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Enhanced Capabilities and Updated Users Manual for Axial-Flow Turbine Preliminary Sizing Code TURBAN

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SUMMARY

This report presents the latest modifications made to the computer code TURBAN, which does a preliminary sizing analysis for axial-flow turbines. The TURBAN analysis is based on mean-diameter flow characteristics. Program input includes flow, speed, and power or pressure ratio. The output presents annulus dimensions, diagram velocities and angles, and efficiencies. Options are provided for varying stage number, mean diameter, reaction, loading, diagram type, and/or work split.

Modifications were recently made to TURBAN to satisfy user needs and convenience. Turbine cooling-air flows and temperature now can be accounted for along with an associated efficiency decrement. Alternative input options have been added for defining the velocity diagram by stage reaction, for setting the mean diameter by stage loading, and for arbitrarily specifying stage work split. The Reynolds number dependency for the loss model was weakened, and an internal calculation of air viscosity was added as a default. The analytical modeling for these modifications are presented herein.

This report also serves as an updated users manual for the modified TURBAN code. Program input and output are described, and sample cases are included for illustration.

INTRODUCTION

Preliminary studies of gas turbine systems require many repetitive calculations of geometry and design-point performance for all the components. For this type of screening analysis, rapid approximate procedures, rather than time-consuming rigorous procedures, are sufficient to yield the desired component overall geometry and performance characteristics. One such analysis code, named TURBAN, for axial-flow turbines was first presented in reference 1 more than 20 years ago. An updated version of this code with numerous modeling improvements was presented in reference 2, and blade geometry modeling subsequently added to the code was reported in reference 3.

Recent use of TURBAN for aircraft propulsion system studies resulted in the desire for additional capabilities that were then added to the code. Turbine cooling now can be included in the analysis. New alternative input options allow direct specification of stage reaction, stage loading, and stage work distribution. The Reynolds number dependency was modified to provide improved loss modeling, and an internal calculation of air viscosity was added for convenience. These modifications require the use of additional input information.

This report presents the analytical modeling associated with the new capabilities added to the TURBAN code. It also serves as an updated users manual for the code. Program input and output are described. Sample cases are included for illustration.

SYMBOLS

c_p	heat capacity, J/kg-K; Btu/lb-°R
D	mean diameter, m; ft
g	dimensional constant, 1; 32.17 lbm-ft/lbf-sec^2
Δh	specific work, J/kg; Btu/lb
J	dimensional constant, 1; ft-lb/Btu
j	stage number for change in meanline slope
m	number of stages for meanline diameter variation
N	rotative speed, rad/sec; rpm
n	number of turbine stages
P	shaft power, W; hp
p	total pressure, N/m^2; lb/ft^2
R	stage reaction
Re	Reynolds number
T	total temperature, K; °R
U	blade speed, m/sec; ft/sec
V	gas absolute velocity, m/sec; ft/sec
W	gas relative velocity, m/sec; ft/sec
w	mass flow rate, kg/sec; lb/sec
x	ratio of stage work to turbine work
y	ratio of blade-row coolant flow to blade-row inlet flow
δ	stage-efficiency specific loss
ε_r	relative roughness
η	total efficiency, overall or stage
μ	viscosity, N-sec/m^2; lb/sec-ft
ψ	stage work factor

Subscripts:

c	coolant
ex	turbine exit
i	index for stage number
in	turbine inlet
n	last stage
p	primary (turbine inlet)
st	stator

ro rotor
rp rotor primary
u tangential component
1 first stage or stator exit
2 rotor exit

Superscript:
γ specific heat ratio
* corrected for coolant

ANALYTICAL MODELING

The analytical modeling for the enhanced capabilities are presented in this section. The added models used for the turbine cooling, velocity diagram, and loss model calculations are discussed.

Turbine Cooling

The model used to account for turbine cooling is based on mixing the primary flow and all the cooling flow (assuming constant heat capacity) at the turbine inlet to obtain a corrected turbine inlet temperature.

$$T^{*}_{in} = (w_p T_{in} + \Sigma w_{c,i} T_c) / (w_p + \Sigma w_{c,i}) \quad (1)$$

Both the array of blade-row cooling flows, $w_{c,i}$, and the coolant temperature, T_c, are required as code input. This methodology is consistent with the turbine thermodynamic efficiency definition based on cooling air pressure being equal to turbine inlet pressure.

$$\eta_{th} = P / \{(w_p T_{in} + \Sigma w_{c,i} T_c) c_p [1 - (p_{ex}/p_{in})^{(\gamma-1)/\gamma}]\} \quad (2)$$

The turbine efficiency provided by the loss model is for an uncooled turbine. To determine cooled turbine thermodynamic efficiency, reference 4 uses assigned values of stage-efficiency specific loss, which is defined as

$$\delta = \Delta\eta / (\eta_{unc} y) \quad (3)$$

for stator and rotor to determine the stage-efficiency loss due to cooling. The cooled stage efficiency is then obtained from the uncooled stage efficiency as

$$\eta_{th}/\eta_{unc} = 1 - y_{st}\delta_{st} - y_{ro}\delta_{ro} \quad (4)$$

Values for stage-efficiency specific loss, which are code inputs for stator and rotor, are given in reference 4 for various cooling configurations. These values are based on limited data and

20-year-old technology. Values relevant to current technology do not appear to be generally available.

Cooled turbine efficiency is often alternately expressed as rotor primary efficiency, which is defined as

$$\eta_{rp} = P / \{(w_p T_{in} + w_{c,1} T_c) c_p [1 - (p_{ex}/p_{in})^{(\gamma-1)/\gamma}]\} \quad (5)$$

Rotor primary efficiency can be obtained from thermodynamic efficiency by combining equations (2) and (5) for the same output power.

$$\eta_{rp} = \eta_{th}(w_p T_{in} + \Sigma w_{c,i} T_c) / (w_p T_{in} + w_{c,1} T_c) \quad (6)$$

Velocity Diagram Options

Options have been added to the code that influence the velocity diagrams. These include specifying the stage reaction to define the velocity diagram, specifying the stage work factor to define the mean diameter, and arbitrarily specifying the stage work split.

Stage reaction input.- The definition of stage reaction, assuming constant blade speed across a rotor, is

$$R = (W_2^2 - W_1^2) / (V_1^2 - V_2^2 + W_2^2 - W_1^2) \quad (7)$$

and the definition of stage work factor is

$$\psi = \Delta V_u / U \quad (8)$$

With the assumption of constant axial velocity across the stage, equations (7) and (8) can be combined with the velocity diagram equations to relate stage swirl split to stage reaction and work factor.

$$V_{u,1}/\Delta V_u = (1 - R) / \psi + 0.5 \quad (9)$$

Therefore, an input value of stage reaction, R, serves to define the velocity diagram since the stage work factor is also known from the input.

Stage work-factor input.- A stage-average work factor can be defined based on the mean squared blade speed.

$$\psi = gJ\Sigma\Delta h_i / \Sigma U_i^2 \quad (10)$$

By inputting this stage work factor, the stage mean blade-speed summation is computed from equation (10) and the stage mean diameter summation from

$$\Sigma D_i^2 = (720 / \pi N)^2 \Sigma U_i^2 \qquad (11)$$

For a single-stage turbine or a constant mean-diameter multistage turbine, the single value of mean diameter, D_i, can be calculated directly from equation (11). With a varying mean diameter, the mean diameter summation is expressed

$$\Sigma D_i^2 = D_1^2 \Sigma(D_i / D_1)^2 \qquad (12)$$

Since the mean diameter variation is linear with stage number (ref. 2), the summation can be expressed using arithmetic progression summation formulas in terms of the exit to inlet diameter ratio, D_n/D_1, which must be input, and the number of stages, m, over which the diameter variation occurs.

$$\Sigma(D_i / D_1)^2 = f(D_n/D_1,m) = m\{D_n/D_1 + (D_n/D_1 - 1)^2(2m - 1) / [6(m - 1)]\} \qquad (13)$$

Corresponding to the three options (ref. 2) available for stage mean-diameter variation, the diameter-ratio summation for equation (12), using the function notation defined by equation (13) becomes:

(1) Linear variation between first and last stages

$$\Sigma(D_i / D_1)^2 = f(D_n/D_1,n) \qquad (14)$$

(2) Constant from first stage to j^{th} stage and then linear to last stage

$$\Sigma(D_i / D_1)^2 = [j - 1 + f(D_n/D_1,n+1-j)] \qquad (15)$$

(3) Linear from first stage to jth stage and then constant to last stage

$$\Sigma(D_i / D_1)^2 = [(n-j)(D_n / D_1)^2 + f(D_n/D_1,j)] \qquad (16)$$

The inlet diameter, D_1, can now be obtained from equation (12) using ΣD_i^2 computed from equation (11) and $\Sigma(D_i / D_1)^2$ computed from equation (14), (15), or (16) as appropriate. The exit diameter, D_n, is then found from the input diameter ratio D_n/D_1.

<u>Stage work-split input</u>.- Previously, the basic assumption of constant stage work factor resulted in stage work split being determined uniquely by the stage diameter variation.

$$\Delta h_i / \Sigma\Delta h_i = U_i^2 / \Sigma U_i^2 = D_i^2 / \Sigma D_i^2 \qquad (17)$$

An option is now available for the direct specification of an arbitrary work split

$$\Delta h_i / \Sigma \Delta h_i = x_i \qquad (18)$$

where the x_i are input. As a result, stage work factor is not constant for this option

$$\psi_i = gJx_i \Sigma \Delta h_i / U_i^2 \qquad (19)$$

and equation (18) replaces equation (17) as required in the analysis of reference 2.

Loss Model

The dependency of loss on Reynolds number was based (ref. 2) on flow in a smooth tube.

$$\text{Loss} \propto Re^{-.2} \qquad (20)$$

Within the limited Reynolds number variation of the turbine database used for loss model calibration, this model appeared satisfactory. Subsequent studies of turbines with larger variations in Reynolds number indicated that this dependency was too strong. Therefore, it was replaced by an implicit approximation (ref. 5) of the Karman-Prandtl equation

$$\text{Loss} \propto \{\log[6.9 / Re + (\varepsilon_r / 7.4)^{1.11}]\}^{-2} \qquad (21)$$

A relative roughness, ε_r, of 0.0002 was used for equation (19).

For user convenience, an internal calculation of viscosity for air using the Sutherland equation was added as a default option.

$$\mu = 7.238 \times 10^{-7}\, T^{1.5} / (T + 199) \qquad (22)$$

DESCRIPTION OF INPUT AND OUTPUT

This section serves as an updated users manual by presenting a detailed description of the program input and normal output. The error messages are as described in reference 2. Included in the input and output sections are example cases illustrating the use of the program with the new options.

Input

The program input, a sample of which is presented in table I, consists of a title record 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 through 78 on the title record. A title, even if it is left blank, must be the first record of the input data. Additional titles can be used to identify different cases in the same data file. This is done by placing a title in front of the data 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 comprise INPUT and the proper units are as follows. These must be input for all cases except where otherwise indicated. Either SI units or U.S. customary units may be used.

PTIN inlet total pressure, N/cm^2; lb/in.^{2}

TTIN inlet total temperature, K; °R

MU gas viscosity, N-sec/m^2; lb/sec-ft.
- <0.0 - internal computation of viscosity for air
- >0.0 - value of viscosity

R gas constant, J/kg-K; ft-lbf/lbm-°R

GAM specific heat ratio

DIN inlet diameter - hub or mean or tip value as specified by IDIAM=1-3, cm; in.
- relative (to exit) value if IDIAM=4

DEX exit diameter - hub or mean or tip value as specified by IDIAM=1-3, cm; in.
- relative (to inlet) value if IDIAM=4

RREX exit radius ratio; RREX may be omitted when IDIAM=2 or 4 and IALPH=0; RREX is used as a first trial when IALPH=0 and IDIAM=1 or 3

RPM rotative speed, rad/sec; rpm

POW shaft power - omit when IPR=1, kW; hp

W mass flow rate, kg/sec;lb/sec

ALPHA stator exit angle from axial direction; ALPHA is used as first trial value when IALPH=1, deg

ALPHA0 turbine inlet flow angle from axial direction; input only when KALPH0=2, deg

VU1DVU ratio of rotor inlet swirl to total change in swirl; input only when IVD=5

REACT stage reaction; input only when IVD=6

WF stage work factor; input only when IDIAM=4

XI(I) I=1,NMIN — ratio of stage work to total work; XI(1)>0.0 triggers this option, which requires that NMIN=NMAX

KLOSS — turbine loss coefficient; a value of 0.3 is recommended in the absence of additional information

NMIN — minimum number of stages for which the calculations are performed

NMAX — maximum number of stages for which the calculations are performed; results are obtained for all stage numbers between NMIN and NMAX

NMID — stage number at which the meanline changes slope; input only when IMID=1

E — squared ratio of stage-exit to stage-average meridional velocities

PRTS — turbine inlet-total to exit-static pressure ratio; input only when IPR=1

WCOWP(I) I=1,NMIN — ratio of blade-row coolant flow to turbine-inlet flow; (default=NMIN*0.0)

TCOTP — ratio of coolant temperature to turbine inlet temperature;

DELS — stage-efficiency specific loss for stator cooling; (default=0.15)

DELR — stage-efficiency specfic loss for rotor cooling; (default=0.30)

IALPH — indicates whether stator exit angle or turbine exit radius ratio is specified:
- = 0 - turbine is designed for specified ALPHA
- = 1 - turbine is designed for specified RREX

IDIAM — indicates whether input diameters are absolute hub, mean, or tip values or a relative mean value:
- = 1 - input diameters are hub values
- = 2 - input diameters are mean values
- = 3 - input diameters are tip values
- = 4 - input diameters are relative mean values

IVD — indicates type of velocity diagram used:
- = 1 - symmetrical diagrams
- = 2 - zero exit swirl diagrams
- = 3 - impulse diagrams

= 4 - zero exit swirl diagrams if $\psi \leq 2.0$ and impulse diagrams if $\psi \geq 2.0$
= 5 - ratio of rotor-inlet swirl to total change in swirl is input as VU1DVU
= 6 - stage reaction is input as REACT

ITIT indicates use of titles in addition to that required as first line of data file:
= 0 - no title precedes next case
= 1 - title line precedes next case; must be input for each additional title because ITIT is set to zero after each title is read

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

IPR indicates whether shaft power or pressure ratio is specified:
= 0 - shaft power is input
= 1 - turbine inlet-total to exit-static pressure ratio is input

IU indicates type of units used for input and output:
= 1 - SI units
= 2 - U.S.customary units

KALPH0 indicates turbine-inlet flow angle option:
= 0 - turbine-inlet flow is axial (default)
= 1 - turbine-inlet flow angle equals stage-exit flow angle
= 2 - turbine-inlet flow angle is input as ALPHA0

IAR indicates blading aspect ratio:
= 1 - high aspect-ratio blading
= 2 - medium aspect-ratio blading (default)
= 3 - low aspect-ratio blading

IMID indicates meanline shape:
= 0 - meanline linear from stage 1 to stage N (default)
= 1 - meanline constant from stage 1 to stage NMID; then linear to stage N
= 2 - meanline linear from stage 1 to stage NMID; then constant to stage N

The sample input file shown in table I contains four cases, each illustrating one of the new capabilities added to the code. Each case begins with a title card, which is indented for demarcation purposes. The first case is a two-stage cooled turbine with the coolant flow ratios, coolant temperature, and stage-efficiency specific losses included as input. The next three cases are a five-stage turbine. For the first of these, stage reaction (REACT) is specified as input (option IVD=6). The next case uses stage work factor (WF) as an input (option IDIAM=4) along with exit/inlet diameter ratio to determine the stage diameters. These inputs were determined from the solution to the previous case and, therefore, should provide the same solution. The last case illustrates the use of stage work fraction (XI) as input. The output corresponding to this sample input is described in the following section.

Output

Table II presents the output that corresponds to the sample input of table I. A program identification title is automatically printed as the top line of the page for each new case. That is followed by the input title record message. The next four lines for each case are the input variables and their associated values. The input variable names are spelled out. The units for the input variable values are as described in the "Input" section. The input diameters for the first case are mean diameters as indicated by the MN in the variable name. Hub and tip diameters would be indicated by HB and TP, respectively. If diameters are calculated from an input work factor, as for the last two cases, the letters WF are used in the variable name. Note that the input diameters for the last two cases are the relative values. For a cooled turbine, such as the first case, two additional lines are printed to echo the coolant input parameters. Where stage work split is input, as for the last case, an additional line is printed to show the stage work fractions.

The next group of nine lines is the computation results satisfying the input requirements. The output parameters are spelled out and are self-explanatory. These temperatures, pressures, velocities and angles are meanline values, and the continuity and efficiency calculations are based on these values. Note that identical solutions are achieved by taking the work factor and exit/inlet diameter ratio from the second case and using them as input for the third case to compute the absolute values for the diameters. For the cooled turbine, note the differences between total efficiency, which is the thermodynamic efficiency (eqn. (2)), rotor primary efficiency (eqn. (5)), and uncooled efficiency. These values are all the same for the uncooled turbine.

The next group of four lines is the hub and tip free-vortex values of Mach number and angles for the last stage, where the radial variations are the largest. These flow parameters do not enter into the continuity and efficiency calculations, but are shown only for information. Following this is the meanline slope for the stages where the diameter is varying.

Where the stage work split is input, the stage work factors are no longer assumed equal and the stage velocity diagrams are not necessarily geometrically similar. For this option, the velocity diagram parameters and efficiency for each stage are printed, as shown for the last case. Note the variation in stage work factor from 3.24 at the inlet diameter to 2.33 at the exit diameter for this case of equal stage work.

The final output for each case are the blading geometries. Given for each stage are the chords, solidities, stagger angles and blade count for the stator and the rotor. Also shown for the last stage is the rotor blade centrifugal stress parameter AN^2, where A is the exit annulus area and N is the rotative speed.

SUMMARY OF RESULTS

This report presents the latest modifications made to the computer code TURBAN, which is a preliminary sizing analysis for axial-flow turbines. The TURBAN analysis is based on mean-diameter flow characteristics. Program input includes flow, speed, and power or pressure ratio. The output presents annulus dimensions, diagram velocities and angles, and efficiencies. Options are provided for varying stage number, mean diameter, reaction, loading, diagram type, and/or work split.

Modifications were recently made to TURBAN to satisfy user needs and convenience. Turbine cooling now can be accounted for in the overall energy balance and efficiency estimate by inputting:

(1) ratios of cooling flow to turbine-inlet flow for each blade row;
(2) ratio of coolant temperature to turbine-inlet temperature; and
(3) stage-efficiency decrements due to stator and rotor cooling.

Both thermodynamic efficiency and rotor primary efficiency are computed.

Alternative input options have been added for defining the velocity diagrams:

(1) specifying stage reaction to calculate stage swirl split;
(2) specifying stage loading to calculate mean diameter; and
(3) arbitrarily specifying stage work split.

These options can be used in any combination.

The Reynolds number dependency for the loss model was weakened, and an internal calculation of air viscosity was added as a default for convenience. The analytical modeling for all these modications was presented herein.

This report also serves as an updated users manual for the modified TURBAN code. Program input and output are described, and sample cases illustrating the new capabilities are included.

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3. Glassman, A.J.: Blading Models for TURBAN and CSPAN Turbomachine Design Codes. NASA CR-191164, 1993.
4. Gauntner, J.W.: Algorithm for Calculating Turbine Cooling Flow and the Resulting Decrease in Turbine Efficiency. NASA TM-81453, 1980.
5. Granger, R.A.: Fluid Mechanics. Holt, Rinehart and Winston, 1985.

TABLE I - SAMPLE INPUT

```
  COOLED HPT - 2 STAGES - Cooling parameters are input.
&INPUT TTIN=1277.,PTIN=50.,MU=2.69E-5,R=53.37,GAM=1.38,DIN=27.14,
DEX=27.25,RPM=8285.,POW=3630.7,W=25.7,ALPHA=71.6,NMIN=2,NMAX=2,E=1.17,
IALPH=0,IDIAM=2,IVD=2,IEV=0,IPR=0,IU=2,KLOSS=.30,ITIT=1,
WCOWP=.094,.070,.025,0.0,TCOTP=.48,DELS=.45,DELR=0.9 &END
  LPT - 5 STAGES - Reaction is input (IVD=6 option)
&INPUT TTIN=750.,PTIN=45.,MU=1.55E-5,R=53.37,GAM=1.4,DIN=21.2,DEX=25.0,
RPM=3208.7,POW=5045.8,W=62.58,ALPHA=61.,NMIN=5,NMAX=5,E=1.0,REACT=0.5,
IALPH=0,IDIAM=2,IVD=6,IEV=0,IPR=0,IU=2,IMID=2,NMID=3,KLOSS=.30,ITIT=1,
WCOWP=10*0.0 &END
  LPT - 5 STAGES - Stage work factor and relative diameters are input (IDIAM=4)
&INPUT DIN=1.0,DEX=1.17925,IDIAM=4,WF=2.5465,ITIT=1 &END
  LPT - 5 STAGES - Stage work split is input.
&INPUT XI=5*0.2 &END
```

TABLE II - SAMPLE OUTPUT

TURBINE VELOCITY DIAGRAM ANALYSIS

COOLED HPT - 2 STAGES

SHAFT POWER	MASS FLOW	INLET TEMP	INLET PRESS	ROTATIVE SPEED	INLET MN DIA	EXIT MN DIA	EXIT RADIUS RATIO	STATOR EX ANG	GAS CONST	HEAT CAPAC RATIO	GAS VISCOSITY	TURBINE LOSS COEF	AXIAL VEL SQ RATIO	T-S PRESS RATIO
3630.7	25.70	1277.00	50.00	8285.00	27.14	27.25	.0000	71.60	53.37	1.380	.269E-04	.300	1.170	.000

```
COOLANT TEMP RATIO= .480   STATOR LOSS DELTA=   .450    ROTOR LOSS DELTA =  .900
COOLANT FLOW RATIOS=   .0940    .0700    .0250   .0000

STAGES= 2                   STAGE WORK FACTOR= 1.29     REYNOLDS NO.= .8449E+06    DIAGRAMS ARE ZERO EX SWRL
EXIT TIP DIAMETER = 30.60   EXIT TOTAL TEMP  = 770.55   STATOR EXIT ANGLE= 71.60   FIRST STAGE MEAN SPEED=  981.12
EXIT HUB DIAMETER = 23.90   EXIT STATIC TEMP = 753.70   STAGE EXIT ANGLE =   .00   LAST STAGE MEAN SPEED =  985.09
EXIT RADIUS RATIO = .7809   EXIT TOTAL PRESS =   8.51   ROTOR INLET ANGLE= 34.27   LAST STAGE INLET SWIRL= 1273.85
INLET TIP DIAMETER= 28.64   EXIT STATIC PRESS=   7.86   ROTOR EXIT ANGLE =-66.72   LAST STAGE EXIT SWIRL =     .00
INLET HUB DIAMETER= 25.64   T-T PRESS RATIO  =  5.873   TOTAL EFFICIENCY =  .887   LAST STAGE MERID VELOC=  458.39
INLET RADIUS RATIO= .8954   T-S PRESS RATIO  =  6.364   STATIC EFFICIENCY=  .857   EXIT MERID MACH NUMBER=   .3430
LAST STG M1 ABS   = .9589   LAST STG M1 REL  =  .3663   LAST STG M2 REL  = .8131   LAST STG M2 ABS       =   .3430
STAGE REACTION    =  .353   STG TOT EFF-UNC  =   .909   TOTAL EFF - UNC  =  .917   TOTAL EFF - ROT PRIM  =    .926

HUB: LAST STG M1 ABS   =1.1073   LAST STG M1 REL   =  .5308   LAST STG M2 REL  = .7189   LAST STG M2 ABS    =  .3166
     STATOR EXIT ANGLE = 73.74   ROTOR INLET ANGLE = 54.25   ROTOR EXIT ANGLE =-63.87   STAGE EXIT ANGLE   =   .00

TIP: LAST STG M1 ABS   = .8511   LAST STG M1 REL   =  .2985   LAST STG M2 REL  = .8851   LAST STG M2 ABS    =  .3166
     STATOR EXIT ANGLE = 69.51   ROTOR INLET ANGLE =  3.77   ROTOR EXIT ANGLE =-69.04   STAGE EXIT ANGLE   =   .00

STAGE 1- 2 MEANLINE SLOPE =    .76 DEG BASED ON MID ASPECT-RATIO BLADING
```

STAGE	STATOR AXIAL CHORD (IN.)	STATOR AXIAL SOLID	STATOR ACTUAL SOLID	STATOR STAG. ANGLE	STATOR NO. OF VANES	ROTOR AXIAL CHORD (IN.)	ROTOR AXIAL SOLID	ROTOR ACTUAL SOLID	ROTOR STAG. ANGLE	ROTOR NO. OF BLADES	AN**2
1	1.557	.749	1.435	58.55	41.	1.557	1.174	1.331	-28.12	64.	
2	1.562	.749	1.435	58.55	41.	1.562	1.174	1.331	-28.12	64.	.1970E+11

TABLE II - Continued

TURBINE VELOCITY DIAGRAM ANALYSIS

LPT - 5 STAGES - Inlet and exit mean diameters and reaction are input.

SHAFT POWER	MASS FLOW	INLET TEMP	INLET PRESS	ROTATIVE SPEED	INLET MN DIA	EXIT MN DIA	EXIT RADIUS RATIO	STATOR EX ANG	GAS CONST	HEAT CAPAC RATIO	GAS VISCOSITY	TURBINE LOSS COEF	AXIAL VEL SQ RATIO	T-S PRESS RATIO
5045.8	62.58	750.00	45.00	3208.70	21.20	25.00	.0000	61.00	53.37	1.400	.155E-04	.300	1.000	.000

	STAGES= 5	STAGE WORK FACTOR= 2.55	REYNOLDS NO.= .4571E+07	DIAGRAMS ARE INPT REACT.
	EXIT TIP DIAMETER = 31.76	EXIT TOTAL TEMP = 512.59	STATOR EXIT ANGLE= 61.00	FIRST STAGE MEAN SPEED= 296.81
	EXIT HUB DIAMETER = 18.24	EXIT STATIC TEMP = 496.65	STAGE EXIT ANGLE =-38.19	LAST STAGE MEAN SPEED = 350.02
	EXIT RADIUS RATIO = .5745	EXIT TOTAL PRESS = 10.15	ROTOR INLET ANGLE= 38.19	LAST STAGE INLET SWIRL= 620.66
	INLET TIP DIAMETER= 24.76	EXIT STATIC PRESS= 9.09	ROTOR EXIT ANGLE =-61.00	LAST STAGE EXIT SWIRL = -270.65
	INLET HUB DIAMETER= 17.64	T-T PRESS RATIO = 4.434	TOTAL EFFICIENCY = .913	LAST STAGE MERID VELOC= 344.05
	INLET RADIUS RATIO= .7128	T-S PRESS RATIO = 4.952	STATIC EFFICIENCY= .863	EXIT MERID MACH NUMBER= .3149
	LAST STG M1 ABS = .6332	LAST STG M1 REL = .3906	LAST STG M2 REL = .6495	LAST STG M2 ABS = .4006
	STAGE REACTION = .500	STG TOT EFF-UNC = .899	TOTAL EFF - UNC = .913	TOTAL EFF - ROT PRIM = .913
HUB:	LAST STG M1 ABS = .8415	LAST STG M1 REL = .6305	LAST STG M2 REL = .6576	LAST STG M2 ABS = .4655
	STATOR EXIT ANGLE = 67.98	ROTOR INLET ANGLE = 59.96	ROTOR EXIT ANGLE =-61.22	STAGE EXIT ANGLE = -47.15
TIP:	LAST STG M1 ABS = .5271	LAST STG M1 REL = .3059	LAST STG M2 REL = .6777	LAST STG M2 ABS = .3695
	STATOR EXIT ANGLE = 54.85	ROTOR INLET ANGLE = 7.29	ROTOR EXIT ANGLE =-62.39	STAGE EXIT ANGLE = -31.77

STAGE 1- 3 MEANLINE SLOPE = 14.11 DEG BASED ON MID ASPECT-RATIO BLADING

	STATOR					ROTOR					
STAGE	AXIAL CHORD (IN.)	AXIAL SOLID	ACTUAL SOLID	STAG. ANGLE	NO. OF VANES	AXIAL CHORD (IN.)	AXIAL SOLID	ACTUAL SOLID	STAG. ANGLE	NO. OF BLADES	AN**2
1	1.290	1.060	1.556	47.07	55.	1.290	1.522	1.604	-18.39	79.	
2	1.374	1.522	1.604	18.39	80.	1.374	1.522	1.604	-18.39	80.	
3	1.460	1.522	1.604	18.39	82.	1.460	1.522	1.604	-18.39	82.	
4	1.460	1.522	1.604	18.39	82.	1.460	1.522	1.604	-18.39	82.	
5	1.460	1.522	1.604	18.39	82.	1.460	1.522	1.604	-18.39	82.	.5463E+10

TABLE II - Continued

TURBINE VELOCITY DIAGRAM ANALYSIS

LPT - 5 STAGES - Stage work factor and relative diameters are input.

SHAFT POWER	MASS FLOW	INLET TEMP	INLET PRESS	ROTATIVE SPEED	INLET WF DIA	EXIT WF DIA	EXIT RADIUS RATIO	STATOR EX ANG	GAS CONST	HEAT CAPAC RATIO	GAS VISCOSITY	TURBINE LOSS COEF	AXIAL VEL SQ RATIO	T-S PRESS RATIO
5045.8	62.58	750.00	45.00	3208.70	1.00	1.18	.0000	61.00	53.37	1.400	.155E-04	.300	1.000	.000

STAGES= 5	STAGE WORK FACTOR= 2.55	REYNOLDS NO.= .4571E+07	DIAGRAMS ARE INPT REACT.
EXIT TIP DIAMETER = 31.76	EXIT TOTAL TEMP = 512.59	STATOR EXIT ANGLE= 61.00	FIRST STAGE MEAN SPEED= 296.81
EXIT HUB DIAMETER = 18.24	EXIT STATIC TEMP = 496.65	STAGE EXIT ANGLE =-38.19	LAST STAGE MEAN SPEED = 350.02
EXIT RADIUS RATIO = .5745	EXIT TOTAL PRESS = 10.15	ROTOR INLET ANGLE= 38.19	LAST STAGE INLET SWIRL= 620.67
INLET TIP DIAMETER= 24.76	EXIT STATIC PRESS= 9.09	ROTOR EXIT ANGLE =-61.00	LAST STAGE EXIT SWIRL = -270.65
INLET HUB DIAMETER= 17.64	T-T PRESS RATIO = 4.434	TOTAL EFFICIENCY = .913	LAST STAGE MERID VELOC= 344.06
INLET RADIUS RATIO= .7128	T-S PRESS RATIO = 4.952	STATIC EFFICIENCY= .863	EXIT MERID MACH NUMBER= .3149
LAST STG M1 ABS = .6332	LAST STG M1 REL = .3906	LAST STG M2 REL = .6495	LAST STG M2 ABS = .4006
STAGE REACTION = .500	STG TOT EFF-UNC = .899	TOTAL EFF - UNC = .913	TOTAL EFF - ROT PRIM = .913

HUB:	LAST STG M1 ABS = .8415	LAST STG M1 REL = .6305	LAST STG M2 REL = .6576	LAST STG M2 ABS = .4655
	STATOR EXIT ANGLE = 67.98	ROTOR INLET ANGLE = 59.96	ROTOR EXIT ANGLE =-61.22	STAGE EXIT ANGLE = -47.15
TIP:	LAST STG M1 ABS = .5271	LAST STG M1 REL = .3059	LAST STG M2 REL = .6777	LAST STG M2 ABS = .3695
	STATOR EXIT ANGLE = 54.85	ROTOR INLET ANGLE = 7.29	ROTOR EXIT ANGLE =-62.39	STAGE EXIT ANGLE = -31.77

STAGE 1- 3 MEANLINE SLOPE = 14.11 DEG BASED ON MID ASPECT-RATIO BLADING

	STATOR					ROTOR					
STAGE	AXIAL CHORD (IN.)	AXIAL SOLID	ACTUAL SOLID	STAG. ANGLE	NO. OF VANES	AXIAL CHORD (IN.)	AXIAL SOLID	ACTUAL SOLID	STAG. ANGLE	NO. OF BLADES	AN**2
1	1.290	1.060	1.556	47.07	55.	1.290	1.522	1.604	-18.39	79.	
2	1.374	1.522	1.604	18.39	80.	1.374	1.522	1.604	-18.39	80.	
3	1.460	1.522	1.604	18.39	82.	1.460	1.522	1.604	-18.39	82.	
4	1.460	1.522	1.604	18.39	82.	1.460	1.522	1.604	-18.39	82.	
5	1.460	1.522	1.604	18.39	82.	1.460	1.522	1.604	-18.39	82.	.5463E+10

TABLE II - Concluded
TURBINE VELOCITY DIAGRAM ANALYSIS

LPT - 5 STAGES - Stage work split is input.

SHAFT POWER	MASS FLOW	INLET TEMP	INLET PRESS	ROTATIVE SPEED	INLET WF DIA	EXIT WF DIA	EXIT RADIUS RATIO	STATOR EX ANG	GAS CONST	HEAT CAPAC RATIO	GAS VISCOSITY	TURBINE LOSS COEF	AXIAL VEL SQ RATIO	T-S PRESS RATIO
5045.8	62.58	750.00	45.00	3208.70	1.00	1.18	.0000	61.00	53.37	1.400	.155E-04	.300	1.000	.000

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     STAGE WORK SPLIT=  .200   .200   .200   .200   .200

     STAGES= 5                     STAGE WORK FACTOR= 2.55        REYNOLDS NO.= .4571E+07       DIAGRAMS ARE INPT REACT.
     EXIT TIP DIAMETER = 32.08     EXIT TOTAL TEMP   = 512.59     STATOR EXIT ANGLE= 61.00      FIRST STAGE MEAN SPEED=   296.81
     EXIT HUB DIAMETER = 17.92     EXIT STATIC TEMP  = 499.41     STAGE EXIT ANGLE =-35.76      LAST STAGE MEAN SPEED =   350.02
     EXIT RADIUS RATIO = .5587     EXIT TOTAL PRESS  =  10.18     ROTOR INLET ANGLE= 35.76      LAST STAGE INLET SWIRL=   582.60
     INLET TIP DIAMETER= 24.40     EXIT STATIC PRESS=    9.29     ROTOR EXIT ANGLE =-61.00      LAST STAGE EXIT SWIRL = -232.58
     INLET HUB DIAMETER= 18.00     T-T PRESS RATIO   =  4.421     TOTAL EFFICIENCY =  .915      LAST STAGE MERID VELOC=   322.95
     INLET RADIUS RATIO= .7376     T-S PRESS RATIO   =  4.843     STATIC EFFICIENCY=  .872      EXIT MERID MACH NUMBER=    .2948
     LAST STG M1 ABS   = .5940     LAST STG M1 REL   =  .3549     LAST STG M2 REL  = .6080      LAST STG M2 ABS       =    .3632
     STAGE REACTION    =  .500     STG TOT EFF-UNC   =   .900     TOTAL EFF - UNC  =  .915      TOTAL EFF - ROT PRIM  =     .915

HUB: LAST STG M1 ABS   = .8005     LAST STG M1 REL   =  .5931     LAST STG M2 REL  = .6048      LAST STG M2 ABS       =    .4196
     STATOR EXIT ANGLE = 68.33     ROTOR INLET ANGLE = 60.10      ROTOR EXIT ANGLE =-60.69      STAGE EXIT ANGLE      =   -45.13

TIP: LAST STG M1 ABS   = .4917     LAST STG M1 REL   =  .2850     LAST STG M2 REL  = .6453      LAST STG M2 ABS       =    .3374
     STATOR EXIT ANGLE = 54.58     ROTOR INLET ANGLE =    .88     ROTOR EXIT ANGLE =-62.87      STAGE EXIT ANGLE      =   -29.31

     STAGE 1- 3 MEANLINE SLOPE =   14.11 DEG BASED ON MID ASPECT-RATIO BLADING

     STG  1 M1 ABS     = .5517     STG  1 M1 REL     =  .3695     STG  1 M2 REL    = .5612      STG  1 M2 ABS         =    .3758
     STATOR EXIT ANGLE = 61.00     ROTOR INLET ANGLE = 43.62      ROTOR EXIT ANGLE =-61.00      STAGE EXIT ANGLE      =   -43.62
     STAGE WORK FACTOR = 3.239     STAGE REACTION    =   .500     STAGE TOTAL EFFIC=  .903

     STG  2 M1 ABS     = .5460     STG  2 M1 REL     =  .3450     STG  2 M2 REL    = .5560      STG  2 M2 ABS         =    .3514
     STATOR EXIT ANGLE = 61.00     ROTOR INLET ANGLE = 39.90      ROTOR EXIT ANGLE =-61.00      STAGE EXIT ANGLE      =   -39.90
     STAGE WORK FACTOR = 2.728     STAGE REACTION    =   .500     STAGE TOTAL EFFIC=  .891

     STG  3 M1 ABS     = .5465     STG  3 M1 REL     =  .3265     STG  3 M2 REL    = .5573      STG  3 M2 ABS         =    .3330
     STATOR EXIT ANGLE = 61.00     ROTOR INLET ANGLE = 35.76      ROTOR EXIT ANGLE =-61.00      STAGE EXIT ANGLE      =   -35.76
     STAGE WORK FACTOR = 2.329     STAGE REACTION    =   .500     STAGE TOTAL EFFIC=  .902

     STG  4 M1 ABS     = .5688     STG  4 M1 REL     =  .3398     STG  4 M2 REL    = .5810      STG  4 M2 ABS         =    .3471
     STATOR EXIT ANGLE = 61.00     ROTOR INLET ANGLE = 35.76      ROTOR EXIT ANGLE =-61.00      STAGE EXIT ANGLE      =   -35.76
     STAGE WORK FACTOR = 2.329     STAGE REACTION    =   .500     STAGE TOTAL EFFIC=  .902

     STG  5 M1 ABS     = .5940     STG  5 M1 REL     =  .3549     STG  5 M2 REL    = .6080      STG  5 M2 ABS         =    .3632
     STATOR EXIT ANGLE = 61.00     ROTOR INLET ANGLE = 35.76      ROTOR EXIT ANGLE =-61.00      STAGE EXIT ANGLE      =   -35.76
     STAGE WORK FACTOR = 2.329     STAGE REACTION    =   .500     STAGE TOTAL EFFIC=  .902
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	STATOR					ROTOR					
STAGE	AXIAL CHORD (IN.)	AXIAL SOLID	ACTUAL SOLID	STAG. ANGLE	NO. OF VANES	AXIAL CHORD (IN.)	AXIAL SOLID	ACTUAL SOLID	STAG. ANGLE	NO. OF BLADES	AN**2
1	1.290	1.060	1.556	47.07	55.	1.290	1.620	1.668	-13.72	84.	
2	1.374	1.551	1.622	16.91	82.	1.374	1.551	1.622	-16.91	82.	
3	1.460	1.483	1.584	20.49	80.	1.460	1.483	1.584	-20.49	80.	
4	1.460	1.483	1.584	20.49	80.	1.460	1.483	1.584	-20.49	80.	
5	1.460	1.483	1.584	20.49	80.	1.460	1.483	1.584	-20.49	80.	.5723E+10

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13. ABSTRACT ***(Maximum 200 words)***

Several modifications have been made to the axial-flow turbine preliminary sizing code TURBAN. Turbine cooling has been added to the analysis. New alternative input options allow direct specification of stage reaction, stage work factor, and stage work split. The Reynolds number loss dependency was modified and an internal calculation of air viscosity was added. A complete description of input and output along with sample cases are included.

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