or.(n3.eq.-77.and.
     $nrotcs.eq.2)) then
      if(n3.eq.-71)tc=(tt1c(ist)+tt2c(ist))*.5
      if(n3.eq.-72)tc=(tt2c(ist)+tt3c(ist))*.5
      if(i2.eq.3.and.(n3.eq.-73.or.n3.eq.-74))tc=t0cas
      if(i2.eq.4.and.n3.eq.-74)tc=trotor
      if(n3.eq.-76)tc=trotor
      if(n3.eq.-77.and.nrotcs.eq.2)tc=trotin
      rrv(ipel)=rrv(ipel)-(vtmp(i2)*tc)
      vtmp(i2)=0.
      endif
      if((n3.gt.0.or.(n3.eq.-77.and.nrotcs.eq.3)).and.vtmp(i2).ne.0.)
     $then
      val=vtmp(i2)
      jpc=n3
      if(n3.eq.-77) then
      if(i1.eq.3) jpc=((ist-1)*8)+12
      if(i1.eq.8) jpc=((ist-1)*8)+7
      endif
      call spear(nemax,ipel,jpc,nele,lcur,lmax,inl,val,vl,2,ier)
      ichk=120
      if(ier.ne.0)goto1005
      endif
120   continue
c     write(*,*)'120:ipel,ipst,nele,lmax:',ipel,ipst,nele,lmax
c     read(*,3)rkey
      ipel=ipel+1
180   continue
      ipst=ipst+1
1000  continue
```

```
c
c   post-stage
c
      nadj=ndtop(ipst,1,2)
      do210i2=1,nadj
      vtmp(i2)=0.
      n3=ndtop(ipst,1,i2+2)
      nnv(i2)=n3
      if(n3.gt.0.or.n3.eq.-74)vtmp(i2)=arnod(ipst,1,i2)
     $/splen(ipst,1,i2)
      if(n3.eq.-72) then
      xl=abs(xlcso(2,ipel)-xlcso(1,ipel))*.0254
      tc=tt3c(ns)
      xmu=1.8366e-5*(tc/300.)**.6
      xk=xmu*1415.493
      re=tro3c(ns)*tcm3c(ns)*xl/xmu
      nu=0.02063*re**0.8
      vtmp(i2)=arnod(ipst,1,i2)/((xl/(nu*xk))+splen(ipst,1,i2))
      endif
      if(n3.eq.-73) then
      x1=xlcso(1,ipel)*0.0254
      x2=xlcso(2,ipel)*0.0254
      xmu=1.8366e-5*(tcas/300.)**0.6
      xk=xmu*1415.493
      re1=rocas*ucas*x1/xmu
      re2=rocas*ucas*x2/xmu
      nu=0.02063*abs(re2**0.8-re1**0.8)/0.8
      vtmp(i2)=arnod(ipst,i1,i2)/((abs(x2-x1)/(nu*xk))+splen(ipst,i1,
     $i2))
      endif
c     write(*,*)'110:i1,i2,nadj,n3,vtmp(i2):',i1,i2,nadj,n3,vtmp(i2)
210   continue
      sum=0.
      do212i2=1,nadj
212   sum=sum+vtmp(i2)
      do213i2=1,nadj
213   vtmp(i2)=vtmp(i2)/sum
      call spear(nemax,ipel,ipel,nele,lcur,lmax,inl,-1.,vl,2,ier)
      ichk=214
      if(ier.ne.0)goto1005
      do220i2=1,nadj
      n3=nnv(i2)
      if(n3.eq.-75)vtmp(i2)=0.
      if(n3.lt.0.and.n3.ne.-75) then
      if(n3.eq.-72)tc=(tt2c(ist)+tt3c(ist))*.5
      if(i2.eq.3.and.(n3.eq.-73.or.n3.eq.-74))tc=t0cas
      rrv(ipel)=rrv(ipel)-(vtmp(i2)*tc)
      vtmp(i2)=0.
      endif
      val=vtmp(i2)
      if(n3.gt.0.and.val.ne.0.) then
```

```
      jpc=n3
      call spear(nemax,ipel,jpc,nele,lcur,lmax,inl,val,vl,2,ier)
      ichk=220
      if(ier.ne.0)goto1005
      endif
220   continue
c      write(*,*)'220:ipel,ipst,nele,lmax:',ipel,ipst,nele,lmax
c      read(*,3)rkey
      if(lmax.ge.nemax) then
      write(*,*)'insufficient space in arrays inl(),vl().'
      write(*,*)'increase value of nemax, and array size of ',
     $'inl(),vl() to more than',lmax
      write(*,*)'recompile and run after correction'
      stop
      endif
c     solution of equations
      call spmsol(nele,lmax,nemax,inl,vl,rrv,cwork)
      if(nrotcs.gt.1) then
      rair=8314.3/28.964
      do230i1=1,ns
      txwc(i1)=txw0(i1)
      ttawc(i1)=ttawm(i1)
      tpawc(i1)=tpawm(i1)
      tmasa(i1)=tpawm(i1)*1.e5*tvol(i1)/(rair*ttawm(i1))
      if(nrotcs.eq.3)rrv(((i1-1)*8)+12)=ttawc(i1)
230   continue
      endif
      return
1005  write(*,*)
     $'err stop in sub stcoef, ichk,ier,lcur,lmax,nemax= ',
     $ichk,ier,lcur,lmax,nemax
      stop
      end
      subroutine tdcoef
c      character rkey
c     computing coefficients for steady solution of heat conduction
c     ---------------------------------------------------------------
c     ns=number of stages, nsf=number of fan stages
c     nopt=1/2 for steady-state/time-dependent solution
c
      common /htd1/ndum(5),ndtop(20,8,6),ndmax(20),splen(20,8,4),
     $arnod(20,8,4),htcap(20,8),casrad(20),excfcs,nexpr(20),excfr
     $(20,4),radex(20,4),tradd(145),xlcso(2,170),xlro(2,170),rotdis(20)
     $,dtimcl,rrv(145),cwork(300),rrvp(145),nexnod(4,20),
     $nexcas(20),t0cas,tcas,rocas,ucas,trotor,rpm,rorot,urot,deltem
     $,nboht,twcas,nemax,wfstrf,nrotcs,trchi(20),trcho(20),txw0(20),
     $ttawm(20),tpawm(20),tvol(20),permax,txwc(20),ttawc(20),tpawc(20)
     $,tmasa(20),dwat
c     xlcso=(begin,end) coordinates [in] in axial direction
c              outside/inside casing for specified nodes
c     xlro=(begin,end) coordinates [in] in axial direction
```

```
c          at outer/inner rotor radius for specified nodes
c    t0cas[K],tcas[K],rocas[kg/m3],ucas[m/s] are gas-states outside
c    casing
c
      common /hdat/tt1c(20),tt2c(20),tt3c(20),tro1c(20),tro2c(20),
     $tro3c(20),tcm1c(20),tcm2c(20),tcm3c(20),tw1c(20),tw2c(20),tc1c
     $(20),tc2c(20),tc3c(20),inl(600),vl(600),twcasr(20),twbr(20),
     $twbs(20),trpmc(20)
c
      common /cdat3/jperfm,rhog(3),rerup,rerlow,resup,reslow
     &,preb,rrtip(20),srtip(20),aaa1,aaa2,aaa3,sarea(20),sareas(20)
     &,p(3),tg(3),xa,xv(3),xch4,xw(3),xww(3),xwt(3),tw(3),tww(3)
     &,omegs(20),omegr(20),gapr(20),gaps(20),tsg(3),psg(3)
     &,rrhub(20) , rc(20) , rblade(20) , stager(20)
     &,srhub(20) , sc(20) , sblade(20),stages(20)
     &,sigumr(20) , bet1sr(20) , bet2sr(20) , aincsr(20) , adevsr(20)
     &,sigums(20) , bet1ss(20) , bet2ss(20) , aincss(20) , adevss(20)
     &,utipg(20),utip(20),utipd(20),uou(20),umean(20),uhub(20),u(20),fai
     &,area(20),areas(20),uu2(20),utip2(20),umean2(20),uhub2(20),iprint
     &,icent,iicent,fmr1(20),fma2(20),idesin,faid
     &,ns,nsf,nslpc,bypass,ns1,rt(20),rm(20),rh(20),st(20),sm(20),sh(20)
     &,dsmass,aarea(20),aareas(20),pr12d(20),pr13d(20),etard(20)
     &,dr(20),ds(20),deqr(20),deqs(20),block(20),blocks(20)
     &,bet1mr(20),bet2mr(20),bet1ms(20),bet2ms(20),radi1(20),radi2(20)
     &,fairin(20),faiout(20),etasg(20),psid(20),taud(20),sitadr(20)
     &,sitads(20),wwd(20),vvd(20)
c
      dimension nnv(4),vtmp(4)
      real nu
c
      pi=atan(1.)*4.
      ns1=ns+1
c    if(nrotcs.eq.3), compute heat capacity for 8th node in each stage.
      if(nrotcs.eq.3) then
      do401i=1,ns
      xwc=txwc(i)
      xvc=txw0(i)-txwc(i)
      tc=ttawc(i)
      pb=tpawc(i)
      call mixprp(tc,pb,xvc,xwc,cpm,rhom,xmum,xkm,xkwat)
      htcap(i+1,8)=rhom*tvol(i)*cpm
c     write(*,*)'tdc:i,rho,vol,cpm,Mc=',i,rhom,tvol(i),cpm,htcap(i+1,8)
401   continue
c     read(*,3)rkey
      endif
c3    format(a)
c
c    clear space in inl,vl; store away old data to rrvp
c
      nele=(ns*7)+5
      if(nrotcs.eq.3)nele=(ns*8)+5
```

```
      do1i=1,nemax
      inl(i)=0
1      vl(i)=0.
      do2i=1,nele
      rrvp(i)=rrv(i)
2      rrv(i)=0.
c
c      calculate coefficient matrix, ipst=pointer on stages
c      ipel = pointer on element = pointer on row
      jpc = pointer on column
c
      ipst=1
      ipel=1
      lcur=0
      lmax=0
      do1000ist=1,ns
      if((ipst-1).ne.nsf)goto100
c      for IGV: nerow= no.of elements in IGV,nadj=no.of adjacent nodes
      dtime=dtimcl
      nerow=ndmax(ipst)
      tblad=(tt2c(ns1)+tt3c(ns1))*.5
      ub=(tc2c(ns1)+tc3c(ns1))*.5
      rhob=(tro2c(ns1)+tro3c(ns1))*.5
      do80i1=1,nerow
      nadj=ndtop(ipst,i1,2)
      htc=htcap(ipst,i1)
      con=dtime*.5/htc
      ajtj=0.
      aktk=0.
      aos=0.
      do10i2=1,nadj
      heff=0.
      n3=ndtop(ipst,i1,i2+2)
      nnv(i2)=n3
      if(n3.gt.0.or.n3.eq.-74)heff=arnod(ipst,i1,i2)
     $/splen(ipst,i1,i2)
      if(n3.eq.-72) then
      if(i1.eq.1.or.i1.eq.2) then
      if(i1.eq.1) then
      x1=xlro(1,i1)
      x2=xlro(2,i1)
      tc=tblad
      endif
      if(i1.eq.2) then
      x1=xlcso(1,i1)
      x2=xlcso(2,i1)
      tc=tt2c(ns1)
      endif
      x1=x1*0.0254
      x2=x2*0.0254
      xmu=1.8366e-5*(tc/300.)**.6
```

```
ro=tro2c(ns1)
uz=tcm2c(ns1)
re1=ro*uz*x1/xmu
re2=ro*uz*x2/xmu
nu=0.02063*abs(re2**0.8-re1**0.8)/0.8
xl=abs(x2-x1)
endif
if(i1.eq.4) then
xl=sc(ns1)*.0254
tc=tblad
xmu=1.8366e-5*(tblad/300.)**0.6
re=rhob*ub*xl/xmu
nu=0.02063*re**0.8
endif
xk=xmu*1415.493
heff=arnod(ipst,i1,i2)/((xl/(nu*xk))+splen(ipst,i1,i2))
endif
if(n3.eq.-73) then
tc=t0cas
x1=xlcso(1,i1)*0.0254
x2=xlcso(2,i1)*0.0254
xmu=1.8366e-5*(tcas/300.)**0.6
xk=xmu*1415.493
re1=rocas*ucas*x1/xmu
re2=rocas*ucas*x2/xmu
nu=0.02063*abs(re2**0.8-re1**0.8)/0.8
heff=arnod(ipst,i1,i2)/((abs(x2-x1)/(nu*xk))+splen(ipst,i1,
$i2))
endif
if(n3.eq.-76) then
tc=trotor
x1=xlro(1,i1)*.0254
x2=xlro(2,i1)*.0254
xmu=1.8366e-5*(trotor/300.)**.6
re1=rorot*urot*x1/xmu
re2=rorot*urot*x2/xmu
nu=0.02063*abs(re2**0.8-re1**0.8)/0.8
xl=abs(x2-x1)
xk=xmu*1415.493
heff=arnod(ipst,i1,i2)/((xl/(nu*xk))+splen(ipst,i1,i2))
endif
if(twcas.ne.0.) then
if(i2.eq.3.and.(i1.eq.2.or.i1.eq.3)) then
tout=t0cas
tnode=rrvp(ipel)
tsurfo=((tout-tnode)*heff*splen(ipst,i1,i2))+tnode
tsurf=(tsurfo*(1.-wfstrf))+(wfstrf*twcas)
hcor=(tsurf-tnode)/(splen(ipst,i1,i2)*(tout-tsurf))
heff=1./((1./abs(hcor))+splen(ipst,i1,i2))
endif
endif
```

```
      twc=twbs(ns1)
      if(twc.gt.0..and.i1.eq.4.and.i2.eq.2) then
      tout=tblad
      tnode=rrvp(ipel)
      tsurfo=((tout-tnode)*heff*splen(ipst,i1,i2))+tnode
      tsurf=(tsurfo*(1.-wfstrf))+(wfstrf*twc)
      hcor=(tsurf-tnode)/(splen(ipst,i1,i2)*(tout-tsurf))
      heff=1./((1./abs(hcor))+splen(ipst,i1,i2))
      endif
      vtmp(i2)=heff*con
c      write(*,*)'10:i1,i2,nadj,n3,vtmp(i2):',i1,i2,nadj,n3,vtmp(i2)
      if(n3.eq.-74.and.i2.eq.3)tc=t0cas
      if(n3.eq.-74.and.i2.eq.4)tc=trotor
      if(n3.gt.0)ajtj=ajtj+(vtmp(i2)*rrvp(n3))
      aos=aos+vtmp(i2)
      if(n3.gt.0.or.n3.eq.-75)goto 10
      aktk=aktk+(tc*vtmp(i2))
      vtmp(i2)=0.
10    continue
c     aktk=sum(ak'*Tk); ajtj=sum(aj'*Tj), j.ne.(k.or.l)
      do14i2=1,nadj
      n3=nnv(i2)
13    if(n3.lt.0)goto 14
      val=-vtmp(i2)
      jpc=n3
      call spear(nemax,ipel,jpc,nele,lcur,lmax,inl,val,vl,2,ier)
      ichk=13
      if(ier.ne.0)goto1005
14    continue
      rrv(ipel)=(rrvp(ipel)*(1.-aos))+ajtj+(aktk*2.)
      vc=1.+aos
      call spear(nemax,ipel,ipel,nele,lcur,lmax,inl,vc,vl,2,ier)
      ichk=14
      if(ier.ne.0)goto1005
c      write(*,*)'80:ipel,ipst,nele,lmax:',ipel,ipst,nele,lmax
c      read(*,3)rkey
      ipel=ipel+1
80    continue
      ipst=ipst+1
100   continue
c     for stage nerow= no.of elements,nadj=no.of adjacent nodes
      nerow=ndmax(ipst)
      dtime=dtimcl
      tbladr=(tt1c(ist)+tt2c(ist))*.5
      ubr=(tw1c(ist)+tw2c(ist))*.5
      ubmr=(tcm1c(ist)+tcm2c(ist))*.5
      xmur=1.8366e-5*(tbladr/300.)**.6
      xkr=xmur*1415.493
      rhobr=(tro1c(ist)+tro2c(ist))*.5
      tblads=(tt3c(ist)+tt2c(ist))*.5
      ubs=(tc3c(ist)+tc2c(ist))*.5
```

```
 ubms=(tcm3c(ist)+tcm2c(ist))*.5
 xmus=1.8366e-5*(tblads/300.)**.6
 xks=xmus*1415.493
 rhobs=(tro2c(ist)+tro3c(ist))*.5
 do180i1=1,nerow
 if(i1.gt.4)dtime=dtimcl
 nadj=ndtop(ipst,i1,2)
 htc=htcap(ipst,i1)
 con=dtime*.5/htc
 aktk=0.
 ajtj=0.
 aos=0.
 do110i2=1,nadj
 heff=0.
 n3=ndtop(ipst,i1,i2+2)
 nnv(i2)=n3
 if(n3.gt.0.or.n3.eq.-74)heff=arnod(ipst,i1,i2)
$/splen(ipst,i1,i2)
 if(n3.eq.-71) then
 if(i1.eq.1)xl=rc(ist)*0.0254
 if(i1.eq.5)xl=abs(xlcso(2,ipel)-xlcso(1,ipel))*0.0254
 re=rhobr*ubr*xl/xmur
 nu=0.02063*re**0.8
 heff=arnod(ipst,i1,i2)/((xl/(nu*xk))+splen(ipst,i1,i2))
 tc=tbladr
 endif
 if(n3.eq.-72) then
 if(i1.eq.7)xl=sc(ist)*0.0254
 if(i1.eq.4)xl=abs(xlro(2,ipel)-xlro(1,ipel))*0.0254
 re=rhobs*ubs*xl/xmur
 nu=0.02063*re**0.8
 heff=arnod(ipst,i1,i2)/((xl/(nu*xk))+splen(ipst,i1,i2))
 tc=tblads
 endif
 if(n3.eq.-73.and.i2.eq.3) then
 x1=xlcso(1,ipel)*0.0254
 x2=xlcso(2,ipel)*0.0254
 xmu=1.8366e-5*(tcas/300.)*0.6
 xk=xmu*1415.493
 re1=rocas*ucas*x1/xmu
 re2=rocas*ucas*x2/xmu
 nu=0.02063*abs(re2**0.8-re1**0.8)/0.8
 heff=arnod(ipst,i1,i2)/((abs(x2-x1)/(nu*xk))+splen(ipst,
$i1,i2))
 tc=t0cas
 endif
 if(n3.eq.-76) then
 tc=trotor
 xmu=1.8366e-5*(trotor/300.)**.6
 xk=xmu*1415.493
 if(i1.eq.4) then
```

```
      x1=xlro(1,ipel)*.0254
      x2=xlro(2,ipel)*.0254
      re1=rorot*urot*x1/xmu
      re2=rorot*urot*x2/xmu
      nu=0.02063*abs(re2**0.8-re1**0.8)/0.8
      xl=abs(x2-x1)
      heff=arnod(ipst,i1,i2)/((xl/(nu*xk))+splen(ipst,i1,i2))
      endif
      if(i1.eq.3) then
      rroti=rotdis(ist)*.0254
      omega=pi*trpmc(ist)/30.
      delt=deltem
      do105il=1,10
      betdt=abs(delt)/trotor
      nu=0.0054*(rorot*2.*urot*rroti/xmu)**0.3*((rorot*omega/xmu)**2
     $*betdt)**0.25
      arn=arnod(ipst,i1,i2)
      heff=arn/((1./(nu*xk))+splen(ipst,i1,i2))
      deltn=abs((rrvp(ipel)-trotor)*(1.-(splen(ipst,i1,i2)*heff/arn)))
      dell=deltn-delt
      delt=deltn
      if(abs(dell).lt.(abs(delt)*1.e-5))goto106
  105 continue
  106 continue
      endif
      endif
      if(n3.eq.-77) then
      if(nrotcs.eq.2.or.(nrotcs.eq.3.and.i1.eq.3)) then
      xwc=txwc(ist)
      tc=ttawc(ist)
      trotin=tc
      xvc=txw0(ist)-xwc
      pb=tpawc(ist)
      rmc=(trchi(ist)+trcho(ist))*.0127
      xl=abs(trcho(ist)-trchi(ist))*.0254
      call mixprp(tc,pb,xvc,xwc,cpm,rhom,xmum,xkm,xkwat)
      omega=pi*trpmc(ist)/30.
      pran=xmum*cpm/xkm
      if(nrotcs.eq.3)tmet=rrvp(((ist-1)*8)+7)
      if(nrotcs.eq.2)tmet=rrvp(((ist-1)*7)+7)
      xls=splen(ipst,i1,i2)
      arn=arnod(ipst,i1,i2)
c     if water present water thickness taken as given
      dw=0.
      if(xwc.gt.0.)dw=dwat
      delt=deltem
      do107il=1,10
      gr=rmc*(omega*rhom/xmum)**2*abs(delt)*xl**3/tc
      if(gr.le.1.e9)nu=0.508*(pran*gr/(pran+0.952))**0.25
      if(gr.gt.1.e9)nu=0.024*(pran**1.17*gr/(1.+(pran**.666667*.494)
     $))**.4
```

```
      heff=abs(arn/((xl/(xkm*nu))+(dw/xkwat)+xls))
      deltn=abs(tc-tmet)*(1.-(heff*xls/arn))
      dell=deltn-delt
      delt=abs(deltn)
      if(abs(dell).lt.(abs(delt*1.e-5)))goto108
107   continue
108   continue
      heffs=heff
      endif
      if(nrotcs.eq.3)heff=heffs
      endif
      if(twcas.ne.0) then
      if(i2.eq.3.and.(i1.eq.5.or.i1.eq.6))then
      tout=t0cas
      tnode=rrvp(ipel)
      tsurfo=((tout-tnode)*heff*splen(ipst,i1,i2))+tnode
      tsurf=(tsurfo*(1.-wfstrf))+(wfstrf*twcas)
      hcor=(tsurf-tnode)/(splen(ipst,i1,i2)*(tout-tsurf))
      heff=1./((1./abs(hcor))+splen(ipst,i1,i2))
      endif
      endif
      twc=twbr(ist)
      if(twc.gt.0..and.(i1.eq.1.or.i1.eq.5)) then
      if((i1.eq.1.and.i2.eq.2).or.(i1.eq.5.and.i2.eq.4)) then
      tout=tbladr
      tnode=rrvp(ipel)
      tsurfo=((tout-tnode)*heff*splen(ipst,i1,i2))+tnode
      tsurf=(tsurfo*(1.-wfstrf))+(wfstrf*twc)
      hcor=(tsurf-tnode)/(splen(ipst,i1,i2)*(tout-tsurf))
      heff=1./((1./abs(hcor))+splen(ipst,i1,i2))
      endif
      endif
      twc=twbs(ist)
      if(twc.gt.0..and.i1.eq.7.and.i2.eq.2) then
      tout=tblads
      tnode=rrvp(ipel)
      tsurfo=((tout-tnode)*heff*splen(ipst,i1,i2))+tnode
      tsurf=(tsurfo*(1.-wfstrf))+(wfstrf*twc)
      hcor=(tsurf-tnode)/(splen(ipst,i1,i2)*(tout-tsurf))
      heff=1./((1./abs(hcor))+splen(ipst,i1,i2))
      endif
      vtmp(i2)=heff*con
      aos=aos+vtmp(i2)
      if(n3.eq.-74.and.i2.eq.3)tc=t0cas
      if(n3.eq.-74.and.i2.eq.4)tc=trotor
      if(n3.gt.0)ajtj=ajtj+(vtmp(i2)*rrvp(n3))
      if(n3.eq.-77.and.nrotcs.eq.3) then
      if(i1.eq.3)jpc=((ist-1)*8)+12
      if(i1.eq.8)jpc=((ist-1)*9)+7
      ajtj=ajtj+(vtmp(i2)*rrvp(jpc))
      endif
```

```
c     write(*,*)'110:i1,i2,nadj,n3,heff,con:',i1,i2,nadj,n3,heff,con
      if(n3.gt.0.or.n3.eq.-75.or.(n3.eq.-77.and.nrotcs.eq.3))goto 110
      aktk=aktk+(tc*vtmp(i2))
      vtmp(i2)=0.
110   continue
      do114i2=1,nadj
      n3=nnv(i2)
113   if((n3.lt.-70.and.n3.gt.-77).or.(n3.eq.-77.and.nrotcs.eq.2))
     $goto 114
      val=-vtmp(i2)
      jpc=n3
      if(n3.eq.-77) then
      if(i1.eq.3)jpc=((ist-1)*8)+12
      if(i1.eq.8)jpc=((ist-1)*9)+7
      endif
      call spear(nemax,ipel,jpc,nele,lcur,lmax,inl,val,vl,2,ier)
      ichk=113
      if(ier.ne.0)goto1005
114   continue
      rrv(ipel)=(rrvp(ipel)*(1.-aos))+ajtj+(aktk*2.)
      vc=1.+aos
      call spear(nemax,ipel,ipel,nele,lcur,lmax,inl,vc,vl,2,ier)
      ichk=114
      if(ier.ne.0)goto1005
c     write(*,*)'120:ipel,ipst,nele,lmax:',ipel,ipst,nele,lmax
c     read(*,3)rkey
      ipel=ipel+1
180   continue
      ipst=ipst+1
1000  continue
c
c     post-stage
c
      dtime=dtimcl
      nadj=ndtop(ipst,1,2)
      htc=htcap(ipst,1)
      con=dtime*.5/htc
      aktk=0.
      ajtj=0.
      aos=0.
      i1=1
      do210i2=1,nadj
      heff=0.
      n3=ndtop(ipst,1,i2+2)
      nnv(i2)=n3
      if(n3.gt.0.or.n3.eq.-74)heff=arnod(ipst,1,i2)
     $/splen(ipst,1,i2)
      if(n3.eq.-72) then
      xl=abs(xlcso(2,ipel)-xlcso(1,ipel))*.0254
      tc=tt3c(ns)
      xmu=1.8366e-5*(tc/300.)**.6
```

```
      xk=xmu*1415.493
      re=tro3c(ns)*tcm3c(ns)*xl/xmu
      nu=0.02063*re**0.8
      heff=arnod(ipst,1,i2)/((xl/(nu*xk))+splen(ipst,1,i2))
      endif
      if(n3.eq.-73) then
      x1=xlcso(1,ipel)*0.0254
      x2=xlcso(2,ipel)*0.0254
      xmu=1.8366e-5*(tcas/300.)**0.6
      xk=xmu*1415.493
      re1=rocas*ucas*x1/xmu
      re2=rocas*ucas*x2/xmu
      nu=0.02063*abs(re2**0.8-re1**0.8)/0.8
      heff=arnod(ipst,i1,i2)/((abs(x2-x1)/(nu*xk))+splen(ipst,
     $i1,i2))
      tc=t0cas
      endif
      if(twcas.ne.0.and.i2.eq.3) then
      tout=t0cas
      tnode=rrvp(ipel)
      tsurfo=((tout-tnode)*heff*splen(ipst,i1,i2))+tnode
      tsurf=(tsurfo*(1.-wfstrf))+(wfstrf*twcas)
      hcor=(tsurf-tnode)/(splen(ipst,i1,i2)*(tout-tsurf))
      heff=1./((1./abs(hcor))+splen(ipst,i1,i2))
      endif
      twc=twbs(ns)
      if(twc.gt.0..and.i2.eq.4) then
      tout=tt3c(ns)
      tnode=rrvp(ipel)
      tsurfo=((tout-tnode)*heff*splen(ipst,i1,i2))+tnode
      tsurf=(tsurfo*(1.-wfstrf))+(wfstrf*twc)
      hcor=(tsurf-tnode)/(splen(ipst,i1,i2)*(tout-tsurf))
      heff=1./((1./abs(hcor))+splen(ipst,i1,i2))
      endif
      vtmp(i2)=heff*con
c       write(*,*)'210:i1,i2,nadj,n3,heff,con:',i1,i2,nadj,n3,heff,con
      if(n3.eq.-74.and.i2.eq.3)tc=t0cas
      if(n3.eq.-74.and.i2.eq.4)tc=trotor
      aos=aos+vtmp(i2)
      if(n3.gt.0)ajtj=ajtj+(vtmp(i2)*rrvp(n3))
      if(n3.gt.0.or.n3.eq.-75)goto 210
      aktk=aktk+(tc*vtmp(i2))
      vtmp(i2)=0.
210   continue
c       read(*,3)rkey
      do214i2=1,nadj
      n3=nnv(i2)
213   if(n3.lt.0)goto 214
      val=-vtmp(i2)
      jpc=n3
      call spear(nemax,ipel,jpc,nele,lcur,lmax,inl,val,vl,2,ier)
```

```
      ichk=213
      if(ier.ne.0)goto1005
214   continue
      rrv(ipel)=(rrvp(ipel)*(1.-aos))+ajtj+(aktk*2.)
      vc=1.+aos
      call spear(nemax,ipel,ipel,nele,lcur,lmax,inl,vc,vl,2,ier)
      ichk=214
      if(ier.ne.0)goto1005
220   continue
c     solution of equations
      call spmsol(nele,lmax,nemax,inl,vl,rrv,cwork)
c     for (nrotcs=3), check evaporation and renewal of fluid
      if(nrotcs.eq.3) then
      rair=8314.3/28.964
      do 408i=1,ns
      xwmin=txw0(i)*(1.-(pemax*.01))
      xwc=txwc(i)
      xvc=txw0(i)-txwc(i)
      ind=((i-1)*8)+12
      tcp=rrvp(ind)
      tcnew=rrv(ind)
      pb=tpawc(i)
      call mixprp(tcp,pb,xvc,xwc,cpm,rhom,xmum,xkm,xkwat)
c     boiling temperature
      tc=tcnew
      tb=tcnew
      do402j=1,2
      if(tb.le.373.16) then
       aa=5.96659
       ab=2224.4
      endif
      if(tb.gt.373.16.and.tb.lt.473.16) then
       aa=5.63729
       ab=2101.1
      endif
      if(tb.ge.473.16) then
       aa=5.44021
       ab=2010.8
      endif
      tb=ab/(aa-alog10(pb))
402   continue
      if(tc.lt.tb) then
       ttawc(i)=tc
       goto 408
      endif
      if(tc.gt.645.155) then
       txwc(i)=0.
       goto403
      endif
      if(tc.gt.tb) then
c     Latent heat of vaporization (J/kg)
```

```
      if(tb.lt.373.16)alv=(3169.151-(2.444599*tb))*1000.
      if(tb.ge.373.16.and.tb.lt.473.16)alv=(3439.074-(3.16802*tb))
     $*1000.
      if(tb.ge.473.16.and.tb.lt.573.16)alv=(4473.395-(5.3541*tb))
     $*1000.
      if(tb.ge.573.16.and.tb.lt.645.155)alv=(12586.86-(19.5984*tb))
     $*1000.
      delxw=(1.+txw0(i))*cpm*(tc-tb)/alv
      xwc=xwc+delxw
      txwc(i)=xwc
      tc=tb
      rrv(ind)=tb
      endif
      pair=tmasa(i)*rair*tc/(tvol(i)*1.e-5)
      tpawc(i)=pair*(1.+(1.609*(txw0(i)-txwc(i))))
      ttawc(i)=tc
403   if(txwc(i).le.xwmin) then
c     renewal of fluid, if water content goes less than a minimum value
      txwc(i)=ttawm(i)
      tpawc(i)=tpawm(i)
      ttawc(i)=ttawm(i)
      rrv(ind)=ttawc(i)
      endif
408   continue
      endif
      return
1005  write(*,*)'err stop in sub tdcoef, ichk,ier,lcur,lmax= ',
     $ichk,ier,lcur,lmax
      stop
      end
      subroutine mixprp(tkin,pbar,xv,xw,cpm,rhom,xmum,xkm,xkw)
c     mixture properties of air+water+vapor (homogeneous fluid model)
c     input: tkin(oK)=temp.in degrees Kelvin,pbar=pressure in bar;
c            xv=kg_vapor/kg_air,xw=kg_water/kg_air
c     output:cpm(J/kg-K)=spec.heat,rhom(kg/m**3)=density;
c            xmum(kg/m-s)=dyn.viscosity,xkm(W/m-K)=heat conductivity.
      tk=tkin
      if(tk.lt.273.16.and.xw.gt.0.) tk=273.16
c     water can not remain liquid at temp.<= 0C, property calculation
c     is done at 0C.
      if(tk.ge.645.16)then
      xv=xv+xw
      xw=0.
      endif
c     water and vapor content converted into mass fraction
      xm=1.+xv+xw
      xxa=1./xm
      xxv=xv/xm
      xxv=xw/xm
c     specific heat (J/kg-K)
      ra=8314.3/28.964
```

```
      cpa=(3.65359-(1.33736e-3*tk)+(3.29421e-6*tk**2)-(1.91142e-9*tk**3)
     $+(0.275462e-12*tk**4))*ra
      cpv=1795.419
      if(tk.ge.273.16.and.tk.le.473.16)cpv=563.8315+(4.508666*tk)
      if(tk.gt.473.16)cpv=-12840.96+(32.83839*tk)
      cpw=4183.
      if(tk.lt.290.16)cpw=4852.528-(2.305889*tk)
      if(tk.gt.373.16.and.tk.le.583.16)cpw=2058.532+(5.641311*tk)
      if(tk.gt.583.16)cpw=-77253.31+(142.6763*tk)
      cpm=(xxa*cpa)+(xxv*cpv)+(xxw*cpw)
c     density(kg/m**3)
      rhom=pbar*1.e5/(tk*ra)*xm
c     viscosity coefficients (kg/m-K)
      if(tk.le.573.16)xmuv=(-0.3970778+(0.03456057*tk))*1.e-6
      if(tk.gt.573.16.and.tk.le.645.16)xmuv=(-169.9568+(0.3303916*tk))
     $*1.e-6
      if(tk.gt.645.16)xmuv=4.3199e-5*(tk/645.16)**0.6
      if(tk.lt.293.16)xmuw=(12571.45-(39.56894*tk))*1.e-6
      if(tk.ge.293.16.and.tk.lt.373.16)xmuw=(3547.392-(8.786854*tk))
     $*1.e-6
      if(tk.ge.373.16)xmuw=(1210.4-(3.51718*tk)+(2.661133e-3*tk**2))
     $*1.e-6
      xmua=1.872e-5*(tk/300.)**.6
      xmum=(xxv*xmuv)+(xxa*xmua)+(xxw*xmuw)
c     heat conductivity coefficient (W/m-K)
      xka=xmua*cpa/0.71
      if(tk.lt.473.16)xkv=(-15.04779+(0.1140167*tk))*0.001
      if(tk.ge.473.16.and.tk.lt.573.16)xkv=(-105.84+(0.3059*tk))*0.001
      if(tk.ge.573.16.and.tk.le.645.16)xkv=(-10673.88+(18.74326*tk))
     $*0.001
      if(tk.gt.645.16)xkv=1.419*(tk/645.16)**0.6
      if(tk.lt.573.16)xkw=(596.9995+(0.02097965*tk))*0.001
      if(tk.ge.573.16)xkw=(-5838.816+(11.24961*tk))*0.001
      xkm=(xxv*xkv)+(xxa*xka)+(xxw*xkw)
      return
      end
```

# APPENDIX D

File 1: A1: case1.inp (for dry air)

Input Data - Dry Case
0.450
01
01
01
00
02 00 02 00
06.95 07.64
2.520 2.453
2.170 2.436
1.909 2.383
36.00 26.00
49.20 51.40
37.20 38.10
18.10 18.50
07.35 08.10 08.73
2.142 1.844 1.617
1.880 1.665 1.484
1.563 1.451 1.326
36.00 40.00 46.00
37.00 37.80 37.90
28.70 30.90 31.80
20.80 23.90 25.40
1.000 0.715
1.106 0.891
1.541 1.260
0.857 0.834 0.853
0.958 0.929 0.940
1.198 1.125 1.099
32.03 33.20 32.39
23.91 25.81 26.12
12.54 14.46 16.02
1.00
0.000 1 0.000 1 0
0602.00 0597.00 1944.00
0020.0 0600.0
08879.0 0602.00 1944.00 08879.0 08879.0
0.000 0000.00000
028.970 18.000 16.00
050.0 00300.0
0.57700 0.72800
0.79000 0.86000
14.469 14.237
14.366 14.116 13.913
2
14.47 14.24
11.28 11.30
6.947 7.639
14.47 14.24
14.37 14.12

11.21 11.36
07.35 08.10
14.37 14.12
0.985 0.950
0.945 0.955 0.965
1 1 2
51.00 56.15
42.70 45.60
37.90 31.85
47.40 46.65
31.70 30.60
-1.70 5.150
54.22 54.00 55.65
40.40 43.95 46.25
37.00 41.75 45.00
26.22 26.80 25.05
17.00 17.85 17.35
04.60 06.05 05.80
011.300000 000.0000000
1.288 1.232
1.254 1.233
1.277 1.201
1.277 1.222
1.248 1.227
1.262 1.184
0.886 0.943
0.912 0.962
0.911 0.927
00.3758249 00.3220294
00.3386056 00.2975193
00.3498541 00.2657488
00.3650267 00.3138522 00.2768841
00.3095849 00.2832251 00.2416014
00.2780559 00.2453565 00.2246608
080.00
0.0010 0.0010
04.503 04.534
2
02116.2 00518.7
2.3000 1.4600
0.0900 0.0900
1.0000 1.5000
588.5 576.6 558.3
653.9 634.6 625.3
613.4 725.9 684.6
526.5 511.4 502.8
632.0 606.5 591.6
722.3 729.5 680.0
560.5 543.5
623.2 610.3
718.2 676.2

0.3759 0.3219
0.3692 0.3241
0.3290 0.2545
done

APPENDIX D

File 2: A2:case2.inp (for air with 4 percent water)

Input Data - Wet Case 1
0.450
01
01
02
04
02 00 02 00
06.95 07.64
2.520 2.453
2.170 2.436
1.909 2.383
36.00 26.00
49.20 51.40
37.20 38.10
18.10 18.50
07.35 08.10 08.73
2.142 1.844 1.617
1.880 1.665 1.484
1.563 1.451 1.326
36.00 40.00 46.00
37.00 37.80 37.90
28.70 30.90 31.80
20.80 23.90 25.40
1.000 0.715
1.106 0.891
1.541 1.260
0.857 0.834 0.853
0.958 0.929 0.940
1.198 1.125 1.099
32.03 33.20 32.39
23.91 25.81 26.12
12.54 14.46 16.02
1.00
0.000 1 1.000 1 0
0602.00 0597.00 1944.00
0020.0 0600.0
08879.0 0602.00 1944.00 08879.0 08879.0
0.000 0000.00000
028.970 18.000 16.00
050.0 00300.0
0.57700 0.72800
0.79000 0.86000
14.469 14.237
14.366 14.116 13.913
2
14.47 14.24
11.28 11.30
6.947 7.639
14.47 14.24
14.37 14.12

11.21 11.36
07.35 08.10
14.37 14.12
0.985 0.950
0.945 0.955 0.965
1 1 2
51.00 56.15
42.70 45.60
37.90 31.85
47.40 46.65
31.70 30.60
-1.70 5.15
54.22 54.00 55.65
40.40 43.95 46.25
37.00 41.75 45.00
26.22 26.80 25.05
17.00 17.85 17.35
04.60 06.05 05.80
011.300000 000.0000000
1.288 1.232
1.254 1.233
1.277 1.201
1.277 1.222
1.248 1.227
1.262 1.184
0.886 0.943
0.912 0.962
0.911 0.927
00.3758249 00.3220294
00.3386056 00.2975193
00.3498541 00.2657488
00.3650267 00.3138522 00.2768841
00.3095849 00.2832251 00.2416014
00.2780559 00.2453565 00.2246608
080.00
0.0010 0.0010
04.503 04.534
2
02116.2 00518.7
2.3000 1.4600
0.0900 0.0900
1.0000 1.5000
588.5 576.6 558.3
653.9 634.6 625.3
613.4 725.9 684.6
526.5 511.4 502.8
632.0 606.5 591.6
722.3 729.5 680.0
560.5 543.5
623.2 610.3
718.2 676.2

0.375 90.3219
0.369 20.3241
0.329 00.2545
done

APPENDIX D

File 3: B1: blheat1.inp (for solid rotor disk)

```
 2  0  7  4  1
  2   4  2.4145E+02
-75   6 -72 -76
 9.2520E-04  9.2520E-04  2.7860E-03  2.4660E-03
 4.7800E-04  7.6910E-04  2.7710E-04  2.7710E-04
 12   4  1.6219E+02
-75   3 -73 -72
 2.6280E-03  2.6280E-03  1.4020E-03  1.2260E-03
 1.2460E-04  2.8170E-04  2.4930E-04  2.4930E-04
 14   4  2.0453E+02
 2   9 -73   4
 2.6280E-03  2.6280E-03  1.7680E-03  1.5460E-03
 2.8170E-04  5.4300E-04  2.4930E-04  3.5380E-03
  6   2  1.3700E+01
 3 -72
 1.5460E-03  1.0350E-02
 3.5380E-03  5.6540E-04
 7
  6   2  3.4170E+01
 6 -71
 1.3520E-03  2.1190E-02
 5.0520E-03  6.8900E-05
 11   4  1.1540E+02
 1   8   5   7
 9.2520E-04  9.2520E-04  1.3520E-03  1.1580E-03
 7.6910E-04  8.2630E-04  5.0520E-03  2.7710E-04
 15   2  1.1943E+02
 6 -76
 1.1580E-03  3.1290E-03
 5.0530E-04  1.9404E-04
  2   4  2.8021E+02
 6  13 -72 -76
 9.2520E-04  1.1820E-03  3.0470E-03  2.6320E-03
 8.2630E-04  9.0380E-04  2.7710E-04  2.7710E-04
 12   4  5.8508E+02
 3  10 -73 -71
 2.6280E-03  3.4610E-03  4.9390E-03  4.3270E-03
 5.4300E-04  5.7260E-04  2.4930E-04  2.4930E-04
 14   4  3.5465E+02
 9  16 -73  11
 5.3460E-03  5.3460E-03  3.0600E-03  2.6860E-02
 5.9260E-04  6.1760E-04  2.4930E-04  4.7070E-03
  6   2  2.9360E+01
10 -72
 2.6860E-03  1.7510E-02
 4.7070E-03  7.1630E-05
 7
  6   2  3.7990E+01
13 -71
```

```
 2.6070E-03  2.0980E-02
 4.4680E-03  7.7340E-05
 11   4  2.2407E+02
 8  15  12  14
 1.1820E-03  1.1820E-03  2.6070E-03  2.2660E-03
 9.0380E-04  9.2270E-04  4.4680E-03  2.7710E-04
 15   2  2.4196E+02
13 -76
 2.2660E-03  5.1180E-03
 5.0530E-04  2.4580E-04
  2   4  3.5765E+02
12 -75 -72 -76
 1.1820E-03  1.1820E-03  4.1450E-02  3.6320E-03
 9.2270E-04  5.5410E-04  2.7710E-04  2.7710E-04
 12   4  7.5884E+02
10  17 -73 -71
 3.4610E-03  3.0640E-03  6.5450E-03  5.7390E-03
 6.1760E-04  6.4890E-04  2.4930E-04  2.4930E-04
 14   4  2.7030E+02
16  19 -73  18
 3.0640E-03  3.0640E-03  2.3340E-03  2.0450E-03
 6.4890E-04  3.0260E-04  2.4930E-04  4.0720E-03
  6   2  1.9880E+01
17 -72
 2.0450E-03  1.3390E-02
 4.0720E-03  6.3440E-05
 12   4  1.8915E+02
17 -75 -73 -72
 3.0640E-03  3.0640E-03  1.6340E-03  1.4310E-03
 3.0260E-04  1.2460E-04  2.4930E-04  2.4930E-04
0.0000E+00  0.0000E+00
0.0000E+00  2.8380E+00
0.0000E+00  1.0000E+00
0.0000E+00  0.0000E+00
1.0000E+00  2.2610E+00
0.0000E+00  0.0000E+00
0.0000E+00  0.0000E+00
0.0000E+00  0.0000E+00
0.0000E+00  0.0000E+00
0.0000E+00  0.0000E+00
0.0000E+00  0.0000E+00
2.8380E+00  4.6660E+00
0.0000E+00  0.0000E+00
0.0000E+00  0.0000E+00
0.0000E+00  0.0000E+00
4.6660E+00  7.8440E+00
2.2610E+00  5.3560E+00
0.0000E+00  0.0000E+00
5.3560E+00  7.0160E+00
0.0000E+00  0.0000E+00
0.0000E+00  0.0000E+00
```

```
0.0000E+00 0.0000E+00
0.0000E+00 0.0000E+00
0.0000E+00 0.0000E+00
0.0000E+00 0.0000E+00
7.8440E+00 1.0033E+01
0.0000E+00 0.0000E+00
0.0000E+00 0.0000E+00
0.0000E+00 0.0000E+00
1.0033E+01 1.3322E+01
7.0160E+00 1.0793E+01
0.0000E+00 0.0000E+00
1.0793E+01 1.2222E+01
0.0000E+00 0.0000E+00
0.0000E+00 0.0000E+00
0.0000E+00 0.0000E+00
1.2222E+01 1.3322E+01
0.0000E+00 0.0000E+00
  5.88000E-06
 2 9 14.477 2.950
5 6
 1.1760E-05 1.1760E-05
 7.5200E+00 6.9500E+00
 2 16 14.247 3.640
12 13
 1.1760E-05 1.1760E-05
 6.6000E+00 7.6400E+00
```

APPENDIX D

File 4: B2:blheat2.inp (for rotor disk internally cooled with dry air)

```
 2 0 7 4 2
  2   4  2.4145E+02
-75   6 -72 -76
 9.2520E-04  9.2520E-04  2.7860E-03  2.4660E-03
 4.7800E-04  7.6910E-04  2.7710E-04  2.7710E-04
 12   4  1.6219E+02
-75   3 -73 -72
 2.6280E-03  2.6280E-03  1.4020E-03  1.2260E-03
 1.2460E-04  2.8170E-04  2.4930E-04  2.4930E-04
 14   4  2.0453E+02
 2   9 -73   4
 2.6280E-03  2.6280E-03  1.7680E-03  1.5460E-03
 2.8170E-04  5.4300E-04  2.4930E-04  3.5380E-03
  6   2  1.3700E+01
 3 -72
 1.5460E-03  1.0350E-02
 3.5380E-03  5.6540E-04
 7
  6   2  3.4170E+01
 6 -71
 1.3520E-03  2.1190E-02
 5.0520E-03  6.8900E-05
 11   4  1.1540E+02
 1   8   5   7
 9.2520E-04  9.2520E-04  1.3520E-03  1.1580E-03
 7.6910E-04  8.2630E-04  5.0520E-03  2.7710E-04
 16   3  6.5591e+02
 6 -76 -77
 6.9460e-03  1.8770e-02  1.3400e-03
 5.0530E-04  1.9404E-04  6.5410e-05
  2   4  2.8021E+02
 6  13 -72 -76
 9.2520E-04  1.1820E-03  3.0470E-03  2.6320E-03
 8.2630E-04  9.0380E-04  2.7710E-04  2.7710E-04
 12   4  5.8508E+02
 3  10 -73 -71
 2.6280E-03  3.4610E-03  4.9390E-03  4.3270E-03
 5.4300E-04  5.7260E-04  2.4930E-04  2.4930E-04
 14   4  3.5465E+02
 9  16 -73  11
 5.3460E-03  5.3460E-03  3.0600E-03  2.6860E-02
 5.9260E-04  6.1760E-04  2.4930E-04  4.7070E-03
  6   2  2.9360E+01
 10 -72
 2.6860E-03  1.7510E-02
 4.7070E-03  7.1630E-05
 7
  6   2  3.7990E+01
 13 -71
 2.6070E-03  2.0980E-02
```

4.4680E-03 7.7340E-05
11 4 2.2407E+02
8 15 12 14
1.1820E-03 1.1820E-03 2.6070E-03 2.2660E-03
9.0380E-04 9.2270E-04 4.4680E-03 2.7710E-04
16 3 1.1970e+03
13 -76 -77
1.1800e-03 2.6610e-02 1.3400e-03
5.0530E-04 2.4580E-04 7.5550e-05
2 4 3.5765E+02
12 -75 -72 -76
1.1820E-03 1.1820E-03 4.1450E-02 3.6320E-03
9.2270E-04 5.5410E-04 2.7710E-04 2.7710E-04
12 4 7.5884E+02
10 17 -73 -71
3.4610E-03 3.0640E-03 6.5450E-03 5.7390E-03
6.1760E-04 6.4890E-04 2.4930E-04 2.4930E-04
14 4 2.7030E+02
16 19 -73 18
3.0640E-03 3.0640E-03 2.3340E-03 2.0450E-03
6.4890E-04 3.0260E-04 2.4930E-04 4.0720E-03
6 2 1.9880E+01
17 -72
2.0450E-03 1.3390E-02
4.0720E-03 6.3440E-05
12 4 1.8915E+02
17 -75 -73 -72
3.0640E-03 3.0640E-03 1.6340E-03 1.4310E-03
3.0260E-04 1.2460E-04 2.4930E-04 2.4930E-04
0.0000E+00 0.0000E+00
0.0000E+00 2.8380E+00
0.0000E+00 1.0000E+00
0.0000E+00 0.0000E+00
1.0000E+00 2.2610E+00
0.0000E+00 0.0000E+00
0.0000E+00 0.0000E+00
0.0000E+00 0.0000E+00
0.0000E+00 0.0000E+00
0.0000E+00 0.0000E+00
0.0000E+00 0.0000E+00
2.8380E+00 4.6660E+00
0.0000E+00 0.0000E+00
0.0000E+00 0.0000E+00
0.0000E+00 0.0000E+00
4.6660E+00 7.8440E+00
2.2610E+00 5.3560E+00
0.0000E+00 0.0000E+00
5.3560E+00 7.0160E+00
0.0000E+00 0.0000E+00
0.0000E+00 0.0000E+00
0.0000E+00 0.0000E+00

```
0.0000E+00  0.0000E+00
0.0000E+00  0.0000E+00
0.0000E+00  0.0000E+00
7.8440E+00  1.0033E+01
0.0000E+00  0.0000E+00
0.0000E+00  0.0000E+00
0.0000E+00  0.0000E+00
1.0033E+01  1.3322E+01
7.0160E+00  1.0793E+01
0.0000E+00  0.0000E+00
1.0793E+01  1.2222E+01
0.0000E+00  0.0000E+00
0.0000E+00  0.0000E+00
0.0000E+00  0.0000E+00
1.2222E+01  1.3222E+01
0.0000E+00  0.0000E+00
  5.88000E-06
 2  9  14.477 2.950
 5  6
 1.1760E-05  1.1760E-05
 7.5200E+00  6.9500E+00
 2  16  14.247 3.640
12 13
 1.1760E-05  1.1760E-05
 6.6000E+00  7.6400E+00
3.05 5.85 1.676e-3 0. 288. 1.1
3.44 6.54 1.676e-3 0. 288. 1.1
5.e-6
```

APPENDIX D

File 5: B3:blheat3.inp
(for rotor disk internally cooled with air-water mixture)

```
 2 0 7 4 2
  2  4 2.4145E+02
-75  6 -72 -76
 9.2520E-04 9.2520E-04 2.7860E-03 2.4660E-03
 4.7800E-04 7.6910E-04 2.7710E-04 2.7710E-04
 12  4 1.6219E+02
-75  3 -73 -72
 2.6280E-03 2.6280E-03 1.4020E-03 1.2260E-03
 1.2460E-04 2.8170E-04 2.4930E-04 2.4930E-04
 14  4 2.0453E+02
 2  9 -73  4
 2.6280E-03 2.6280E-03 1.7680E-03 1.5460E-03
 2.8170E-04 5.4300E-04 2.4930E-04 3.5380E-03
  6  2 1.3700E+01
 3 -72
 1.5460E-03 1.0350E-02
 3.5380E-03 5.6540E-04
 7
  6  2 3.4170E+01
 6 -71
 1.3520E-03 2.1190E-02
 5.0520E-03 6.8900E-05
 11  4 1.1540E+02
 1  8  5  7
 9.2520E-04 9.2520E-04 1.3520E-03 1.1580E-03
 7.6910E-04 8.2630E-04 5.0520E-03 2.7710E-04
 16  3 6.5591e+02
 6 -76 -77
 6.9460e-03 1.8770e-02 1.3400e-03
 5.0530E-04 1.9404E-04 6.5410e-05
  2  4 2.8021E+02
 6 13 -72 -76
 9.2520E-04 1.1820E-03 3.0470E-03 2.6320E-03
 8.2630E-04 9.0380E-04 2.7710E-04 2.7710E-04
 12  4 5.8508E+02
 3 10 -73 -71
 2.6280E-03 3.4610E-03 4.9390E-03 4.3270E-03
 5.4300E-04 5.7260E-04 2.4930E-04 2.4930E-04
 14  4 3.5465E+02
 9 16 -73 11
 5.3460E-03 5.3460E-03 3.0600E-03 2.6860E-02
 5.9260E-04 6.1760E-04 2.4930E-04 4.7070E-03
  6  2 2.9360E+01
 10 -72
 2.6860E-03 1.7510E-02
 4.7070E-03 7.1630E-05
 7
  6  2 3.7990E+01
 13 -71
 2.6070E-03 2.0980E-02
```

4.4680E-03 7.7340E-05
11 4 2.2407E+02
8 15 12 14
1.1820E-03 1.1820E-03 2.6070E-03 2.2660E-03
9.0380E-04 9.2270E-04 4.4680E-03 2.7710E-04
16 3 1.1970e+03
13 -76 -77
1.1800e-03 2.6610e-02 1.3400e-03
5.0530E-04 2.4580E-04 7.5550e-05
2 4 3.5765E+02
12 -75 -72 -76
1.1820E-03 1.1820E-03 4.1450E-02 3.6320E-03
9.2270E-04 5.5410E-04 2.7710E-04 2.7710E-04
12 4 7.5884E+02
10 17 -73 -71
3.4610E-03 3.0640E-03 6.5450E-03 5.7390E-03
6.1760E-04 6.4890E-04 2.4930E-04 2.4930E-04
14 4 2.7030E+02
16 19 -73 18
3.0640E-03 3.0640E-03 2.3340E-03 2.0450E-03
6.4890E-04 3.0260E-04 2.4930E-04 4.0720E-03
6 2 1.9880E+01
17 -72
2.0450E-03 1.3390E-02
4.0720E-03 6.3440E-05
12 4 1.8915E+02
17 -75 -73 -72
3.0640E-03 3.0640E-03 1.6340E-03 1.4310E-03
3.0260E-04 1.2460E-04 2.4930E-04 2.4930E-04
0.0000E+00 0.0000E+00
0.0000E+00 2.8380E+00
0.0000E+00 1.0000E+00
0.0000E+00 0.0000E+00
1.0000E+00 2.2610E+00
0.0000E+00 0.0000E+00
0.0000E+00 0.0000E+00
0.0000E+00 0.0000E+00
0.0000E+00 0.0000E+00
0.0000E+00 0.0000E+00
0.0000E+00 0.0000E+00
2.8380E+00 4.6660E+00
0.0000E+00 0.0000E+00
0.0000E+00 0.0000E+00
0.0000E+00 0.0000E+00
4.6660E+00 7.8440E+00
2.2610E+00 5.3560E+00
0.0000E+00 0.0000E+00
5.3560E+00 7.0160E+00
0.0000E+00 0.0000E+00
0.0000E+00 0.0000E+00
0.0000E+00 0.0000E+00

```
0.0000E+00  0.0000E+00
0.0000E+00  0.0000E+00
0.0000E+00  0.0000E+00
7.8440E+00  1.0033E+01
0.0000E+00  0.0000E+00
0.0000E+00  0.0000E+00
0.0000E+00  0.0000E+00
1.0033E+01  1.3322E+01
7.0160E+00  1.0793E+01
0.0000E+00  0.0000E+00
1.0793E+01  1.2222E+01
0.0000E+00  0.0000E+00
0.0000E+00  0.0000E+00
0.0000E+00  0.0000E+00
1.2222E+01  1.3222E+01
0.0000E+00  0.0000E+00
   5.88000E-06
 2  9  14.477 2.950
 5  6
 1.1760E-05  1.1760E-05
 7.5200E+00  6.9500E+00
 2  16  14.247 3.640
12 13
 1.1760E-05  1.1760E-05
 6.6000E+00  7.6400E+00
3.05 5.85 1.676e-3 .08 288. 1.1
3.44 6.54 1.676e-3 .08 288. 1.1
5.0000E-6
```

APPENDIX D

File 6: B4: blheat4.inp
(for rotor disk internally cooled with stagnant air-water mixture renewed periodically)

```
2 0 7 4 3
 2  4 2.4145E+02
-75  6 -72 -76
 9.2520E-04 9.2520E-04 2.7860E-03 2.4660E-03
 4.7800E-04 7.6910E-04 2.7710E-04 2.7710E-04
 12  4 1.6219E+02
-75  3 -73 -72
 2.6280E-03 2.6280E-03 1.4020E-03 1.2260E-03
 1.2460E-04 2.8170E-04 2.4930E-04 2.4930E-04
 14  4 2.0453E+02
 2  9 -73  4
 2.6280E-03 2.6280E-03 1.7680E-03 1.5460E-03
 2.8170E-04 5.4300E-04 2.4930E-04 3.5380E-03
 6  2 1.3700E+01
 3 -72
 1.5460E-03 1.0350E-02
 3.5380E-03 5.6540E-04
8
 6  2 3.4170E+01
 6 -71
 1.3520E-03 2.1190E-02
 5.0520E-03 6.8900E-05
 11  4 1.1540E+02
 1  8  5  7
 9.2520E-04 9.2520E-04 1.3520E-03 1.1580E-03
 7.6910E-04 8.2630E-04 5.0520E-03 2.7710E-04
 16  3 6.5591e+02
 6 -76 -77
 6.9460e-03 1.8770e-02 1.3400e-03
 5.0530E-04 1.9404E-04 6.5410e-05
 2  4 2.8021E+02
 6 14 -72 -76
 9.2520E-04 1.1820E-03 3.0470E-03 2.6320E-03
 8.2630E-04 9.0380E-04 2.7710E-04 2.7710E-04
 12  4 5.8508E+02
 3 10 -73 -71
 2.6280E-03 3.4610E-03 4.9390E-03 4.3270E-03
 5.4300E-04 5.7260E-04 2.4930E-04 2.4930E-04
 14  4 3.5465E+02
 9 17 -73 11
 5.3460E-03 5.3460E-03 3.0600E-03 2.6860E-02
 5.9260E-04 6.1760E-04 2.4930E-04 4.7070E-03
 6  2 2.9360E+01
10 -72
 2.6860E-03 1.7510E-02
 4.7070E-03 7.1630E-05
 8  1 0.0000E+00
 -77
 1.3400e-3
 6.5410e-5
```

```
8
 6  2  3.7990E+01
14 -71
 2.6070E-03  2.0980E-02
 4.4680E-03  7.7340E-05
 11   4  2.2407E+02
 8  16  13  15
 1.1820E-03  1.1820E-03  2.6070E-03  2.2660E-03
 9.0380E-04  9.2270E-04  4.4680E-03  2.7710E-04
 16   3  1.1970e+03
14 -76 -77
 1.1800e-03  2.6610e-02  1.3400e-03
 5.0530E-04  2.4580E-04  7.5550e-05
 2   4  3.5765E+02
14 -75 -72 -76
 1.1820E-03  1.1820E-03  4.1450E-02  3.6320E-03
 9.2270E-04  5.5410E-04  2.7710E-04  2.7710E-04
 12   4  7.5884E+02
10  18 -73 -71
 3.4610E-03  3.0640E-03  6.5450E-03  5.7390E-03
 6.1760E-04  6.4890E-04  2.4930E-04  2.4930E-04
 14   4  2.7030E+02
17  21 -73  19
 3.0640E-03  3.0640E-03  2.3340E-03  2.0450E-03
 6.4890E-04  3.0260E-04  2.4930E-04  4.0720E-03
 6   2  1.9880E+01
18 -72
 2.0450E-03  1.3390E-02
 4.0720E-03  6.3440E-05
 8   1  0.0000E+00
-77
 1.3400E-03
 7.5550E-05
 12   4  1.8915E+02
18 -75 -73 -72
 3.0640E-03  3.0640E-03  1.6340E-03  1.4310E-03
 3.0260E-04  1.2460E-04  2.4930E-04  2.4930E-04
0.0000E+00  0.0000E+00
0.0000E+00  2.8380E+00
0.0000E+00  1.0000E+00
0.0000E+00  0.0000E+00
1.0000E+00  2.2610E+00
0.0000E+00  0.0000E+00
0.0000E+00  0.0000E+00
0.0000E+00  0.0000E+00
0.0000E+00  0.0000E+00
0.0000E+00  0.0000E+00
0.0000E+00  0.0000E+00
2.8380E+00  4.6660E+00
0.0000E+00  0.0000E+00
0.0000E+00  0.0000E+00
```

```
0.0000E+00 0.0000E+00
4.6660E+00 7.8440E+00
2.2610E+00 5.3560E+00
0.0000E+00 0.0000E+00
5.3560E+00 7.0160E+00
0.0000E+00 0.0000E+00
0.0000E+00 0.0000E+00
0.0000E+00 0.0000E+00
0.0000E+00 0.0000E+00
0.0000E+00 0.0000E+00
0.0000E+00 0.0000E+00
0.0000E+00 0.0000E+00
0.0000E+00 0.0000E+00
7.8440E+00 1.0033E+01
0.0000E+00 0.0000E+00
0.0000E+00 0.0000E+00
0.0000E+00 0.0000E+00
1.0033E+01 1.3322E+01
7.0160E+00 1.0793E+01
0.0000E+00 0.0000E+00
1.0793E+01 1.2222E+01
0.0000E+00 0.0000E+00
0.0000E+00 0.0000E+00
0.0000E+00 0.0000E+00
0.0000E+00 0.0000E+00
0.0000E+00 0.0000E+00
1.2222E+01 1.3222E+01
0.0000E+00 0.0000E+00
  5.88000E-06
 2  9  14.477 2.950
 5  6
 1.1760E-05  1.1760E-05
 7.5200E+00  6.9500E+00
 2  17  14.247 3.640
13 14
 1.1760E-05  1.1760E-05
 6.6000E+00  7.6400E+00
3.05 5.85 1.676e-3 .08 288. 1.1
3.44 6.54 1.676e-3 .08 288. 1.1
5.0000E-06
50.
```

APPENDIX E

File 1: case1.out

```
Input Data - Dry Case
Compressor flow adiabatic
icase=   0

 phi design  = 0.7773584

 inlet phi =0.4500000
0psi=  9.1772E-01 psi1=  7.4815E-01 loss=  1.6957E-01
 jsweep=   100

  MEAN
  fraction of design speed = 1.00000
 >>>>>>>>>> loop number 2 <<<<<<<<<<
 igv area=    0.241601
 nhg number of streamlines =    10.22089
1      ***************************** input data
*************************************
    heat transfer after rotor and stator version
0 number of stages=  2 (fan 0, lpc 2, hpc 0)
  performance at mean
0 vapor is centrifuged
0 large droplets in rotor free stream are not centrifuged


  stage       1    2    3
  rrhub(i)    6.95  7.64
  rc(i)      2.170 2.436
  rblade(i)  36.00 26.00
  stager(i)  37.20 38.10
  stages(i)  28.70 30.90 31.80
  srhub(i)    7.35  8.10  8.73
  sc(i)      1.880 1.665 1.484
  sblade(i)  36.00 40.00 46.00
  sigumr(i)  1.106 0.891
  sigums(i)  0.958 0.929 0.940
  bet2ss(i)  23.91 25.81 26.12
  gapr(i)    0.577 0.728
  gaps(i)    0.790 0.860
  rrtip(i)   14.47 14.24
  srtip(i)   14.37 14.12 13.91
  rt(i)      14.47 14.24
  rm(i)      11.28 11.30
  rh(i)       6.95  7.64
  st(i)      14.37 14.12
  sm(i)      11.21 11.36
  sh(i)       7.35  8.10
  block(i)   0.985 0.950
  blocks(i)  0.945 0.955 0.965
  bet1mr(i)  42.70 45.60
  bet2mr(i)  31.70 30.60
```

```
 bet1ms(i)  40.40 43.95 46.25
 bet2ms(i)  17.00 17.85 17.35
 pr12d(i)   1.254 1.233
 pr13d(i)   1.248 1.227
 etard(i)   0.912 0.962
 dvz1(i)   653.9 634.6 625.3
 dvz2(i)   632.0 606.5 591.6
 dvz3(i)   623.2 610.3
 ak1(i)   2.300 1.460
 ak2(i)   0.090 0.090
 ak3(i)   1.000 1.500
1     ***************************** input data *****************************
0 fnf(fraction of design corrected speed)=1.000
0 xdin(initial water content of small droplet)=0.000
 xddin(initial water content of large droplet)=0.000
 rhumid(initial relative humidity)=  0.00 per cent
 xch4(initial methane content)=0.000
0 t0g(compressor inlet total temprature of gas)= 602.00
 t0w(compressor inlet temperature of droplret)= 597.00
 p0(compressor inlet total pressure)=1944.00
0 din(initial droplet diameter of small droplet)=  20.0
 ddin(initial droplet diameter of large droplet)= 600.0
0 fnd(design rotational speed)= 8879.0
0 dsmass(design stream  mass flow rate)=   11.3000
0 bypass ratio =     0.0000
0 compressor inlet total temperature(gas phase) 602.00 r
0 compressor inlet total pressure=1944.00 lb/ft**2
0 preb(percent of water that rebound after impingement)= 50.0 percent
0 rotor speed= 9565.4 rpm
0 corrected rotor speed=  8879.0 rpm(  100.0per cent of design corrected speed)
0 molecular weight of air= 28.9700
0 maximum diameter of small droplets=   300.0 microns
0 rotor corrected speed at design point=  8879.0
 rotor corrected speed of lpc at design point=  8879.0
 rotor corrected speed of hpc at the design point=  8879.0
 design flow coefficient at inlet =   0.777358

1*************** design point information ************ ***
0 ***** compressor inlet *****
0 total temperature at compressor inlet(R)= 602.00000
 total pressure at compressor inlet(lbf/ft**2)=   1944.00
 static temperature at compressor inlet(R)= 556.98975
 static pressure at compressor inlet(lbf/ft**2)=   1480.37
 static density at compressor inlet(lbm/ft**3)=   0.04982
0 acoustic speed at compressor inlet(ft/s)=1156.55713
 axial velocity at compressor inlet(ft/s)= 625.29999
 mach number at compressor inlet=  -0.63642
 streamtube area at compressor inlet(ft**2)=   0.24160
 flow coefficient at compressor inlet=   0.77736
1*************** design point information ************ ***
0 ***** stage= 1 *****
```

```
0           total     total     static    static    static
            temp      pressure  temp      pressure  density
0 rotor inlet   602.000   1944.000   554.852   1460.540   0.049
 rotor outlet   646.018   2437.776   582.467   1694.070   0.055
0           axial     absolute  relative  tan comp  tan comp
            velocity  velocity  velocity  of abs vel of rel vel
0 rotor inlet  653.90002  728.27600  901.76440  320.62540  620.96191
 rotor outlet 632.00000  875.68225  762.34113  606.13159  329.61261
0           rotor     abs mach  rel mach  rel total rel total
            speed     number    number    temp      pressure
0 rotor inlet   941.587    0.653    0.781    622.410   2185.063
 rotor outlet   935.744    0.741    0.645    630.648   5747.708
0           abs flow  rel flow  streamtube          flow
            angle     angle     area      radius    coefficient
0 rotor inlet  26.12000   43.52000   0.33861   11.28000   0.54140
 rotor outlet  43.80309   25.61799   0.30958   11.21000   0.52327
0 stage total pressure ratio at design point=  1.24800
 stage adiabatic efficiency at design point=  0.89109
 rotor total pressure ratio at design point=  1.25400
 rotor adiabatic efficiency at design point=  0.91200
 rotor total temperature ratio at design point=  1.07312
1*************** design point information ************ ***
0 ***** stage= 2 *****
0           total     total     static    static    static
            temp      pressure  temp      pressure  density
0 rotor inlet   646.018   2426.112   606.280   1941.056   0.060
 rotor outlet   687.268   2991.396   632.514   2232.765   0.066
0           axial     absolute  relative  tan comp  tan comp
            velocity  velocity  velocity  of abs vel of rel vel
0 rotor inlet  634.59998  694.17151  916.97321  281.34848  661.90845
 rotor outlet 606.50000  813.80762  725.84167  542.62378  405.64148
0           rotor     abs mach  rel mach  rel total rel total
            speed     number    number    temp      pressure
0 rotor inlet   943.257    0.574    0.760    675.988   2845.161
 rotor outlet   948.265    0.661    0.589    676.086   6382.674
0           abs flow  rel flow  streamtube          flow
            angle     angle     area      radius    coefficient
0 rotor inlet  23.91000   46.20665   0.29752   11.30000   0.53399
 rotor outlet  41.81838   33.97677   0.28323   11.36000   0.51034
0 stage total pressure ratio at design point=  1.22700
 stage adiabatic efficiency at design point=  0.93777
 rotor total pressure ratio at design point=  1.23300
 rotor adiabatic efficiency at design point=  0.96200
 rotor total temperature ratio at design point=  1.06385
1*************** design point information ************ ***
0********** overall performance at design point ****  ******
0 compressor inlet total temperature=  602.00
0 compressor inlet total pressure=  1944.00
0 corrected mass flow rate= 135.446
0 overall total pressure ratio=  1.5313
0 overall total temperature ratio=1.1416
```

```
0 overall adiabatic efficiency=0.9102
0 overall temperature rise=  85.268
0          1    2    3    4    5    6    7    8    9    10   11   12   13   14   15   16
 bet1sr(i)  43.52 46.21
 bet2sr(i)  25.62 33.98
 aincsr(i)    0.82   0.61
 adevsr(i)   -6.08   3.38
 bet1ss(i)  43.80 41.82
 bet2ss(i)  23.91 25.81 26.12
 aincss(i)    3.40 -2.13
 adevss(i)    6.91   7.96
 td(i)       602.  646.
 omegr(i)   0.063 0.026
 omegs(i)   0.016 0.019
 sitadr(i)   .0399 .0174
 sitads(i)   .0120 .0136
 deqr(i)      1.601 1.587
 deqs(i)      1.660 1.523
1  fai=0.4500000
 xddin =   0.
 nhg main ws(1) tg(1) p(1) rhumid =   0.00000 602.000001944.00000   0.00001
 nhg main xv(1) xwt(1) xch4 =   0.00000   0.00000   0.00000
0 vz at igv inlet =  543.50366 mach number =    0.46153
  i     xwt      watrgn
  1  0.  0.
  2  0.  0.
  3  0.  0.
  4  0.  0.
  5  0.  0.
  6  0.  0.
  7  0.  0.
  8  0.  0.
  9  0.  0.
  10  0.  0.
 xv(1) =      1.18659E-09
 watrgt =   0.
0    istage=0  (igv)
0         0.45000        543.50366          1.00000
 clear( 1)=     1.00000E-03
 nhg main start calculations for stage  1
 d1 dwakem,w2=   0.    514.381
 d2 dwakem,rdelv1=   0.   10.00000
 d3 dwakem,rdelv2=   0.  0.
ddave(n-2)(n)=  3  0.  0.
 nhg wicsiz wmasss wmassl aming1 2 3 dl,ds,d1,d2,d3 =   0.00000   0.00000   0.00000   0.00000
0.00000   0.00000   0.00000   0.00000   0.00000   0.00000
 nhg ds dl dlge dsll amlge amsll=   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000
 nhg wicsiz wmasss wmassl aming1 2 3 dsll,dlge,d1,d2,d3   =   0.00000   0.00000   0.00000
0.00000   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000
 filmas( 1) =    0.
 ui =    0.
```

```
hhc =   0.
htotl =   0.
1 ******************** initial flow coefficient= 0.450 (stage= 1 ) ******************
0    stage total pressure ratio=      1.35248
     stage total temperature ratio=     1.10863
     stage adiabatic efficiency=     0.82645
0    stage flow coefficient=0.305
     axial velocity= 368.37
     rotor speed=1207.79

0                    *rotor inlet* *rotor outlet* *stator outlet*
  total pressure            1944.0000     2636.5400     2629.2144
  static pressure           1805.3267     2192.1331     2450.7463
  total temperature(gas)    602.0000      667.3978      667.3978
  static temperature(gas)   589.4261      633.1794      654.1548
  static density(gas)       0.0574        0.0649        0.0702
  static density(mixture)   0.0574        0.0649        0.0702
0 axial velocity            368.3687      336.4398      339.1703
  absolute velocity         389.0349      641.8840      399.3185
  relative velocity         895.7287      514.3813
  blade speed               941.5873      935.7442      943.2569
  tang. comp. of abs. vel.  125.1105      546.6473
  tang. comp. of rel. vel.  816.4768      389.0969
  acoustic speed            1189.7568     1253.3921     1253.3827
  absolute mach number      0.3270        0.5205        0.3186
  relative mach number      0.7529        0.4171
0 flow coefficient          0.3050        0.2786        0.2854
  flow area                 0.3386        0.3280        0.3007
0 absolute flow angle       18.7592       58.3893       31.8565
  relative flow angle       65.7166       49.1511
  incidence                 23.0166       17.9893
  deviation                               17.4511       14.8565
  diffusion ratio                         3.6653        2.6688
  momentum thickness                      0.1314        0.0192
  omega (gas)                             0.17564       0.01648
  omega (total)                           0.17564       0.01648
 d1 dwakem,v3=  0.   399.318
 d2 dwakem,sdelv1=  0.  10.00000
 d3 dwakem,sdelv2=  0.  0.
 n,ddave(n-2)(n)=  4  0.  0.
 nhg wicsiz wmasss wmassl aming1 2 3 dl,ds,d1,d2,d3 =  0.00000  0.00000  0.00000  0.00000
0.00000  0.00000  0.00000  0.00000  0.00000  0.00000
 nhg ds dl dlge dsll amlge amsll=  0.00000  0.00000  0.00000  0.00000  0.00000  0.00000
 nhg wicsiz wmasss wmassl aming1 2 3 dsll,dlge,d1,d2,d3  =  0.00000  0.00000  0.00000
0.00000  0.00000  0.00000  0.00000  0.00000  0.00000  0.00000
1 ******************** initial flow coefficient= 0.450 (istage=  1 )
********************
0    stage total pressure ratio=       1.35248
     stage total temperature ratio=    1.10863
     stage adiabatic efficiency=       0.82645
  stage  1 total ETA    0.82645del T   65.39777
```

```
0psi=  5.4154E-01 psi1=  4.4755E-01 loss=  9.3985E-02
0          **stage inlet**    **stage outlet**    **stage outlet**
                              (before inter-      (after inter-
                              stage adjust-       stage adjust-
                              ment)               ment)
    xv=           0.00000          0.00000          0.00000
    xw=           0.00000          0.00000          0.00000
    xww=          0.00000          0.00000          0.00000
    xf=           0.00000          0.00000          0.00000
    xwt=          0.00000          0.00000          0.00000
    xair=         1.00000          1.00000          1.00000
    xmetan=       0.00000          0.00000          0.00000
    xgas=         1.00000          1.00000          1.00000
    wmass=        0.00000          0.00000          0.00000
    wwmass=       0.00000          0.00000          0.00000
    fmmass=       0.00000          0.00000          0.00000
    wtmass=       0.00000          0.00000          0.00000
    amass=        7.16060          7.16060          7.16060
    chmass=       0.00000          0.00000          0.00000
    vmass=        0.00000          0.00000          0.00000
    gmass=        7.16060          7.16060          7.16060
    tmass=        7.16060          7.16060          7.16060
    ws=           0.00000          0.00000          0.00000
    rhoa=         0.06054          0.06333          0.07015
    rhom=         0.05453          0.06332          0.07013
    rhog=         0.05741          0.06332          0.07013
    tg=         602.00000        667.39777        667.39777
    tw=         597.00000        597.00000        597.00000
    tww=        597.00000          0.00000        597.00000
 nhg: tragas, trawat =   1.10863   1.00000
    p=     1944.00000       2636.54004       2629.21436
    tb=     667.26837          0.00000        682.17615
    tdew=   272.00754        274.47519        274.47519
writing to external plot files
 clear( 2)=    1.00000E-03
 nhg main start calculations for stage  2
 d1 dwakem,w2=  0.   581.754
 d2 dwakem,rdelv1=  0.   10.00000
 d3 dwakem,rdelv2=  0.  0.
ddave(n-2)(n)=  5  0.  0.
 nhg wicsiz wmasss wmassl aming1 2 3 dl,ds,d1,d2,d3 =   0.00000   0.00000   0.00000   0.00000
0.00000   0.00000   0.00000   0.00000   0.00000   0.00000
 nhg ds dl dlge dsll amlge amsll=   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000
 nhg wicsiz wmasss wmassl aming1 2 3 dsll,dlge,d1,d2,d3   =   0.00000   0.00000   0.00000
0.00000   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000
 filmas( 2) =   0.
 ui =   0.
 hhc =   0.
 htotl =   0.
1 *******************   initial flow coefficient= 0.450 (stage= 2 )  *****************
0    stage total pressure ratio=     1.18858
```

```
    stage total temperature ratio=    1.06192
    stage adiabatic efficiency=    0.81180
0    stage flow coefficient=0.289
    axial velocity= 343.18
    rotor speed=1188.42

0                     *rotor inlet* *rotor outlet* *stator outlet*
  total pressure            2629.2144    3143.2791    3125.0420
  static pressure           2446.6165    2724.6399    2926.7351
  total temperature(gas)    667.3978     708.7260     708.7260
  static temperature(gas)   653.8803     680.5155     695.6440
  static density(gas)       0.0701       0.0750       0.0789
  static density(mixture)   0.0701       0.0750       0.0789
0 axial velocity            343.1790     338.8469     322.4617
  absolute velocity         404.0381     583.7838     397.5432
  relative velocity         806.6497     581.7538
  blade speed               943.2569     948.2653     0.0000
  tang. comp. of abs. vel.  213.2487     475.3802
  tang. comp. of rel. vel.  730.0082     472.8851
  acoustic speed            1252.2930    1291.6169    1291.6661
  absolute mach number      0.3226       0.4570       0.3078
  relative mach number      0.6441       0.4554
0 flow coefficient          0.2888       0.2851       0.2713
  flow area                 0.2975       0.2816       0.2816
0 absolute flow angle       31.8565      54.5191      35.7936
  relative flow angle       64.8217      54.3764
  incidence                 19.2217      10.5691
  deviation                              23.7764      17.9436
  diffusion ratio                        3.9221       3.4434
  momentum thickness                     0.0816       0.0371
  omega (gas)                            0.13314      0.04356
  omega (total)                          0.13314      0.04356
 d1 dwakem,v3=  0.   397.543
 d2 dwakem,sdelv1=  0.  10.00000
 d3 dwakem,sdelv2=  0.  0.
 n,ddave(n-2)(n)=  6  0.  0.
 nhg wicsiz wmasss wmassl aming1 2 3 dl,ds,d1,d2,d3 =  0.00000  0.00000  0.00000  0.00000
0.00000  0.00000  0.00000  0.00000  0.00000  0.00000
 nhg ds dl dlge dsll amlge amsll=  0.00000  0.00000  0.00000  0.00000  0.00000  0.00000
 nhg wicsiz wmasss wmassl aming1 2 3 dsll,dlge,d1,d2,d3  =  0.00000  0.00000  0.00000
0.00000  0.00000  0.00000  0.00000  0.00000  0.00000  0.00000
1 ********************  initial flow coefficient= 0.450 (istage=  2 )
********************
0    stage total pressure ratio=       1.18858
    stage total temperature ratio=    1.06192
    stage adiabatic efficiency=       0.81180
  stage  2 total ETA    0.81378del T   41.32819
0psi=  8.8609E-01 psi1=  7.2108E-01 loss=  1.6501E-01
0          **stage inlet**    **stage outlet**    **stage outlet**
                              (before inter-      (after inter-
                              stage adjust-       stage adjust-
```

```
                 ment)           ment)
    xv=       0.00000       0.00000       0.00000
    xw=       0.00000       0.00000       0.00000
    xww=      0.00000       0.00000       0.00000
    xf=       0.00000       0.00000       0.00000
    xwt=      0.00000       0.00000       0.00000
    xair=     1.00000       1.00000       1.00000
    xmetan=   0.00000       0.00000       0.00000
    xgas=     1.00000       1.00000       1.00000
    wmass=    0.00000       0.00000       0.00000
    wwmass=   0.00000       0.00000       0.00000
    fmmass=   0.00000       0.00000       0.00000
    wtmass=   0.00000       0.00000       0.00000
    amass=    7.16060       7.16060       7.16060
    chmass=   0.00000       0.00000       0.00000
    vmass=    0.00000       0.00000       0.00000
    gmass=    7.16060       7.16060       7.16060
    tmass=    7.16060       7.16060       7.16060
    ws=       0.00000       0.00000       0.00000
    rhoa=     0.07385       0.07516       0.07892
    rhom=     0.05453       0.07515       0.07890
    rhog=     0.07013       0.07515       0.07890
    tg=     667.39777     708.72595     708.72595
    tw=     597.00000     597.00000     597.00000
    tww=    597.00000       0.00000     597.00000
 nhg: tragas, trawat =  1.06192  1.00000
    p=    2629.21436    3143.27905    3125.04199
    tb=    682.17615       0.00000    692.03601
    tdew=  274.47519     268.01367     268.01367
writing to external plot files
1********** overall performance *********
0 initial flow coefficient=0.450
0 corrected speed= 8879.0    1.000 fraction of design corrected speed
0 initial water content(small droplet)=0.000
  initial water content(large droplet)=0.000
  initial water content(total)=0.000
  initial relative humidity=  0.0 per cent
  initial methane content=0.000
0 compressor inlet total temperature=  602.00
0 compressor inlet total pressure= 1944.00
0 corrected mass flow rate of mixture= 120.29
0 corrected mass flow rate of gas phase  120.29
0 overall total pressure ratio= 1.6075
0 overall total temperature ratio=1.1773
0 overall adiabatic efficiency=0.8152
0********** performance of fan,lpc,hpc **********
0      gas phase  stagnation  stagnation  adiabatic
0      corrected  pressure    temperature efficiency
0      mass flow    ratio       ratio
0 fan    0.0000     0.0000     0.0000     0.0000
0 lpc    0.0000     0.0000     0.0000     0.0000
```

```
0 hpc     0.0000    0.0000    0.0000    0.0000
0psi= 9.1772E-01 psi1= 7.4815E-01 loss= 1.6957E-01
 i=  55
 Number of loops =  100
 total mass =    1.00000E-08
0psi= 9.1772E-01 psi1= 7.4815E-01 loss= 1.6957E-01
 i=  55
 gemach =   0.273104
```

APPENDIX E

File 2: blheat1.out

Compressor flow adiabatic
initial clearance at ref.temp. (R)= 518.700
stage 1 : clearance[in]= 7.00092E-03
stage 2 : clearance[in]= 6.99997E-03
----------------------------------------
initial steady thermal node and blade clearance
node no. Node temp.(K):
1 3.0957E+02 2 3.1387E+02 3 3.1467E+02 4 3.0996E+02 5 3.1591E+02 6
3.1536E+02 7 3.1469E+02 8 3.2398E+02

9 3.1757E+02 10 3.2224E+02 11 3.2962E+02 12 3.4331E+02 13 3.3565E+02 14
3.3425E+02 15 3.5303E+02 16 3.2337E+02

17 3.2321E+02 18 3.5220E+02 19 3.2239E+02
stage 1 : clearance[in]= 4.82655E-03
stage 2 : clearance[in]= 1.40285E-03
--------------------------------
jsweep= 1
i,T(K):
1 3.0973E+02 2 3.1399E+02 3 3.1470E+02 4 3.1573E+02 5 3.2717E+02 6
3.1540E+02 7 3.1469E+02 8 3.2418E+02

9 3.1767E+02 10 3.2240E+02 11 3.3681E+02 12 3.5115E+02 13 3.3570E+02 14
3.3424E+02 15 3.5519E+02 16 3.2348E+02

17 3.2325E+02 18 3.5983E+02 19 3.2280E+02
stage 1 : clearance[in]= 3.83663E-03
stage 2 : clearance[in]= 7.99179E-04
--------------------------------
jsweep= 10
stage 1 : clearance[in]= 3.88718E-03
stage 2 : clearance[in]= 8.18253E-04
--------------------------------
jsweep= 20
stage 1 : clearance[in]= 3.93486E-03
stage 2 : clearance[in]= 8.36372E-04
--------------------------------
jsweep= 30
stage 1 : clearance[in]= 3.98064E-03
stage 2 : clearance[in]= 8.53539E-04
--------------------------------
jsweep= 40
stage 1 : clearance[in]= 4.02260E-03
stage 2 : clearance[in]= 8.70705E-04
--------------------------------
jsweep= 50
stage 1 : clearance[in]= 4.06456E-03
stage 2 : clearance[in]= 8.86917E-04
--------------------------------

```
jsweep= 60
stage 1 : clearance[in]=   4.10271E-03
stage 2 : clearance[in]=   9.04083E-04
--------------------------------
jsweep= 70
stage 1 : clearance[in]=   4.13990E-03
stage 2 : clearance[in]=   9.18388E-04
--------------------------------
jsweep= 80
stage 1 : clearance[in]=   4.17519E-03
stage 2 : clearance[in]=   9.32693E-04
--------------------------------
jsweep= 90
stage 1 : clearance[in]=   4.20761E-03
stage 2 : clearance[in]=   9.47952E-04
--------------------------------
jsweep= 100
i,T(K):
 1 3.0977E+02  2 3.1402E+02  3 3.1473E+02  4 3.1477E+02  5 3.2591E+02  6
3.1546E+02  7 3.1470E+02  8 3.2424E+02

 9 3.1770E+02 10 3.2262E+02 11 3.3682E+02 12 3.5125E+02 13 3.3577E+02 14
3.3424E+02 15 3.5568E+02 16 3.2351E+02

 17 3.2333E+02 18 3.5944E+02 19 3.2312E+02
stage 1 : clearance[in]=   3.94630E-03
stage 2 : clearance[in]=   7.85828E-04
```

APPENDIX E

File 3: Case2.out

```
Input Data - Wet Case 1
Compressor flow adiabatic
icase=  4

 phi design  = 0.7773584

 inlet phi =0.4500000
0psi=  9.1772E-01 psi1=  7.4815E-01 loss=  1.6957E-01
 jsweep=   100

  MEAN
  fraction of design speed = 1.00000
 >>>>>>>>>> loop number 2 <<<<<<<<<<
 igv area=    0.241601
 nhg number of streamlines =    10.22089
1     ***************************** input data
*************************************
    heat transfer after rotor and stator version
0 number of stages=  2 (fan 0, lpc 2, hpc 0)
  performance at mean
0 vapor is centrifuged
0 large droplets in rotor free stream are not centrifuged


  stage       1    2    3
  rrhub(i)    6.95  7.64
  rc(i)      2.170 2.436
  rblade(i)  36.00 26.00
  stager(i)  37.20 38.10
  stages(i)  28.70 30.90 31.80
  srhub(i)    7.35  8.10  8.73
  sc(i)      1.880 1.665 1.484
  sblade(i)  36.00 40.00 46.00
  sigumr(i)  1.106 0.891
  sigums(i)  0.958 0.929 0.940
  bet2ss(i)  23.91 25.81 26.12
  gapr(i)    0.577 0.728
  gaps(i)    0.790 0.860
  rrtip(i)   14.47 14.24
  srtip(i)   14.37 14.12 13.91
  rt(i)      14.47 14.24
  rm(i)      11.28 11.30
  rh(i)       6.95  7.64
  st(i)      14.37 14.12
  sm(i)      11.21 11.36
  sh(i)       7.35  8.10
  block(i)   0.985 0.950
  blocks(i)  0.945 0.955 0.965
  bet1mr(i)  42.70 45.60
  bet2mr(i)  31.70 30.60
```

bet1ms(i) 40.40 43.95 46.25
bet2ms(i) 17.00 17.85 17.35
pr12d(i) 1.254 1.233
pr13d(i) 1.248 1.227
etard(i) 0.912 0.962
dvz1(i) 653.9 634.6 625.3
dvz2(i) 632.0 606.5 591.6
dvz3(i) 623.2 610.3
ak1(i) 2.300 1.460
ak2(i) 0.090 0.090
ak3(i) 1.000 1.500

```
1     ***************************** input data *****************************
0 fnf(fraction of design corrected speed)=1.000
0 xdin(initial water content of small droplet)=0.000
  xddin(initial water content of large droplet)=1.000
  rhumid(initial relative humidity)=  0.00 per cent
  xch4(initial methane content)=0.000
0 t0g(compressor inlet total temprature of gas)= 602.00
  t0w(compressor inlet temperature of droplret)= 597.00
  p0(compressor inlet total pressure)=1944.00
0 din(initial droplet diameter of small droplet)=  20.0
  ddin(initial droplet diameter of large droplet)= 600.0
0 fnd(design rotational speed)= 8879.0
0 dsmass(design stream  mass flow rate)=   11.3000
0 bypass ratio =     0.0000
0 compressor inlet total temperature(gas phase) 602.00 r
0 compressor inlet total pressure=1944.00 lb/ft**2
0 preb(percent of water that rebound after impingement)= 50.0 percent
0 rotor speed= 9565.4 rpm
0 corrected rotor speed=  8879.0 rpm(  100.0per cent of design corrected speed)
0 molecular weight of air= 28.9700
0 maximum diameter of small droplets=   300.0 microns
0 rotor corrected speed at design point=  8879.0
  rotor corrected speed of lpc at design point=  8879.0
  rotor corrected speed of hpc at the design point=  8879.0
 design flow coefficient at inlet =   0.777358

1*************** design point information ************ ***
0 ***** compressor inlet *****
0 total temperature at compressor inlet(R)= 602.00000
  total pressure at compressor inlet(lbf/ft**2)=   1944.00
  static temperature at compressor inlet(R)= 556.98975
  static pressure at compressor inlet(lbf/ft**2)=   1480.37
  static density at compressor inlet(lbm/ft**3)=   0.04982
0 acoustic speed at compressor inlet(ft/s)=1156.55713
  axial velocity at compressor inlet(ft/s)= 625.29999
  mach number at compressor inlet=  -0.63642
  streamtube area at compressor inlet(ft**2)=   0.24160
  flow coefficient at compressor inlet=   0.77736
1*************** design point information ************ ***
0 ***** stage= 1 *****
```

```
0             total       total       static      static      static
              temp      pressure      temp      pressure     density
0 rotor inlet   602.000     1944.000     554.852     1460.540      0.049
 rotor outlet   646.018     2437.776     582.467     1694.070      0.055
0             axial     absolute     relative    tan comp    tan comp
            velocity    velocity     velocity   of abs vel  of rel vel
0 rotor inlet  653.90002   728.27600   901.76440   320.62540   620.96191
 rotor outlet 632.00000   875.68225   762.34113   606.13159   329.61261
0             rotor     abs mach     rel mach    rel total    rel total
              speed      number       number       temp       pressure
0 rotor inlet   941.587      0.653       0.781      622.410    2185.063
 rotor outlet   935.744      0.741       0.645      630.648    5747.708
0           abs flow    rel flow    streamtube                 flow
              angle       angle        area      radius    coefficient
0 rotor inlet  26.12000    43.52000     0.33861     11.28000     0.54140
 rotor outlet  43.80309    25.61799     0.30958     11.21000     0.52327
0 stage total pressure ratio at design point=  1.24800
 stage adiabatic efficiency at design point=  0.89109
 rotor total pressure ratio at design point=  1.25400
 rotor adiabatic efficiency at design point=  0.91200
 rotor total temperature ratio at design point=  1.07312
1*************** design point information ************ ***
0 ***** stage= 2 *****
0             total       total       static      static      static
              temp      pressure      temp      pressure     density
0 rotor inlet   646.018     2426.112     606.280     1941.056      0.060
 rotor outlet   687.268     2991.396     632.514     2232.765      0.066
0             axial     absolute     relative    tan comp    tan comp
            velocity    velocity     velocity   of abs vel  of rel vel
0 rotor inlet  634.59998   694.17151   916.97321   281.34848   661.90845
 rotor outlet 606.50000   813.80762   725.84167   542.62378   405.64148
0             rotor     abs mach     rel mach    rel total    rel total
              speed      number       number       temp       pressure
0 rotor inlet   943.257      0.574       0.760      675.988    2845.161
 rotor outlet   948.265      0.661       0.589      676.086    6382.674
0           abs flow    rel flow    streamtube                 flow
              angle       angle        area      radius    coefficient
0 rotor inlet  23.91000    46.20665     0.29752     11.30000     0.53399
 rotor outlet  41.81838    33.97677     0.28323     11.36000     0.51034
0 stage total pressure ratio at design point=  1.22700
 stage adiabatic efficiency at design point=  0.93777
 rotor total pressure ratio at design point=  1.23300
 rotor adiabatic efficiency at design point=  0.96200
 rotor total temperature ratio at design point=  1.06385
1*************** design point information ************ ***
0********** overall performance at design point ****  ******
0 compressor inlet total temperature=  602.00
0 compressor inlet total pressure=  1944.00
0 corrected mass flow rate= 135.446
0 overall total pressure ratio=  1.5313
0 overall total temperature ratio=1.1416
```

```
0 overall adiabatic efficiency=0.9102
0 overall temperature rise=  85.268
0          1   2    3    4    5    6    7    8    9    10   11   12   13   14   15   16
 bet1sr(i)  43.52 46.21
 bet2sr(i)  25.62 33.98
 aincsr(i)   0.82   0.61
 adevsr(i)   -6.08   3.38
 bet1ss(i)  43.80 41.82
 bet2ss(i)  23.91 25.81 26.12
 aincss(i)   3.40 -2.13
 adevss(i)   6.91   7.96
 td(i)      602.  646.
 omegr(i)   0.063 0.026
 omegs(i)   0.016 0.019
 sitadr(i)   .0399 .0174
 sitads(i)   .0120 .0136
 deqr(i)     1.601 1.587
 deqs(i)     1.660 1.523
1  fai=0.4500000
 xddin =   0.
 nhg main ws(1) tg(1) p(1) rhumid =   0.00000 602.000001944.00000   0.00001
 nhg main xv(1) xwt(1) xch4 =   0.00000   0.00000   0.00000
0 vz at igv inlet =  543.50366 mach number =    0.46153
  i     xwt      watrgn
  1  0.  0.
  2  0.  0.
  3  0.  0.
  4  0.  0.
  5  0.  0.
  6  0.  0.
  7  0.  0.
  8  0.  0.
  9  0.  0.
  10  0.  0.
 xv(1) =     1.18659E-09
 watrgt =  0.
0    istage=0  (igv)
0         0.45000        543.50366         1.00000
 clear( 1)=     1.00000E-03
 nhg main start calculations for stage  1
 d1 dwakem,w2=  0.   514.381
 d2 dwakem,rdelv1=  0.   10.00000
 d3 dwakem,rdelv2=  0.  0.
ddave(n-2)(n)=  3  0.   472.146
 nhg wicsiz wmasss wmassl aming1 2 3 dl,ds,d1,d2,d3 =   0.00000   0.00000   0.00000   0.00000
0.00000 472.14648   0.00000   0.00000   0.00000   0.00000
 nhg ds dl dlge dsll amlge amsll=  0.00000 472.14648   0.00000   0.00000   0.00000   0.00000
 nhg wicsiz wmasss wmassl aming1 2 3 dsll,dlge,d1,d2,d3  =  0.00000   0.00000   0.00000
0.00000   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000
 filmas( 1) =     5.55582E-02
 ui =     23.5166
```

```
hhc =    0.750000
htotl =    7.50000E-04
1 ******************** initial flow coefficient= 0.450 (stage= 1 ) *******************
0    stage total pressure ratio=     1.35248
     stage total temperature ratio=    1.10863
     stage adiabatic efficiency=    0.82645
0    stage flow coefficient=0.305
     axial velocity= 368.37
     rotor speed=1207.79

0                    *rotor inlet* *rotor outlet* *stator outlet*
  total pressure          1944.0000     2636.5400     2629.2144
  static pressure         1805.3267     2192.1331     2450.7463
  total temperature(gas)   602.0000      667.3978      667.3978
  static temperature(gas)  589.4261      633.1794      654.1548
  static density(gas)        0.0574        0.0649        0.0702
  static density(mixture)    0.0574        0.0649        0.0702
0 axial velocity           368.3688      336.4398      339.1703
  absolute velocity        389.0350      641.8840      399.3185
  relative velocity        895.7287      514.3813
  blade speed              941.5873      935.7442      943.2569
  tang. comp. of abs. vel. 125.1105      546.6473
  tang. comp. of rel. vel. 816.4768      389.0969
  acoustic speed          1189.7568     1253.3921     1253.3827
  absolute mach number       0.3270        0.5205        0.3186
  relative mach number       0.7529        0.4171
0 flow coefficient           0.3050        0.2786        0.2854
  flow area                  0.3386        0.3280        0.3007
0 absolute flow angle       18.7592       58.3893       31.8565
  relative flow angle       65.7166       49.1511
  incidence                 23.0166       17.9893
  deviation                               17.4511       14.8565
  diffusion ratio                          3.6653        2.6688
  momentum thickness                       0.1314        0.0192
  omega (gas)                              0.17564       0.01648
  omega (total)                            0.17564       0.01648
 d1 dwakem,v3=  0.   399.318
 d2 dwakem,sdelv1=  0.  10.00000
 d3 dwakem,sdelv2=  0.  0.
 n,ddave(n-2)(n)=  4  0.   465.064
 nhg wicsiz wmasss wmassl amingl 2 3 dl,ds,d1,d2,d3 =  0.00000   0.00000   0.00000   0.00000
0.00000 465.06369  0.00000  0.00000  0.00000  0.00000
 nhg ds dl dlge dsll amlge amsll=  0.00000 465.06369  0.00000  0.00000  0.00000  0.00000
 nhg wicsiz wmasss wmassl amingl 2 3 dsll,dlge,d1,d2,d3  =  0.00000  0.00000  0.00000
0.00000  0.00000  0.00000  0.00000  0.00000  0.00000  0.00000
1 ******************** initial flow coefficient= 0.450 (istage=  1 )
********************
0    stage total pressure ratio=       1.35248
     stage total temperature ratio=    1.10863
     stage adiabatic efficiency=       0.82645
  stage  1 total ETA    0.82645del T   65.39777
```

```
0psi=  5.4154E-01 psi1=  4.4755E-01 loss=  9.3985E-02
0          **stage inlet**   **stage outlet**   **stage outlet**
                             (before inter-     (after inter-
                              stage adjust-      stage adjust-
                              ment)              ment)
    xv=          0.00000         0.00000         0.00000
    xw=          0.00000         0.00000         0.00000
    xww=         0.00000         0.00000         0.00000
    xf=          0.00000         0.00000         0.00076
    xwt=         0.00000         0.00000         0.00000
    xair=        1.00000         1.00000         1.00000
    xmetan=      0.00000         0.00000         0.00000
    xgas=        1.00000         1.00000         1.00000
    wmass=       0.00000         0.00000         0.00000
    wwmass=      0.00000         0.00000         0.00000
    fmmass=      0.07102         0.07102         0.05556
    wtmass=      0.00000         0.00000         0.00000
    amass=       7.16060         7.16060         7.16060
    chmass=      0.00000         0.00000         0.00000
    vmass=       0.00000         0.00000         0.00000
    gmass=       7.16060         7.16060         7.16060
    tmass=       7.16060         7.16060         7.16060
    ws=          0.00000         0.00000         0.00000
    rhoa=        0.06054         0.06333         0.07015
    rhom=        0.05453         0.06332         0.07013
    rhog=        0.05741         0.06332         0.07013
    tg=        602.00000       667.39777       667.39777
    tw=        597.00000       597.00000       597.00000
    tww=       597.00000         0.00000       597.00000
 nhg: tragas, trawat =  1.10863   1.00000
    p=    1944.00000       2636.54004        2629.21436
    tb=    667.26837          0.00000         682.17615
    tdew=    272.00754       274.47519        274.47519
writing to external plot files
 clear( 2)=    1.00000E-03
 nhg main start calculations for stage  2
 d1 dwakem,w2=  0.   581.754
 d2 dwakem,rdelv1=  0.  10.00000
 d3 dwakem,rdelv2=  0.  0.
ddave(n-2)(n)=  5  0.   410.474
 nhg wicsiz wmasss wmassl aming1 2 3 dl,ds,d1,d2,d3 =  0.00000  0.00000  0.00000  0.00000
0.00000 410.47403  0.00000  0.00000  0.00000  0.00000
 nhg ds dl dlge dsll amlge amsll=  0.00000 410.47403  0.00000  0.00000  0.00000  0.00000
 nhg wicsiz wmasss wmassl aming1 2 3 dsll,dlge,d1,d2,d3  =  0.00000  0.00000  0.00000
0.00000  0.00000  0.00000  0.00000  0.00000  0.00000  0.00000
 filmas( 2) =    5.71048E-02
 ui =    272.208
 hhc =    7.78868E-03
 htotl =    7.78868E-06
1 *******************  initial flow coefficient= 0.450 (stage= 2 )  ******************
0    stage total pressure ratio=     1.18858
```

```
    stage total temperature ratio=    1.06192
    stage adiabatic efficiency=    0.81180
0    stage flow coefficient=0.289
    axial velocity= 343.18
    rotor speed=1188.42

0                   *rotor inlet* *rotor outlet* *stator outlet*
 total pressure          2629.2144     3143.2776     3125.0408
 static pressure         2446.6165     2724.6399     2926.7351
 total temperature(gas)   667.3978      708.7259      708.7259
 static temperature(gas)  653.8803      680.5155      695.6439
 static density(gas)        0.0701        0.0750        0.0789
 static density(mixture)    0.0701        0.0750        0.0789
0 axial velocity          343.1790      338.8469      322.4617
 absolute velocity        404.0382      583.7836      397.5429
 relative velocity        806.6497      581.7543
 blade speed              943.2569      948.2653        0.0000
 tang. comp. of abs. vel.  213.2488     475.3798
 tang. comp. of rel. vel.  730.0081     472.8856
 acoustic speed          1252.2930     1291.6169     1291.6661
 absolute mach number       0.3226        0.4570        0.3078
 relative mach number       0.6441        0.4554
0 flow coefficient          0.2888        0.2851        0.2713
 flow area                  0.2975        0.2816        0.2816
0 absolute flow angle      31.8565       54.5190       35.7935
 relative flow angle       64.8216       54.3764
 incidence                 19.2216       10.5690
 deviation                               23.7764       17.9435
 diffusion ratio                          3.9221        3.4434
 momentum thickness                       0.0816        0.0371
 omega (gas)                              0.13314       0.04356
 omega (total)                            0.13314       0.04356
 d1 dwakem,v3=  0.   397.543
 d2 dwakem,sdelv1=  0.  10.00000
 d3 dwakem,sdelv2=  0.  0.
 n,ddave(n-2)(n)=  6  0.   420.337
 nhg wicsiz wmasss wmassl amingl 2 3 dl,ds,d1,d2,d3 =  0.00000  0.00000  0.00000  0.00000
0.00000 420.33719  0.00000  0.00000  0.00000  0.00000
 nhg ds dl dlge dsll amlge amsll=  0.00000 420.33719  0.00000  0.00000  0.00000  0.00000
 nhg wicsiz wmasss wmassl amingl 2 3 dsll,dlge,d1,d2,d3  =  0.00000  0.00000  0.00000
0.00000  0.00000  0.00000  0.00000  0.00000  0.00000  0.00000
1 ********************  initial flow coefficient= 0.450 (istage=  2 )
********************
0    stage total pressure ratio=       1.18858
    stage total temperature ratio=    1.06192
    stage adiabatic efficiency=       0.81180
 stage  2 total ETA    0.81378del T  41.32812
0psi=  8.8609E-01 psi1=  7.2108E-01 loss=  1.6501E-01
0          **stage inlet**   **stage outlet**   **stage outlet**
                          (before inter-     (after inter-
                           stage adjust-      stage adjust-
```

| | | | |
|---|---|---|---|
| | ment) | ment) | |
| xv= | 0.00000 | 0.00000 | 0.00000 |
| xw= | 0.00000 | 0.00000 | 0.00000 |
| xww= | 0.00000 | 0.00000 | 0.00000 |
| xf= | 0.00076 | 0.00076 | 0.00078 |
| xwt= | 0.00000 | 0.00000 | 0.00000 |
| xair= | 1.00000 | 1.00000 | 1.00000 |
| xmetan= | 0.00000 | 0.00000 | 0.00000 |
| xgas= | 1.00000 | 1.00000 | 1.00000 |
| wmass= | 0.00000 | 0.00000 | 0.00000 |
| wwmass= | 0.00000 | 0.00000 | 0.00000 |
| fmmass= | 0.05556 | 0.05556 | 0.05710 |
| wtmass= | 0.00000 | 0.00000 | 0.00000 |
| amass= | 7.16060 | 7.16060 | 7.16060 |
| chmass= | 0.00000 | 0.00000 | 0.00000 |
| vmass= | 0.00000 | 0.00000 | 0.00000 |
| gmass= | 7.16060 | 7.16060 | 7.16060 |
| tmass= | 7.16060 | 7.16060 | 7.16060 |
| ws= | 0.00000 | 0.00000 | 0.00000 |
| rhoa= | 0.07385 | 0.07516 | 0.07892 |
| rhom= | 0.05453 | 0.07515 | 0.07890 |
| rhog= | 0.07013 | 0.07515 | 0.07890 |
| tg= | 667.39777 | 708.72589 | 708.72589 |
| tw= | 597.00000 | 597.00000 | 597.00000 |
| tww= | 597.00000 | 0.00000 | 597.00000 |

nhg: tragas, trawat = 1.06192 1.00000

| | | | |
|---|---|---|---|
| p= | 2629.21436 | 3143.27759 | 3125.04077 |
| tb= | 682.17615 | 0.00000 | 692.03601 |
| tdew= | 274.47519 | 268.01367 | 268.01367 |

writing to external plot files
1********** overall performance *********
0 initial flow coefficient=0.450
0 corrected speed= 8879.0 1.000 fraction of design corrected speed
0 initial water content(small droplet)=0.000
initial water content(large droplet)=0.000
initial water content(total)=0.000
initial relative humidity= 0.0 per cent
initial methane content=0.000
0 compressor inlet total temperature= 602.00
0 compressor inlet total pressure= 1944.00
0 corrected mass flow rate of mixture= 120.29
0 corrected mass flow rate of gas phase 120.29
0 overall total pressure ratio= 1.6075
0 overall total temperature ratio=1.1773
0 overall adiabatic efficiency=0.8152
0********** performance of fan,lpc,hpc **********

| | | | | |
|---|---|---|---|---|
| 0 | gas phase | stagnation | stagnation | adiabatic |
| 0 | corrected | pressure | temperature | efficiency |
| 0 | mass flow | ratio | ratio | |
| 0 fan | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| 0 lpc | 0.0000 | 0.0000 | 0.0000 | 0.0000 |

```
0 hpc     0.0000     0.0000     0.0000     0.0000
0psi=  9.1772E-01 psi1=  7.4815E-01 loss=  1.6957E-01
 i=  55
1  fai=0.4500000
 xddin =     4.00000E-02
 nhg main ws(1) tg(1) p(1) rhumid =   0.01187 602.000001944.00000 100.00000
 nhg main xv(1) xwt(1) xch4 =   0.01126   0.04000   0.00000
0 vz at igv inlet = 543.50366 mach number =    0.46995
  i     xwt      watrgn
  1   4.00000E-02   0.301641
  2   4.00000E-02   0.301641
  3   4.00000E-02   0.301641
  4   4.00000E-02   0.301641
  5   4.00000E-02   0.301641
  6   4.00000E-02   0.301641
  7   4.00000E-02   0.301641
  8   4.00000E-02   0.301641
  9   4.00000E-02   0.301641
  10   4.00000E-02   0.301641
 xv(1) =    1.12577E-02
 watrgt =    3.01641
 d0 dwakem,w2=     600.000    543.504
0    istage=0  (igv)
0        0.45000       543.50366          0.94874
 clear( 1)=    1.00000E-03
 nhg main start calculations for stage  1
 d1 dwakem,w2=  0.   515.749
 d2 dwakem,rdelv1=     600.000    18.9275
 d3 dwakem,rdelv2=     433.842  0.
ddave(n-2)(n)=  3    600.000  0.
 nhg wicsiz wmasss wmassl aming1 2 3 dl,ds,d1,d2,d3 =   0.00000   0.14756   0.00000   0.03402
0.11354   0.00000   0.00000   0.00000 600.00000 433.84219
 nhg ds dl dlge dsll amlge amsll=   0.00000   0.00000 472.14655   0.00000   0.14756   0.14756
 nhg wicsiz wmasss wmassl aming1 2 3 dsll,dlge,d1,d2,d3  =   0.00000   0.14756   0.00000
0.03402   0.11354   0.00000 472.14655   0.00000 600.00000 433.84219
 filmas( 1) =    0.169656
 ui =    23.5166
 hhc =    0.750000
 htotl =    7.50000E-04
n,ddave(n-1)(n)=  3    600.000    472.147
n,ddave(n-1)(n)=  3    600.000    472.147
1 ********************   initial flow coefficient= 0.450 (stage= 1 )  *******************
0    stage total pressure ratio=      1.33462
     stage total temperature ratio=      1.10833
     stage adiabatic efficiency=      0.78831
0    stage flow coefficient=0.304
     axial velocity= 367.58
     rotor speed=1207.79

0                    *rotor inlet* *rotor outlet* *stator outlet*
  total pressure          1944.0000     2608.4819     2594.5100
```

```
 static pressure        1801.3136    2148.7932    2409.4758
 total temperature(gas)  602.0000     667.2146     667.2146
 static temperature(gas)  589.0900     632.7929     653.9154
 static density(gas)       0.0569       0.0632       0.0686
 static density(mixture)    0.0593       0.0658       0.0714
0 axial velocity          367.5780     341.7137     343.5442
 absolute velocity         388.1998     647.0368     402.8692
 relative velocity         895.6487     515.7485
 blade speed              941.5873     935.7442     943.2569
 tang. comp. of abs. vel.  124.8420     549.4436
 tang. comp. of rel. vel.  816.7454     386.3006
 acoustic speed           1168.8855    1211.4681    1230.6973
 absolute mach number        0.3321       0.5341       0.3274
 relative mach number       0.7662       0.4257
0 flow coefficient          0.3043       0.2829       0.2891
 flow area                  0.3386       0.3280       0.3007
0 absolute flow angle       18.7592      58.1214      31.4886
 relative flow angle        65.7698      48.5047
 incidence                  23.0698      17.7214
 deviation                               16.8047      14.4886
 diffusion ratio                          3.6611       2.6438
 momentum thickness                         0.1380       0.0191
 omega (gas)                              0.17676      0.01646
 omega (total)                            0.20246      0.03734
 d1 dwakem,v3=     600.000   402.869
 d2 dwakem,sdelv1=     600.000   18.9275
 d3 dwakem,sdelv2=    400.076  0.
 n,ddave(n-2)(n)=  4    600.000  0.
 nhg wicsiz wmasss wmassl aming1 2 3 dl,ds,d1,d2,d3 =   0.08616   0.12958   0.06140   0.00584
0.01213   0.00000   0.00000  20.00000 600.00000 400.07565
 nhg ds dl dlge dsll amlge amsll=   0.00000   0.00000 465.06369   4.43073   0.01798   0.27715
 nhg wicsiz wmasss wmassl aming1 2 3 dsll,dlge,d1,d2,d3  =   0.08616   0.12958   0.06140
0.00584   0.01213   4.43073 465.06369  20.00000 600.00000 400.07565
n,ddave(n-1)(n)=  4    472.147    465.064
n,ddave(n-1)(n)=  4    472.147    465.064
xnp,tg(3),p(3)=    3.20075E+10    667.135    2594.51
1 *******************    initial flow coefficient= 0.450 (istage=  1 )
*******************
0     stage total pressure ratio=        1.33462
      stage total temperature ratio=     1.10820
      stage adiabatic efficiency=        0.78907
 stage  1 total ETA     0.78907del T   65.13525
0psi=  5.4574E-01 psi1=  4.3063E-01 loss=  1.1511E-01
0           **stage inlet**    **stage outlet**    **stage outlet**
                           (before inter-      (after inter-
                            stage adjust-       stage adjust-
                            ment)               ment)
    xv=          0.01126            0.01126            0.01308
    xw=          0.00000            0.00000            0.00000
    xww=          0.04000            0.04000            0.03818
    xf=          0.00007            0.00007            0.00225
```

| | | | |
|---|---|---|---|
| xwt= | 0.04000 | 0.04000 | 0.03818 |
| xair= | 0.94874 | 0.94874 | 0.94874 |
| xmetan= | 0.00000 | 0.00000 | 0.00000 |
| xgas= | 0.96000 | 0.96000 | 0.96182 |
| wmass= | 0.00000 | 0.00000 | 0.00000 |
| wwmass= | 0.29512 | 0.29512 | 0.28170 |
| fmmass= | 0.05556 | 0.05556 | 0.16966 |
| wtmass= | 0.29512 | 0.29512 | 0.28170 |
| amass= | 6.99987 | 6.99987 | 6.99987 |
| chmass= | 0.00000 | 0.00000 | 0.00000 |
| vmass= | 0.08306 | 0.08306 | 0.09648 |
| gmass= | 7.08293 | 7.08293 | 7.09635 |
| tmass= | 7.37806 | 7.37806 | 7.37806 |
| ws= | 0.01187 | 0.01187 | 0.01378 |
| rhoa= | 0.06054 | 0.06216 | 0.06484 |
| rhom= | 0.05619 | 0.06428 | 0.07118 |
| rhog= | 0.05691 | 0.06171 | 0.06847 |
| tg= | 602.00000 | 667.21460 | 667.13525 |
| tw= | 597.00000 | 597.00000 | 597.00000 |
| tww= | 597.00000 | 597.00000 | 597.44580 |

nhg: tragas, trawat = 1.10820 1.00075

| | | | |
|---|---|---|---|
| p= | 1944.00000 | 2608.48193 | 2594.51001 |
| tb= | 667.26837 | 0.00000 | 681.50610 |
| tdew= | 518.09930 | 526.80371 | 531.09418 |

writing to external plot files
clear( 2)= 1.00000E-03
nhg main start calculations for stage 2
d1 dwakem,w2= 0. 585.055
d2 dwakem,rdelv1= 600.000 18.8394
d3 dwakem,rdelv2= 363.792 0.
ddave(n-2)(n)= 5 472.147 0.
nhg wicsiz wmasss wmassl aming1 2 3 dl,ds,d1,d2,d3 = 0.00000 0.14085 0.00000 0.02855 0.11230 0.00000 0.00000 0.00000 600.00000 363.79233
nhg ds dl dlge dsll amlge amsll= 0.00000 0.00000 411.66669 0.00000 0.14085 0.14085
nhg wicsiz wmasss wmassl aming1 2 3 dsll,dlge,d1,d2,d3 = 0.00000 0.14085 0.00000 0.02855 0.11230 0.00000 411.66669 0.00000 600.00000 363.79233
filmas( 2) = 0.476775
ui = 30.7086
hhc = 0.718209
htotl = 7.18209E-04
n,ddave(n-1)(n)= 5 465.064 411.667
n,ddave(n-1)(n)= 5 465.064 411.667
1 ******************** initial flow coefficient= 0.450 (stage= 2 ) ******************
0 stage total pressure ratio= 1.17666
stage total temperature ratio= 1.06177
stage adiabatic efficiency= 0.76247
0 stage flow coefficient=0.293
axial velocity= 348.37
rotor speed=1188.42

0 *rotor inlet* *rotor outlet* *stator outlet*

```
 total pressure        2594.5100    3081.0574    3052.8523
 static pressure       2404.7615    2649.0469    2846.5596
 total temperature(gas)   667.1353     708.3432     708.3432
 static temperature(gas)  652.9359     679.7630     695.0020
 static density(gas)      0.0685       0.0724       0.0761
 static density(mixture)    0.0712       0.0753       0.0792
0 axial velocity       348.3744     347.8579     330.9785
 absolute velocity       408.5336     591.0604     404.3733
 relative velocity      808.7470     585.0549
 blade speed           943.2569     948.2653       0.0000
 tang. comp. of abs. vel.  213.3892     477.8569
 tang. comp. of rel. vel.  729.8677     470.4084
 acoustic speed        1231.5189    1256.5637    1269.8992
 absolute mach number       0.3317       0.4704       0.3184
 relative mach number      0.6567       0.4656
0 flow coefficient         0.2931       0.2927       0.2785
 flow area             0.2975       0.2816       0.2816
0 absolute flow angle      31.4886      53.9471      35.0653
 relative flow angle     64.4843      53.5178
 incidence            18.8843       9.9971
 deviation                  22.9178      17.2153
 diffusion ratio              3.8691       3.3655
 momentum thickness              0.0829       0.0355
 omega (gas)                   0.13046      0.04166
 omega (total)                  0.15583      0.06932
 d1 dwakem,v3=    600.000  404.373
 d2 dwakem,sdelv1=    600.000  18.8394
 d3 dwakem,sdelv2=    342.674  0.
 n,ddave(n-2)(n)= 6  465.064  0.
 nhg wicsiz wmasss wmassl aming1 2 3 dl,ds,d1,d2,d3 =  0.09618  0.12391  0.04467  0.00517
0.01177  0.00000  0.00000  20.00000 600.00000 342.67392
 nhg ds dl dlge dsll amlge amsll=  0.00000  0.00000 421.20795  3.37468  0.01694  0.26476
 nhg wicsiz wmasss wmassl aming1 2 3 dsll,dlge,d1,d2,d3  =  0.09618  0.12391  0.04467
0.00517  0.01177  3.37468 421.20795  20.00000 600.00000 342.67392
n,dave(n-1)(n)=  6  0.   3.37468
n,ddave(n-1)(n)=  6   411.667   421.208
n,dave(n-1)(n)=  6  0.   3.37468
n,ddave(n-1)(n)=  6   411.667   421.208
xnp,tg(3),p(3)=   3.20075E+10   708.218   3052.85
xnp,tg(3),p(3)=   3.05521E+10   708.218   3052.85
1 ********************  initial flow coefficient= 0.450 (istage=  2 )
********************
0    stage total pressure ratio=        1.17666
     stage total temperature ratio=     1.06158
     stage adiabatic efficiency=        0.76428
 stage  2 total ETA    0.77133del T   41.08319
0psi=  8.9614E-01 psi1=  6.9122E-01 loss=  2.0492E-01
0          **stage inlet**   **stage outlet**   **stage outlet**
                             (before inter-     (after inter-
                              stage adjust-      stage adjust-
                              ment)              ment)
```

```
    xv=        0.01308        0.01308        0.01789
    xw=        0.00000        0.00000        0.00000
    xww=       0.03818        0.03818        0.03337
    xf=        0.00225        0.00225        0.00632
    xwt=       0.03818        0.03818        0.03337
    xair=      0.94874        0.94874        0.94874
    xmetan=    0.00000        0.00000        0.00000
    xgas=      0.96182        0.96182        0.96663
    wmass=     0.00000        0.00000        0.00000
    wwmass=    0.28170        0.28170        0.24623
    fmmass=    0.16966        0.16966        0.47678
    wtmass=    0.28170        0.28170        0.24623
    amass=     6.99987        6.99987        6.99987
    chmass=    0.00000        0.00000        0.00000
    vmass=     0.09648        0.09648        0.13196
    gmass=     7.09635        7.09635        7.13183
    tmass=     7.37806        7.37806        7.37806
    ws=        0.01378        0.01378        0.01885
    rhoa=      0.07291        0.07330        0.07230
    rhom=      0.05619        0.07557        0.07862
    rhog=      0.06847        0.07269        0.07600
    tg=      667.13525      708.34320      708.21844
    tw=      597.00000      597.00000      597.00000
    tww=     597.44580      597.44580      598.18591
 nhg: tragas, trawat =   1.06158   1.00124
    p=   2594.51001     3081.05737     3052.85229
    tb=   681.50610        0.00000      690.75311
    tdew=   531.09418      530.05609      539.78143
writing to external plot files
1********** overall performance *********
0 initial flow coefficient=0.450
0 corrected speed= 8879.0    1.000 fraction of design corrected speed
0 initial water content(small droplet)=0.000
  initial water content(large droplet)=0.040
  initial water content(total)=0.040
  initial relative humidity=100.0 per cent
  initial methane content=0.000
0 compressor inlet total temperature=  602.00
0 compressor inlet total pressure= 1944.00
0 corrected mass flow rate of mixture= 123.94
0 corrected mass flow rate of gas phase  118.99
0 overall total pressure ratio= 1.5704
0 overall total temperature ratio=1.1764
0 overall adiabatic efficiency=0.7729
0********** performance of fan,lpc,hpc **********
0      gas phase  stagnation  stagnation   adiabatic
0      corrected  pressure    temperature  efficiency
0      mass flow    ratio       ratio
0 fan     0.0000     0.0000     0.0000     0.0000
0 lpc     0.0000     0.0000     0.0000     0.0000
0 hpc     0.0000     0.0000     0.0000     0.0000
```

```
0psi=  9.1336E-01 psi1=  7.0596E-01 loss=  2.0739E-01
 i=  55
 Number of loops =   100
 total mass =    0.378182
0psi=  9.1336E-01 psi1=  7.0596E-01 loss=  2.0739E-01
 i=  55
 gemach =    0.273104
```

APPENDIX E

File 4: blheat2.out

```
Compressor flow adiabatic
initial clearance at ref.temp. (R)=    518.700
stage  1 : clearance[in]=    7.00092E-03
stage  2 : clearance[in]=    6.99997E-03
----------------------------------------
initial steady thermal node and blade clearance
node no.  Node temp.(K):
  1  3.0957E+02  2  3.1387E+02  3  3.1467E+02  4  3.0996E+02  5  3.1591E+02  6
3.1536E+02  7  3.1469E+02  8  3.2398E+02

  9  3.1757E+02  10  3.2224E+02  11  3.2962E+02  12  3.4331E+02  13  3.3565E+02  14
3.3425E+02  15  3.5303E+02  16  3.2337E+02

 17  3.2321E+02  18  3.5220E+02  19  3.2239E+02
stage  1 : clearance[in]=    4.82655E-03
stage  2 : clearance[in]=    1.40285E-03
 --------------------------------
 jsweep=   1
i,T(K):
  1  3.0992E+02  2  3.1436E+02  3  3.1634E+02  4  3.1852E+02  5  3.3901E+02  6
3.1566E+02  7  3.1471E+02  8  3.2444E+02

  9  3.3160E+02  10  3.2711E+02  11  3.5678E+02  12  3.6971E+02  13  3.3610E+02  14
3.3426E+02  15  3.5800E+02  16  3.3190E+02

 17  3.3556E+02  18  3.7663E+02  19  3.8593E+02
stage  1 : clearance[in]=    3.95489E-03
stage  2 : clearance[in]=    2.67029E-05
 --------------------------------
 jsweep=   10
stage  1 : clearance[in]=    3.89576E-03
stage  2 : clearance[in]=   -3.91006E-05
 --------------------------------
 jsweep=   20
stage  1 : clearance[in]=    3.93009E-03
stage  2 : clearance[in]=   -6.67572E-06
 --------------------------------
 jsweep=   30
stage  1 : clearance[in]=    3.89862E-03
stage  2 : clearance[in]=   -3.71933E-05
 --------------------------------
 jsweep=   40
stage  1 : clearance[in]=    3.92628E-03
stage  2 : clearance[in]=   -1.23978E-05
 --------------------------------
 jsweep=   50
stage  1 : clearance[in]=    3.89957E-03
stage  2 : clearance[in]=   -3.71933E-05
 --------------------------------
 jsweep=   60
```

```
stage  1 : clearance[in]=   3.92246E-03
stage  2 : clearance[in]=   -1.62125E-05
 --------------------------------
 jsweep=  70
stage  1 : clearance[in]=   3.89957E-03
stage  2 : clearance[in]=   -3.71933E-05
 --------------------------------
 jsweep=  80
stage  1 : clearance[in]=   3.91865E-03
stage  2 : clearance[in]=   -2.00272E-05
 --------------------------------
 jsweep=  90
stage  1 : clearance[in]=   3.90053E-03
stage  2 : clearance[in]=   -3.71933E-05
 --------------------------------
 jsweep=  100
i,T(K):
  1  3.1010E+02  2  3.1475E+02  3  3.1708E+02  4  3.1948E+02  5  3.3932E+02  6
3.1580E+02  7  3.1473E+02  8  3.2468E+02

  9  3.3161E+02  10  3.2908E+02  11  3.5725E+02  12  3.7011E+02  13  3.3636E+02  14
3.3428E+02  15  3.6021E+02  16  3.3192E+02

 17  3.4101E+02  18  3.7951E+02  19  3.8587E+02
stage  1 : clearance[in]=   3.91674E-03
stage  2 : clearance[in]=   -2.38419E-05
```

APPENDIX E

File 5: case3.out

```
Input Data - Wet Case 1
Compressor flow adiabatic
icase=  4

 phi design  = 0.7773584

 inlet phi =0.4500000
0psi=  9.1772E-01 psi1=  7.4815E-01 loss=  1.6957E-01
 jsweep=   100

  MEAN
  fraction of design speed = 1.00000
 >>>>>>>>>> loop number 2 <<<<<<<<<<
 igv area=   0.241601
 nhg number of streamlines =   10.22089
1     ****************************** input data
**************************************
    heat transfer after rotor and stator version
0 number of stages=  2 (fan 0, lpc 2, hpc 0)
  performance at mean
0 vapor is centrifuged
0 large droplets in rotor free stream are not centrifuged


  stage        1    2    3
  rrhub(i)    6.95  7.64
  rc(i)      2.170 2.436
  rblade(i)  36.00 26.00
  stager(i)  37.20 38.10
  stages(i)  28.70 30.90 31.80
  srhub(i)    7.35  8.10  8.73
  sc(i)      1.880 1.665 1.484
  sblade(i)  36.00 40.00 46.00
  sigumr(i)  1.106 0.891
  sigums(i)  0.958 0.929 0.940
  bet2ss(i)  23.91 25.81 26.12
  gapr(i)    0.577 0.728
  gaps(i)    0.790 0.860
  rrtip(i)   14.47 14.24
  srtip(i)   14.37 14.12 13.91
  rt(i)      14.47 14.24
  rm(i)      11.28 11.30
  rh(i)      6.95  7.64
  st(i)      14.37 14.12
  sm(i)      11.21 11.36
  sh(i)      7.35  8.10
  block(i)   0.985 0.950
  blocks(i)  0.945 0.955 0.965
  bet1mr(i)  42.70 45.60
  bet2mr(i)  31.70 30.60
```

```
 bet1ms(i)  40.40 43.95 46.25
 bet2ms(i)  17.00 17.85 17.35
 pr12d(i)   1.254 1.233
 pr13d(i)   1.248 1.227
 etard(i)   0.912 0.962
 dvz1(i)   653.9 634.6 625.3
 dvz2(i)   632.0 606.5 591.6
 dvz3(i)   623.2 610.3
 ak1(i)   2.300 1.460
 ak2(i)   0.090 0.090
 ak3(i)   1.000 1.500
1     **************************** input data *****************************
0 fnf(fraction of design corrected speed)=1.000
0 xdin(initial water content of small droplet)=0.000
 xddin(initial water content of large droplet)=1.000
 rhumid(initial relative humidity)=  0.00 per cent
 xch4(initial methane content)=0.000
0 t0g(compressor inlet total temprature of gas)= 602.00
 t0w(compressor inlet temperature of droplret)= 597.00
 p0(compressor inlet total pressure)=1944.00
0 din(initial droplet diameter of small droplet)=  20.0
 ddin(initial droplet diameter of large droplet)= 600.0
0 fnd(design rotational speed)= 8879.0
0 dsmass(design stream  mass flow rate)=   11.3000
0 bypass ratio =     0.0000
0 compressor inlet total temperature(gas phase) 602.00 r
0 compressor inlet total pressure=1944.00 lb/ft**2
0 preb(percent of water that rebound after impingement)= 50.0 percent
0 rotor speed= 9565.4 rpm
0 corrected rotor speed=  8879.0 rpm(  100.0per cent of design corrected speed)
0 molecular weight of air= 28.9700
0 maximum diameter of small droplets=   300.0 microns
0 rotor corrected speed at design point=  8879.0
 rotor corrected speed of lpc at design point=  8879.0
 rotor corrected speed of hpc at the design point=  8879.0
 design flow coefficient at inlet =   0.777358

1*************** design point information ************ ***
0 ***** compressor inlet *****
0 total temperature at compressor inlet(R)= 602.00000
 total pressure at compressor inlet(lbf/ft**2)=   1944.00
 static temperature at compressor inlet(R)= 556.98975
 static pressure at compressor inlet(lbf/ft**2)=  1480.37
 static density at compressor inlet(lbm/ft**3)=  0.04982
0 acoustic speed at compressor inlet(ft/s)=1156.55713
 axial velocity at compressor inlet(ft/s)= 625.29999
 mach number at compressor inlet=  -0.63642
 streamtube area at compressor inlet(ft**2)=  0.24160
 flow coefficient at compressor inlet=  0.77736
1*************** design point information ************ ***
0 ***** stage= 1 *****
```

```
0           total      total      static      static      static
            temp     pressure     temp      pressure    density
0 rotor inlet   602.000    1944.000    554.852    1460.540     0.049
  rotor outlet  646.018    2437.776    582.467    1694.070     0.055
0           axial     absolute    relative   tan comp    tan comp
          velocity    velocity    velocity  of abs vel  of rel vel
0 rotor inlet  653.90002  728.27600  901.76440  320.62540  620.96191
  rotor outlet 632.00000  875.68225  762.34113  606.13159  329.61261
0           rotor     abs mach    rel mach   rel total   rel total
            speed      number      number      temp      pressure
0 rotor inlet   941.587     0.653      0.781     622.410   2185.063
  rotor outlet  935.744     0.741      0.645     630.648   5747.708
0          abs flow   rel flow   streamtube              flow
            angle      angle       area      radius   coefficient
0 rotor inlet  26.12000   43.52000   0.33861   11.28000    0.54140
  rotor outlet 43.80309   25.61799   0.30958   11.21000    0.52327
0 stage total pressure ratio at design point=  1.24800
  stage adiabatic efficiency at design point=  0.89109
  rotor total pressure ratio at design point=  1.25400
  rotor adiabatic efficiency at design point=  0.91200
  rotor total temperature ratio at design point=  1.07312
1*************** design point information ************ ***
0 ***** stage= 2 *****
0           total      total      static      static      static
            temp     pressure     temp      pressure    density
0 rotor inlet   646.018    2426.112    606.280    1941.056     0.060
  rotor outlet  687.268    2991.396    632.514    2232.765     0.066
0           axial     absolute    relative   tan comp    tan comp
          velocity    velocity    velocity  of abs vel  of rel vel
0 rotor inlet  634.59998  694.17151  916.97321  281.34848  661.90845
  rotor outlet 606.50000  813.80762  725.84167  542.62378  405.64148
0           rotor     abs mach    rel mach   rel total   rel total
            speed      number      number      temp      pressure
0 rotor inlet   943.257     0.574      0.760     675.988   2845.161
  rotor outlet  948.265     0.661      0.589     676.086   6382.674
0          abs flow   rel flow   streamtube              flow
            angle      angle       area      radius   coefficient
0 rotor inlet  23.91000   46.20665   0.29752   11.30000    0.53399
  rotor outlet 41.81838   33.97677   0.28323   11.36000    0.51034
0 stage total pressure ratio at design point=  1.22700
  stage adiabatic efficiency at design point=  0.93777
  rotor total pressure ratio at design point=  1.23300
  rotor adiabatic efficiency at design point=  0.96200
  rotor total temperature ratio at design point=  1.06385
1*************** design point information ************ ***
0********** overall performance at design point ****  ******
0 compressor inlet total temperature=  602.00
0 compressor inlet total pressure=  1944.00
0 corrected mass flow rate= 135.446
0 overall total pressure ratio=  1.5313
0 overall total temperature ratio=1.1416
```

```
0 overall adiabatic efficiency=0.9102
0 overall temperature rise=  85.268
0          1   2   3   4   5   6   7   8   9  10  11  12  13  14  15  16
 bet1sr(i)  43.52 46.21
 bet2sr(i)  25.62 33.98
 aincsr(i)   0.82   0.61
 adevsr(i)  -6.08   3.38
 bet1ss(i)  43.80 41.82
 bet2ss(i)  23.91 25.81 26.12
 aincss(i)   3.40 -2.13
 adevss(i)   6.91   7.96
 td(i)      602.  646.
 omegr(i)  0.063 0.026
 omegs(i)  0.016 0.019
 sitadr(i)  .0399 .0174
 sitads(i)  .0120 .0136
 deqr(i)    1.601 1.587
 deqs(i)    1.660 1.523
1  fai=0.4500000
 xddin =  0.
 nhg main ws(1) tg(1) p(1) rhumid =   0.00000 602.000001944.00000   0.00001
 nhg main xv(1) xwt(1) xch4 =  0.00000   0.00000   0.00000
0 vz at igv inlet =  543.50366 mach number =    0.46153
 i    xwt     watrgn
 1  0.  0.
 2  0.  0.
 3  0.  0.
 4  0.  0.
 5  0.  0.
 6  0.  0.
 7  0.  0.
 8  0.  0.
 9  0.  0.
 10  0.  0.
 xv(1) =    1.18659E-09
 watrgt =  0.
0    istage=0  (igv)
0        0.45000       543.50366         1.00000
 clear( 1)=    1.00000E-03
 nhg main start calculations for stage  1
 d1 dwakem,w2=  0.   514.381
 d2 dwakem,rdelv1=  0.   10.00000
 d3 dwakem,rdelv2=  0.  0.
ddave(n-2)(n)=  3  0.    472.146
 nhg wicsiz wmasss wmassl aming1 2 3 dl,ds,d1,d2,d3 =   0.00000   0.00000   0.00000   0.00000
0.00000 472.14648   0.00000   0.00000   0.00000   0.00000
 nhg ds dl dlge dsll amlge amsll=  0.00000 472.14648   0.00000   0.00000   0.00000   0.00000
 nhg wicsiz wmasss wmassl aming1 2 3 dsll,dlge,d1,d2,d3  =   0.00000   0.00000   0.00000
0.00000   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000
 filmas( 1) =    5.55582E-02
 ui =    23.5166
```

```
 hhc =    0.750000
 htotl =    7.50000E-04
1 ********************  initial flow coefficient= 0.450 (stage= 1 )  *******************
0    stage total pressure ratio=     1.35248
     stage total temperature ratio=    1.10863
     stage adiabatic efficiency=    0.82645
0    stage flow coefficient=0.305
     axial velocity= 368.37
     rotor speed=1207.79

0                   *rotor inlet* *rotor outlet* *stator outlet*
  total pressure          1944.0000     2636.5400     2629.2144
  static pressure         1805.3267     2192.1331     2450.7463
  total temperature(gas)   602.0000      667.3978      667.3978
  static temperature(gas)  589.4261      633.1794      654.1548
  static density(gas)        0.0574        0.0649        0.0702
  static density(mixture)    0.0574        0.0649        0.0702
0 axial velocity           368.3688      336.4398      339.1703
  absolute velocity        389.0350      641.8840      399.3185
  relative velocity        895.7287      514.3813
  blade speed              941.5873      935.7442      943.2569
  tang. comp. of abs. vel. 125.1105      546.6473
  tang. comp. of rel. vel. 816.4768      389.0969
  acoustic speed          1189.7568     1253.3921     1253.3827
  absolute mach number       0.3270        0.5205        0.3186
  relative mach number       0.7529        0.4171
0 flow coefficient           0.3050        0.2786        0.2854
  flow area                  0.3386        0.3280        0.3007
0 absolute flow angle       18.7592       58.3893       31.8565
  relative flow angle       65.7166       49.1511
  incidence                 23.0166       17.9893
  deviation                               17.4511       14.8565
  diffusion ratio                          3.6653        2.6688
  momentum thickness                       0.1314        0.0192
  omega (gas)                              0.17564       0.01648
  omega (total)                            0.17564       0.01648
 d1 dwakem,v3=  0.   399.318
 d2 dwakem,sdelv1=  0.  10.00000
 d3 dwakem,sdelv2=  0.  0.
 n,ddave(n-2)(n)=  4  0.   465.064
 nhg wicsiz wmasss wmassl aming1 2 3 dl,ds,d1,d2,d3 =  0.00000  0.00000  0.00000  0.00000
0.00000 465.06369  0.00000  0.00000  0.00000  0.00000
 nhg ds dl dlge dsll amlge amsll=  0.00000 465.06369  0.00000  0.00000  0.00000  0.00000
 nhg wicsiz wmasss wmassl aming1 2 3 dsll,dlge,d1,d2,d3  =  0.00000  0.00000  0.00000
0.00000  0.00000  0.00000  0.00000  0.00000  0.00000  0.00000
1 ********************  initial flow coefficient= 0.450 (istage=  1 )
********************
0    stage total pressure ratio=       1.35248
     stage total temperature ratio=    1.10863
     stage adiabatic efficiency=       0.82645
  stage  1 total ETA    0.82645del T   65.39777
```

```
0psi=  5.4154E-01 psi1=  4.4755E-01 loss=  9.3985E-02
0          **stage inlet**    **stage outlet**    **stage outlet**
                              (before inter-      (after inter-
                               stage adjust-       stage adjust-
                               ment)               ment)
    xv=         0.00000          0.00000          0.00000
    xw=         0.00000          0.00000          0.00000
    xww=        0.00000          0.00000          0.00000
    xf=         0.00000          0.00000          0.00076
    xwt=        0.00000          0.00000          0.00000
    xair=       1.00000          1.00000          1.00000
    xmetan=     0.00000          0.00000          0.00000
    xgas=       1.00000          1.00000          1.00000
    wmass=      0.00000          0.00000          0.00000
    wwmass=     0.00000          0.00000          0.00000
    fmmass=     0.07102          0.07102          0.05556
    wtmass=     0.00000          0.00000          0.00000
    amass=      7.16060          7.16060          7.16060
    chmass=     0.00000          0.00000          0.00000
    vmass=      0.00000          0.00000          0.00000
    gmass=      7.16060          7.16060          7.16060
    tmass=      7.16060          7.16060          7.16060
    ws=         0.00000          0.00000          0.00000
    rhoa=       0.06054          0.06333          0.07015
    rhom=       0.05453          0.06332          0.07013
    rhog=       0.05741          0.06332          0.07013
    tg=       602.00000        667.39777        667.39777
    tw=       597.00000        597.00000        597.00000
    tww=      597.00000          0.00000        597.00000
 nhg: tragas, trawat =   1.10863   1.00000
    p=    1944.00000       2636.54004       2629.21436
    tb=    667.26837          0.00000        682.17615
    tdew=  272.00754        274.47519        274.47519
writing to external plot files
 clear( 2)=    1.00000E-03
 nhg main start calculations for stage  2
 d1 dwakem,w2=  0.   581.754
 d2 dwakem,rdelv1=  0.  10.00000
 d3 dwakem,rdelv2=  0.  0.
ddave(n-2)(n)= 5  0.   410.474
 nhg wicsiz wmasss wmassl aming1 2 3 dl,ds,d1,d2,d3 =   0.00000   0.00000   0.00000   0.00000
0.00000 410.47403   0.00000   0.00000   0.00000   0.00000
 nhg ds dl dlge dsll amlge amsll=   0.00000 410.47403   0.00000   0.00000   0.00000   0.00000
 nhg wicsiz wmasss wmassl aming1 2 3 dsll,dlge,d1,d2,d3   =   0.00000   0.00000   0.00000
0.00000   0.00000   0.00000   0.00000   0.00000   0.00000   0.00000
 filmas( 2) =     5.71048E-02
 ui =     272.208
 hhc =     7.78868E-03
 htotl =     7.78868E-06
1 *******************   initial flow coefficient= 0.450 (stage= 2 )  ******************
0     stage total pressure ratio=     1.18858
```

```
    stage total temperature ratio=    1.06192
    stage adiabatic efficiency=   0.81180
0    stage flow coefficient=0.289
    axial velocity= 343.18
    rotor speed=1188.42

0                  *rotor inlet* *rotor outlet* *stator outlet*
 total pressure        2629.2144    3143.2776    3125.0408
 static pressure       2446.6165    2724.6399    2926.7351
 total temperature(gas)  667.3978     708.7259     708.7259
 static temperature(gas) 653.8803     680.5155     695.6439
 static density(gas)       0.0701       0.0750       0.0789
 static density(mixture)   0.0701       0.0750       0.0789
0 axial velocity        343.1790     338.8469     322.4617
 absolute velocity      404.0382     583.7836     397.5429
 relative velocity      806.6497     581.7543
 blade speed            943.2569     948.2653       0.0000
 tang. comp. of abs. vel.  213.2488     475.3798
 tang. comp. of rel. vel.  730.0081     472.8856
 acoustic speed        1252.2930    1291.6169    1291.6661
 absolute mach number      0.3226       0.4570       0.3078
 relative mach number      0.6441       0.4554
0 flow coefficient         0.2888       0.2851       0.2713
 flow area                 0.2975       0.2816       0.2816
0 absolute flow angle     31.8565      54.5190      35.7935
 relative flow angle      64.8216      54.3764
 incidence                19.2216      10.5690
 deviation                             23.7764      17.9435
 diffusion ratio                        3.9221       3.4434
 momentum thickness                     0.0816       0.0371
 omega (gas)                            0.13314      0.04356
 omega (total)                          0.13314      0.04356
 d1 dwakem,v3=  0.   397.543
 d2 dwakem,sdelv1=  0.  10.00000
 d3 dwakem,sdelv2=  0.  0.
 n,ddave(n-2)(n)=  6  0.   420.337
 nhg wicsiz wmasss wmassl amingl 2 3 dl,ds,d1,d2,d3 =  0.00000  0.00000  0.00000  0.00000
0.00000 420.33719  0.00000  0.00000  0.00000  0.00000
 nhg ds dl dlge dsll amlge amsll=  0.00000 420.33719  0.00000  0.00000  0.00000  0.00000
 nhg wicsiz wmasss wmassl amingl 2 3 dsll,dlge,d1,d2,d3  =  0.00000  0.00000  0.00000
0.00000  0.00000  0.00000  0.00000  0.00000  0.00000  0.00000
1 *******************  initial flow coefficient= 0.450 (istage=  2 )
*******************
0    stage total pressure ratio=      1.18858
    stage total temperature ratio=    1.06192
    stage adiabatic efficiency=       0.81180
 stage  2 total ETA    0.81378del T  41.32812
0psi=  8.8609E-01 psi1=  7.2108E-01 loss=  1.6501E-01
0          **stage inlet**   **stage outlet**   **stage outlet**
                       (before inter-     (after inter-
                        stage adjust-      stage adjust-
```

```
                 ment)          ment)
   xv=       0.00000        0.00000        0.00000
   xw=       0.00000        0.00000        0.00000
   xww=      0.00000        0.00000        0.00000
   xf=       0.00076        0.00076        0.00078
   xwt=      0.00000        0.00000        0.00000
   xair=     1.00000        1.00000        1.00000
   xmetan=   0.00000        0.00000        0.00000
   xgas=     1.00000        1.00000        1.00000
   wmass=    0.00000        0.00000        0.00000
   wwmass=   0.00000        0.00000        0.00000
   fmmass=   0.05556        0.05556        0.05710
   wtmass=   0.00000        0.00000        0.00000
   amass=    7.16060        7.16060        7.16060
   chmass=   0.00000        0.00000        0.00000
   vmass=    0.00000        0.00000        0.00000
   gmass=    7.16060        7.16060        7.16060
   tmass=    7.16060        7.16060        7.16060
   ws=       0.00000        0.00000        0.00000
   rhoa=     0.07385        0.07516        0.07892
   rhom=     0.05453        0.07515        0.07890
   rhog=     0.07013        0.07515        0.07890
   tg=       667.39777      708.72589      708.72589
   tw=       597.00000      597.00000      597.00000
   tww=      597.00000      0.00000        597.00000
 nhg: tragas, trawat =  1.06192   1.00000
   p=    2629.21436       3143.27759       3125.04077
   tb=    682.17615       0.00000        692.03601
   tdew=  274.47519       268.01367      268.01367
writing to external plot files
1********** overall performance *********
0 initial flow coefficient=0.450
0 corrected speed= 8879.0    1.000 fraction of design corrected speed
0 initial water content(small droplet)=0.000
  initial water content(large droplet)=0.000
  initial water content(total)=0.000
  initial relative humidity=  0.0 per cent
  initial methane content=0.000
0 compressor inlet total temperature=  602.00
0 compressor inlet total pressure= 1944.00
0 corrected mass flow rate of mixture= 120.29
0 corrected mass flow rate of gas phase  120.29
0 overall total pressure ratio= 1.6075
0 overall total temperature ratio=1.1773
0 overall adiabatic efficiency=0.8152
0********** performance of fan,lpc,hpc **********
0      gas phase  stagnation  stagnation  adiabatic
0      corrected  pressure    temperature efficiency
0      mass flow    ratio       ratio
0 fan    0.0000     0.0000     0.0000     0.0000
0 lpc    0.0000     0.0000     0.0000     0.0000
```

```
0 hpc     0.0000    0.0000    0.0000    0.0000
0psi=  9.1772E-01 psi1=  7.4815E-01 loss=  1.6957E-01
 i=  55
1  fai=0.4500000
 xddin =    4.00000E-02
 nhg main ws(1) tg(1) p(1) rhumid =   0.01187 602.000001944.00000 100.00000
 nhg main xv(1) xwt(1) xch4 =  0.01126   0.04000   0.00000
0 vz at igv inlet =  543.50366 mach number =    0.46995
  i     xwt     watrgn
  1   4.00000E-02   0.301641
  2   4.00000E-02   0.301641
  3   4.00000E-02   0.301641
  4   4.00000E-02   0.301641
  5   4.00000E-02   0.301641
  6   4.00000E-02   0.301641
  7   4.00000E-02   0.301641
  8   4.00000E-02   0.301641
  9   4.00000E-02   0.301641
  10   4.00000E-02   0.301641
 xv(1) =    1.12577E-02
 watrgt =    3.01641
 d0 dwakem,w2=    600.000    543.504
0    istage=0  (igv)
0        0.45000       543.50366        0.94874
 clear( 1)=    1.00000E-03
 nhg main start calculations for stage  1
 d1 dwakem,w2=  0.   515.749
 d2 dwakem,rdelv1=    600.000    18.9275
 d3 dwakem,rdelv2=    433.842  0.
ddave(n-2)(n)=  3    600.000  0.
 nhg wicsiz wmasss wmassl amingl 2 3 dl,ds,d1,d2,d3 =   0.00000   0.14756   0.00000   0.03402
0.11354   0.00000   0.00000   0.00000 600.00000 433.84219
 nhg ds dl dlge dsll amlge amsll=  0.00000   0.00000 472.14655   0.00000   0.14756   0.14756
 nhg wicsiz wmasss wmassl amingl 2 3 dsll,dlge,d1,d2,d3  =   0.00000   0.14756   0.00000
0.03402   0.11354   0.00000 472.14655   0.00000 600.00000 433.84219
 filmas( 1) =    0.169656
 ui =    23.5166
 hhc =    0.750000
 htotl =    7.50000E-04
n,ddave(n-1)(n)=  3    600.000    472.147
n,ddave(n-1)(n)=  3    600.000    472.147
1 *******************   initial flow coefficient= 0.450 (stage= 1 )  ******************
0    stage total pressure ratio=     1.33462
     stage total temperature ratio=    1.10833
     stage adiabatic efficiency=    0.78831
0    stage flow coefficient=0.304
     axial velocity= 367.58
     rotor speed=1207.79

0                    *rotor inlet* *rotor outlet* *stator outlet*
  total pressure          1944.0000     2608.4819     2594.5100
```

```
 static pressure        1801.3136    2148.7932    2409.4758
 total temperature(gas)  602.0000     667.2146     667.2146
 static temperature(gas)  589.0900     632.7929     653.9154
 static density(gas)       0.0569       0.0632       0.0686
 static density(mixture)   0.0593       0.0658       0.0714
0 axial velocity          367.5780     341.7137     343.5442
 absolute velocity        388.1998     647.0368     402.8692
 relative velocity        895.6487     515.7485
 blade speed              941.5873     935.7442     943.2569
 tang. comp. of abs. vel.  124.8420     549.4436
 tang. comp. of rel. vel.  816.7454     386.3006
 acoustic speed          1168.8855    1211.4681    1230.6973
 absolute mach number       0.3321       0.5341       0.3274
 relative mach number       0.7662       0.4257
0 flow coefficient          0.3043       0.2829       0.2891
 flow area                  0.3386       0.3280       0.3007
0 absolute flow angle      18.7592      58.1214      31.4886
 relative flow angle       65.7698      48.5047
 incidence                 23.0698      17.7214
 deviation                              16.8047      14.4886
 diffusion ratio                         3.6611       2.6438
 momentum thickness                      0.1380       0.0191
 omega (gas)                             0.17676      0.01646
 omega (total)                           0.20246      0.03734
 d1 dwakem,v3=    600.000   402.869
 d2 dwakem,sdelv1=    600.000   18.9275
 d3 dwakem,sdelv2=    400.076  0.
 n,ddave(n-2)(n)= 4   600.000  0.
 nhg wicsiz wmasss wmassl aming1 2 3 dl,ds,d1,d2,d3 =  0.08616   0.12958   0.06140   0.00584
0.01213   0.00000   0.00000  20.00000 600.00000 400.07565
 nhg ds dl dlge dsll amlge amsll=  0.00000  0.00000 465.06369   4.43073   0.01798   0.27715
 nhg wicsiz wmasss wmassl aming1 2 3 dsll,dlge,d1,d2,d3  =  0.08616   0.12958   0.06140
0.00584   0.01213   4.43073 465.06369  20.00000 600.00000 400.07565
n,ddave(n-1)(n)= 4   472.147   465.064
n,ddave(n-1)(n)= 4   472.147   465.064
xnp,tg(3),p(3)=   3.20075E+10   667.135   2594.51
1 ******************   initial flow coefficient= 0.450 (istage=  1 )
******************
0    stage total pressure ratio=       1.33462
     stage total temperature ratio=    1.10820
     stage adiabatic efficiency=       0.78907
 stage  1 total ETA    0.78907del T   65.13525
0psi=  5.4574E-01 psi1=  4.3063E-01 loss=  1.1511E-01
0          **stage inlet**    **stage outlet**    **stage outlet**
                             (before inter-      (after inter-
                              stage adjust-       stage adjust-
                              ment)               ment)
    xv=         0.01126          0.01126          0.01308
    xw=         0.00000          0.00000          0.00000
    xww=        0.04000          0.04000          0.03818
    xf=         0.00007          0.00007          0.00225
```

| | | | |
|---|---|---|---|
| xwt= | 0.04000 | 0.04000 | 0.03818 |
| xair= | 0.94874 | 0.94874 | 0.94874 |
| xmetan= | 0.00000 | 0.00000 | 0.00000 |
| xgas= | 0.96000 | 0.96000 | 0.96182 |
| wmass= | 0.00000 | 0.00000 | 0.00000 |
| wwmass= | 0.29512 | 0.29512 | 0.28170 |
| fmmass= | 0.05556 | 0.05556 | 0.16966 |
| wtmass= | 0.29512 | 0.29512 | 0.28170 |
| amass= | 6.99987 | 6.99987 | 6.99987 |
| chmass= | 0.00000 | 0.00000 | 0.00000 |
| vmass= | 0.08306 | 0.08306 | 0.09648 |
| gmass= | 7.08293 | 7.08293 | 7.09635 |
| tmass= | 7.37806 | 7.37806 | 7.37806 |
| ws= | 0.01187 | 0.01187 | 0.01378 |
| rhoa= | 0.06054 | 0.06216 | 0.06484 |
| rhom= | 0.05619 | 0.06428 | 0.07118 |
| rhog= | 0.05691 | 0.06171 | 0.06847 |
| tg= | 602.00000 | 667.21460 | 667.13525 |
| tw= | 597.00000 | 597.00000 | 597.00000 |
| tww= | 597.00000 | 597.00000 | 597.44580 |

nhg: tragas, trawat = 1.10820 1.00075

| | | | |
|---|---|---|---|
| p= | 1944.00000 | 2608.48193 | 2594.51001 |
| tb= | 667.26837 | 0.00000 | 681.50610 |
| tdew= | 518.09930 | 526.80371 | 531.09418 |

writing to external plot files
clear( 2)= 1.00000E-03
nhg main start calculations for stage 2
d1 dwakem,w2= 0. 585.055
d2 dwakem,rdelv1= 600.000 18.8394
d3 dwakem,rdelv2= 363.792 0.
ddave(n-2)(n)= 5 472.147 0.
nhg wicsiz wmasss wmassl aming1 2 3 dl,ds,d1,d2,d3 = 0.00000 0.14085 0.00000 0.02855 0.11230 0.00000 0.00000 0.00000 600.00000 363.79233
nhg ds dl dlge dsll amlge amsll= 0.00000 0.00000 411.66669 0.00000 0.14085 0.14085
nhg wicsiz wmasss wmassl aming1 2 3 dsll,dlge,d1,d2,d3 = 0.00000 0.14085 0.00000 0.02855 0.11230 0.00000 411.66669 0.00000 600.00000 363.79233
filmas( 2) = 0.476775
ui = 30.7086
hhc = 0.718209
htotl = 7.18209E-04
n,ddave(n-1)(n)= 5 465.064 411.667
n,ddave(n-1)(n)= 5 465.064 411.667
1 ******************** initial flow coefficient= 0.450 (stage= 2 ) *******************
0 stage total pressure ratio= 1.17666
stage total temperature ratio= 1.06177
stage adiabatic efficiency= 0.76247
0 stage flow coefficient=0.293
axial velocity= 348.37
rotor speed=1188.42

0 *rotor inlet* *rotor outlet* *stator outlet*

```
  total pressure        2594.5100    3081.0574    3052.8523
  static pressure       2404.7615    2649.0469    2846.5596
  total temperature(gas)   667.1353    708.3432    708.3432
  static temperature(gas)  652.9359    679.7630    695.0020
  static density(gas)       0.0685      0.0724      0.0761
  static density(mixture)   0.0712      0.0753      0.0792
0 axial velocity        348.3744     347.8579     330.9785
  absolute velocity      408.5336     591.0604     404.3733
  relative velocity     808.7470     585.0549
  blade speed           943.2569     948.2653      0.0000
  tang. comp. of abs. vel.  213.3892    477.8569
  tang. comp. of rel. vel.  729.8677    470.4084
  acoustic speed        1231.5189    1256.5637    1269.8992
  absolute mach number      0.3317      0.4704      0.3184
  relative mach number      0.6567      0.4656
0 flow coefficient          0.2931      0.2927      0.2785
  flow area                 0.2975      0.2816      0.2816
0 absolute flow angle      31.4886     53.9471     35.0653
  relative flow angle      64.4843     53.5178
  incidence                18.8843      9.9971
  deviation                            22.9178     17.2153
  diffusion ratio                       3.8691      3.3655
  momentum thickness                    0.0829      0.0355
  omega (gas)                           0.13046     0.04166
  omega (total)                         0.15583     0.06932
 d1 dwakem,v3=    600.000   404.373
 d2 dwakem,sdelv1=    600.000   18.8394
 d3 dwakem,sdelv2=    342.674  0.
 n,ddave(n-2)(n)=  6   465.064  0.
 nhg wicsiz wmasss wmassl aming1 2 3 dl,ds,d1,d2,d3 =  0.09618   0.12391   0.04467   0.00517
0.01177   0.00000   0.00000  20.00000 600.00000 342.67392
 nhg ds dl dlge dsll amlge amsll=  0.00000   0.00000 421.20795   3.37468   0.01694   0.26476
 nhg wicsiz wmasss wmassl aming1 2 3 dsll,dlge,d1,d2,d3  =  0.09618   0.12391   0.04467
0.00517   0.01177   3.37468 421.20795  20.00000 600.00000 342.67392
n,dave(n-1)(n)=  6  0.    3.37468
n,ddave(n-1)(n)=  6   411.667   421.208
n,dave(n-1)(n)=  6  0.    3.37468
n,ddave(n-1)(n)=  6   411.667   421.208
xnp,tg(3),p(3)=   3.20075E+10   708.218   3052.85
xnp,tg(3),p(3)=   3.05521E+10   708.218   3052.85
1 *******************  initial flow coefficient= 0.450 (istage=  2 )
*******************
0    stage total pressure ratio=        1.17666
     stage total temperature ratio=     1.06158
     stage adiabatic efficiency=        0.76428
  stage  2 total ETA    0.77133del T   41.08319
0psi=  8.9614E-01 psi1=  6.9122E-01 loss=  2.0492E-01
0           **stage inlet**    **stage outlet**    **stage outlet**
                               (before inter-      (after inter-
                                stage adjust-       stage adjust-
                                ment)               ment)
```

```
    xv=        0.01308        0.01308        0.01789
    xw=        0.00000        0.00000        0.00000
    xww=       0.03818        0.03818        0.03337
    xf=        0.00225        0.00225        0.00632
    xwt=       0.03818        0.03818        0.03337
    xair=      0.94874        0.94874        0.94874
    xmetan=    0.00000        0.00000        0.00000
    xgas=      0.96182        0.96182        0.96663
    wmass=     0.00000        0.00000        0.00000
    wwmass=    0.28170        0.28170        0.24623
    fmmass=    0.16966        0.16966        0.47678
    wtmass=    0.28170        0.28170        0.24623
    amass=     6.99987        6.99987        6.99987
    chmass=    0.00000        0.00000        0.00000
    vmass=     0.09648        0.09648        0.13196
    gmass=     7.09635        7.09635        7.13183
    tmass=     7.37806        7.37806        7.37806
    ws=        0.01378        0.01378        0.01885
    rhoa=      0.07291        0.07330        0.07230
    rhom=      0.05619        0.07557        0.07862
    rhog=      0.06847        0.07269        0.07600
    tg=      667.13525      708.34320      708.21844
    tw=      597.00000      597.00000      597.00000
    tww=     597.44580      597.44580      598.18591
 nhg: tragas, trawat =  1.06158  1.00124
    p=    2594.51001     3081.05737     3052.85229
    tb=    681.50610        0.00000      690.75311
    tdew=  531.09418      530.05609      539.78143
writing to external plot files
1********** overall performance *********
0 initial flow coefficient=0.450
0 corrected speed= 8879.0    1.000 fraction of design corrected speed
0 initial water content(small droplet)=0.000
  initial water content(large droplet)=0.040
  initial water content(total)=0.040
  initial relative humidity=100.0 per cent
  initial methane content=0.000
0 compressor inlet total temperature=  602.00
0 compressor inlet total pressure= 1944.00
0 corrected mass flow rate of mixture= 123.94
0 corrected mass flow rate of gas phase  118.99
0 overall total pressure ratio= 1.5704
0 overall total temperature ratio=1.1764
0 overall adiabatic efficiency=0.7729
0********** performance of fan,lpc,hpc **********
0       gas phase  stagnation  stagnation   adiabatic
0       corrected  pressure    temperature  efficiency
0       mass flow    ratio       ratio
0 fan     0.0000     0.0000     0.0000     0.0000
0 lpc     0.0000     0.0000     0.0000     0.0000
0 hpc     0.0000     0.0000     0.0000     0.0000
```

```
0psi=  9.1336E-01 psi1=  7.0596E-01 loss=  2.0739E-01
 i=  55
 Number of loops =   100
 total mass =    0.378182
0psi=  9.1336E-01 psi1=  7.0596E-01 loss=  2.0739E-01
 i=  55
 gemach =    0.273104
```

APPENDIX E

File 6: blheat3.out

Compressor flow adiabatic
initial clearance at ref.temp. (R)= 518.700
stage 1 : clearance[in]= 7.00092E-03
stage 2 : clearance[in]= 6.99997E-03
----------------------------------------
initial steady thermal node and blade clearance
node no. Node temp.(K):
1 3.0957E+02 2 3.1387E+02 3 3.1467E+02 4 3.0996E+02 5 3.1591E+02 6 3.1536E+02 7 3.1469E+02 8 3.2398E+02

9 3.1757E+02 10 3.2224E+02 11 3.2962E+02 12 3.4331E+02 13 3.3565E+02 14 3.3425E+02 15 3.5303E+02 16 3.2337E+02

17 3.2321E+02 18 3.5220E+02 19 3.2239E+02
stage 1 : clearance[in]= 4.82655E-03
stage 2 : clearance[in]= 1.40285E-03
--------------------------------
jsweep= 1
i,T(K):
1 3.0992E+02 2 3.1436E+02 3 3.1634E+02 4 3.1852E+02 5 3.3901E+02 6 3.1566E+02 7 3.1471E+02 8 3.2444E+02

9 3.3160E+02 10 3.2711E+02 11 3.5678E+02 12 3.6971E+02 13 3.3610E+02 14 3.3426E+02 15 3.5800E+02 16 3.3190E+02

17 3.3556E+02 18 3.7663E+02 19 3.8593E+02
stage 1 : clearance[in]= 3.95489E-03
stage 2 : clearance[in]= 2.67029E-05
--------------------------------
jsweep= 10
stage 1 : clearance[in]= 3.89576E-03
stage 2 : clearance[in]= -3.91006E-05
--------------------------------
jsweep= 20
stage 1 : clearance[in]= 3.93009E-03
stage 2 : clearance[in]= -6.67572E-06
--------------------------------
jsweep= 30
stage 1 : clearance[in]= 3.89862E-03
stage 2 : clearance[in]= -3.71933E-05
--------------------------------
jsweep= 40
stage 1 : clearance[in]= 3.92628E-03
stage 2 : clearance[in]= -1.23978E-05
--------------------------------
jsweep= 50
stage 1 : clearance[in]= 3.89957E-03
stage 2 : clearance[in]= -3.71933E-05
--------------------------------
jsweep= 60

stage 1 : clearance[in]= 3.92246E-03
stage 2 : clearance[in]= -1.62125E-05
---------------------------------
jsweep= 70
stage 1 : clearance[in]= 3.89957E-03
stage 2 : clearance[in]= -3.71933E-05
---------------------------------
jsweep= 80
stage 1 : clearance[in]= 3.91865E-03
stage 2 : clearance[in]= -2.00272E-05
---------------------------------
jsweep= 90
stage 1 : clearance[in]= 3.90053E-03
stage 2 : clearance[in]= -3.71933E-05
---------------------------------
jsweep= 100
i,T(K):
1 3.1010E+02 2 3.1475E+02 3 3.1708E+02 4 3.1948E+02 5 3.3932E+02 6 3.1580E+02 7 3.1473E+02 8 3.2468E+02

9 3.3161E+02 10 3.2908E+02 11 3.5725E+02 12 3.7011E+02 13 3.3636E+02 14 3.3428E+02 15 3.6021E+02 16 3.3192E+02

17 3.4101E+02 18 3.7951E+02 19 3.8587E+02
stage 1 : clearance[in]= 3.91674E-03
stage 2 : clearance[in]= -2.38419E-05

## Appendix F: Sample Data for Thermal Load and Clearance Program

The following set of data are for the nodal temperature distribution and blade clearance program, to which texts have been added after semi-colon to explain properly (*in actual data file these explanations are not there*).

```
 2 0 7 4 1                ; no.of stages, no.of fan stages, max.no.of nodes per stage,
                          ; max.no.of adjacent nodes, type of rotor intern.cooling
                          ; IGV has 4 centrod node
 2  4 2.4145E+02          ; IGV 1: node type, no.of adj.nodes, heat capacity [J/K]
-75  6 -72 -76            ; node numbers
 9.2520E-04 9.2520E-04 2.7860E-03 2.4660E-03 ; Sij [m2]
 4.7800E-04 7.6910E-04 2.7710E-04 2.7710E-04 ; ls [m2-K/W]
 12  4 1.6219E+02         ; for IGV2, same as IGV1
-75  3 -73 -72
 2.6280E-03 2.6280E-03 1.4020E-03 1.2260E-03
 1.2460E-04 2.8170E-04 2.4930E-04 2.4930E-04
 14  4 2.0453E+02         ; for IGV3, same as IGV1
 2  9 -73  4
 2.6280E-03 2.6280E-03 1.7680E-03 1.5460E-03
 2.8170E-04 5.4300E-04 2.4930E-04 3.5380E-03
  6  2 1.3700E+01         ; for IGV4, same as IGV1
 3 -72
 1.5460E-03 1.0350E-02
 3.5380E-03 5.6540E-04
 7                        ; no. of centroid nodes in stage 1
                          ; stage 1, centroid node 1:
  6  2 3.4170E+01         ; node type, number of adjacent nodes, heat capacity
 6 -71                    ; node numbers
 1.3520E-03 2.1190E-02    ; Sij [m2]
 5.0520E-03 6.8900E-05    ; ls [m2-K/W]
                          ; stage 1, centroid node 2:
 11  4 1.1540E+02
 1  8  5  7
 9.2520E-04 9.2520E-04 1.3520E-03 1.1580E-03
 7.6910E-04 8.2630E-04 5.0520E-03 2.7710E-04
                          ; stage 1, centroid node 3:
 15  2 1.1943E+02
 6 -76
 1.1580E-03 3.1290E-03
 5.0530E-04 1.9404E-04
                          ; stage 1, centroid node 4:
  2  4 2.8021E+02
 6 13 -72 -76
 9.2520E-04 1.1820E-03 3.0470E-03 2.6320E-03
 8.2630E-04 9.0380E-04 2.7710E-04 2.7710E-04
                               ; stage 1, centroid node 5:
 12  4 5.8508E+02
 3 10 -73 -71
 2.6280E-03 3.4610E-03 4.9390E-03 4.3270E-03
```

```
5.4300E-04  5.7260E-04  2.4930E-04  2.4930E-04
                                        ; stage 1, centroid node 6:
 14   4  3.5465E+02
 9  16 -73  11
5.3460E-03  5.3460E-03  3.0600E-03  2.6860E-02
5.9260E-04  6.1760E-04  2.4930E-04  4.7070E-03
                                        ; stage 1, centroid node 7
 6   2  2.9360E+01
10 -72
2.6860E-03  1.7510E-02
4.7070E-03  7.1630E-05
7                                       ; no. of centroid node in stage 2
                                        ; stage 2, centrod node 1
 6   2  3.7990E+01
13 -71
2.6070E-03  2.0980E-02
4.4680E-03  7.7340E-05
                                        ; stage 2, centroid node 2
 11   4  2.2407E+02
 8  15  12  14
1.1820E-03  1.1820E-03  2.6070E-03  2.2660E-03
9.0380E-04  9.2270E-04  4.4680E-03  2.7710E-04
                                        ; stage 2, centroid node 3
 15   2  2.4196E+02
13 -76
2.2660E-03  5.118E-03
5.0530E-04  2.4580E-04
                                        ; stage 2, centroid node 4
 2   4  3.5765E+02
12 -75 -72 -76
1.1820E-03  1.1820E-03  4.1450E-02  3.6320E-03
9.2270E-04  5.5410E-04  2.7710E-04  2.7710E-04
                                        ; stage 2, centroid node 5
 12   4  7.5884E+02
10  17 -73 -71
3.4610E-03  3.0640E-03  6.5450E-03  5.7390E-03
6.1760E-04  6.4890E-04  2.4930E-04  2.4930E-04
                                        ; stage 2, centroid node 6
 14   4  2.7030E+02
16  19 -73  18
3.0640E-03  3.0640E-03  2.3340E-03  2.0450E-03
6.4890E-04  3.0260E-04  2.4930E-04  4.0720E-03
                                        ; stage 2, centroid node 7
 6   2  1.9880E+01
17 -72
2.0450E-03  1.3390E-02
4.0720E-03  6.3440E-05
                                        ; post node
 12   4  1.8915E+02
17 -75 -73 -72
3.0640E-03  3.0640E-03  1.6340E-03  1.4310E-03
```

3.0260E-04 1.2460E-04 2.4930E-04 2.4930E-04
; for Reynolds number and Nusselt number calculations upstream and downstream axial ; lengths are required. These are given (*in inches*) for all global nodes, so long they are rel- ; evant (otherwise put equal to zero), first for casing in one line, followed by rotor in ano-; ther line in the following:

0.0000E+00 0.0000E+00
0.0000E+00 2.8380E+00
0.0000E+00 1.0000E+00
0.0000E+00 0.0000E+00
1.0000E+00 2.2610E+00
0.0000E+00 0.0000E+00
0.0000E+00 0.0000E+00
0.0000E+00 0.0000E+00
0.0000E+00 0.0000E+00
0.0000E+00 0.0000E+00
0.0000E+00 0.0000E+00
2.8380E+00 4.6660E+00
0.0000E+00 0.0000E+00
0.0000E+00 0.0000E+00
0.0000E+00 0.0000E+00
4.6660E+00 7.8440E+00
2.2610E+00 5.3560E+00
0.0000E+00 0.0000E+00
5.3560E+00 7.0160E+00
0.0000E+00 0.0000E+00
0.0000E+00 0.0000E+00
0.0000E+00 0.0000E+00
0.0000E+00 0.0000E+00
0.0000E+00 0.0000E+00
0.0000E+00 0.0000E+00
7.8440E+00 1.0033E+01
0.0000E+00 0.0000E+00
0.0000E+00 0.0000E+00
0.0000E+00 0.0000E+00
1.0033E+01 1.3322E+01
7.0160E+00 1.0793E+01
0.0000E+00 0.0000E+00
1.0793E+01 1.2222E+01
0.0000E+00 0.0000E+00
0.0000E+00 0.0000E+00
0.0000E+00 0.0000E+00
1.2222E+01 1.3222E+01
0.0000E+00 0.0000E+00
1.17600E-05 ; casing material thermal expansion coefficient ($K^{-1}$)
; for stage 1: how many thermal expansion nodes are there (excluding casing), global node ; number on casing, casing radius (*in inches*), rotor disk internal radius (*in inches*):
2 9 14.489 2.950
5 6 ; global node numbers being considered (excluding casing)
8.4100E-06 1.1760E-05 ; corresponding coeff. of thermal expansion ($K^{-1}$)

```
 7.5200E+00  6.9500E+00   ; corresponding radial lengths (in inches)
; for stage 2 (similar to stage 1):
 2  16  14.257 3.640
12 13
 8.4100E-06  1.1760E-05
 6.6000E+00  7.6400E+00
```