COMPUTER PROGRAM
FOR PRELIMINARY DESIGN ANALYSIS
OF AXIAL-FLOW TURBINES

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The program method is based on a mean-diameter flow analysis. Input design requirements include power or pressure ratio, flow, temperature, pressure, and speed. Turbine designs are generated for any specified number of stages and for any of three types of velocity diagrams (symmetrical, zero exit swirl, or impulse). Exit turning vanes can be included in the design. Program output includes inlet and exit annulus dimensions, exit temperature and pressure, total and static efficiencies, blading angles, and last-stage critical velocity ratios. The report presents the analysis method, a description of input and output with sample cases, and the program listing.
This report presents a computer program for the preliminary design analysis of axial-flow turbines. The computations are based on mean-diameter flow properties and do not consider any radial gradients. Given as input to the program are power or pressure ratio, mass flow rate, inlet temperature and pressure, rotative speed, inlet and exit diameters (either hub, mean, or tip), exit radius ratio or stator exit angle, turbine loss coefficient, and gas properties. Computations are then performed for any specified number of stages and for any of three types of velocity diagrams (symmetrical, zero exit swirl, or impulse). Exit turning vanes can be included in the design. The program output includes inlet and exit annulus dimensions, exit temperature and pressure, total and static efficiencies, blading angles, and last-stage critical velocity ratios.

The analysis method, a complete description of input and output, and a FORTRAN IV program listing are presented in this report. Sample cases are included to illustrate use of the program.

INTRODUCTION

The preliminary analysis of a power or propulsion system involves many repetitive calculations to determine system performance, component performance, and component geometries over a range of conditions. This must be done in order to eventually determine the best system and operating conditions. For this type of screening analysis, complete design accuracy and detail for the components are not necessary. Approximate and rapid generalized procedures rather than complex and time-consuming detailed design procedures are sufficient to yield the desired component overall geometry and performance characteristics.

This report presents a computer program for the preliminary design analysis of
axial-flow turbines. The analysis is based on mean-diameter flow properties and does not consider any radial gradients. Input design requirements include power or pressure ratio, mass flow rate, inlet temperature and pressure, and rotative speed. The design variables include inlet and exit diameters, stator angle, and number of stages. Computations are performed for any of three types of velocity diagrams (symmetrical, impulse, or zero exit swirl) by assuming the same shape diagrams for each stage. The program output includes inlet and exit annulus dimensions, exit temperature and pressure, total and static efficiencies, blading angles, and last-stage velocity ratios.

The analysis method, a complete description of input and output, and a FORTRAN IV program listing are presented in this report. Sample cases are included to illustrate use of the program.

SYMBOLS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>stage loss parameter</td>
</tr>
<tr>
<td>A_{an}</td>
<td>annulus area, m²; ft²</td>
</tr>
<tr>
<td>B</td>
<td>exit loss parameter</td>
</tr>
<tr>
<td>C</td>
<td>blade loss parameter</td>
</tr>
<tr>
<td>C_A</td>
<td>dimensional constant, 2π rad/rev; 60 sec/min</td>
</tr>
<tr>
<td>C_B</td>
<td>dimensional constant, 1; 550 ft-lb/(sec)(hp)</td>
</tr>
<tr>
<td>c_p</td>
<td>heat capacity, joules/(kg)(K); Btu/(lb)(°R)</td>
</tr>
<tr>
<td>D</td>
<td>diameter, m; ft</td>
</tr>
<tr>
<td>E</td>
<td>squared ratio of stage-exit axial velocity to stage-average axial velocity</td>
</tr>
<tr>
<td>F</td>
<td>blade loss weighting factor</td>
</tr>
<tr>
<td>g</td>
<td>dimensional constant, 1; 32.2 ft-lbm/(sec²)(lbf)</td>
</tr>
<tr>
<td>Δh</td>
<td>specific work, joules/kg; Btu/lb</td>
</tr>
<tr>
<td>i</td>
<td>stage number i, i = 1, 2, ... , n</td>
</tr>
<tr>
<td>J</td>
<td>dimensional constant, 1; 778 ft-lb/Btu</td>
</tr>
<tr>
<td>K</td>
<td>turbine loss coefficient</td>
</tr>
<tr>
<td>M</td>
<td>Mach number</td>
</tr>
<tr>
<td>N</td>
<td>rotative speed, rad/sec; rpm</td>
</tr>
<tr>
<td>n</td>
<td>number of stages</td>
</tr>
<tr>
<td>P</td>
<td>shaft power, watts; hp</td>
</tr>
<tr>
<td>2</td>
<td></td>
</tr>
</tbody>
</table>
p  pressure, N/m²; lb/ft²
R  gas constant, joules/(kg)(K); ft-lbf/(lbm)(°R)
Re Reynolds number
r  radius, m; ft
T  temperature, K; °R
U  blade speed, m/sec; ft/sec
V  absolute gas velocity, m/sec; ft/sec
W  relative gas velocity, m/sec; ft/sec
w  mass flow rate, kg/sec; lb/sec
α  absolute-flow angle from axial direction, deg
β  relative-flow angle from axial direction, deg
γ  heat capacity ratio
η  static efficiency
η' total efficiency
λ  speed-work parameter
μ  viscosity, (N)(sec)/m²; lb/(sec)(ft)
ρ  density, kg/m³; lb/ft³

Subscripts:
a  first stage
cr critical
ev exit vane
ex turbine exit
h  hub
i  stage  i, i = 1, 2, . . . , n
in turbine inlet
m  mean section
n  last stage
ro rotor
st stator
t  tip
METHOD OF ANALYSIS

The method is based upon an analysis of the flow at the turbine mean diameter. Radial gradients of the flow properties are not considered. Specific heat ratio is assumed constant throughout the turbine. For any given turbine, all stages, except the first, are specified to have the same shape velocity diagram. The first stage differs only in that the inlet flow is axial. The velocity diagram shape depends upon the speed-work parameter value and the specified type of velocity diagram. Three types of velocity diagram are considered: symmetrical, zero exit swirl, and impulse. These three types of velocity diagram are shown in figure 1 for three values of speed-work parameter.

Various input options dictate the exact nature of the calculation procedure. There is, however, one basic procedure that is direct and without iteration. This basic procedure will be presented and then the alternate procedures required for the various input options will be discussed. The computations can be done either in SI units or in U.S. customary units.

Basic Calculation Procedure

The required inputs for the basic procedure are shaft power $P$, mass flow rate $w$, inlet total temperature $T'_{in}$, inlet total pressure $p'_{in}$, rotative speed $N$, inlet mean diameter $D_{m,in}$, exit mean diameter $D_{m,ex}$, stator exit angle $\alpha_1$, gas constant $R$, specific heat ratio $\gamma$, viscosity $\mu$, loss coefficient $K$, and squared ratio of stage-exit to stage-average axial velocities $E$. Also specified for each calculation are the number of stages $n$ and the type of velocity diagram. For a multistage turbine, the input variable specified as inlet diameter is used to calculate first rotor blade speed and annulus
dimensions at the first rotor exit. Therefore, it is truly an inlet diameter only if the hub and tip diameters are assumed constant across the first stage. For a one-stage turbine, the specified exit diameter is used for the calculations, and the inlet diameter is of no significance.

The first- and last-stage blade speeds are

\[ U_a = \frac{\pi ND m, in}{C_A} \quad (1) \]

\[ U_n = \frac{\pi ND m, ex}{C_A} \quad (2) \]

For more than two stages, it is assumed that the stage blade speeds vary linearly between the first- and last-stage values. Therefore,

\[ U_i = \frac{U_n - U_a}{n - 1} (i - 1) + U_a \quad (3) \]

Turbine specific work is

\[ \bar{\Delta h}' = \frac{C_B P}{J w} \quad (4) \]

and is equal to the sum of the specific work of the stages:

\[ \bar{\Delta h}' = \sum_{i=1}^{n} \Delta h'_i \quad (5) \]

Expressing stage specific work in terms of stage speed-work parameter as

\[ \Delta h'_i = \frac{U_i^2}{gJ\lambda} \quad (6) \]

and substituting equation (6) into equation (5) yield
\[
\frac{\Delta h'}{\gamma J' h} = \sum_{i=1}^{n} \frac{U_{i}^{2}}{gJ' h}
\]  
(7)

Since the velocity diagram shape is specified to be the same for all stages, the speedwork parameter is the same for all stages and is computed by rearranging equation (7) as

\[
\lambda = \frac{\sum_{i=1}^{n} U_{i}^{2}}{gJ' \Delta h'}
\]  
(8)

The value of \( \lambda \) is the primary factor determining turbine efficiency.

The method used for computing turbine static efficiency is basically similar to that presented in reference 1, but has the following additional features: (1) the turbines considered in this report are not restricted to a constant mean-section diameter, (2) exit vanes to provide axial flow leaving the turbine can be included in the design, and (3) the velocity diagrams can be specified to be symmetrical. The efficiency computation method is explained fully in reference 1, and only the key equations are presented in this section.

With turbine reheat neglected, turbine static efficiency can be expressed as

\[
\bar{\eta} = \frac{\Delta h'}{\Delta h'_{id,a} + \sum_{i=2}^{n-1} \Delta h'_{id,i} + \Delta h'_{id,n}}
\]  
(9)

Dividing numerator and denominator by \( \Delta h' \) and introducing stage efficiencies yield

\[
\bar{\eta} = \frac{1}{\frac{1}{\eta_{a} \Delta h'} + \sum_{i=2}^{n-1} \frac{\Delta h'_{i}}{\Delta h'} + \frac{1}{\eta_{n} \Delta h'}}
\]  
(10)

Dividing equation (6) by equation (7) shows that
\[
\Delta h_i' = \frac{U_i^2}{\Delta h'} \sum_{i=1}^{n} U_i^2
\]

Substituting equation (11) into equation (10) and recognizing that

\[
\sum_{i=2}^{n-1} \left( \frac{U_i^2}{\sum_{i=1}^{n} U_i^2} \right) = 1 - \frac{U_a^2}{\sum_{i=1}^{n} U_i^2} - \frac{U_n^2}{\sum_{i=1}^{n} U_i^2}
\]

finally yield

\[
\bar{\eta} = \frac{1}{\frac{1}{\eta'_a} \sum_{i=1}^{n} U_i^2 + \frac{1}{\eta'_i} \left( 1 - \frac{U_a^2}{\sum_{i=1}^{n} U_i^2} - \frac{U_n^2}{\sum_{i=1}^{n} U_i^2} \right) + \frac{1}{\eta_n} \sum_{i=1}^{n} U_i^2}
\]

The stage-total and last-stage-static efficiencies are

\[
\eta' = \frac{\lambda}{\lambda + \frac{A}{2}}
\]

and

\[
\eta_n = \frac{\lambda}{\lambda + \frac{1}{2}(A + B)}
\]

The stage loss parameter $A$ is expressed as
The constant of proportionality $K$, called the turbine loss coefficient in this report, must be determined empirically. On the basis of comparisons of predicted with experimental efficiencies, a value of $K = 0.4$ was selected in reference 1. For large turbines of recent airbreathing engines, a value of $K = 0.35$ seems better. The Reynolds number used in this calculation is defined as

$$\text{Re} = \frac{2w}{\mu D_{m,in}}$$ (17)

Some of the terms within the parentheses in equation (16) are the same for all cases, while others depend on stage location, velocity diagram type, and use of exit vanes. The rotor weighting factor $F_{r o}$ and rotor loss parameter $C_{r o}$ are the same for all cases:

$$F_{r o} = 2$$ (18)

$$C_{r o} = 2 \cot^2 \alpha \left( \frac{V_{u,1}}{\Delta V_u} \right)^2 + \left( \frac{V_{u,1}}{\Delta V_u} - \lambda \right)^2 + \left( \frac{V_{u,2}}{\Delta V_u} - \lambda \right)^2$$ (19)

For all stages other than last stages and for last stages where exit vanes are not used, the exit vane loss parameter is

$$C_{e v} = 0$$ (20)

For last stages of turbines having exit vanes,

$$C_{e v} = 2 \cot^2 \alpha \left( \frac{V_{u,1}}{\Delta V_u} \right)^2 + \left( \frac{V_{u,2}}{\Delta V_u} \right)^2$$ (21)

Axial inlet flow is assumed for all first-stage stators, for which the stator loss parameter is expressed
For all stators other than first-stage stators,

\[ C_{st} = \left(1 + 2 \cot^2 \alpha_1 \right) \left( \frac{V_{u,1}}{\Delta V_u} \right)^2 \]  

(22)

The stator weighting factor \( F_{st} \) also depends on whether or not the stator is a first-stage stator and further depends on the type of velocity diagram. The inlet and exit swirl parameters \( V_{u,1}/\Delta V_u \) and \( V_{u,2}/\Delta V_u \) of equations (19) to (23) also depend on the type of velocity diagram. The following table presents the relations for evaluating the stator weighting factor and the swirl parameters:

<table>
<thead>
<tr>
<th>Stage</th>
<th>Velocity diagram type</th>
<th>Stator weighting factor, ( F_{st} )</th>
<th>Inlet swirl parameter, ( V_{u,1}/\Delta V_u )</th>
<th>Exit swirl parameter, ( V_{u,2}/\Delta V_u )</th>
</tr>
</thead>
<tbody>
<tr>
<td>First</td>
<td>Symmetrical</td>
<td>1</td>
<td>( \frac{\lambda + 1}{2} )</td>
<td>( \frac{\lambda - 1}{2} )</td>
</tr>
<tr>
<td></td>
<td>Zero exit swirl</td>
<td>1</td>
<td>( \frac{\lambda + 1}{2} )</td>
<td>( \frac{\lambda - 1}{2} )</td>
</tr>
<tr>
<td></td>
<td>Impulse with ( \lambda \leq 0.5 )</td>
<td>1</td>
<td>( \lambda + \frac{1}{2} )</td>
<td>( \frac{\lambda - 1}{2} )</td>
</tr>
<tr>
<td></td>
<td>Impulse with ( \lambda &gt; 0.5 )</td>
<td>1</td>
<td>( \lambda + \frac{1}{2} )</td>
<td>( \frac{\lambda - 1}{2} )</td>
</tr>
<tr>
<td>Intermediate and last</td>
<td>Symmetrical</td>
<td>2 - ( \lambda )</td>
<td>( \frac{\lambda + 1}{2} )</td>
<td>( \frac{\lambda - 1}{2} )</td>
</tr>
<tr>
<td></td>
<td>Zero exit swirl</td>
<td>1</td>
<td>( \lambda + \frac{1}{2} )</td>
<td>( \frac{\lambda - 1}{2} )</td>
</tr>
<tr>
<td></td>
<td>Impulse with ( \lambda \leq 0.5 )</td>
<td>2(1 - (\lambda ))</td>
<td>( \lambda + \frac{1}{2} )</td>
<td>( \frac{\lambda - 1}{2} )</td>
</tr>
<tr>
<td></td>
<td>Impulse with ( \lambda &gt; 0.5 )</td>
<td>1</td>
<td>( \lambda + \frac{1}{2} )</td>
<td>( \frac{\lambda - 1}{2} )</td>
</tr>
</tbody>
</table>
The exit loss parameter $B$ of equation (15) is expressed as

$$B = E \cot^2 \alpha_1 \left( \frac{V_{u,1}}{\Delta V_u} \right)^2 + \left( \frac{V_{u,2}}{\Delta V_{u,\text{ex}}} \right)^2$$  \hspace{1cm} (24)$$

where

$$\left( \frac{V_{u,2}}{\Delta V_u} \right)_{\text{ex}} = \frac{V_{u,2}}{\Delta V_u}$$  \hspace{1cm} (25)$$

with no exit vanes and

$$\left( \frac{V_{u,2}}{\Delta V_u} \right)_{\text{ex}} = 0$$  \hspace{1cm} (26)$$

with exit vanes.

The turbine exit velocities and state conditions are computed as follows:

$$\Delta V_{u,n} = \frac{U_n}{\lambda}$$  \hspace{1cm} (27)$$

$$V_{u,1,n} = \frac{V_{u,1}}{\Delta V_u} \Delta V_{u,n}$$  \hspace{1cm} (28)$$

$$V_{u,2,n} = \frac{V_{u,2}}{\Delta V_u} \Delta V_{u,n}$$  \hspace{1cm} (29)$$

$$V_{x,n} = V_{u,1,n} \cot \alpha_1$$  \hspace{1cm} (30)$$

$$V_{x,ex} = \sqrt{E} \cdot V_{x,n}$$  \hspace{1cm} (31)$$

$$V_{u,ex} = \begin{cases} V_{u,2,n} & \text{no exit vanes} \\ 0 & \text{exit vanes} \end{cases}$$  \hspace{1cm} (32)$$
\[ V_{\text{ex}} = \sqrt{V_{x,\text{ex}}^2 + V_{u,\text{ex}}^2} \]  

(33)

\[ c_p = \frac{\gamma}{\gamma - 1} \frac{R}{J} \]  

(34)

\[ p_{\text{ex}} = p_{\text{in}}' \left(1 - \frac{\Delta h'}{c_p T_{\text{in}}' \bar{\eta}'}\right)^{\gamma/(\gamma - 1)} \]  

(35)

\[ T_{\text{ex}}' = T_{\text{in}}' - \frac{\Delta h'}{c_p} \]  

(36)

\[ T_{\text{ex}} = T_{\text{ex}}' - \frac{V_{\text{ex}}^2}{2gJc_p} \]  

(37)

\[ p_{\text{ex}}' = p_{\text{ex}} \left(\frac{\frac{T_{\text{ex}}'}{T_{\text{ex}}}}{\gamma/(\gamma - 1)}\right) \]  

(38)

In order that the turbine total and static efficiencies be consistent with the computed exit velocity, the total efficiency is computed as

\[ \bar{\eta}' = \frac{\Delta h'}{c_p T_{\text{in}}' \left[1 - \left(\frac{p_{\text{ex}}'}{p_{\text{in}}'}\right)^{(\gamma - 1)/\gamma}\right]} \]  

(39)

Exit annulus area, radius ratio, and hub and tip diameters are obtained as follows:

\[ \rho_{\text{ex}} = \frac{p_{\text{ex}}}{R T_{\text{ex}}} \]  

(40)

\[ A_{\text{an,ex}} = \frac{w}{\rho_{\text{ex}} V_{x,\text{ex}}} \]  

(41)
Absolute and relative flow angles, which are the same for each stage, are computed from the last-stage velocities:

$$\alpha_2 = \tan^{-1} \frac{V_{u,2,n}}{V_{x,n}}$$

$$W_{u,1,n} = V_{u,1,n} - U_n$$

$$W_{u,2,n} = V_{u,2,n} - U_n$$

$$\beta_1 = \tan^{-1} \frac{W_{u,1,n}}{V_{x,n}}$$

$$\beta_2 = \tan^{-1} \frac{W_{u,2,n}}{V_{x,n}}$$

Critical velocity ratios are computed for the last stage, where temperatures are lowest and the velocity ratios are most severe:

$$V_{2,n} = \sqrt{V_{u,2,n}^2 + V_{x,ex}^2}$$
\[ W_{2,n} = \sqrt{W_{u,2,n}^2 + V_{x,ex}^2} \]  \hspace{1cm} (51)

\[ W_{1,n} = \sqrt{W_{u,1,n}^2 + V_{x,n}^2} \]  \hspace{1cm} (52)

\[ V_{1,n} = \sqrt{V_{u,1,n}^2 + V_{x,n}^2} \]  \hspace{1cm} (53)

\[ T''_2, n = T'_{1, n} = T'_{ex} - \frac{V_{2,n}^2 - W_{2,n}^2}{2gJc_p} \]  \hspace{1cm} (54)

\[ T'_{1, n} = T''_{1, n} - \frac{W_{1,n}^2 - V_{1,n}^2}{2gJc_p} \]  \hspace{1cm} (55)

\[ \left( \frac{V_{2}}{V_{cr,2,n}} \right) = \frac{V_{2,n}}{\sqrt{2 \frac{\gamma}{\gamma + 1} gRT'_{ex}}} \]  \hspace{1cm} (56)

\[ \left( \frac{W_{2}}{W_{cr,2,n}} \right) = \frac{W_{2,n}}{\sqrt{2 \frac{\gamma}{\gamma + 1} gRT''_{2,n}}} \]  \hspace{1cm} (57)

\[ \left( \frac{W_{1}}{W_{cr,1,n}} \right) = \frac{W_{1,n}}{\sqrt{2 \frac{\gamma}{\gamma + 1} gRT'_{1,n}}} \]  \hspace{1cm} (58)

\[ \left( \frac{V_{1}}{V_{cr,2,n}} \right) = \frac{V_{1,n}}{\sqrt{2 \frac{\gamma}{\gamma + 1} gRT'_{1,n}}} \]  \hspace{1cm} (59)

\[ M_{x,ex} = \frac{V_{x,ex}}{\sqrt{\gamma gRT_{ex}}} \]  \hspace{1cm} (60)
In order to establish the flow annulus geometry near the turbine inlet, a flow analysis is made at the first-stage exit as follows:

\[ \Delta h'_a = \frac{U_{a}^2}{g J \lambda} \]  
\[ T'_{2,a} = T'_{in} - \frac{\Delta h'_a}{c_p} \]  
\[ p'_{2,a} = p'_{in} \left( 1 - \frac{\Delta h'_a}{c_p T'_{in} \eta'_a} \right)^\gamma/(\gamma-1) \]  
\[ \Delta V_{u,a} = \frac{U_a}{\lambda} \]  
\[ V_{u,2,a} = \frac{V_{u,2,a} \Delta V_{u,a}}{\Delta V_{u}} \]  
\[ V_{x,2,a} = \sqrt{V_{u,1,a}^2 + V_{x,2,a}^2} \]  
\[ V_{2,a} = \sqrt{V_{u,2,a}^2 + V_{x,2,a}^2} \]  
\[ T_{2,a} = T_{2,a} - \frac{V_{2,a}^2}{2g J c_p} \]  
\[ p_{2,a} = p_{2,a} \left( \frac{T_{2,a}}{T_{2,a}} \right)^\gamma/(\gamma-1) \]  
\[ \rho_{2,a} = \frac{p_{2,a}}{RT_{2,a}} \]
When a constant annulus is assumed for the first stage, the first-stage exit dimensions become the turbine inlet dimensions.

**Alternative Calculation Procedure**

The basic calculation procedure described in the previous section requires as inputs the inlet and exit mean diameters, stator exit angle, and shaft power. Alternatively, the hub or tip diameters could be specified as input and the mean diameters computed, the exit radius ratio could be specified as input and the stator exit angle computed, and the turbine pressure ratio could be specified as input and the shaft power computed. These alternative input options require iterative calculation procedures such as described in this section.

With hub or tip diameters rather than mean diameters specified at the inlet and exit, it is necessary to assume initial values for the inlet and exit radius ratios. Initial values for inlet and exit mean diameters are then obtained as
\[ D_m = \frac{(1 + \frac{r_h}{r_t})D_h}{2 \frac{r_h}{r_t}} \]  

when hub diameter is input and

\[ D_m = \frac{(1 + \frac{r_h}{r_t})D_t}{2} \]  

when tip diameter is input. The computation then proceeds from equation (1) through equation (42) and the computed exit radius ratio is compared with the assumed value. If they are not the same (within a given tolerance), then the computed value of exit radius ratio is used to calculate a new value for exit mean diameter (from eq. (75) or (76)) and the computation procedure is repeated until convergence is obtained. Then, computation proceeds through equation (72) and the computed inlet radius ratio is compared with the assumed value. If they are not the same, the computed value of inlet radius ratio is used to calculate a new value for inlet mean diameter, and the computation procedure is repeated from equation (1). This entire procedure is repeated until both inlet and exit radius ratios in the same calculation pass converge to previous values.

With exit radius ratio rather than stator exit angle specified, a value of stator exit angle is assumed for the evaluation of equation (16). The computation proceeds through equation (40). Equation (42) is then used to compute the exit annulus area from the input value of radius ratio, and the exit axial velocity is then obtained from equation (41). The density used in equation (41), however, is not consistent with the exit area, and equations (41), (33), (37), and (40) must be iterated until convergence is obtained. Then, the stator exit angle is computed as

\[ \alpha_1 = \tan^{-1} \frac{V_{u,1,n}}{V_{x,n}} \]  

and compared with the assumed value. If they are not the same, the computed value of stator exit angle is used for the evaluation of equation (16), and the computation procedure just given is repeated until two consecutive values of stator exit angle are the same. The remainder of the computation is then completed.
With the turbine inlet-total- to exit-static-pressure ratio rather than shaft power specified as input, an initial value of turbine static efficiency is assumed. Turbine work is then computed from

\[
\Delta h' = \eta_c \frac{T_i}{P_{in}} \left[ 1 - \left( \frac{p_{ex}}{p_{in}} \right)^{(\gamma - 1) / \gamma} \right]
\]

(78)

instead of from equation (4). The computation then proceeds through equation (26) in order to compute a static efficiency from equation (16). If the computed value is not the same as the assumed value, a new value of static efficiency is assumed, and the computation is repeated until two successive values are the same. The remainder of the computation is then completed.

DESCRIPTION OF INPUT AND OUTPUT

This section presents a detailed description of the program input, normal output, and error messages. Included in the input and output sections are several example cases illustrating the use of the program and the various options.

Input

The program input, a sample of which is presented in table I, consists of a title card and the required physical data and option indicators in NAMELIST form. The title, which is printed as a heading on the output listing, can contain up to 77 characters located anywhere in columns 2 to 78 on the title card. A title card, even if it is left blank, must be the first card of the data package. Additional title cards can be used to identify different cases being run in the same data package. This is done by placing a title card in front of the data record for the particular case and using the option indicator ITIT as subsequently described.

The physical data and option indicators are input in data records having the NAMELIST name INPUT. The variables and indicators that compose INPUT and the proper units are as follows. These must be inputed for all cases except where otherwise indicated. Either the SI units or the U.S. customary units shown after them may be used.
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>PTIN</td>
<td>inlet total pressure, (N/cm^2); lb/in.(^2)</td>
</tr>
<tr>
<td>TTIN</td>
<td>inlet total temperature, (K); (^0)R</td>
</tr>
<tr>
<td>MU</td>
<td>gas viscosity, ((N)(sec)/m^2); lb/(sec)(ft)</td>
</tr>
<tr>
<td>R</td>
<td>gas constant, ((Joule)/(kg)(K)); ft-lbf/(lbm)((^0)R)</td>
</tr>
<tr>
<td>GAM</td>
<td>heat capacity ratio</td>
</tr>
<tr>
<td>DIN</td>
<td>inlet diameter - hub or mean or tip value as specified by the indicator IDIAM, cm; in.</td>
</tr>
<tr>
<td>DEX</td>
<td>exit diameter - hub or mean or tip value as specified by the indicator IDIAM, cm; in.</td>
</tr>
<tr>
<td>RREX</td>
<td>exit radius ratio; RREX may be omitted in the case where both IDIAM = 2 and IALPH = 0; RREX is used as first trial value when IALPH = 0 and IDIAM = 1 or 3</td>
</tr>
<tr>
<td>RPM</td>
<td>rotative speed, rad/sec; rpm</td>
</tr>
<tr>
<td>POW</td>
<td>shaft power - omit when IPR = 1, kW; hp</td>
</tr>
<tr>
<td>W</td>
<td>mass flow rate, kg/sec; lb/sec</td>
</tr>
<tr>
<td>ALPHA</td>
<td>stator exit angle from axial direction; ALPHA is used as first trial value when IALPH = 1, deg</td>
</tr>
<tr>
<td>KLOSS</td>
<td>turbine loss coefficient; a value in the range of 0.35 to 0.40 is usually applicable</td>
</tr>
<tr>
<td>NMIN</td>
<td>minimum number of stages for which the calculations are performed</td>
</tr>
<tr>
<td>NMAX</td>
<td>maximum number of stages for which the calculations are performed; results are obtained for all stage numbers between NMIN and NMAX</td>
</tr>
<tr>
<td>E</td>
<td>squared ratio of stage-exit to stage-average axial velocities</td>
</tr>
<tr>
<td>PRTS</td>
<td>turbine inlet-total- to exit-static-pressure ratio; omit when IPR = 0</td>
</tr>
<tr>
<td>IALPH</td>
<td>indicates whether stator exit angle or turbine exit radius ratio is specified: IALPH = 0 - turbine is designed for specified ALPHA IALPH = 1 - turbine is designed for specified RREX</td>
</tr>
<tr>
<td>IDIAM</td>
<td>indicates whether inputed diameters are hub, mean, or tip values: IDIAM = 1 - inputed diameters are hub values IDIAM = 2 - inputed diameters are mean values IDIAM = 3 - inputed diameters are tip values</td>
</tr>
</tbody>
</table>
indicates type of velocity diagram used:

IVD = 1 - symmetrical diagrams
IVD = 2 - zero exit swirl diagrams
IVD = 3 - impulse diagrams
IVD = 4 - zero exit swirl diagrams if \( \lambda \geq 0.5 \) and impulse diagrams if \( \lambda \leq 0.5 \)

indicates use of title cards in addition to that required as first card of data package:

ITIT = 1 - title card precedes next data set; must be inputed for each additional title card because ITIT is automatically restored to zero after each title card is read

indicates use of exit vanes:

IEV = 0 - no exit vanes
IEV = 1 - exit vanes are used to turn turbine exit flow to axial direction

indicates whether shaft power or pressure ratio is specified:

IPR = 0 - shaft power is inputed
IPR = 1 - turbine inlet-total- to exit-static-pressure ratio is inputed

indicates type of units used for input and output:

IU = 1 - SI units
IU = 2 - U.S. customary units

Each line of the input form shown in table I represents one data card. The first card is the mandatory title card, which can contain any desired message. The next three cards are the first data set, which contains all required inputs. This first case represents computation in accordance with the basic calculation procedure described previously. Data inputed for subsequent cases need only include those values that differ from previous case data. The fifth card is the second data set and represents the option where hub diameter is input. Also, the second case data specify that a title card, which is the sixth data card, precedes the third case data. Cards 7 to 10 represent four additional cases illustrating use of different input options. The output corresponding to this sample input is described in the following section.

Output

The program output consists of title headings, the input variables, and computed results. This section presents normal output. Error message output is described in the next section.
Table II presents the output that corresponds to the sample input shown in Table I. The top line of output is a program identification title that is automatically printed. The second line is the title card message. The next four lines are the input variables and their associated values for the first data set. The input variable names are spelled out. The units for the input variable values are as described in the Input section. The zeros printed under EXIT RADIUS RATIO and T-S PRESSURE RATIO indicate that these are computed for this case and not specified by the input. The fact that the input diameters are mean diameters is indicated by the MN in the variable name. Hub and tip diameters would be indicated by HB and TP, respectively. These four lines of output are printed for each new data set.

The next two groups of eight lines each are the computation results for a one-stage turbine and a two-stage turbine, each satisfying the input requirements. Only one- and two-stage designs were specified by the input. The output parameters are spelled out and are self-explanatory. On the first line of each group are the number of stages, the stage speed-work parameter, and the diagram type, which is symmetrical for this first case. The remainder of the output includes exit and inlet tip and hub diameters in the first column, exit total and static temperatures and pressures in the second column, total and static efficiencies and velocity diagram angles in the third column, and first- and last-stage blade speeds and last-stage absolute velocity components in the last column. The last line of each output group presents the last-stage absolute and relative critical velocity ratios.

After the computations for each input case are completed, the input data for the next case are printed. The second case presented here is that where the specified diameters are hub values. The third input case in Table I is preceded by an additional title card. This causes the next output to begin at the top of a new page with the program identification title and the title card message. The third to sixth cases are computed for two stages only.

The third case is for a specified exit radius ratio rather than for a specified stator exit angle. This is indicated by a zero appearing under STATOR EX ANG in the row of input variables. Exit vanes are included in this case, as indicated by WITH EXIT VANES printed after number of stages on the first line of result output. The fourth and fifth cases, as indicated by the top line of the fourth column of result output, are for zero exit swirl and impulse diagrams, respectively. Turbine pressure ratio rather than shaft power is specified in the sixth case. For this case, the inputed pressure ratio was chosen to be the same as the computed value obtained for the two-stage design of the second case. It is seen that, as should be expected, the program converges to identical solutions for both cases. An extra line of output consisting of shaft power and specific work is printed for the case where pressure ratio is specified as input.
Error Messages

The program contains five output messages indicating the nonexistence of a solution satisfying the specified input requirements. These messages are presented in this section, and their causes are discussed.

(1) INSUFFICIENT ENERGY - This message is caused by the computed turbine exit total temperature being less than zero. It indicates that the turbine specific work requirement is greater than the energy available in the gas. Therefore, either the specified shaft power must be decreased or the specified flow must be increased.

(2) INSUFFICIENT IDEAL ENERGY - This message is caused by the computed ideal energy being more than that available from an infinite expansion of the gas. It indicates that the computed static efficiency is too low to yield a valid solution. Corrective action includes decreasing power, increasing flow, using more stages, or perhaps using a different velocity diagram.

(3) NEGATIVE TEX - This message is caused by the computed turbine exit static temperature being less than zero. It indicates a low value of turbine exit total temperature and/or a high value of turbine exit velocity. Corrective action could be the same as for message (2) or decreasing a too high value of stage exit to average axial kinetic energy ratio.

(4) INSUFFICIENT EXIT AREA - This message is caused by the computed exit area being larger than that available in the turbine. Such a situation can be remedied in many ways, including increasing exit diameter, decreasing stator exit angle, increasing inlet pressure, decreasing mass flow, and increasing stage exit to average axial kinetic energy ratio.

(5) INSUFFICIENT INLET AREA - This message is caused by the computed inlet area being larger than that available in the turbine. Corrective measures are the same as for message (4).

PROGRAM DESCRIPTION

The computer program is called TURBAN. All computations are performed in one main program written in IBM 7090/7094 FORTRAN IV language. The program variables are defined in this section and the program listing is presented.

Program Variables

\[
\begin{align*}
A & \quad \text{factor in eq. (16), } KRe^{-0.2/\cot \alpha_1} \\
AA & \quad \text{factor in eq. (42), } A_{an,ex}/zD_{m,ex}^2
\end{align*}
\]
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA1</td>
<td>factor in eq. (72), $A_{an,2,a}/\pi D_m^2$, in</td>
</tr>
<tr>
<td>AEX</td>
<td>turbine exit annulus area</td>
</tr>
<tr>
<td>AI</td>
<td>stage loss parameter for intermediate stage and last stage having no exit vanes</td>
</tr>
<tr>
<td>AIL</td>
<td>stage loss parameter for last stage having exit vanes</td>
</tr>
<tr>
<td>ALP</td>
<td>stator exit angle value printed in input section of output</td>
</tr>
<tr>
<td>ALPHA</td>
<td>previous value of stator exit angle</td>
</tr>
<tr>
<td>ALPHA1</td>
<td>input value of stator exit angle</td>
</tr>
<tr>
<td>ALPHA2</td>
<td>output value of stator exit angle</td>
</tr>
<tr>
<td>ALPH1</td>
<td>output value of stage exit angle</td>
</tr>
<tr>
<td>ALPH2</td>
<td>stage exit angle</td>
</tr>
<tr>
<td>ASEX</td>
<td>speed of sound at turbine exit</td>
</tr>
<tr>
<td>A1</td>
<td>stage loss parameter for first stage or single stage having no exit vanes</td>
</tr>
<tr>
<td>A1L</td>
<td>stage loss parameter for single stage having exit vanes</td>
</tr>
<tr>
<td>A21</td>
<td>first-stage-exit annulus area</td>
</tr>
<tr>
<td>B</td>
<td>turbine exit loss parameter with no exit vanes</td>
</tr>
<tr>
<td>BETA1</td>
<td>output value of rotor inlet angle</td>
</tr>
<tr>
<td>BETA2</td>
<td>output value of rotor exit angle</td>
</tr>
<tr>
<td>BET1</td>
<td>rotor inlet angle</td>
</tr>
<tr>
<td>BET2</td>
<td>rotor exit angle</td>
</tr>
<tr>
<td>BL</td>
<td>turbine exit loss parameter with exit vanes</td>
</tr>
<tr>
<td>CCN</td>
<td>dimensional constant</td>
</tr>
<tr>
<td>CCP</td>
<td>dimensional constant</td>
</tr>
<tr>
<td>CI</td>
<td>blade row loss parameter for intermediate stage stator</td>
</tr>
<tr>
<td>CL</td>
<td>blade row loss parameter for exit vanes</td>
</tr>
<tr>
<td>CONV</td>
<td>tolerance for radius ratio convergence</td>
</tr>
<tr>
<td>COT</td>
<td>cotangent of stator exit angle</td>
</tr>
<tr>
<td>CP</td>
<td>heat capacity</td>
</tr>
<tr>
<td>C1</td>
<td>blade row loss parameter for first-stage stator</td>
</tr>
</tbody>
</table>
D  blade loss parameter for rotor
DELHT  turbine specific work
DELHI  first-stage specific work
DEX  input value of turbine exit diameter
DH  data statement word HB for output use
DHEX  turbine exit hub diameter
DHID  turbine ideal work based on inlet-total- to exit-static-pressure ratio
DHTID  turbine ideal work based on inlet-total- to exit-total-pressure ratio
DH1  first-stage-exit hub diameter
DIN  input value of first-stage-exit diameter
DM  data statement word MN for output use
DMEX  turbine exit mean diameter
DMIN  first-stage-exit mean diameter
DN  turbine exit mean diameter
DT  data statement word TP for output use
DTEX  turbine exit tip diameter
DT1  first-stage-exit tip diameter
DVUN  change in swirl velocity across last-stage rotor
DVU1  change in swirl velocity across first-stage rotor
DX  output word set equal to DH, DM, or DT as appropriate
D1  first-stage-exit mean diameter
E  ratio of stage-exit to stage-average axial kinetic energies
ES  turbine static efficiency
ESA  previous value of turbine static efficiency
ESI  static efficiency of last stage with no exit vanes
ESIL  static efficiency of last stage with exit vanes
ES1  static efficiency of single stage with no exit vanes
ES1L  static efficiency of single stage with exit vanes
ET  turbine total efficiency
ETI  total efficiency of intermediate stage or last stage with no exit vanes
ETIL  total efficiency of last stage with exit vanes
ETI1  total efficiency of first stage or single stage with no exit vanes
ETI1L total efficiency of single stage with exit vanes
FLS   stator weighting factor
FLSL  exit vane weighting factor
G     dimensional constant
GAM   heat capacity ratio
IALPH option indicator - see Input section
IDIAM option indicator - see Input section
IEV   option indicator - see Input section
IPR   option indicator - see Input section
ITIT  option indicator - see Input section
IU    option indicator - see Input section
IVD   option indicator - see Input section
J     dimensional constant
KLOSS turbine loss coefficient
LAM   stage speed-work parameter
MU    gas viscosity
MXEX  turbine exit axial Mach number
N     number of stages
NMAX  maximum number of stages
NMIN  minimum number of stages
NN    number of stages
PEX   turbine exit static pressure
PI    π
POW   shaft power
PRS   computed value of inlet-total- to exit-static-pressure ratio
PRT   computed value of inlet-total- to exit-total-pressure ratio
PRTS  input value of inlet-total- to exit-static-pressure ratio
PTEX  turbine exit total pressure

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PTIN  turbine inlet total pressure
PT21  first-stage-exit total pressure
P21   first-stage-exit static pressure
Q     ratio of rotor inlet swirl velocity to change in swirl velocity
Q2    ratio of rotor exit swirl velocity to change in swirl velocity
R     gas constant
RE    Reynolds number
REX   computed value of turbine exit radius ratio
REX1  previous value of turbine exit radius ratio
RHOEX turbine exit gas density
RHOEX1 previous value of turbine exit gas density
RHO21 first-stage-exit gas density
RPM   rotative speed
RREX  input value of turbine exit radius ratio
R1    first-stage-exit radius ratio
R11   previous value of first-stage-exit radius ratio
ST    output word set equal to ST1 or ST2 as appropriate
ST1   blank data statement words for output use
ST2   data statement words WITH EXIT VANES for output use
SUMUSQ sum of squares of stage blade speeds
TEX   turbine exit static temperature
TITLE input/output array for title card message
TTEX  turbine exit total temperature
TTIN  turbine inlet total temperature
TTRN  last-stage-rotor inlet and exit relative total temperature
TT1N  last-stage-stator exit absolute total temperature
TT21  first-stage-exit absolute total temperature
T21   first-stage-exit static temperature
U     rotor mean blade speed
UISQ  rotor mean blade speed squared
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>VCR1N</td>
<td>last-stage-stator-exit absolute critical velocity</td>
</tr>
<tr>
<td>VCR2N</td>
<td>last-stage-exit absolute critical velocity</td>
</tr>
<tr>
<td>VD1</td>
<td>data statement word SYMMET for output use</td>
</tr>
<tr>
<td>VD2</td>
<td>data statement word RICAL for output use</td>
</tr>
<tr>
<td>VD3</td>
<td>data statement word (blank) for output use</td>
</tr>
<tr>
<td>VD4</td>
<td>data statement word ZERO E for output use</td>
</tr>
<tr>
<td>VD5</td>
<td>data statement word XIT SW for output use</td>
</tr>
<tr>
<td>VD6</td>
<td>data statement word HIRL for output use</td>
</tr>
<tr>
<td>VD7</td>
<td>data statement word IMPULS for output use</td>
</tr>
<tr>
<td>VD8</td>
<td>data statement word E for output use</td>
</tr>
<tr>
<td>VU1N</td>
<td>last-stage-rotor inlet swirl velocity</td>
</tr>
<tr>
<td>VU11</td>
<td>first-stage-rotor inlet swirl velocity</td>
</tr>
<tr>
<td>VU2N</td>
<td>last-stage-rotor exit swirl velocity</td>
</tr>
<tr>
<td>VU21</td>
<td>first-stage-exit swirl velocity</td>
</tr>
<tr>
<td>VXN</td>
<td>turbine exit axial velocity</td>
</tr>
<tr>
<td>VXND</td>
<td>last-stage average axial velocity</td>
</tr>
<tr>
<td>VX1</td>
<td>first-stage exit axial velocity</td>
</tr>
<tr>
<td>VX11</td>
<td>output word set equal to VD1, VD4, or VD7 as appropriate</td>
</tr>
<tr>
<td>VX2</td>
<td>output word set equal to VD2, VD5, or VD8 as appropriate</td>
</tr>
<tr>
<td>VX3</td>
<td>output word set equal to VD3 or VD6 as appropriate</td>
</tr>
<tr>
<td>V1N</td>
<td>last-stage-stator-exit absolute velocity</td>
</tr>
<tr>
<td>V1OVCR</td>
<td>last-stage-stator-exit critical velocity ratio</td>
</tr>
<tr>
<td>V2N</td>
<td>turbine exit absolute velocity</td>
</tr>
<tr>
<td>V2NR</td>
<td>last-stage-rotor-exit absolute velocity</td>
</tr>
<tr>
<td>V2OVCR</td>
<td>last-stage-rotor-exit absolute critical velocity ratio</td>
</tr>
<tr>
<td>V21</td>
<td>first-stage-exit absolute velocity</td>
</tr>
<tr>
<td>W</td>
<td>mass flow rate</td>
</tr>
<tr>
<td>WC</td>
<td>factor in eqs. (56) to (59), $[2\gamma g R/(\gamma + 1)]^{1/2}$</td>
</tr>
<tr>
<td>WCRN</td>
<td>last-stage-rotor-inlet and exit relative critical velocity</td>
</tr>
<tr>
<td>WU1N</td>
<td>tangential component of last-stage-rotor-inlet relative velocity</td>
</tr>
</tbody>
</table>

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tangential component of last-stage-rotor-exit relative velocity

last-stage-rotor-inlet relative velocity

1st-stage-rotor-inlet relative critical velocity ratio

last-stage-rotor-exit relative velocity

last-stage-rotor-exit relative critical velocity ratio

function of $\gamma, \gamma/(\gamma - 1)$

exit radius ratio value printed in input section of output

factor in eq. (35), $\Delta h'/c_p T_1' n^{\eta}$

Program Listing

$1BFTC$ TURBAN DECK

THIS PROGRAM PERFORMS TURBINE GEOMETRY AND EFFICIENCY CALCULATION ON A MEAN SECTION BASIS ASSUMING SAME SHAPE DIAGRAMS FOR EACH STAGE (EXCEPT FIRST, WHICH HAS AXIAL INLET FLOW) AND IF

IVO=1 - SYMMETRICAL DIAGRAMS
IVO=2 - ZERO EXIT SWIRL DIAGRAMS
IVO=3 - IMPULSE DIAGRAMS
IVO=4 - ZTS FOR LAM $\leq 0.5$ AND IMP FOR LAM $> 0.5$

Ialph=0 - EXIT DIAMETER RATIO IS COMPUTED FOR INPUT VALUE OF ALPHA
- INPUT RREX IS FIRST TRIAL VALUE IF IDIAM=1 OR 3
Ialph=1 - ALPHA IS COMPUTED FOR INPUT VALUE OF EXIT DIAMETER RATIO
- INPUT ALPHA IS FIRST TRIAL VALUE

DIAMETERS ARE INPUT AT INLET AND EXIT, AND BLADE SPEED VARIES LIN.
IDIAM=1 - INPUT DIAMETERS ARE HUB VALUES
IDIAM=2 - INPUT DIAMETERS ARE MEAN VALUES
IDIAM=3 - INPUT DIAMETERS ARE TIP VALUES

IEV=0 - NO EXIT VANES
IEV=1 - EXIT VANES TO TURN FLOW TO AXIAL DIRECTION

IPR=0 - POWER IS INPUT AND PRESSURE RATIO IS COMPUTED
IPR=1 - PRESSURE RATIO (T/S) IS INPUT AND POWER IS COMPUTED

ITIT=1 - TITLE CARD PRECEDES NEXT DATA SET
IU=1 - SI UNITS ARE USED FOR INPUT AND OUTPUT
IU=2 - U.S. CUSTOMARY UNITS ARE USED FOR INPUT AND OUTPUT

REAL LAM,NN,J,MXEX,KLOSS,MU
DIMENSION U(99),TITLE(13),ST1(3),ST2(3),ST(3)
NAMELIST/INPUT/PTIN,TITIN,MUr,GAM,DIN,DEX,RREX,RPM,POwW,ALPHA,
Ikluss,IALPH,NMIN,NMAX,DIAM,E,IVO,ITIT,IEV,IPR,PKTS,IU
DATA DH,DIM,DT/2HHB,2HMN,2HTP/
DATA VDI,VD2,VD3,VD4,VD5,VD6,VD7,VSYM,SHRICAL,1H,6HZERO E
1,6HEXIT SW,6HIMPULS,1HE/
DATA ST1,ST2/1H,1H,1H,6H WITH 6HEXIT V,6HANES /
PI= 3.1416
98 WRITE(6,100)
100 FORMAT(1H1,49X,33HTURBINE VELOCITY DIAGRAM ANALYSIS)
READ(5,99) TITLE
99 FORMAT(13A6)
WRITE (6,1(U1,14I4)) TITLE
101 FORMAT(1H1,49X,33HTURBINE VELOCITY DIAGRAM ANALYSIS)
READ(5,INPUT)
GO TO (95,96),IU
95 J=1,
G=1.,
CCN=2.*PI
CCP=1300.
GO TO 97
96 J=778,
G=3.,17
CCN=63.
CCP=550.
97 R=0.
ES=.8
ALP=ALPHA
REX=REX
XREX=XREX
IF(ALPH.EQ.1) ALP=0.0
IF(ALPH.EQ.0) XREX=0.0
IF(IRP.EQ.0) PRTS=0.0
IF(IRP.EQ.1) POW=0.0
DO 4 I=1,3
ST(I)=ST(I-1)
4 ST(I)=ST(I)
IF(IEV.EQ.I) ST(I)=ST(I-1)
GO TO (13,19,17),DIAM
13 DX=0.
DMEX=(1.*REX/2.*DEX/REX
DMIN=(1.*R)/2.*DIN/R
GO TO 19
15 DX=0.
DMEX=DEX
DMIN=DIN
GO TO 19
17 DX=0.
DMEX=(1.*REX/2.*DEX
DMIN=(1.*R)/2.*DIN
19 WRITE(6,109)
109 FORMAT(1H1)
WRITE(6,110)DX,DX,POW,W,TTIN,PTIN,RP,M,DIN,DEX,REX,ALP,R,GAM,MU,
1 KLOSS,E,PRTS
110 FORMAT(126H SHAFT MASS INLET INLET ROTATIVE INLET
1 EXIT EXIT STATOR GAS HEAT GAS TURBINE AXIAL
1 T=5/
2 POWER FLOW TEMP PRESS SPEED *A2,6H DIA *A2,
2 69H DIA RADIUS
35 KX ANG CONST CAPAC VISCOSITY LOSS VcL SQ PRESS/
465X,5HRATIO,19X,5HRATIO,4X,19HOEFT RATIO RATIO/
5 101,13F9,2,F10,2,F7,2,F8,2,F9,4,F8,2,F8,3,
6 E11,3,F7,3,F8,3)
ALPH=ALPHA*017453
X=GAM/(GAM-1.)
CP= X/R
IF(IRP.EQ.1) DHID=CP*TTIN*(1.-(-1./PRTS)**(1./X))
IF(IRP.EQ.1) PEX=PTIN/PRTS
IF(IPR.EQ.1) GO TO 53
DELH=T*CP*PG/W/J
TEX=TT/TIN-DELH/CP
IF(TEX.LT.0) GO TO 20
53 N=MIN
CD=V*.01
37 IF(IU.EQ.1) DN=UMEX/100.
   IF(IU.EQ.2) DN=UMEX/12.
   IF(IU.EQ.1) U1=DMIN/100.
   IF(IU.EQ.2) U1=DMIN/12.
11 U(I)=PI*RP*M*01/CCN
   U(I)=PI*RP*M*DN/CCN
   NN=FLOAT(N)
   IF(.,EQ.1) SUMUSQ=U(N)*U(N)
   IF(.,EQ.1) GO TO 3
   SUMUSQ=0.
   DO : I=1, N
   U(I) = (U(N)-U(I))/(NN-1.)*(FLOAT(I)-1.) + U(I)
   UISO=J(I)**2
2 SUMUSQ=SUMUSQ+UISQ
   IF(IPR.EQ.0) GO TO 55
54 DELH=ES*DI/NO
   TEX=TT/TIN-DELH/CP
   ESA=ES
55 LAM=SUMUSQ/G/J/DELH
   GO TO (61, 62, 63, 64), JD
61 Q=(LAM+1.1)/Q*
   Q2=(LAM-1.1)/Q*
   FLS=2.*LAM
   VX1=VD1
   VX2=VD2
   VX3=VD3
   GO TO 65
62 Q=1.0
   Q2=.0
   FLS=1.0
   VX1=VD4
   VX2=VD5
   VX3=VD6
   GO TO 65
63 Q=LAM+.5
   Q2=LAM+.5
   FLS=1.0
   IF(LAM.LT.5) FLS=2.*(1.-LAM)
   VX1=VD7
   VX2=VD8
   VX3=VD3
   GO TO 65
64 IF(LAM.GE.5) GO TO 62
   GO TO 53
65 DVU=J(N)/LAM
   VU1=Q*DVUN
   VU2=Q2*DVUN
4 CUT= COTAN(ALPHI)
   C1=(1.+2.*CUT**2)*Q*Q
   C2= C1/(Q-1.1)**2
   Q2=2.*CUT**2*Q*(Q-(Q-LAM)**2+(Q-LAM-1.1)**2
   RE= W/MU/DFI*2.
   IF(N.EQ.1) RE=W/MU/DN**2.
A=KLOSS/COT/RE**2
A1=A*(C1+2.*D)
A11=A*(FLS*CI+2.*D)
B=E*COT**2*Q*Q+Q2**2
ET1=LAM/(LAM+A1/2.)
ET11=LAM/(LAM+A11/2.)
ET111=LAM/(LAM+(A1+B)/2.)
IF (IEV.EQ.1) GO TO 34
IF(V-1) 5,5,6
5 ES= ES1
GO TO 7
6 ES=:./(U(1)*U(1)/ET1/SUMUSQ+(1.-U(1)*U(1)+U(N)*U(N))/SUMUSQ)/ETI
1+U(N)*U(N)/ESI/SUMUSQ)
GO TO 7
34 CL=2.*COT**2*Q*Q+Q2**2
FLSL=1.*
AIL=A1+A*CL*FLSL
AIL1=A1+A*CL*FLSL
BL=E*COT**2*Q*Q
ETIL=LAM/(LAM+AIL/2.)
ESIL=LAM/(LAM+(AIL+BL)/2.)
ETIL1=LAM/(LAM+(AIL+BL)/2.)
IF(V-1) 35,35,36
35 ES=ESIL
GO TO 7
36 ES=:./(U(1)*U(1)/ET1/SUMUSQ+(1.-U(1)*U(1)+U(N)*U(N))/SUMUSQ)/ETI
1+U(N)*U(N)/ESI/SUMUSQ)
7 IF(IPR) 56,56,57
56 ZZ=DELMT/CP/TTIN/ES
IF(Z,GE.1.0) GO TO 21
PEX=PTIN*(1.-ZZ)**X
GO TO 58
57 IF(ABS(ES-ESA).LT..OOOl) GO TO 5a
ES=(ES+ESA)/2.
GO TO 54
58 VXNO=Q*COT*DVUN
VXN=VXNO*SORT(E)
V2N= SORT(VU2N**2+VXN**2)
V2N=V2N
IF(IEV.EQ.1) V2N=VXN
TEX= TTEX-V2N**2/G/CP
IF(TEX.LE.30.0) GO TO 22
IF(IU.EQ.1) RHOEX=PEX/R*100./TEX
IF(IU.EQ.2) RHOEX=PEX/R*44./TEX
IF(IALPH.EQ.1) GO TO 8
AEX=1/RHOEX/VXN
AAA= AEX/PI/UN**2
IF(AA,GE.1.0) GO TO 23
REX=AA
REX= (1.-AA)/(1.+AA)
IF(IDIAM.EQ.2) GO TO 9
IF(V.EQ.1) CONV=.0001
IF(ABS(REX-REX1).LT.Conv) GO TO 9
IF(IDIAM.EQ.3) GO TO 33
DME=(1.+REX)/2.*DEX/REX
GO TO 37
35 DMEX = (1. + RX) / 2. * DEX
GO TO 37
8 AEX = PI*DN**2*(1. - REX)/(1. + REX)
31 VXN = #/AEX/RHOEX
V2N = SQRT(VU2N**2 + VXN**2)
V2N = V2N
IF(I EV, EQ, 1) V2N = VXN
TEX = TTEX - V2N**2 / 2. / G / J / CP
RHO X = 1. = RHOEX
IF(I UI, EQ, 1) RHOEX = PEX / **0000. / T EX
IF(I UI, EQ, 2) RHOEX = PEX / **44. / T EX
IF(^ABS(RHOEX - RH OEX1), GT., 001 * RHOEX) GO TO 31
ALPH = ALPH1
VXN = VXN / SQRT(E)
ALPH = ATAN2(VU1N, VXND)
IF(^ABS(ALPH - ALPH), GT., 02) GO TO 3
9 ALPH = ATAN2(VU2N, VXND)
PTEX = PEX * (TTEX / T EX)** X
DHTID = CP * TTIN * (1. - (PTEX / PTIN)** (1./X))
ET = DELHT / DHTID
POD = DELHT * w / CCP * J
WU1 = VU1N - U(N)
WU2 = VU2N - U(N)
BET = ATAN2(WU1N, VXND)
BET = ATAN2(WU2N, VXND)
W2N = SQRT(WU2N**2 + VXN**2)
W1N = SQRT(WU1N**2 + VXN**2)
V1N = SQRT(VU1N**2 + VXN**2)
TT1 = TTEX - (V2N**2 - W2N**2) / 2. / G / J / CP
TT2 = TTIN - DELH1 / CP
PT2 = PTIN * (1. - DELH1 / CP / TTIN / ET)** X
DVU = U(N) / LAM
VX1 = Q * COT * DVU * SQRT(E)
VU2 = Q2 * DVU
VU1 = Q * DVU
V21 = SQRT(VU21**2 + VX1**2)
T21 = TT21 - V21**2 / 2. / G / J / CP
P21 = PT21 * (T21 / TT21)** X
IF(I UI, EQ, 1) RHO21 = P21 / R*10000. / T21
IF(I UI, EQ, 2) RHO21 = P21 / R*144. / T21
A21 = W / RHO21 / VX1
AA1 = A21 / PI / U1 / D1
IF(^AA1, GE, 1.0) GO TO 24
R11 = R1
RI = (1.0 - AA1) / (1.0 + AA1)
IF(IDIAM .EQ. 2) GO TO 49
IF(ABS(RI - R1) .LT. CONV) GO TO 41
44 IF(IDIAM .EQ. 2) GO TO 49
45 DMI = (1.0 + R1) / 2.0 * DDM/R1
DMEX = (1.0 + REX) / 2.0 * DEX/REX
GO TO 37
47 DMI = (1.0 + R1) / 2.0 * DDM
DMEX = (1.0 + REX) / 2.0 * DEX
GO TO 37
41 IF(CONV .EQ. 0.001) GO TO 42, 43
42 GO TO 49
43 CONV = 0.0001
GO TO 44
49 DTI = DMIN * 2.0 / (1.0 + R1)
DHI = RI * DTI
GO TO 52
51 RI = REX
DTI = REX
DHI = DME
52 ALPHAI = ALPHI / 0.17453
ALPHA2 = ALPHA2 / 0.17453
BETAI = BETI / 0.17453
BETAI2 = BET2 / 0.17453
PRT = PTIN / PTEX
PRS = PTIN / PEX
WRITE(6,120) N, ST, LAM, VX1, VX2, VX3, DTEX, TTEX, ALPHAI, U(1), DHEX,TEX,
1 ALPHA2, U(N), REX, PTEX, BETAI, VUIN, DTI, PTEX, BETAI2, VU2N, DHI, PRT, ET, VXN,
2RI, PRS, ES, MEX
120 FORMAT(80STAGES,=,12,3A6,2X,27STAGE SPEED WORK PARAMETER =,F5.3,
126X,13DIAGRAMS ARE =,3A6
1 /20H EXIT TIP DIAMETER = ,F6.2,4X,18HEXIT TOTAL
1 TEMP =,F7.2,5X,18HEXIT RADIUS EXIT ANGLE =,F6.2,4X,23HFIRST STAGE MEAN
2 SPED =,F8.2,20H EXIT HUB DIAMETER =,F6.2,4X,18HEXIT STATIC TEMP =
3,F7.2,5X,18HSTAGE EXIT ANGLE =,F6.2,4X,23HLAST STAGE MEAN SPEED =
4,F8.2/20H EXIT RADIUS RATIO =,F6.4,4X,18HEXIT TOTAL PRESS =,F7.5X
5,18HEXIT TOTAL INLET ANGLE =,F6.2,4X,23HLAST STAGE INLET SWIRL = ,F8.2/20H
6 INLET TIP DIAMETER =,F6.2,4X,18HEXIT STATIC PRESS =,F7.2,5X,18HROT
7 R EXIT ANGLE =,F6.2,4X,23HLAST STAGE EXIT SWIRL =,F8.2/20H INLT H
8SUB DIAMETER =,F6.2,4X,18HT T PRESS RATIO =,F7.3,5X,18HEXIT EFFICI
9ENCY =,F5.3,5X,23HLAST STAGE AXIAL VELOC =,F8.2/20H INLET RADIUS RA
1TOT =,F6.4,4X,18HT S PRESS RATIO =,F7.3,5X,18HEXIT EFFICIENCY =
2F5.3,5X,23HEXIT AXIAL MACH NUMBER = ,F7.4
IF(IP = EQ. 0.1 AND IT = .EQ. 0.1) DELHT = DELHT/1000.
IF(IP = EQ. 0.1) WRITE(6,121) POW, DELHT
121 FORMAT(17H SHAFT POWER =,F9.1,4X,18HSPECIFIC WORK = ,F7.2)
WRITE(6,122) V10VCR, W10VCR, W20MCR, V20VCR
122 FORMAT(20H LAST STG (VCR1) =,F6.4,4X,18HLAST STG (W1/VCRC) = ,F7.4,
15X, .84LAST STG (W2/VCRC2) =,F6.4,4X,23HLAST STG (V2/VCRC2) =,F7.4)
12 N = N+1
CONV = .01
130 FORMAT(1HG,5X,19HINSUFFICIENT ENERGY)
GO TO 1
131 WRITE(6,140) N
32
Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, December 16, 1971,
764-74.

REFERENCE

**TABLE I. - INPUT FORM WITH SAMPLE DATA**

<table>
<thead>
<tr>
<th>FORTRAN STATEMENT</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>THESE ARE SAMPLE CASES FOR THIS PROGRAM. U.S. CUSTOMARY UNITS ARE USED.</td>
<td></td>
</tr>
<tr>
<td>$INPUT PTIN=113.1, TTIN=2660., MU=.376E-04, R=53.37, GAM=1.302, DIN=22., DEX=24., $</td>
<td></td>
</tr>
<tr>
<td>RPM=11400., FOW=12900., W=53.5, ALPHA=65., KLOSS=.35, NMIN=1, NMAX=2, E=1.2, $</td>
<td></td>
</tr>
<tr>
<td>IALPH=0, IDIAM=2, IV=1, IEV=0, IPR=0, IU=2 $</td>
<td></td>
</tr>
<tr>
<td>$INPUT IDIAM=1, RR=8, DIN=20., DEX=21., IT=1 $</td>
<td></td>
</tr>
<tr>
<td>THIS IS AN ADDITIONAL TITLE CALLED FOR BY IT IN PREVIOUS CASE DATA</td>
<td></td>
</tr>
<tr>
<td>$INPUT IALPH=1, IEV=1, NMIN=2 $</td>
<td></td>
</tr>
<tr>
<td>$INPUT IALPH=0, IEV=0, IV=2 $</td>
<td></td>
</tr>
<tr>
<td>$INPUT IV=3 $</td>
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</tr>
<tr>
<td>$INPUT IPR=1, IV=1, PRTS=3.66 $</td>
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### Table II. Output Form with Sample Data

Turbine Velocity Diagram Analysis

These are sample cases for this program. U.S. customary units are used.

<table>
<thead>
<tr>
<th>Shaft Mass Power Flow Temp</th>
<th>Inlet Pressure MN Dia</th>
<th>Inlet Speed MN Dia</th>
<th>Exit Pressure MN Dia</th>
<th>Exit Speed MN Dia</th>
<th>Exit Stator Angle</th>
<th>Gas Radius</th>
<th>Ex Angle Const</th>
<th>Heat Gas Turbine Axial T-S</th>
<th>Cap Corr Viscosity Loss Vel Sq Press Coef Ratio</th>
<th>Cap Corr Viscosity Loss Vel Sq Press Coef Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>12900.0</td>
<td>53.50</td>
<td>2660.00</td>
<td>111.10</td>
<td>11400.00</td>
<td>22.00</td>
<td>24.00</td>
<td>0.65</td>
<td>53.37</td>
<td>1.302</td>
<td>0.376</td>
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### Stages 1

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<tbody>
<tr>
<td>20.75</td>
<td>21.25</td>
<td>0.7942</td>
<td>20.75</td>
<td>21.25</td>
<td>0.7942</td>
<td>20.75</td>
<td>21.25</td>
<td>0.7942</td>
<td>20.75</td>
<td>21.25</td>
<td>0.7942</td>
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</table>

### Stages 2

<table>
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<tbody>
<tr>
<td>27.11</td>
<td>24.09</td>
<td>0.8268</td>
<td>27.11</td>
<td>24.09</td>
<td>0.8268</td>
<td>27.11</td>
<td>24.09</td>
<td>0.8268</td>
<td>27.11</td>
<td>24.09</td>
<td>0.8268</td>
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### Stages 3

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<tbody>
<tr>
<td>30.84</td>
<td>24.16</td>
<td>0.7602</td>
<td>30.84</td>
<td>24.16</td>
<td>0.7602</td>
<td>30.84</td>
<td>24.16</td>
<td>0.7602</td>
<td>30.84</td>
<td>24.16</td>
<td>0.7602</td>
</tr>
</tbody>
</table>

### Stage Speed Work Parameter

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<tr>
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<tbody>
<tr>
<td>0.334</td>
<td>0.615</td>
<td>0.8441</td>
<td>0.328</td>
<td>0.620</td>
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<td></td>
</tr>
</tbody>
</table>

### Heat Gas Turbine Axial T-S Coef Corr Viscosity Loss Vel Sq Press Coef Ratio

<table>
<thead>
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<tbody>
<tr>
<td>1193.81</td>
<td>1193.81</td>
<td>0.5928</td>
<td>1094.32</td>
<td>1094.32</td>
<td>0.4394</td>
<td>1189.81</td>
<td>1189.81</td>
<td>0.3755</td>
<td>1217.71</td>
<td>1217.71</td>
<td>0.4394</td>
</tr>
</tbody>
</table>

### Diagrams Are Symmetrical

First Stage Mean Speed: 1193.81
Last Stage Mean Speed: 1193.81
Last Stage Inlet Swirl: 2383.74
Last Stage Exit Swirl: -1194.83
Last Stage Axial Velo: 1217.71
Last Stage Exit Mach: 0.5928
Last Stage (V2/VCR2) = 0.8446

### Diagrams Are Symmetrical

First Stage Mean Speed: 1094.32
Last Stage Mean Speed: 1193.81
Last Stage Inlet Swirl: 1567.97
Last Stage Exit Swirl: -374.06
Last Stage Axial Velo: 800.93
Last Stage Exit Mach: 0.3755
Last Stage (V2/VCR2) = 0.4394

### Diagrams Are Symmetrical

First Stage Mean Speed: 1189.81
Last Stage Mean Speed: 1189.81
Last Stage Inlet Swirl: 2394.15
Last Stage Exit Swirl: -1217.65
Last Stage Axial Velo: 1223.03
Last Stage Exit Mach: 0.5960
Last Stage (V2/VCR2) = 0.8552

### Diagrams Are Symmetrical

First Stage Mean Speed: 1098.30
Last Stage Mean Speed: 1198.77
Last Stage Inlet Swirl: 1564.79
Last Stage Exit Swirl: -362.02
Last Stage Axial Velo: -362.02
Last Stage Exit Mach: 0.3756
Last Stage (V2/VCR2) = 0.4379
### TABLE II. - Concluded. OUTPUT FORM WITH SAMPLE DATA

**TURBINE VELOCITY DIAGRAM ANALYSIS**

<table>
<thead>
<tr>
<th>SHAFT POWER M =</th>
<th>INLET ROTATIVE</th>
<th>EXIT</th>
<th>SHP</th>
<th>NO</th>
<th>CAPAC VISCOSITY</th>
<th>LOSS VEL SQ PRESS</th>
<th>T-S</th>
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</thead>
<tbody>
<tr>
<td>PRESS</td>
<td>SPEED</td>
<td>MIA</td>
<td>MIA</td>
<td>RADIUS</td>
<td>EX ANG</td>
<td>CONST</td>
<td>RATIO</td>
</tr>
<tr>
<td>12900.0</td>
<td>53.50</td>
<td>2660.00</td>
<td>113.10</td>
<td>11400.00</td>
<td>20.00</td>
<td>21.00</td>
<td>0.8000</td>
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</tbody>
</table>

**STAGES = 2 WITH EXIT VANE**

- EXIT TIP DIAMETER = 26.25
- EXIT HUB DIAMETER = 21.00
- EXIT RADIUS RATIO = 0.7000
- INLET TIP DIAMETER = 23.50
- INLET HUB DIAMETER = 20.00
- INLET RADIUS RATIO = 0.8526
- LAST STG (V1/VCR1) = 1.0000

**STAGE SPEED-POWER PARAMETER = 0.598**

- EXIT TOTAL TEMP = 2083.64
- EXIT STATIC TEMP = 2015.65
- EXIT TOTAL PRESS = 33.60
- EXIT INLET PRESS = 30.40
- T-T PRESS RATIO = 3.280
- TOTAL EFFICIENCY = 0.889
- LAST STG (V1/VCR1) = 0.6482

**DIAGRAMS ARE SYMMETRICAL**

- FIRST STAGE MEAN SPEED = 1081.87
- LAST STAGE MEAN SPEED = 1175.15
- LAST STAGE INLET SWIRL = 1574.67
- LAST STAGE EXIT SWIRL = 1566.21
- LAST STAGE AXIAL VELOC = 988.85
- EXIT AXIAL MACH NUMBER = 0.4656
- LAST STG (V2/VCR2) = 0.5929

**STAGES = 2**

- EXIT TIP DIAMETER = 26.45
- EXIT HUB DIAMETER = 21.00
- EXIT RADIUS RATIO = 0.7000
- INLET TIP DIAMETER = 23.46
- INLET HUB DIAMETER = 20.00
- INLET RADIUS RATIO = 0.8526
- LAST STG (V1/VCR1) = 1.0000

**STAGE SPEED-POWER PARAMETER = 0.598**

- EXIT TOTAL TEMP = 2083.64
- EXIT STATIC TEMP = 2015.65
- EXIT TOTAL PRESS = 33.60
- EXIT INLET PRESS = 30.40
- T-T PRESS RATIO = 3.280
- TOTAL EFFICIENCY = 0.889
- LAST STG (V1/VCR1) = 0.6482

**DIAGRAMS ARE SYMMETRICAL**

- FIRST STAGE MEAN SPEED = 1081.87
- LAST STAGE MEAN SPEED = 1175.15
- LAST STAGE INLET SWIRL = 1574.67
- LAST STAGE EXIT SWIRL = 1566.21
- LAST STAGE AXIAL VELOC = 988.85
- EXIT AXIAL MACH NUMBER = 0.4656
- LAST STG (V2/VCR2) = 0.5929

**STAGES = 2**

- EXIT TIP DIAMETER = 26.05
- EXIT HUB DIAMETER = 21.00
- EXIT RADIUS RATIO = 0.7103
- INLET TIP DIAMETER = 23.25
- INLET HUB DIAMETER = 20.00
- INLET RADIUS RATIO = 0.8661
- LAST STG (V1/VCR1) = 1.1039

**STAGE SPEED-POWER PARAMETER = 0.598**

- EXIT TOTAL TEMP = 2083.96
- EXIT STATIC TEMP = 2019.29
- EXIT TOTAL PRESS = 33.17
- EXIT INLET PRESS = 30.40
- T-T PRESS RATIO = 3.510
- TOTAL EFFICIENCY = 0.879
- LAST STG (V1/VCR1) = 0.6906

**DIAGRAMS ARE SYMMETRICAL**

- FIRST STAGE MEAN SPEED = 1075.74
- LAST STAGE MEAN SPEED = 1175.14
- LAST STAGE INLET SWIRL = 1575.13
- LAST STAGE EXIT SWIRL = 1562.16
- LAST STAGE AXIAL VELOC = 1022.46
- EXIT AXIAL MACH NUMBER = 0.5215
- LAST STG (V2/VCR2) = 0.5555

**STAGES = 2**

- EXIT TIP DIAMETER = 27.40
- EXIT HUB DIAMETER = 21.00
- EXIT RADIUS RATIO = 0.7721
- INLET TIP DIAMETER = 26.16
- INLET HUB DIAMETER = 20.00
- INLET RADIUS RATIO = 0.8027
- LAST STG (V1/VCR1) = 0.9000

**STAGE SPEED-POWER PARAMETER = 0.620**

- EXIT TOTAL TEMP = 2083.96
- EXIT STATIC TEMP = 2019.29
- EXIT TOTAL PRESS = 33.17
- EXIT INLET PRESS = 30.40
- T-T PRESS RATIO = 3.510
- TOTAL EFFICIENCY = 0.879
- LAST STG (V1/VCR1) = 0.6906

**DIAGRAMS ARE SYMMETRICAL**

- FIRST STAGE MEAN SPEED = 1090.30
- LAST STAGE MEAN SPEED = 1159.70
- LAST STAGE INLET SWIRL = 1566.21
- LAST STAGE EXIT SWIRL = 367.51
- LAST STAGE AXIAL VELOC = 422.90
- EXIT AXIAL MACH NUMBER = 0.3754
- LAST STG (V2/VCR2) = 0.4376
<table>
<thead>
<tr>
<th>Speed-work parameter</th>
<th>Diagram type</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Zero exit swirl</td>
</tr>
<tr>
<td></td>
<td>Impulse</td>
</tr>
<tr>
<td></td>
<td>Symmetrical</td>
</tr>
<tr>
<td>0.25</td>
<td>![Diagram]</td>
</tr>
<tr>
<td>0.5</td>
<td>![Diagram]</td>
</tr>
<tr>
<td>1.0</td>
<td>![Diagram]</td>
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</tbody>
</table>

Figure 1. - Effect of diagram type and speed-work parameter on velocity diagram shape.