ALGORITHM FOR CALCULATING TURBINE COOLING FLOW AND THE RESULTING DECREASE IN TURBINE EFFICIENCY

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SUMMARY

This report documents an algorithm for calculating both the quantity of compressor bleed flow required to cool the turbine(s) and the decrease in turbine efficiency caused by cooling air injection into the gas stream. The technique is presented in the form of a Fortran program which can be used as a subroutine in a properly written thermodynamic cycle code. The user has the option of choosing from ten different cooling configurations for each row of cooled airfoils in the turbine. Results from the algorithm have been substantiated by comparison with flows predicted by major engine manufacturers for given bulk metal temperatures and given cooling configurations. Presented in the report are a listing of the subroutine and a list of definitions for the terms in the subroutine.

This subroutine was originally developed to replace a simpler turbine cooling model in the NAVY NASA Engine Program (NNEP). To use this new routine in NNEP, minor changes are required to three other subroutines. These changes are shown in this report.

INTRODUCTION

The NASA Lewis Research Center employs a general computer program (refs. 1 and 2), for calculating thermodynamic performance of jet propulsion engines. This thermodynamic performance is sensitive to the quantity of compressor bleed flow required to cool the turbine(s). And the quantity of required cooling flow increases with the trend toward higher turbine inlet temperatures. Because of this trend, it becomes increasingly more important to accurately predict the required cooling flow so as to accurately calculate the thermodynamic performance.

The present report documents a turbine cooling algorithm for an axial-flow, air-breathing engine which determines both the quantity of compressor bleed flow required to cool the turbine(s) and the decrease in turbine efficiency caused by cooling air injection into the gas stream. The purpose of this report is to explain the use and to examine the accuracy of this algorithm.

To help explain its use, the turbine cooling algorithm
is discussed from three different aspects. First, the method is presented; next, the flow chart is traced; and finally, the required input is examined. The accuracy of the algorithm is evaluated by comparing its predictions of required cooling flow with those of major engine manufacturers.

The algorithm is presented in the form of a Fortran program which can be used as a subroutine in a properly written thermodynamic cycle code. For example, it is used herein as a new version of subroutine COOLIT in the thermodynamic cycle code NNEP of references 1 and 2. A listing of the subroutine and a list of definitions for the terms in that subroutine are presented. Minor changes to three other subroutines in the code of references 1 and 2, NNEP, which are required for the use of the COOLIT subroutine in that code, are also presented.

ANALYSIS

Turbine Cooling Method

The quantity of required cooling flow and the corresponding decrease in stage efficiency are calculated for each row of airfoils throughout the turbine. These values are then used to obtain the quantity of compressor bleed flow required to cool the turbine and the decrease in cooled-turbine efficiency caused by cooling air injection into the gas stream. The calculations depend on both the type of cooling configuration and the value of cooling effectiveness.

Cooling configuration. - The allowable cooling configurations in this cooling algorithm are described in table I. In this table, column 1 contains NFACT(I) which is used to identify the cooling configuration shown in column 2. Columns 3 and 4 are aids for choosing the proper cooling configuration for each row of airfoils. Column 5 lists the required cooling flow for each configuration relative to that flow required by a full coverage film cooled turbine blade. For example, a transpiration cooled turbine blade requires only 0.8 of the cooling flow required by a full coverage film cooled turbine blade for a given value of cooling effectiveness. Columns 6 and 7 list the percent decrease in stage efficiency for each percent of core flow required to cool the stator(s) and rotor(s), respectively.

The values of relative cooling flow, FACTOR, which appear in column 5 of table I come from both analytical and experimental sources. Reference 3 presents an analysis relating the required flow for convection, advanced convection, full coverage film, and transpiration cooling. These values are sensitive to gas, coolant, and metal
temperatures and to airfoil geometry. However, for the purpose of this investigation, nominal values of relative cooling flow are sufficient. From reference 3 values of FACTOR of 2.0, 1.5, 1.0, and 0.8 are obtained corresponding to cooling configurations 1, 3, 8, and 9, respectively.

From figure 8 of reference 4, a convection cooled turbine blade with a 0.025 centimeter coating requires only three-fourths of the cooling flow of that of an uncoated convection cooled blade. So the value of FACTOR of 1.5 for a coated convection cooled blade can be obtained from the value of 2.0 for a convection cooled blade.

Values of FACTOR for cooling configurations 4, 5, and 6 are 1.3, 1.2, and 1.1, respectively. These values have been obtained by interpolating between values of FACTOR for cooling configurations 3 and 8. The value of FACTOR for cooling configuration 7 was obtained by using a weighted average of FACTOR values for cooling configurations 3 and 9.

Values of the dimensionless loss in stage efficiency, DELV and DELM, which appear in columns 6 and 7 of table I, were obtained in a personal communication from Thomas P. Moffitt, a member of the Turbine Branch at Lewis Research Center.

Cooling effectiveness. - Cooling effectiveness, PHI, is defined as the ratio of the difference between the hot gas temperature and the allowable bulk metal temperature to the difference between the hot gas temperature and the compressor bleed temperature.

\[
\text{PHI} = \frac{T - T_m}{T - T_c}
\]

The hot gas temperature entering a given row of airfoils is the average combustor exhaust temperature incremented to include the following five effects: (1) Hotspot profiles are accounted for by using a pattern factor of 0.3 for the first stage stator of the high pressure turbine and a value of 0.13 for all other rows of cooled airfoils in the turbine(s). (Pattern factor is defined as the ratio of the difference between the hotspot and the average row inlet temperature to the difference between the average row inlet temperature and the combustor inlet temperature.) (2) The correction to the hot gas temperature due to the dilution of upstream cooling air is obtained from a mass averaged enthalpy from which a revised gas temperature is calculated. (3) Currently, the correction due to relative velocity is merely an approximation; the relative total temperature is assumed to equal 0.92 of the absolute total temperature. This value is a modification of the 0.90 value found in reference 3 which included dilution from the stator cooling air. (4) Because work is extracted
from the gas stream, the downstream rows of cooled vanes and blades are subjected to a lower gas temperature. (5) The gas temperature used to determine the required cooling flow is first increased by 150° R to provide a safety factor for the cooled turbine airfoils.

Allowable bulk metal temperature depends upon the year of material technology, the desired life and the duty cycle. (Duty cycle includes mission, atmospheric conditions and power settings.) In an attempt to simplify these relationships the following equations relate state-of-the-art bulk metal temperatures to both life and year of material technology. (See APPENDIX A for the definition of the variables.)

\[ \text{T}_{\text{VANE}} = (10 \times \text{YEAR} - 17640) - (100 \times \log(\text{ELIFE}) - 400) \]
\[ \text{T}_{\text{BLAD}} = (10 \times \text{YEAR} - 17740) - (100 \times \log(\text{ELIFE}) - 400) \]

These equations have been obtained from information similar to that contained in figure 8 of reference 5. In that figure metal temperature is presented as a function of the year of material technology. The figure shows both a turbine blade material temperature of 2110° R for 1985 technology and also a historic increase of almost 10° R per year in the allowable metal temperature. Stator blades are herein assumed to operate at a temperature 100° R higher than the rotor blades so that they will operate at 2210° R for 1985 technology.

The cooling air temperature reflects the stage of the compressor from which the bleed flow is extracted.

Dimensionless cooling flow. - After the relative cooling flow, FACTOR, has been chosen from table I for the row of airfoils, and after the cooling effectiveness, PHI, has been evaluated from the above temperatures, then the dimensionless cooling flow can be determined from the following equation. For example, for a FACTOR of 1.0 and a cooling effectiveness of 0.5, the dimensionless cooling flow is 0.022 for a full coverage film cooled turbine blade.

\[ \frac{W(I)}{W_G} = \text{FACTOR} \times 0.022 \times \frac{\text{PHI}}{(1 - \text{PHI})^{1.25}} \]

The form of this equation is derived from a heat balance across the surface of a turbine blade in which turbulent flow is assumed for both the hot gas and the cooling air. The constant 0.022 is obtained by extrapolating experimental data presented in figure 23 of reference 6 for a full coverage film cooled turbine vane.

To account for endwall, shroud and disk cooling, and leakage, the dimensionless cooling flow for each row of airfoils is increased by a factor of 4/3. Although this
value will vary from engine to engine, its use seems reasonable when comparisons are made with flowrates predicted by other methods.

Cooled turbine efficiency - First, the uncooled-stage efficiency, EFF2, is calculated from the uncooled-turbine efficiency, EFF1, using equation (6.5.6) of reference 7. This calculation assumes that all uncooled-stage efficiencies and all stage pressure ratios are equal.

\[
EFF2 = \frac{1 - (1 - EFF1 \times (1 - RP^{*}GAM))^{**}(1/IN))}{1 - RP^{*}(GAM/XN))}
\]

Next, the dimensionless cooling flows from the stator and the rotor, excluding the endwall, shroud, disk, and leakage flows, are then used to determine the decrease in the thermodynamic efficiency of the turbine stage. This decrease in stage efficiency is equal to the product of the dimensionless cooling flow, one of the last two columns in table I, and the uncooled-stage efficiency. Subtracting the change in stage efficiency from the uncooled-stage efficiency, EFF2, will yield the cooled-stage efficiency, EFF3.

\[
EFF3 = EFF2 - \frac{(W(I)/WG) \times DELV \times EFF2 - (W(I+1)/WG) \times DELN \times EFF2}{EFF2}
\]

Finally, the thermodynamic cooled-turbine efficiency, EFF4, is reconstructed from the cooled-stage efficiencies using equation (6.5.5) also of reference 7. This equation allows a different value of cooled-stage efficiency for each stage.

\[
EFF4 = \frac{1 - \prod_{I=1}^{I}(1 - EFF3(I) \times (1 - RP^{*}(1/XN))^{**GAM}))}{1 - RP^{*}GAM}
\]

Flow Chart of the Algorithm

The sequence for calculating these quantities can be followed with the aid of APPENDIX A and APPENDIX B. The former is a symbol list and the latter is a listing of the new subroutine.

As shown in APPENDIX B, before the "DO 20" loop, the uncooled thermodynamic stage efficiency, EFF2, is calculated from the uncooled thermodynamic turbine efficiency, EFF1.

The "DO 20" loop separates the kind of cooling for the turbine, KINDOF, into the cooling configuration for each row of the turbine, NFACT(I). For example, in a one-stage turbine with a value of KINDOF equal to 86, the values of NFACT(1) equals 8 and NFACT(2) equals 6. This indicates that the stator is cooled by a full coverage film and the
Rotor is cooled partially by film and partially by advanced convection. See table I for NFACT(1)=8 and NFACT(2)=6.

The "DO 80" loop determines for each row of airfoils the effective hot gas temperature, T, the cooling effectiveness, PHI, the required cooling flow for each row, W(I), the change in stage efficiency, DELM, the accumulated required cooling flow made dimensionless by the flow into the turbine, PCBLED, and the cooled-stage efficiency, EFF3.

The "DO 90" loop reconstructs the cooling configuration, KINDOF, from NFACT(I) to reflect any changes made to NFACT(I) inside of subroutine COOLIT. Such changes occur when either a blade row requires cooling but was not originally intended to be cooled or when a blade row does not require cooling but was originally intended to be cooled. For the former case the blade row is assumed to have convection cooled airfoils; for the latter case the blade row is assumed to have solid, uncooled airfoils. See table I where NFACT(I) equals 1 and 0 respectively.

Finally, beyond the "DO 90" loop, the cooled-turbine efficiency, EFF4, is reconstructed from the cooled-stage efficiencies.

Input to the Algorithm

Input to general thermodynamic cycle code. - Input to the algorithm are discussed below. The names marked with an asterisk are not always required because of the reasons cited.

*EFF1 is the thermodynamic efficiency of the uncooled turbine. It is only required if the thermodynamic efficiency of the cooled turbine is to be calculated. If EFF1 is not known then it can be calculated by using the cooling configurations of the airfoils, the corresponding dimensionless cooling flows, and the above three equations relating EFF1, EFF2, EFF3, and EFF4. Or it can be found by a trial and error procedure by varying the input value of EFF1 until the known output value of EFF4 is achieved. An example of such a calculation might be to determine the required cooling flow and cooled-turbine efficiency for a transpiration cooled turbine knowing the corresponding values for a film cooled turbine.

*ELIFE is the desired life of the turbine airfoil. It is assumed to be 10 000 hours if the design values of TVANE and TMBLAD are known.

*FARCX is the fuel to air ratio of the cooling flow. It is used to evaluate the specific enthalpy, HC. If a gas property subroutine is not available and the diluted gas
temperature is obtained by means of a mass averaged temperature, then FARX is not required.

*FARGX is the fuel to air ratio of the hot gas stream. It is used to evaluate both the specific heat ratios, GMIN and GAMOUT, and the specific enthalpy of the hot gas, HG. If an assumption is made for the specific heat ratio and if the diluted gas temperature is obtained by means of a mass averaged temperature, then FARGX is not required.

HPT is the power extracted by the turbine. It is used to adjust the hot gas temperature due to work extracted by upstream stages.

KINDOF is an ordered combination of digits representing the cooling configurations throughout the turbine starting with the stator of the first stage. For example, for a two stage turbine, 9865 indicates that each of the four rows of airfoils in a two stage turbine has a specific cooling configuration as indicated in Table I.

*PR is the pressure ratio across the turbine, inlet over exit. It is only required if the thermodynamic efficiency of the cooled turbine is to be calculated.

PROFIL is the combustor pattern factor. The usual input is 0.30. After the stator of the first stage of the high pressure turbine, the value is set to 0.13 to reflect the radial profile.

STAGES is the number of stages in the turbine. It is used to distribute the work of the turbine and to indicate the number of rows of cooled airfoils.

TC is the total temperature of the cooling flow at the point at which it is extracted from the compressor. It is used to evaluate the cooling effectiveness, PHI, and the specific enthalpy, HG.

TIN is the total temperature of the gas into the turbine. The first stage stator is evaluated at this temperature after adjustment for both combustor pattern factor of 0.3 and safety factor of 1500 R.

*TOUT is the total temperature of the gas out of the turbine. It is only used to evaluate GAMOUT. As with FARX, it is not always required.

WTFLO is the total gas flow into the turbine.

YEAR is the first year of service for the stator vane material. The algorithm allows one level of material technology for the stator(s), YEAR, and another level for
the rotor(s), YEARB. For example, let YEAR=2000.0 and YEARB=1977.8. This indicates that the allowable bulk metal temperature of the stator(s) and rotor(s) are 2360 °R and 2038 °R, respectively. The allowable bulk metal temperature of the rotor blade is assumed to be 100 °R less than that of the stator blade for a given year of material technology.

YEARB is the first year of service for rotor blade material.

Changes to the thermodynamic cycle code NNEP - In the previously published version of NNEP (refs. 1 and 2), one value of turbine efficiency was input and used irrespective of the calculated cooling flow. Now, the new COOLIT subroutine allows (NEWEFF=TRUE.) for the use of a cooled-turbine efficiency which depends upon the cooling configuration of the airfoil, the calculated cooling flow and the thermodynamic uncooled-turbine efficiency.

Formerly, the value of YEAR indicated the same level of material technology for both the stator and the rotor. Now, the new COOLIT subroutine allows one level of material technology for the stator(s), YEARV, and another level for the rotor(s), YEARB.

Formerly, only one type of cooling configuration was input for all rows of airfoils. Now, the new COOLIT subroutine allows a different cooling configuration for each row of airfoils in the turbine.

APPENDICES C, D, and E list changes to subroutines TURBIN, INPRT, and INPUT, respectively, which are part of the engine performance code NNEP. These changes are required for the use of the new COOLIT subroutine in NNEP.

Accuracy of the Algorithm

Comparison of predicted flows - Comparisons can be made between the predictions of the algorithm and those of two engine manufacturers. The first two of these predictions are for hypothetical advanced supersonic transport engines having specific cooling configurations and specific bulk metal temperatures. In one case the algorithm predicted 9.6 percent cooling flow whereas the engine manufacturer predicted 10.0 percent. In another case the algorithm and the engine manufacturer both predicted 19.4 percent. In a third comparison, one for an advanced subsonic Energy Efficient Engine, the algorithm predicted 16.5 percent whereas the engine manufacturer predicted 18.2 percent.

So in general, the flows predicted by the new cooling algorithm agree closely with those predicted by major engine
manufacturers as long as the proper cooling configuration and bulk metal temperatures are used.

To determine the significance of the new cooling algorithm, a comparison was made between its predictions and those of the old version of the COOLIT subroutine for an advanced engine. The comparison of predicted cooling flows shows that the new cooling algorithm predicts a flow which is about 65 percent higher than that predicted by the old COOLIT subroutine. The major reason for the difference in the predicted flows is the fact that the old COOLIT subroutine did not allow for either a safety margin or a hotspot temperature.

**Effect of cooling flow on performance.** - In the new algorithm, compressor bleed flow can affect engine performance in two ways. (1) As the cooling flow exits from the turbine blades and enters the gas stream it causes a loss in total pressure of the mainstream due to increased drag and thereby causes a decrease in turbine efficiency. (2) Any cooling flow which is ejected into the gas stream downstream of the rotor is directly chargeable to the engine cycle since work cannot be extracted from it.

The new cooling algorithm predicts a higher required cooling flow than did the old COOLIT subroutine. It therefore follows from the previous paragraph that NNEP in conjunction with the new cooling algorithm predicts lower thrust levels than that predicted by NNEP in conjunction with the old COOLIT subroutine. In one example the net thrust decreases by over 9.2 percent because of the extra cooling flow which bypassed the rotor.

When NEWEFF=.TRUE., the turbine efficiency is degraded by cooling flow injection. When NEWEFF=.FALSE., turbine efficiency is not degraded by cooling flow injection. The difference between these two options for the case cited above is a decrease in net thrust of 1.1 percent. Most of this difference is due to the decrease in the efficiency of the high pressure turbine (HPT) because most of the total cooling flow is required for the HPT. For the case cited the efficiency of the HPT decreases 3.76 points while the efficiency of the LPT decreases 0.88 points.

It is interesting to differentiate between the relative error in thrust attributed to the decrease in turbine efficiency and that attributed to the cooling flow which bypasses the rotor. The error introduced into the thrust level due to inaccurate cooling flow is several times the error due to uncorrected turbine efficiency.
CONCLUDING REMARKS

A cooling algorithm has been developed for calculating both the quantity of compressor bleed flow required to cool the turbine(s) and the decrease in turbine efficiency caused by cooling flow injection into the gas stream. The technique is presented in the form of a Fortran program which can be used as a subroutine in a properly written thermodynamic cycle code.

1. The cooling algorithm predicts cooling flows which have been substantiated by comparisons with flows predicted by engine manufacturers for the same bulk metal temperatures and cooling configurations.

2. The new cooling algorithm allows for a different cooling configuration for each row of cooled airfoils and allows for different levels of material technology between the stator and rotor. In addition, it will calculate the decrease in turbine efficiency caused by injection of cooling flow into the gas stream.

3. An inaccurate prediction of both required cooling flow and turbine efficiency will result in an inaccurate prediction of engine thrust. However, the error in calculated thrust caused by flow bypassing the rotor is much greater than the error in calculated thrust caused by the decrease in turbine efficiency.
APPENDIX A. - NAMES OF VARIABLES IN SUBROUTINE COOLIT

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIR1</td>
<td>Air content of the hot gas at the entrance to a row of airfoils, lbm/sec</td>
</tr>
<tr>
<td>AIR2</td>
<td>Air content of the bleed flow from the row of airfoils immediately upstream, lbm/sec</td>
</tr>
<tr>
<td>CALBLD</td>
<td>Indicator which is set to .TRUE. when bleed flow requirement is to be determined</td>
</tr>
<tr>
<td>DELN</td>
<td>Percent change in thermodynamic efficiency of a cooled stage for each one percent of required cooling flow; change in thermodynamic stage efficiency due to the rotor</td>
</tr>
<tr>
<td>DELV</td>
<td>Change in thermodynamic stage efficiency due to the stator</td>
</tr>
<tr>
<td>DH</td>
<td>Power extracted from each turbine stage, Btu/sec</td>
</tr>
<tr>
<td>EFF1</td>
<td>Thermodynamic efficiency of an uncooled turbine</td>
</tr>
<tr>
<td>EFF2</td>
<td>Thermodynamic efficiency of an uncooled stage of a turbine</td>
</tr>
<tr>
<td>EFF3</td>
<td>Thermodynamic efficiency of a cooled stage of a turbine</td>
</tr>
<tr>
<td>EFF4</td>
<td>Thermodynamic efficiency of a cooled turbine</td>
</tr>
<tr>
<td>ELIFE</td>
<td>Desired life of the turbine airfoil</td>
</tr>
<tr>
<td>FACTOR</td>
<td>Cooling flow weighting factor</td>
</tr>
<tr>
<td>FARCX</td>
<td>Fuel to air ratio of the cooling flow</td>
</tr>
<tr>
<td>FARG</td>
<td>Fuel to air ratio of the hot gas stream at the inlet to a row of airfoils</td>
</tr>
<tr>
<td>FARGX</td>
<td>Fuel to air ratio of the hot gas stream at the inlet to a row of airfoils</td>
</tr>
<tr>
<td>FUEL1</td>
<td>Fuel content of the hot gas stream at the entrance to a row of airfoils, lbm/sec</td>
</tr>
<tr>
<td>FUEL2</td>
<td>Fuel content of the bleed flow from the row of airfoils immediately upstream, lbm/sec</td>
</tr>
<tr>
<td>GAM</td>
<td>Specific heat ratio of the hot gas as function of TIN and FARGX</td>
</tr>
<tr>
<td>GAMAVG</td>
<td>Specific heat ratio of the hot gas as function of TOUT and FARGX</td>
</tr>
<tr>
<td>GAMIN</td>
<td>Specific heat ratio of the hot gas as function of TOUT and FARGX</td>
</tr>
<tr>
<td>GAMOUT</td>
<td>Specific heat ratio of the hot gas as function of TOUT and FARGX</td>
</tr>
<tr>
<td>HC</td>
<td>Enthalpy of the cooling flow, Btu/lbm</td>
</tr>
<tr>
<td>HG</td>
<td>Enthalpy of the hot gas stream at the inlet to a row of airfoils, Btu/lbm</td>
</tr>
<tr>
<td>HGUP</td>
<td>Enthalpy of the hot gas stream at the inlet to a turbine, Btu/lbm</td>
</tr>
<tr>
<td>HPT</td>
<td>Power extracted by the turbine, hp</td>
</tr>
<tr>
<td>II</td>
<td>Number of rows of cooled airfoils in a turbine which exceed nine</td>
</tr>
<tr>
<td>KVANE</td>
<td>Indicator which determines whether a row of airfoils is a stator or a rotor</td>
</tr>
<tr>
<td>KINDOF</td>
<td>An ordered combination of digits representing the cooling configurations throughout the turbine starting with the stator of the first stage</td>
</tr>
<tr>
<td>M</td>
<td>Rows</td>
</tr>
<tr>
<td>NEWEPP</td>
<td>Indicator which is set equal to .TRUE. when a new thermodynamic efficiency for the cooled turbine is to be calculated</td>
</tr>
</tbody>
</table>
| NFACT(I) | Digit representing a particular cooling configuration for a particular row of airfoils in
a cooled turbine

N
whole number of stages in the turbine

N1STT
component number of the first turbine

PHI
general name for PHIC(X)

PHIC(X)
cooling effectiveness evaluated at the local value of the effective gas stream temperature

PCBLED
accumulated cooling flow required to cool the turbine, made dimensionless by the flow entering the turbine

PR
pressure ratio across turbine, inlet(exit

PROFIL
combustor pattern factor; or radial temperature profile

RP
pressure ratio across turbine, exit/inlet

ROWS
number of rows of cooled airfoils in the turbine

SAFETY
safety margin of 150°R used when determining the required cooling flow

STAGES
number of stages in the turbine

SUMBLD
sum of dimensionless bleeds from all turbines; approaches unity as engine design converges

T
argument of function PHIC(X);

taverage effective gas temperature,°R

TAUT
temperature ratio across turbine as calculated by stage efficiencies

TC
total temperature of the cooling flow at the point at which it is extracted from the compressor,°R

TG
gas temperature at the inlet to a row of airfoils,°R

TIN
total temperature of the gas into the turbine,°R

TM
general name for either TMVANE or TMBLAD,°R

TMVANE
allowable bulk metal temperature for stator vanes,°R

TMBLAD
allowable bulk metal temperature for rotor blades,°R

TOUT
total temperature of the gas out of the turbine,°R

WCOOL
dimensionless cooling flowrate for a row of cooled airfoils

W(I)
the cooling flowrate for a row of airfoils, lbm/sec; or the cooling flowrate for a row of airfoils in the turbine plus endwall, shroud, and disk cooling and leakage, lbm/sec

WG
gas flowrate at the inlet to a row of airfoils, lbm/sec

WG1
WTPLO, lbm/sec

WTPLO
total gas flow into the turbine, lbm/sec

XDELN
general name for DELN

XFACT
general name for FACTOR

XW
N

YEAR
first year of service for stator vane material; called YEARV in INPUT SUBROUTINE

YEARB
first year of service for rotor blade material
APPENDIX B. - LISTING OF SUBROUTINE COOLIT

SUBROUTINE COOLIT (STAGES,KINDOF,TIN,TOUT,TC,PCBLED,EFF1,EFF4,HP
1TFLO,PARCY,FARGX,PR)
IMPLICIT REAL*8 (A-H,O-Z)
COMMON /JBLEED/ SUMBLD,YEAR,ELIFE,CALBLD
COMMON /BLADE/ YEARB,TMVANE,TMBLAD,NEWEFF
COMMON /PF/ PROFIL,N1STT
LOGICAL CALBLD
LOGICAL NEWEFF
DIMENSION NFACT(20), W(20), XFACT(10), XDELN(20)
DATA XFACT,XDELN/0.0,0.2,0.1,0.5,1.4,1.3,1.2,1.1,0.9,1.0,0.8,-
10.0,0.1,0.12,0.15,0.18,0.5,0.35,1.0,-
10.0,0.2,0.24,0.30,0.36,1.0,-60,1.5/
PHIC(X) = (X-TM)/DABS(X-TC)
WCOOL(PHI) = 0.22*(PHI/(1.-PHI))**1.25
N=STAGES+.1
N=AMAX0(1,N)
TMVANE=(10.*YEAR-17640.)-(100.*DLOG10(ELIFE)-400.)
TMBLAD=(10.*YEAR-17740.)-(100.*DLOG10(ELIFE)-400.)
GAMIN=THERM(5,TIN,FARGX)
GAMOUT=THERM(5,TOUT,FARGX)
GAMAVG=(GAMIN+GAMOUT)/2
GAM=(GAMAVG-1)/GAMAVG
TAUT=1
RP=1/PR
XN=N
EFF2=(1.-1.-EFF1*(1.-RP**GAM))**{(1./XN)}/(1.-RP**GAM/XN)
DH=HP/FLOAT(N)/1.415
HC=THERM(4,TC,PARC)
SAFETY=150.
FARG=FARGX
TG=TIN
HG=THERM(4,T3,FARG)
PCBLED=0.
WG1=WTFL0
WG=WG1
HGUP=HG
KVANE=-1
ROWS=2*STAGES+.1
M=ROWS
M=AMAX0(2,M)
II=M-9
DO 20 I=I,M
IF (M.GT.9.AND.I.LE.II) GO TO 10
NFACT(M+I-1)=KINDOP-10*(KINDOP/10)
KINDOP=KINDOP/10
GO TO 20
10 NFACT(M+I-1)=1
20 W(I)=0.
DO 80 I=I,M
KVANE=KVANE*(-1)
C COOLING FLOW WEIGHTING 'FACTOR' ASSIGNED TO 'KINDOF'
COOLING CONFIGURATION

\[ N = N_{\text{FACT}}(I) + 1 \]

FACTOR = \( X_{\text{FACT}}(N) \)

IF (\( \text{KVANE} \cdot \text{LT} \cdot 0 \)) GO TO 30

TM = TMVANE

DIMENSIONLESS CHANGE IN STAGE EFFICIENCY FOR A ONE PERCENT CHANGE IN STATOR COOLING FLOW

\[ \text{DELN} = X_{\text{DELN}}(N) \]

GO TO 40

TM = TMBLAD

DIMENSIONLESS CHANGE IN STAGE EFFICIENCY FOR A ONE PERCENT CHANGE IN ROTOR COOLING FLOW

\[ \text{DELN} = X_{\text{DELN}}(N + 10) \]

APPROXIMATION FOR RELATIVE TOTAL TEMPERATURE

\[ TG = 0.92 \cdot TG \]

CORRECTION TO \( 'T' \) FOR SAFETY MARGIN OF 150 DEG

\[ T = TG + \text{SAFETY} \]

PHI = PHIC(T)

CORRECTION TO \( 'PHI' \) FOR PATTERN FACTOR/RADIAL PROFILE

\[ 'PROFI' \] HAS VALUE OF 0.30 FOR THE FIRST STATOR OF THE HPT

\[ PHI = (\text{PROFI} + PHI)/((\text{PROFI} + 1.) \]

PHI = DMAX \( (PHI, 0.0) \)

IF THE BLADE IS MEANT TO BE COOLED AND IT NEEDS TO BE COOLED

IF \( (N_{\text{FACT}}(I) \cdot \text{GT} \cdot 0.), AND \text{PHI} \cdot \text{GT} \cdot 0.) \) GO TO 50

IF THE BLADE DOES NOT NEED TO BE COOLED

IF \( (\text{PHI} \cdot \text{EQ} \cdot 0.) \) GO TO 60

IF THE BLADE NEEDS TO BE COOLED BUT WAS NOT MEANT TO BE COOLED

FACTOR = 2.0

\[ N_{\text{FACT}}(I) = 1 \]

\[ \text{DELN} = X_{\text{DELN}}(I)/\text{WG} \]

GO TO 65

\[ N_{\text{FACT}}(I) = 0 \]

\[ \text{DELN} = \text{DELN} \cdot \text{WG} \cdot \text{EFF2} \]

IF \( (\text{NEW EFF}) \) \( \text{DELN} = 0 \)

IF \( (\text{KVANE} \cdot \text{GT} \cdot 0.) \) \( \text{DELV} = \text{DELN} \)

CORRECTION FOR ENDWALL COOLING/LEAKAGE

\[ W(I) = W(I) \cdot 4/3 \]

NEW FUEL/AIR RATIO AFTER DILUTION FROM UPSTREAM ROW

\[ \text{AIR1} = \text{WG}/(1 + \text{FARG}) \]

\[ \text{FUEL1} = \text{WG} \cdot \text{FARG} \]

\[ \text{AIR2} = W(I)/(1 + \text{PARCX}) \]

\[ \text{FUEL2} = W(I) \cdot \text{PARCX} \]

\[ \text{FARG} = (\text{FUEL1} + \text{FUEL2})/(\text{AIR1} + \text{AIR2}) \]

IF \( (\text{KVANE} \cdot \text{GT} \cdot 0.) \) GO TO 70

\[ \text{EFF3} = \text{EFF2} - \text{DELN} - \text{DELV} \]

\[ \text{TAUT} = (1 + 1.0^{**} \text{PARCX})^{*} \text{TAUT} \]

\[ \text{HG} = \text{HG} \cdot \text{DG}/\text{WG} \]

\[ \text{HG} = (\text{WG} \cdot \text{HC} + W(I) \cdot \text{HC})/(\text{WG} + W(I)) \]

\[ \text{TG} = \text{TERM}(\text{1}, \text{HG}, \text{FARG}) \]

\[ \text{WG} = \text{WG} + W(I) \]

\[ \text{PROFI} = 0.13 \]

PCBLED = PCBLED \( \cdot W(I)/\text{WG} \)

\[ . \]

\[ . \]

\[ . \]
MM = AMINO(9, M)
DO 90 I = 1, MM
   KINDOF = KINDOF * 10 * NFACT(I)
   EFF4 = (1 - TACT) / (1 - RP * GAM)
RETURN
END
APPENDIX C. - CHANGES TO SUBROUTINE TURBIN

1. After the statement
"IMPLICIT..."
on line 2, insert the statement
"DIMENSION KIND(20)".

2. After the statement
"COMMON /JBLEED/..."
on line 10, insert the two statements
"COMMON /BLADE/YEARV,TMVANE,TMBLAD,NEWEFF"
and
"COMMON /PF/ PROFIL,NISTT".

3. After the statement
"LOGICAL CALBLD"
on line 11, insert the statement
"LOGICAL NEWEFF".

4. After the statement
"EFF=DATINP(6,JCX)"
on line 45, insert the two statements
"IF (.NOT. NEWEFF) DATOUT(8,JCX)=DATINP(11,JCX)"
and
"IF (NEWEFF .AND. NIT.EQ.0) DATOUT(11,JCX)=DATINP(11,JCX)".

5. Replace the statement
"EFF=DATINP(11,JCX)"
on line 95 with the statement
"EFF=DATINP(8,JCX)".

6. After the statement
"TOTEP(JP1)=TOUT"
on line 109, insert the six statements
"IF (NISTT.EQ.0) NISTT=JCX",
"IF (JCX.EQ.NISTT) PROFIL=0.3"
"IF (HPT.EQ.0) KIND(JCX)=DATINP(14,JCX)"
"KINDOF=KIND(JCX)"
"IF (HPT.EQ.0) GO TO 121",
and
"IF (KINDOF.EQ.0.) KINDOF=89".

7. Delete the two statements
"FACTOR=DATINP(14,JCX)"
on line 110 and
"IF (FACTOR.EQ.0) FACTOR =1.0"
on line 111.

8. Change the term "NSTAGE" on line 113 to "STAGE".

9. Change the terms "NSTAGE,FACTOR" on line 114 to "STAGE,KINDOF".

10. Change the term "LED)" on line 115 to the terms
"LED, DATINP(11,JCX), DATOUT(8,JCX), HPT, WT1, FAR2, FAR1, PR"

11. After the statement
"IF (DABS... GO TO 60"
on line 121, insert the statement
"IF (DABS(EFF-DATOUT(8,JCX)).GT.1.E-4) GO TO 60"

12. After the statement
"SUMBLD=SUMBLD..."
on line 122, insert the statement
"CONTINUE"

13. After the statement
"DATOUT(7,JCX)..."
on line 131, insert the statement
"IF (IDONE(JCX).EQ.0) GO TO 125"

14. Change the statement
"DATOUT(9,JCX)=PR"
on line 135, to
"125 DATOUT(9,JCX)=PR"

15. After the previous statement on line 135, insert the statement
"DATINP(14,JCX)=KINDOF"
APPENDIX D. - CHANGES TO SUBROUTINE INPRT

1. After the statement
"COMMON /JBLEED/,..."
on line 11, insert the statement
"COMMON /BLADE/YEARB, TMVANE, TMBLAD, NEWEFF".

2. After the statement
"10) I,DATINP(2,1)"
on line 98 insert the statement
"KINDOF=DATINP(14,1)".

3. After the term "DATINP(2,I)" on line 99, insert the terms ",KINDOF, TMVANE, TMBLAD".

4. Replace on the right-hand-side parenthesis, ")", with a hyphen and add to format statement 520 the continuation
"1." THE COOLING CONFIGURATION IS ,I9,' TMVANE IS
',F6.0,' TMBLAD IS ',F'0)".
(Note the blank after the parenthesis.)
APPENDIX E.- CHANGES TO SUBROUTINE INPUT

1. After the term "CALBLD" on line 16, insert the term ",NEWEFF".

2. After the statement
"COMMON /JBLEED/..."
on line 23, insert the two statements
"COMMON /BLADE/ YEARB, TTVANE, TMBLAD, NEWEFF"
and
"COMMON /PF/ PROFIL, N1STT".

3. Replace the term "YEAR" on line 28 with the terms
"NEWEFF, YEARB, YEARV".

4. After the statement
"CALBLD=.FALSE."on line 38, insert the three statements
"NEWEFF=.FALSE.",
"YEARV=1985.",
and
"YEARB=1985.".

5. Delete the statement
"YEAR=1985."on line 39.

After the statement
"READ (8,D)"
on line 50,
insert the statement
"N1STT=0".

6. After the statement
"READ(8,D)"
on line 76, insert the statement
"YEAR=YEARV".
REFERENCES


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<tr>
<th>Cooling configuration, FACT(I)</th>
<th>Percent trailing edge ejection</th>
<th>Impinge-ent cooling flow, factor</th>
<th>Loss in stage efficiency, stator rotor DELV DELN</th>
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<td>0 uncooled</td>
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**TABLE I.** ALLOWABLE COOLING CONFIGURATIONS