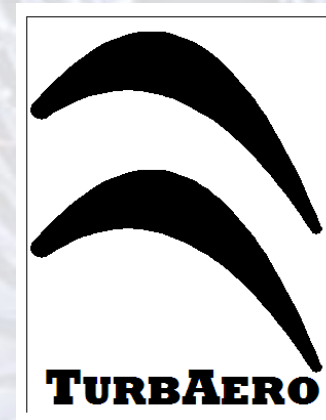


Aeolus to TurbAero

Transfer Link



Aeolus Turbine Preliminary Design & Analysis

Aeolus is an experienced-based, preliminary design tool coupled with a rigorous performance analysis.

This two-part system can design & analyze flow paths for many types of axial turbines, ranging from small waste heat expanders to large power gen units.

Program Capabilities:

- Any number of stages, impulse or reaction type designs
- Real gas properties, supercritical fluids & wet steam with industry standard databases: NIST RefProp and ASME '97
- Partial admission, Curtis stages, impulse and reaction designs
- Extractions/bleeds/inductions, double-flow stages
- Seal leakages, blade forces and axial thrust loads
- Supersonic expanding nozzles, including drilled (axisymmetric)
- AMDC based loss component analysis, refined by Kacker & Okapuu (Ref. 1) and similar to that in **TurbAero** (Refs. 2 & 3).

Aeolus Preliminary Design Tool

The ***Flow Path*** Design tool is a useful complement to ***TurbAero*** in several important areas:

- preliminary sizing & optimization of multi-stage flow paths to establish:
 - flow path radii at hub & tip
 - inlet and exit (gauging) angles for all nozzles & blades
 - airfoil geometry parameters (no. of blades, chord, axial width, max. thickness, trailing edge thickness, clearances)
- graphical displays of design parameters to aid the optimization process
- industry standard fluid properties:
 - Steam (ASME '97) and real gases (NIST RefProp)
- Excel based input and output sheets for convenience in entering data, reviewing results and creating output plots

Aeolus for Performance Analysis

The ***Meanline Performance*** analysis is a useful complement to ***TurbAero*** in several important areas:

- Extended capabilities for steam turbines:
 - supersonic flows (including drilled nozzles)
 - extractions, inductions, double flow stages
 - seal leakages & axial thrust loads
 - converged solutions for a much larger number of stagesRef 4 compares results with AxStream™ for a 17-stage steam turbine
- Graphical output and industry standard fluid properties
- Similar loss component analysis as ***TurbAero/AxTurb*** (Ref. 2), allowing for a close comparison of results between ***Aeolus*** and ***AxTurb***.
- Automatic creation of all input data for ***AxTurb***

Overview of **TurbAero** Design System

TurbAero is a software system comprised of 17 different axial & radial turbine aero design and analysis programs (Refs. 2 & 3)



Axial Turbine Programs

AFTSIZE
AXTURB
AIRFOIL
BLADE

Common Programs

B2B2D/TDB2B
RKMOD
GASDATA
EXHAUST

Radial Turbine Programs:

RIFTSIZE
RIFT
RIFTNOZ
FLOW3D
GASPATH/BEZIER
RIGPAC
VOLUTE

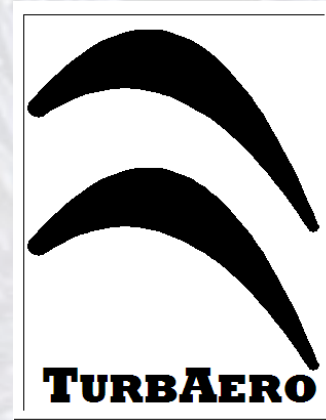
AxTurb Description

AxTurb is the throughflow analysis module for **TurbAero**.

AxTurb Capabilities:

- 2D throughflow analysis for axial turbines based on a streamline curvature approach with full radial equilibrium
- Subsonic to transonic flows including multiple choked rows
- Very good convergence abilities for smaller number of stages (< 10) and subsonic/transonic Mach numbers (< 1.2)
- Real gas properties use Aungier's Modified Redlich-Kwong model
- Program theory & loss models are fully documented (Ref. 2)
- Prediction accuracy has been validated with several test cases (Ref. 2)

Aeolus to *AxTurb* Transfer Demo for a 7-Stage Steam Turbine



Step 1 – Start **Aeolus** then read in a turbine input file

Operating Conditions

Flow Path Model

Input Data Review

The screenshot displays the Aeolus Main software interface. The top menu bar includes File, Analyze, Units, and Help. The main window is divided into three sections. The top-left section, titled 'Operating Condition', contains input fields for Turbine Speed (5033 rpm), Inlet Pressure (145 psia), Inlet Temperature (356.1 Deg F), and Exhaust Pressure (6.5 psia). It also features a 'Gas Properties Reference' section with radio buttons for ASME1997 (selected) and NIST2010, and a 'Type of Fluid' dropdown set to STEAM. The bottom-left section, titled 'Flow Path', shows a graph with a y-axis from 0 to 20 and an x-axis from 0 to 24. The graph displays a series of rectangular pulses in red and blue. The right section, titled 'PerAeroTurbineDesigns', shows a tree view of turbine components: Turbine, Inlet Flange, Stages, Stage 1, Corrections, Stator, Diaphragm, Nozzle, Rotor, and Wheel. The Diaphragm and Nozzle sections are expanded, showing detailed parameters such as Admission Ratio, Exit Pitch Diameter, Full Arc Flow Area, Inlet Annulus Area, Inlet Pitch Diameter, Number of Nozzles, Number of Sectors, Percent Area Blockage, Total Flow Area, Windage Shield, Shrouded?, Name, Type, Exit Height, Inlet Height, Pitch Tip, Pitch, Pitch Hub, Throat Tip, Throat, Throat Hub, and Throat Area. The bottom status bar displays the directory path, file name, and a message: 'Successfully Read and Built Geometry Turbine'.

PerAeroTurbineDesigns

Turbine

Inlet Flange

Stages

Stage 1

Corrections

Stator

Diaphragm

Admission Ratio: 1.000

Exit Pitch Diameter: 25.630

Full Arc Flow Area: 13.60

Inlet Annulus Area: 66.03

Inlet Pitch Diameter: 25.630

Number of Nozzles: 72

Number of Sectors: 1

Percent Area Blockage: 0.000

Total Flow Area: 13.60

Windage Shield: 0.000

Shrouded?: True

Nozzle

Name: Nozzle

Type: Nozzle

Exit Height: 0.820

Inlet Height: 0.820

Pitch Tip: 1.1541

Pitch: 1.1183

Pitch Hub: 1.0825

Throat Tip: 0.2461

Throat: 0.2300

Throat Hub: 0.2151

Throat Area: 0.19

Corrections

Diverging

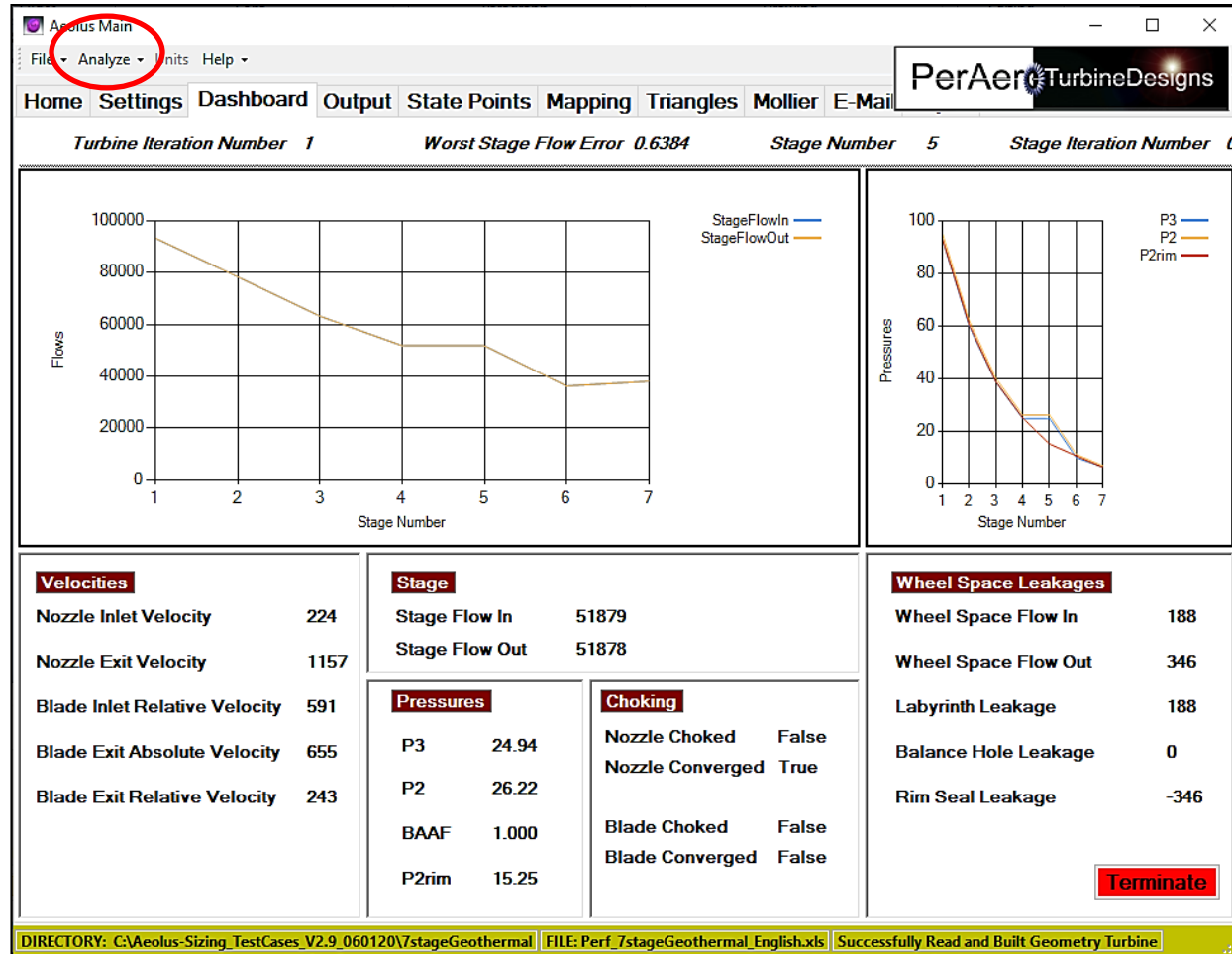
Seal

Rotor

Wheel

DIRECTORY: C:\Aeolus-Sizing_TestCases_V2.9_060120\7stageGeothermal FILE: Perf_7stageGeothermal_English.xls Successfully Read and Built Geometry Turbine

Step 2 – Run **Aeolus** Meanline Analysis by selecting “Analyze”



Step 2 – After reaching convergence, generate the Excel output file

The screenshot displays the 'Aeolus Main' software window. The 'Output' tab is selected in the top navigation bar. The 'Turbine Convergence History' section shows four iterations of convergence data for P3(i, 17) through P3(i, 20). The status at the bottom indicates '*** CONVERGED Turbine Flow Balance: 6/20/2020 4:04:13 PM ***'. Below this, the 'Summary Output' section contains a table with turbine performance metrics. A green 'Generate Output' button is highlighted with a red circle, and a 'Convergence Plots' button is visible below it. The status bar at the bottom shows the directory path, file name, and a success message.

Turbine Convergence History

Filtered P3(i, 17) 110.028 85.760 65.262 47.680 35.010 21.289 6.501
Qs(i, 17) 80539.7 80539.8 80539.7 80539.4 80539.2 80734.8 79562.6
Err(i, 17) 0.001391 0.001392 0.001390 0.001386 0.001384 0.003816 0.010758

Filtered P3(i, 18) 110.029 85.763 65.268 47.690 35.024 21.311 6.501
Qs(i, 18) 80538.3 80538.3 80538.4 80538.3 80538.3 80652.8 80002.1
Err(i, 18) 0.000749 0.000749 0.000749 0.000749 0.000748 0.002171 0.005914

Filtered P3(i, 19) 110.029 85.765 65.270 47.694 35.031 21.323 6.501
Qs(i, 19) 80537.7 80537.7 80537.7 80537.7 80537.7 80603.3 80243.2
Err(i, 19) 0.000406 0.000406 0.000406 0.000406 0.000406 0.001221 0.003252

Filtered P3(i, 20) 110.030 85.765 65.272 47.696 35.035 21.330 6.501
Qs(i, 20) 80537.3 80537.3 80537.3 80537.3 80537.3 80575.1 80374.9
Err(i, 20) 0.000221 0.000221 0.000221 0.000221 0.000221 0.000690 0.001797
*** CONVERGED Turbine Flow Balance: 6/20/2020 4:04:13 PM ***

Summary Output

	Description	Value	Unit
►	Net Efficiency	0.749	
	Inlet Flow	80,588	lbm/hr
	Net Shaft Output	5,140	HP
	Driven Output	5,140	HP

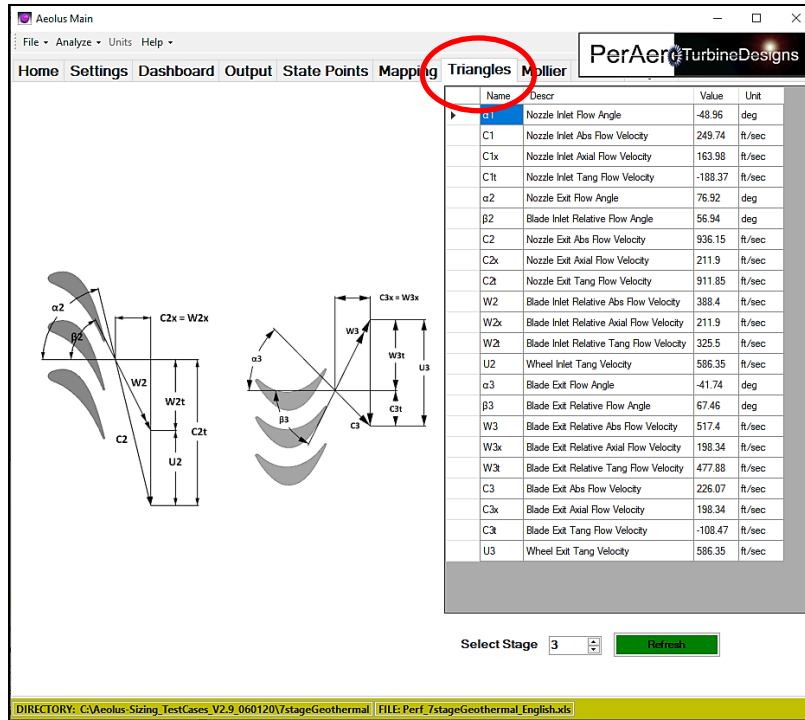
Generate Output

Convergence Plots

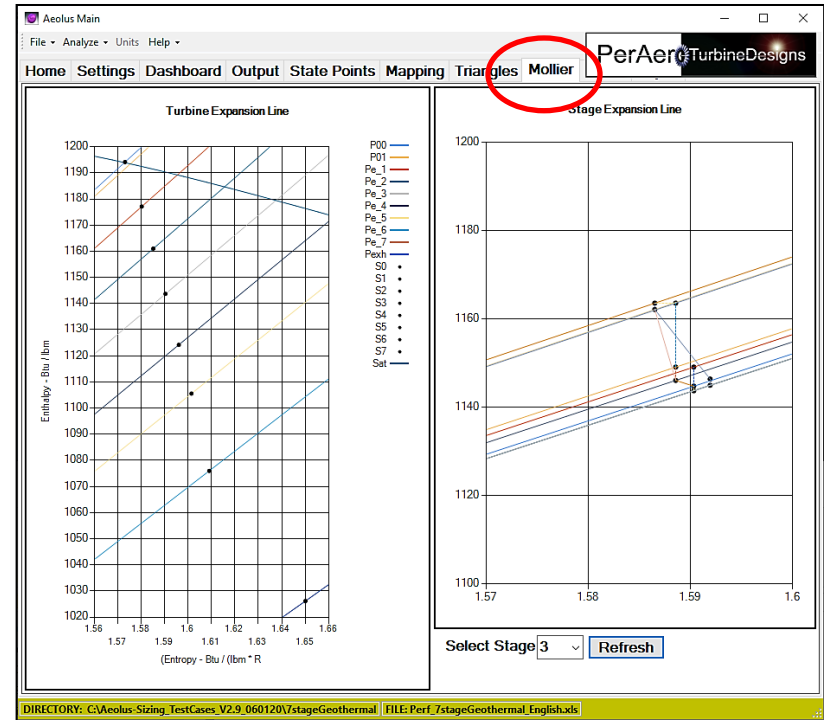
DIRECTORY: C:\Aeolus-Sizing_TestCases_V2.9_060120\7stageGeothermal FILE: Perf_7stageGeothermal_English.xls Successfully Read and Built Geometry Turbine

View Graphical Results if Desired (optional)

Stage Velocity Triangles



Thermo State Points & Expansion Line



Step 3 – Select 'Export' Menu then 'Translate'

The screenshot shows the 'Aeolus Main' application window. The 'Export' menu is highlighted with a red circle. Below it, the 'Translate' button is also highlighted with a red circle. The interface displays a table for 'Aeolus Input File' and a text area for 'AxTurb Input File'.

A	B	C	D	E
	Title	-	CL55 7-S...	
	Customer	-		
	Location	-		
	Fluid	-	STEAM	
	Speed	rpm	5033	
Inlet Fla...				
	Diameter	inches	10	
	P00	psia	145	
	T00	Deg F	356.1	
	Inlet Los...	-	0.03	
Exhaust ...				
	Diameter	inches	20	
	Pexit	psia	6.5	
	Hood Lo...	-	0	
Number ...				
	Stages	-	7	
Mechani...				
	Gear	%	100	
	Generator	%	100	
	Bearing	HP	0	
Shaft E...				
	Leakage ...	lbm/hr	0	
Output ...				
	Output U...	-	English	

The 'AxTurb Input File' text area contains the following data:

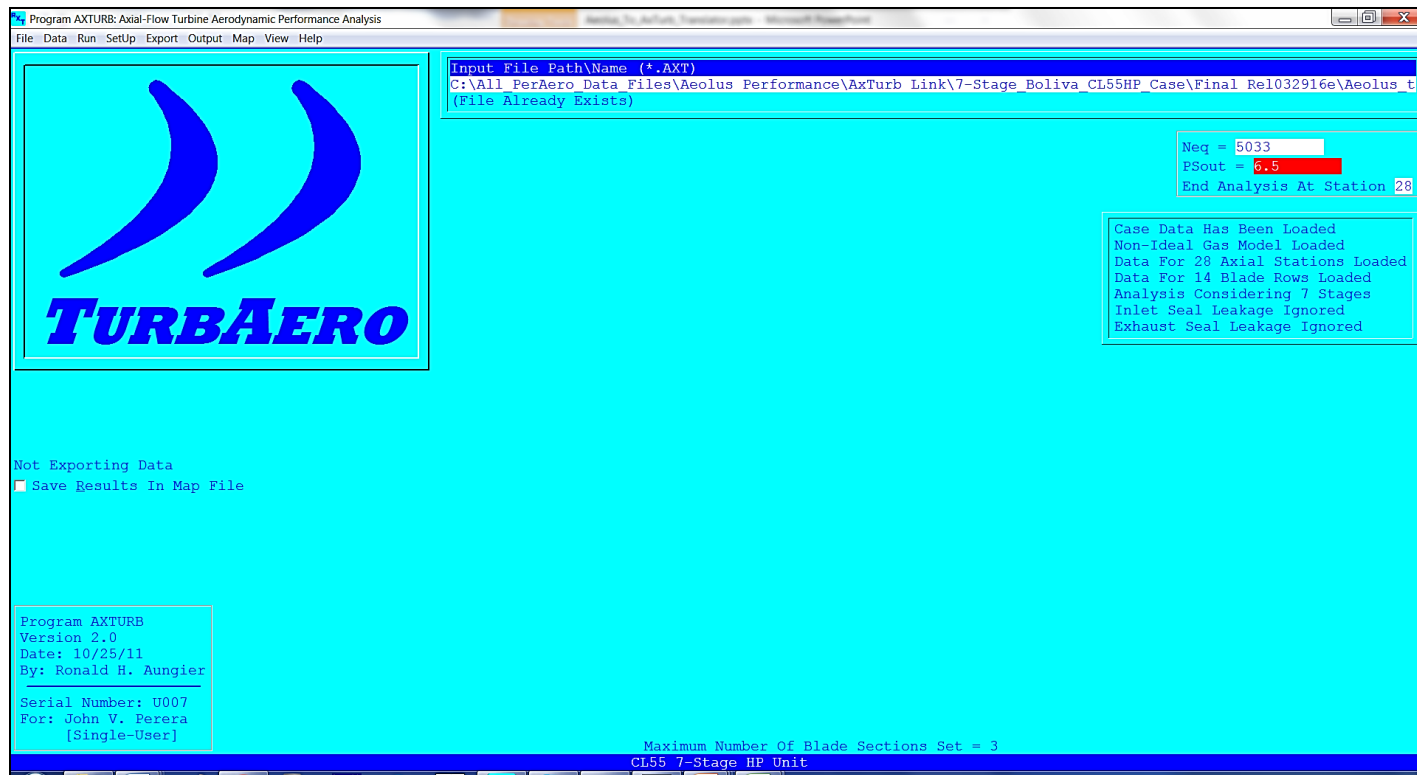
```
CL55 7-Stage HP Unit
3 1 1 5033 6.50 1 1 0.97
0,1,3,1,0,0,0,"Neq=5033"
1 0 0 0 1 1 0 1
1 28 -14 3 28
-1 0 -1 0 0 0 0 0
0. 145.00 356.10 90.
0 0.000 -12.405 0.000 -13.225
1 1.548 12.405 1.548 13.225
0 1.708 -12.375 1.708 -13.275
2 2.333 12.375 2.333 13.275
0 3.227 -12.78 3.227 -13.68
1 4.809 12.780 4.809 13.680
0 4.969 -12.750 4.969 -13.730
2 5.756 12.750 5.756 13.730
0 6.488 -12.78 6.488 -13.9
1 8.059 12.780 8.059 13.900
0 8.219 -12.750 8.219 -13.950
2 9.006 12.750 9.006 13.950
0 9.798 -12.78 9.798 -14.23
1 11.352 12.780 11.352 14.230
0 11.512 -12.750 11.512 -14.280
2 12.299 12.750 12.299 14.280
0 12.755 -12.78 12.755 -14.48
1 14.360 12.780 14.360 14.480
0 14.540 -12.750 14.540 -14.530
2 15.480 12.750 15.480 14.530
0 16.023 -12.78 16.023 -14.89
1 17.610 12.780 17.610 14.890
0 17.790 -12.750 17.790 -14.940
2 18.730 12.750 18.730 14.940
0 19.241 -12.78 19.241 -15.26
```

An **AxTurb** input file is automatically created from the **Aeolus** input data and other experienced-based assumptions

Successfully Created AxTurb Input file.

OK

Step 4 – Start AxTurb Then Read in the New Input File



All input data requirements have been transferred from *Aeolus*

Enter/Edit Case Title (80 Character Maximum)

CL55 7-Stage HP Unit

Flow Option

Exit Static Pressure

Moisture Loss Option

Allow Moisture Loss

Rotor Construction

Diaphragm-Disk Style

Inlet Swirl Option

Flow Angle

Blade End-Wall Option

Linear

Re Correction Option

Re & Surface Finish

Weg/W (or 0) = 1

Neg/N (or 0) = 1

Speed Option

None

Equilibrium Option

Include Curvature

Inlet Valve Pr = 0.97

Streamlines (Odd) = 3

Exhaust LC = 1

PSout = 6.5

Neg = 5033

Inlet Flow Profile (Check To Enter Static Pressure) ☐

(Check To Enter Total Enthalpy) ☐

% Passage Height	Total Pressure	Total Temperature	Flow Angle
0	145	356.1	90

Units: psi, deg F, ft/sec, lbm/hr, cfm, btu/lbm, deg with tangent

Upstream Blade Row Type

None

Hub Axial Coordinate (in) = 0

Hub Radial Coordinate (in) = 12.405

Shroud Axial Coordinate (in) = 0

Shroud Radial Coordinate (in) = 13.225

Listing Of End-Wall Station Data Currently Loaded

Type	Hub Contour	Shroud Contour
None	0.0000	0.0000
Nozzle 1	1.5480	1.5480
None	1.7080	1.7080
Rotor 1	2.3330	2.3330
None	3.2270	3.2270
Nozzle 2	4.8090	4.8090
None	4.9690	4.9690
Rotor 2	5.7560	5.7560
None	6.4880	6.4880
Nozzle 3	8.0590	8.0590
None	8.2190	8.2190
Rotor 3	9.0060	9.0060
None	9.7980	9.7980
Nozzle 4	11.3520	11.3520
None	11.5120	11.5120
Rotor 4	12.2990	12.2990
None	12.7550	12.7550

Blade Row Type

No. 1

Nozzle

No. Of Blades (> 1) = 72

(Optional) Admission = 1

Shaft Base Clearance = 0.4

No. Of Shaft Seal Fins = 49

Shaft Seal Pitch = 0.2

Shaft Seal Radius = 6.5

Shaft Seal Fin Width = 0.015

Shaft Seal Clearance = 0

Throat Blockage (< 1) = 0

Exit Area/Throat Area = 0

Radius	Betal	BetaG	Chord	Tmax	T2
12.405	90	11.46	2.056	0.577	0.015
12.815	90	11.87	2.056	0.577	0.015
13.225	90	12.31	2.056	0.577	0.015

Angles (deg with tangent), Lengths (in), Blank = Repeat Previous Value

Set Seal Pitch = 0 For Stepped And staggered Seals

Exit Area/Throat Area > 1 Specifies A Convergent-Divergent Nozzle

Blade Row Type

No. 1

Rotor

No. Of Blades (> 1) = 212

No. Of Lashing Wires = 0

Shroud Base Clearance = 1.25

No. Of Tip Seal Fins = 1

Tip Seal Pitch =

Tip Seal Radius = 13.325

Tip Seal Fin Width = 0.015

Tip Seal Clearance = 0.03

Throat Blockage (< 1) = 0

Blade Shroud Type

Shrouded

Lashing Wire Diameter =

Loss Scale Factor = 0.667

RMS Surface Finish = 0.000063

Fractional Shielding = 0

No. Of Balance Holes = 0

Balance Hole Diameter =

Shaft Radius = 6.5

Ave. Disk Axial Gap = 0.527

Radius	Betal	BetaG	Chord	Tmax	T2	1/Rc
12.375	29	20.16	0.626	0.225	0.012	0.01
12.825	29	20.21	0.626	0.225	0.012	0.01
13.275	29	20.49	0.626	0.225	0.012	0.01

Angles (deg with tangent), Lengths (in), Blank = Repeat Previous Value

Set Seal Pitch = 0 For Stepped And staggered Seals

Step 5 – Run **AxTurb** then compare results with **Aeolus**

Comparison of Overall Performance:

	Aeolus	AxTurb
Efficiency	74.9%	73.0%
Power, HP	5,140	4,891
Flow, lb/hr	80,588	78,680

Aeolus output

OVERALL TURBINE PERFORMANCE				
POWER OUTPUT & LOSSES			TOTAL TO STATIC	
Total Work Done	btu/lbm	162.49	Net Efficiency (Effic_ts)	0.7488
Gross Aero Power	hp	5518.6	Pressure Ratio (PR_ts)	22.308
Partial Admission Loss	hp	0.0	Available Energy (DeltaH_is_ts)	btu/lbm 216.76
DiskFriction Loss	hp	15.7	Velocity Ratio (U/Co_avg_ts)	0.504
Shroud Friction Loss	hp	0.7	TOTAL TO TOTAL	
Shaft Output	hp	5,140.4	Net Efficiency (Effic_tt)	0.7778
Bearing Loss	hp	0.0	Pressure Ratio (PR_tt)	20.417
Net Shaft Output	hp	5,140.4	Available Energy (DeltaH_is_tt)	btu/lbm 208.66
Output to Driven Equipment	hp	5,140.4	Velocity Ratio (U/Co_avg_tt)	0.520
Net Steam Rate	lbm/hp-hr	15.68		
Net Axial Thrust	lbf	7,974		

AxTurb output

Perf_7stageGeothermal_English-axt...		—	□	×
File Edit Format View Help				
Inlet Governor Valve Pressure Ratio = 0.97				
Inlet Admission = 100 %				
Inlet Mass Flow = 78679.96 lbm/hr				
Inlet Total Pressure = 140.65 psi				
Inlet Total Enthalpy = 343.81 btu/lbm				
Inlet Total Temperature = 355.15 deg F				
Rotation Speed = 5033 rpm				
Discharge Mass Flow = 78679.96 lbm/hr				
PERFORMANCE AT THE LAST STAGE EXIT				
Total Pressure = 7.765 psi				
Static Pressure = 6.501 psi				
Total Enthalpy = 177.39 btu/lbm				
Total Enthalpy Drop = 166.42 btu/lbm				
Total Temperature = 205.61 deg F				
Total Temperature Ratio = 1.226				
Total-To-Total Pressure Ratio = 18.67				
Total-To-Static Pressure Ratio = 22.3				
Total-To-Total Adiabatic Efficiency = 0.7737				
Total-To-Total Polytropic Efficiency = 0.755				
Total-To-Static Adiabatic Efficiency = 0.7298				
Total-To-Static Polytropic Efficiency = 0.7088				
Total Power = 5146.03 Hp				

References

1. Kacker, SC, and Okapuu, U, 1981, “A Meanline Prediction Method for Axial Flow Turbine Efficiency,” ASME J Eng. for Power, Vol. 103, No. 1.
2. Aungier, R. H., *Turbine Aerodynamics: Axial-Flow and Radial-Inflow Turbine Design and Analysis*, ASME Press, New York, 2006
3. **TurbAero** software system developed by Mr. Ron Aungier and now owned by Flexware Inc., <https://www.turbo-aero.com/turbaero>
4. Perera, J V, “Aeolus and AxStream™ Performance Calculations for a 22 MW Steam Turbine”, 2016