ADVANCED TURBINE DESIGN FOR COAL-FUELED ENGINES
QUARTERLY TECHNICAL REPORT

CONTRACT NUMBER: DE-AC21-89MC26052

Objective

The primary objective of this project is to identify and test turbine airfoil shapes and aerodynamic characteristics which may result in improved turbine and vane life for coal-fueled heat engines. The effects of particles on turbine airfoil erosion and deposition will be determined analytically with the airfoil aerodynamic flowfield and a particle trajectory analysis. Although most of the analytical work with the 2-D trajectory analysis will be focused on the aerodynamics at the midspan location, a literature survey and an exploratory analysis of the 3-D flow effects on the erosion and deposition characteristics will be conducted. The anticipated result of this program will be a better understanding of the effects of the turbine stage design parameters on erosion and deposition which, ultimately, may lead to improved turbine and vane life through the effective management of particles from the combustion process.

Current stationary gas turbines have been developed to burn relatively clean fuels, i.e. oil and natural gas. Much of the stationary gas turbine technology has been derived from aircraft gas turbines where the emphasis has been placed on high temperatures, light-weight components and high thrust. The aircraft engines burn clean petroleum fuels which produce relatively small amounts of particulates and condensable solids during normal combustion. Coal-fueled gas turbines will operate in a significantly different and hostile environment, with particulates and condensable material in the combustion products, where durability is more important than weight. Coal-fueled gas turbines require the development of a number of new technologies which are being identified by METC and its Heat Engines Contractors. Three significant problems, that were identified early in the development of coal-fueled engines, are the rapid wear of the turbine airfoils due to particulate erosion, the accumulation of deposits on portions of the airfoil surfaces due to slag deposition and the rapid corrosion of airfoils after the breakdown of surface coatings. The technology development study contained in this program is focused on improving the durability of the turbine through the development of erosion and deposition resistant airfoils and turbine operating conditions.

Summary of Progress

The baseline turbine meanline design was modified to prevent a local shock on the suction side of the rotor airfoil. New particle dimensionless parameters to be varied were determined. Three first-stage turbine meanline designs have been completed. The design of new turbine airfoil shapes has been initiated. The calculation of particle trajectories has been completed for the baseline turbine vane and blade airfoils. The erosion model described in the previous technical report was incorporated in the Post Processing Trajectory Analysis Code. Current program activity has focused on the calculation of airfoil surface erosion for the baseline turbine

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stage. The development of the three-dimensional particle trajectory code has continued under a parallel effort. A synopsis, paper and slide presentation were prepared for the Advanced Research and Development Direct Utilization, Instrumentation and Diagnostics Contractors Review Meeting. The technical items mentioned are discussed in detail below.

Technical Discussion of Progress

Turbine Meanline Designs

Baseline Turbine Design - The baseline turbine design outlined in the previous technical report was modified to prevent a local shock on the suction side of the rotor airfoil. The modification included a reduction in through-flow and a relaxation of the power requirement to maintain the overall pressure ratio. The details of the change are noted in Table 1. The original baseline meanline design parameters are shown in parenthesis.

New Turbine Designs - Three first-stage turbine meanline designs have been completed during this reporting period. In all cases the overall total turbine pressure ratio was maintained. The changes that were made to the baseline design are listed below.

1. Added a fourth stage to reduce stage loading.
2. Increased meanline radius from 35.2 to 42.2 while maintaining blade height, aspect ratio and pitch/chord ratio to reduce flow velocities relative to the airfoils.
3. Decreased pitch/chord ratio (no essential changes to the meanline output).

Summaries of the meanline designs for modifications 1 and 2 are listed in Tables 2 and 3.

The design of new turbine airfoil contours, consistent with the meanline designs presented in Tables 2 and 3, has been initiated. One of the proposed airfoil shapes is a fore-loaded design which may reduce the particle turning radius of curvature. Reducing the turning radius of curvature has the potential of reducing airfoil surface erosion through the modification of surface impact interaction.

Post Processing Trajectory Analysis Code (PPTAC)

The PPTAC is used to analyze trajectory results from the "First Pass" and "Second Pass" particle trajectory calculations. Two sets of statistics from the PPTAC analysis of "First Pass" results are used for subsequent calculations. The first set indicates where to concentrate particle initial positions for the "Second Pass". The second set indicates the average and standard deviation of the speed and direction of the particles which pass through the cascade without impacting the airfoil surface. These results are then used for initial conditions for the following airfoil row. The statistics from the PPTAC analysis of the "Second Pass" are used to determine surface interaction statistics for erosion prediction and to provide initial conditions for subsequent airfoil rows for the particles which impact the airfoil before passing through the airfoil row.

The erosion results are obtained by dividing the pressure and suction sides of the airfoil into an equal number of surface elements. Surface impact statistics for each surface element are generated from the "Second Pass" trajectory results. Erosion is determined from the sum of the erosion values predicted for each impacting particle on each surface element. Adjustment factors are applied to the predicted erosion rates (volume removed/mass of impacting particles) to normalize the results with the particle impact efficiency (i.e. percent of particles which impact the vane and/or the rotor airfoil). Additionally, the erosion results are normalized with annular impact exposure based on airfoil height, number of airfoils and airfoil surface arc length. Assuming a uniformly distributed particle loading at the turbine inlet, the normalized surface erosion predictions consist of surface recession rates which are dependent on particulate loading level at the turbine inlet. The equations used to normalize the erosion rate (surface recession/mass of particles in the turbine inlet) are shown below.

$$e_i (\text{recession/mass particulates in}) = \frac{(\sum E_i / \text{NPS}) * A_r * \text{IE}}{A_{\text{total}} * S_i * (\text{unit height})}$$

where:

- e_i = Local recession rate based on particle inlet loading
- E_i = Cumulative erosion of particle which impact surface element, i
- NPS = Total number of particles started in defined initial start region which impact airfoil
- A_r = Area of unit airfoil height and one pitch
- IE = Particle impact efficiency based on "First" and "Second" passes (i.e., $\% \text{hit}_{\text{first}} * \% \text{hit}_{\text{second}}$)
- A_{total} = Total inlet annulus area
- S_i = Surface arc length of element, i

which reduces to:

$$e_i = \frac{(\sum E_i) * (\% \text{First}) * (\% \text{Second})}{\text{NPS} * H * N * S_i}$$

where:

- e_i = Local recession rate based on particle inlet loading inches/lb
- E_i = Cumulative erosion of particle which impact surface element, i, in³/lb
- $\% \text{First}$ = Percent of particles which hit airfoil from the "First Pass"
- $\% \text{Second}$ = Percent of particles which hit airfoil from the "Second Pass" defined by the "First Pass"
- NPS = Total number of particles started in defined initial start region which impact airfoil from "Second Pass"
- H = Airfoil height, in inches
- S_i = Surface arc length of element, i, in inches
- N = Number of airfoils in blade row

and:

$$e_i(\text{cm/gm}_{\text{in}}) = e_i(\text{inches/lb}_{\text{m,in}}) * 0.0056$$

The formulations shown above were used to calculate the airfoil surface recession rate based on the particle loading at the turbine inlet. These results may be used with the particle loading factor (i.e. $\text{lb}_{\text{m,particles}}/\text{lb}_{\text{m,turbine inlet}}$) and the total turbine inlet flowrate to estimate the recession rate per unit time. In this manner turbine airfoil life can be estimated.

Baseline Turbine Trajectory Calculations

The reduction in the through-flow (discussed in the Turbine Meanline Design section) resulted in new ranges of the particle dimensionless parameters to be varied. The simulated particle diameters and densities were not changed from those previously noted. The new dimensionless parameters to be varied are listed in Table 4. An additional particle density has been added to the matrix for the baseline turbine to increase the application of the results to smaller scale turbines.

The calculation of particle trajectories has been completed for the vane and blade airfoils. A total of 18000 particle trajectory paths were calculated for the five Stokes numbers ($St = 0.068, 0.272, 1.70, 6.80$ and 27.2) for three particle density Reynolds numbers ($\sigma_p = 1781, 3563$ and 7126). A post processing trajectory analysis code (PPTAC) was used to determine particle/surface interaction statistics and calculate surface erosion. This analysis code performs a statistical analysis of the impacting particles calculated through the airfoil row and also plots surface interaction statistics. A description of the function of the PPTAC code is provided in the previous section. Percentages of particle impacts for the first vane for the selected particle parameters are shown in Table 5. Typical particle trajectory paths are shown in Figure 1. Surface impact velocity, impact angle and erosion results are shown in Figure 2.

The particle impact percentage results for the first vane of the baseline turbine show that as Stokes number (i.e. particle diameter) is increased more particles impact the airfoil surface. Therefore, for a given turbine inlet particle loading (i.e. $\text{lb}_{\text{m,particles}}/\text{lb}_{\text{m,turbine inlet}}$), erosion is expected to increase with Stokes number due to an increase in collision efficiency. The results in the table also indicate an increase in collision efficiency as particle density increases (i.e. lower values of σ_p).

Particle impact speed and impact angle strongly affect the airfoil surface erosion rate. In general, erosion rate increases with increasing impact speed. Additionally, erosion is a maximum for impact angles near 30 degrees for ductile metals. The surface impact data shown in Figure 2 show that particle velocities through the airfoil rows are increased a lesser amount for particles with large Stokes numbers compared to those with smaller Stokes numbers. This is due to the increased mass of those particles. Particles with smaller Stokes numbers tend to follow the fluid streamlines more closely, as shown in Figure 1, and therefore, accelerate with the fluid. Particle/surface impact angles (Figure 2) tend to increase with increasing Stokes number. (Note, for particles with infinite Stokes

numbers, the impact angle is a geometric function of the airfoil geometry.) Particles with smaller Stokes numbers tend to follow the fluid streamlines more closely and, for those particle which do impact the airfoil, impact at shallow angles.

The calculation of erosion rate requires the cumulative surface impact information, as well as, the airfoil impact efficiency (see discussion in the section describing the PPTAC code). The erosion results shown in Figure 2 for the first vane and blade of the baseline turbine generally reflect the observations and conclusions thus far. In summary, erosion rate generally increases with increases in either the Stokes number or the particle density. However, due to the aerodynamics of the particles leaving the vane which enter the blade airfoil row, the maximum erosion for the blade airfoil is caused by medium sized particles, $St_{vane} = 1.7$, and is not caused by the largest particles, $St_{vane} = 27.2$. This behavior is due to the blade airfoil impact efficiency. For the particles with the largest Stokes number, the initial particle trajectories are aligned with the airfoil chordline (see Figure 1 for $St_{vane} = 27.2$) which results in a substantially lower airfoil surface impact efficiency. Therefore, maximum erosion rate on the blade airfoil is not associated with the largest particles.

Three-Dimensional Trajectory Calculation Code

The development of a three-dimensional particle trajectory code has continued under a parallel, corporate-sponsored effort. The 3-D code is operational and has been modified for cylindrical coordinates with rotation terms. A 3-D flow "restart" file has been obtained to check out the code. The "restart" file has the same data storage format as that used by the NASTAR program. A suitable interpolation code will be incorporated to determine the local flow properties from the "restart" database file which is necessary for the trajectory calculation.

Reports

At the request of the DOE COTR a project synopsis, a paper entitled "ADVANCED TURBINE DESIGN FOR COAL-FUELED ENGINES" and slides for presentation were prepared for the Advanced Research and Development Direct Utilization, Instrumentation and Diagnostics Contractors Review Meeting of October 3-5, 1989 in Morgantown, West Virginia. The paper and presentation summarized completed and current activity.

Problems

No program-limiting problems currently exist.

Plans for Next Reporting Period

It is anticipated that the midspan airfoil contours for the new turbine stage designs will be generated. Flowfield calculations will be completed and trajectory calculations initiated. The development of the three dimensional trajectory calculation code will be continued.

Assessment of Prospects of Future Progress

At the present time, the prospects for future progress are good.

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Table 1. Modified Baseline Turbine Meanline Design

(Original Meanline Design Parameters in Parenthesis)

Baseline

Net Power Unit Rating, MW	79 (88)
Turbine Flowrate, lbm/sec	670 (750)
Pressure Ratio	11.3 P_{tin}/P_{tout}
Turbine Inlet Temp., F	2100

Stage Parameters:

	First Stage	Second Stage	Third Stage
Pressure Reaction (%)	50.0 (30.0)	50.0 (48.0)	50.0 (45.0)
Temperature Reaction (%)	54.7 (32.4)	61.9 (59.3)	63.5 (57.4)
Percent Work Split	26.9 (30.4)	36.6 (35.3)	36.5 (34.3)
Inlet Radius Tip, in.	37.89	38.08(39.00)	43.37
Inlet radius Root, in.	32.51	32.17(31.60)	28.98
Vane Exit Alpha	21.5 (21.7)	---	---
Blade Exit Beta	25.2 (25.5)	---	---
P_t/P_s	1.73(1.88)	---	---
Efficiency	87.8 (87.1)	---	---
Stage Power, Btu/sec	54265.4 (67792.0)	---	---
C_x/U	0.58(0.62)	---	---

Overall Turbine Parameters:

P_t/P_s	11.27 (11.31)
P_t/P_t	14.08 (13.96)
Turbine Power, Btu/s	201730.0 (223000.0)

Table 2. Modification 1: Turbine Meanline Design - Four Stage

Net Power Unit Rating, MW	84.5
Turbine Flowrate, lbm/sec	670
Pressure Ratio	11.6 P_{tin}/P_{tout}
Turbine Inlet Temp., F	2100

Stage Parameters:

		First	Second	Third	Fourth
Pressure Reaction (%)	50.0	50.0	50.0	50.0	50.0
Temperature Reaction (%)	53.5	58.1	58.8	60.0	60.0
Percent Work Split	20.2	25.0	27.4	27.4	27.4
Inlet Radius Tip, in.	37.89	39.73	43.18	46.87	46.87
Inlet radius Root, in.	32.51	32.28	30.17	27.91	27.91
Vane Exit Alpha	23.3	---	---	---	---
Blade Exit Beta	25.9	---	---	---	---
P_t/P_s	1.60	---	---	---	---
Efficiency	88.6	---	---	---	---
Stage Power, Btu/sec	41864.5	---	---	---	---
C_x/U	0.53	---	---	---	---

Overall Turbine Parameters:

P_t/P_s	11.56
P_t/P_t	13.43
Turbine Power, Btu/s	207250.0

Table 3. Modification 2: Turbine Meanline Design - Increased Radius

Net Power Unit Rating, MW	84.9
Turbine Flowrate, lbm/sec	670
Pressure Ratio	11.7 P_{tin}/P_{tout}
Turbine Inlet Temp., F	2100

Stage Parameters:

	First	Stage Second	Third
Pressure Reaction (%)	50.0	50.0	50.0
Temperature Reaction (%)	54.8	61.1	62.6
Percent Work Split	26.9	36.6	36.5
Inlet Radius Tip, in.	44.89	47.72	53.00
Inlet radius Root, in.	39.51	36.44	33.02
Vane Exit Alpha	18.1	---	---
Blade Exit Beta	21.1	---	---
P_t/P_s	1.83	---	---
Efficiency	89.6	---	---
Stage Power, Btu/sec	55849.8	---	---
C_x/U	0.39	---	---

Overall Turbine Parameters:

P_t/P_t	11.68
P_t/P_s	13.21
Turbine Power, Btu/s	207250.0

Table 4. Stokes Number and Sigma Parameter Values

Particle Diameter, D_p $St = \rho_p U_i D_p^2 / (18 \mu_i b_x)$
Microns 1st Stator Inlet

5	0.068
10	0.272
25	1.70
50	6.80
100	27.2

$\sigma_p = Re_{bx} \rho_i / \rho_p$
1st Stator Inlet

1781	(i.e. for $\rho_p = 5.00$ gm/cc)
3563	(i.e. for $\rho_p = 2.50$ gm/cc)
7126	(i.e. for $\rho_p = 1.25$ gm/cc)

Table 5. Particle Impact/No Impact Statistics

Percentage of Inlet Particles Which Impact Airfoil - First Vane (Baseline)

Stokes Number	σ_p	Percentage of Impact
0.068	1781.0	5.0
0.272	1781.0	16.0
1.70	1781.0	51.0
6.80	1781.0	72.0
27.2	1781.0	82.5
0.068	3563.0	4.5
0.272	3563.0	14.0
1.70	3563.0	46.5
6.80	3563.0	68.0
27.2	3563.0	79.0
0.068	7126.0	4.5
0.272	7126.0	12.5
1.70	7126.0	42.5
6.80	7126.0	64.0
27.2	7126.0	76.0

a.) Vane

b.) Blade

$St_v = 0.068$ $St_v = 1.70$ $St_v = 27.2$ Figure 1 Particle Trajectories for Baseline Turbine, $\sigma_v = 3563$.

Figure 2 Average Impact Statistics and Predicted Erosion for Baseline Turbine.

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