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Use of Cascade and Small Turbine Tests to Determine Erosion of Utility Turbines

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Experiments using cascades and small turbines have been conducted or are being considered to simulate large utility turbine operation with future coal-fired power plants. The purpose of these experiments is to evaluate utility turbine tolerances to particulates and to determine gas cleanup requirements for successful turbine performance. Since these tests do not fully reproduce the flow and erosion conditions in large utility turbines, this paper explores the interpretation of data from simulation experiments to assess erosion in large utility turbines. Effects of physical scale, rotation speed, and pressure differences between test cascades and small test turbines and large utility turbines are considered.

INTRODUCTION

Many of the advanced power plants being considered for utilization of coal derived fuels require large combustion turbine operation with expansion gases containing particulates. These gases must be cleaned prior to entering the turbine in order to reduce erosion, deposition, and corrosion to levels which enable acceptable turbine performance, reliability, and availability. Since large utility turbines have not previously expanded gases containing the particulates produced by advanced coal fired power plants, the degree of gas cleanup necessary for acceptable turbine operation is not yet known.

Several cascade and small turbine experiments have been conducted (1,2) or are being considered for evaluating utility turbine tolerance to coal derived fuels, especially pressurized fluidized bed combustion (PFBC) gases. Such tests are essential to determining gas cleanup requirements for successful turbine operation. However, a cascade or small test turbine cannot fully reproduce the flow and erosion environment of a large utility turbine. Consequently, the question arises as to what extent do cascade and small turbine test results indicate tolerances of large utility turbines.

This paper evaluates differences between the erosion environments produced in large utility turbines and cascades or small turbines. Some effects on erosion of physical scale, rotation speed, and test pressure are quantified. The question of the extent which cascade and small turbine test results indicate erosion tolerances of large utility turbines is explored.

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DIFFERENCES BETWEEN SIMULATORS AND UTILITY TURBINES

Large utility turbines typically operate at mass flow rates of 227 kg/sec (500 lb/sec) to 454 kg/sec (1000 lb/sec). Existing advanced coal fired pilot plants and combustion simulation facilities typically provide about two orders or magnitude lower mass flow rates. Consequently, the cascades and test turbines that have been considered to evaluate turbine tolerance to coal derived fuels have typically been quite small compared to utility turbines. Their small flow passage areas provide at acceptable experimental cost the high gas velocities necessary to simulate utility turbine erosion environments. In many cases, small cascade and test turbine simulators have also been operated at lower inlet pressures than utility turbines to provide the necessary high gas velocities with yet lower mass flow rate requirements.

Turbine design practice for high efficiencies and acceptable rotor stresses results in rotor trip speeds in the vicinity of 305 m/sec (1000 ft/sec). Consequently, small diameter turbines (with low mass flow rates for relatively inexpensive experiments) rotate at much higher speeds than large utility turbines.

Some major differences between small cascades and small test turbines and large utility turbines are then:

i) scale differences
ii) rotation speed differences
iii) operating pressure differences

For example, chord lengths of the vanes of a cascade tested at both the EXXON and Leatherhead PFBC pilot plants were less than 0.25 of the stator chord lengths of large utility turbines and the vane passage chord length is even smaller for the turbine that has been tested at the NASA PFBC pilot plant. Rotation speeds for large utility turbines typically range from 3000 to 4000 rpm. On one hand, the rotation speeds for small turbines (mass flow rate < 10 lb/sec) typically approach order of magnitude higher values while on the other hand cascade tests simulate a non-rotating environment (0 rpm). Several PFBC pilot plant cascade tests have operated at about 5 atmospheres inlet pressure while turbine inlet pressures considered for many future PFBC power plants range up to 10 or 15 atmospheres. Some effects on erosion of operating pressure, scale, and rotation speed differences between large utility turbines and cascades or small test turbines are described in the following sections.

PRESSURE EFFECTS

Erosion rate e of an object (e.g., vane or blade) in a channel of area A containing a gas flowing at velocity V with uniformly entrained particles is related to the particle arrival rate r per unit area multiplied by V to a power n which experimentally has been shown to range from 2 to 3 for most materials.

$$\frac{r\ v^n}{A} \qquad (1)$$

The particle mass arrival rate r is related to the gas mass flow rate M multiplied by the particle concentration. Uhen the particle concentration c is expressed in the usual standard condition terms of grains/standard cubic feet (gr/scf) or parts per million (ppm),

$$r\ a\ m\ c \qquad (2)$$

where by the continuity equation,

$$m = I\ VA \qquad (3)$$

Gas density $_1$ is written in terms of gas pressure P, temperature T and a constant R using the gas equation of state.

$$= P/RT \qquad (4)$$

Substitution of Equations (2) through (4) into Equation (1) gives

$$e\ a\ c\ \ V^{n+1} \qquad (5)$$

Equation (5) suggests that erosion rates measured in a simulation which provides the same gas velocity and particle concentration (expressed in gr/scf or ppm) as a utility turbine should approximately be scaled by the ratio of P/T for the gas turbine to P/T for the simulator to be indicative of erosion rates in the turbine. For example, erosion rates measured in full scale stator cascade vane tests conducted at an inlet pressure of 5 atmospheres are about a factor of 3 lower than erosion rates for a represented first stage turbine stator which operates at 15 atmospheres inlet pressure (assuming the same cascade and turbine inlet temperatures, gas velocities, particle concentrations expressed in gr/scf or ppm and passage geometries).

SCALE EFFECTS

Primary Flows

In the following, relative erosion rates are obtained for a large utility turbine first stage stator vane passage scaled from full size down to one-fourth size while maintaining the same velocity triangles. These evaluations provide an indication of the relative rates of erosion that might be experienced in a typical large utility turbine stator compared to erosion rates for small scale cascades or small turbine stators with the same velocity triangles. This initial analysis considers only the effects on erosion of the primary flow field in the stator. Secondary flow effects will be considered later.

In Figure 1, the nature of similitude used for stator vanes is illustrated. Passage mean radius, height, and axial chord are reduced by the scale factor, k, while the angular circumferential coordinates are kept the same.

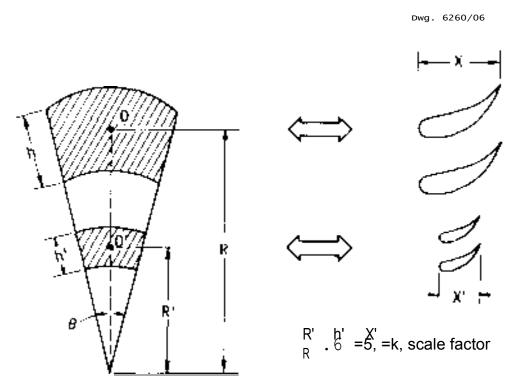

Fig. 1 - Geometric similitude for stator passages. Unprimed variables refer to full size turbine, primed variables to scaled-down model.

A turbine erosion damage model (3,4) has been used to evaluate effects of varying scale factor k on stator erosion. For this model, the flow velocity fields in turbine flow passages are determined with a standard computer program used by turbine designers. Aerodynamic forces on particles are calculated and particle equations of motion are integrated to obtain particle trajectories and impact angles, velocities, and locations in addition to rates of particle arrival. Empirical data for turbine material removed as a function of impact angle and velocity are then used to determine erosion rates versus location on the vane and blade surfaces. Results using the turbine erosion damage model will be here presented only for nine micron diameter particles. However, conclusions derived are qualitatively applicable for all sizes.

In Figures 2 and 3, particle trajectories obtained with the erosion model are shown in the stator passages with k = 1, 3/4, 1/2, and 1/4. The axes in these figures are scaled in such a way that the stator vanes appear to be of the same size for all scale factors. In this way, it is possible to see the deviation in the trajectories. In each case, particles are given a uniform distribution over the passage inlet and are assumed to be entering at the gas velocity. It is apparent from these figures that geometric scaling has a definite effect on the particle trajectories. The smaller the scale factor, the less able are the particles to follow the gas streamlines. This is not surprising, because, although the geometric boundaries and the flow streamlines are similar, and the velocities are equal at points of correspondence, the time and physical space available for particles to respond to flow accelerations and turning are

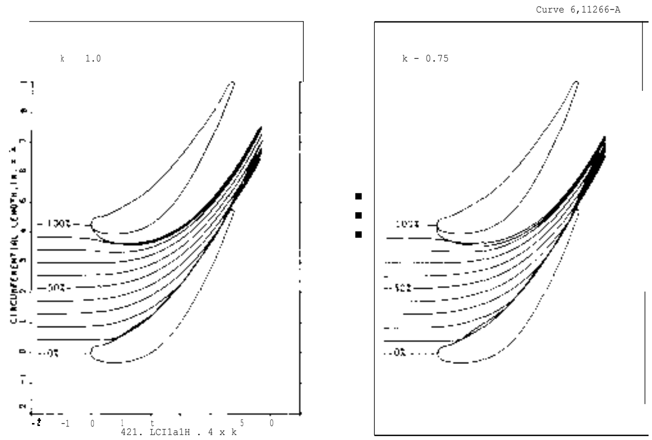

Fig. 2 - 9 pm particle trajectories in full-scale and 3/4-scale stator passages.

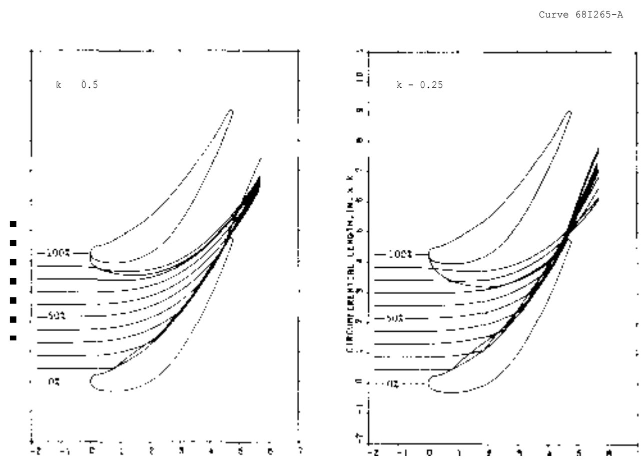

Fig. 3 - 9 pm particle trajectories in 1/2-scale and 1/4-scale stator passages.

directly reduced by the scale factor. Therefore, particles tend to deviate more and more from the gas field as the stator dimensions are decreased. This has an important bearing on the erosion damage. As will be described in greater detail, decreasing time for particles to respond to flow accelerations and turning in flow passages of decreasing scale results in (i) lower particle impact velocities, (ii) higher particle impact angles and (iii) higher particle capture efficiencies. (Capture efficiency is the fraction of particles entering the passage that impact the vanes). Lower impact velocities tend to produce lower erosion rates for smaller scales while higher capture efficiencies tend to produce higher erosion rates. Higher impact angles also tend to produce higher erosion rates for smaller scales because vane trailing edge impact angles tend to more closely approach the angle of maximum impact damage for turbine materials. Observations from materials erosivity data for a typical ductile alloy illustrates effects of particle impact angle and velocity.

Figure 4 gives erosion data collected by Grant (5) for impacts of alumina particles (of 100 micron diameter) on 2024 aluminum alloy. Although the rate of damage will be different for different materials, particle size, etc., the general shape of the curves is typical for turbine alloys and most ductile materials. Maximum erosion occurs at angles between 20 and 30 degrees,' and the specific erosion rate (mgm of material eroded per gm of particles hitting surface) is a function of at least the square of impact velocities.

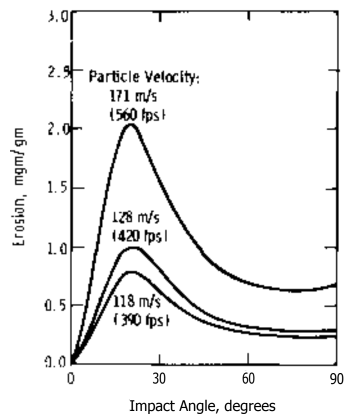

Fig. 4 - Erosion results obtained for alumina particles impacting 2024 aluminum alloy.

Under the light of these observations, we can now study the changes in impact parameters and determine their effect on the erosion damage. The increase in particle capture efficiency (and corresponding number of particle impacts) for decreasing scale of the vane passage described above is shown in Figure 5. Impact velocities and angles for various scale factors are shown in Figures 6 and 7, respectively. In accordance with the reasoning presented before, smaller scale factors imply larger deviations from the gas flow, and consequently, corresponding particle velocity curves are flatter. Except for a small region at the leading edge, impact velocities tend to decrease as the scale is reduced. The overall effect is a considerable tendency to decrease erosion damage. The impact angles plotted in Figure 7 tell a different story. The angles increase with a decrease in scale factor because the particle lag behind the gas flow increases, and the particles approach the vane surface with smaller curvatures. However, the effect of this phenomenon on erosion is mostly in a direction opposite to the velocity effect. With 9 micron particles, the impact angles are around 7 degrees for most of the full-scale vanes. One-fourth scale factor raises the impact angles to about 20 degrees where maximum erosion should occur for the material of Figure 4. This results in a steep increase in the erosion rate.

For brittle materials, maximum erosion angle shifts toward 90 . (The impact angle is defined as the acute angle formed by the tangent to the surface and the velocity vector).

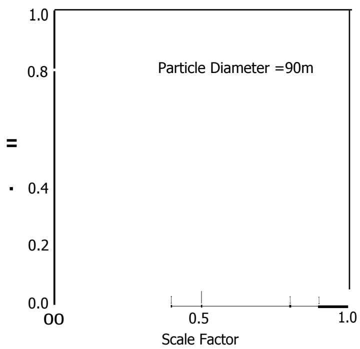

Fig. 5 Effect of scale factor on capture efficiency. (Capture efficiency = number of particles that hit blade surface/total number of particles at inlet)

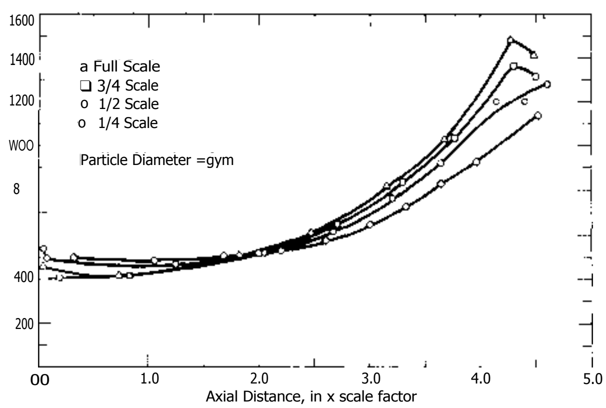

Fig. 6 - Effect of scale factor on particle impact velocities.

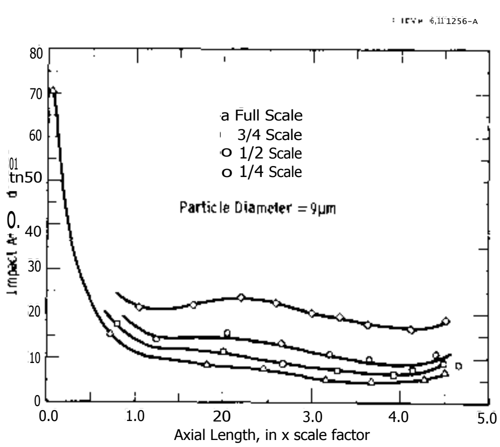

Fig. 7 - Effect of scale factor on particle impact angles.

The above results indicate the strong dependence of erosion on the scale factor. This dependence has been established through the variations in particle capture efficiencies, impact velocities, and impact angles. In order to emphasize this point, the percentage changes in capture efficiencies, impact velocities, and impact angles from their full-scale values are plotted in Figure 8 as a function of the scale factor. Since the impact velocities and angles are also a function of the axial distance, their average values are taken near the trailing edge where the erosion damage is greatest for the nine micron particles.

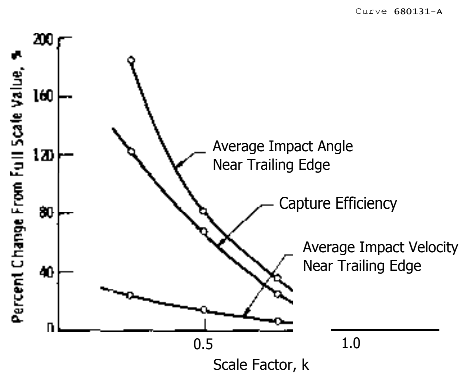

Fig. 8 - Percentage change from full scale value as a function of scale factor shown for capture efficiencies and impact velocities - angles averaged near trailing edge. Particle diameter = 9 um

In Figure 9 total relative erosion damage in the stator is plotted as a function of scale factor. The relative erosion damage was determined for a typical ductile alloy with an angle of maximum erosion in the

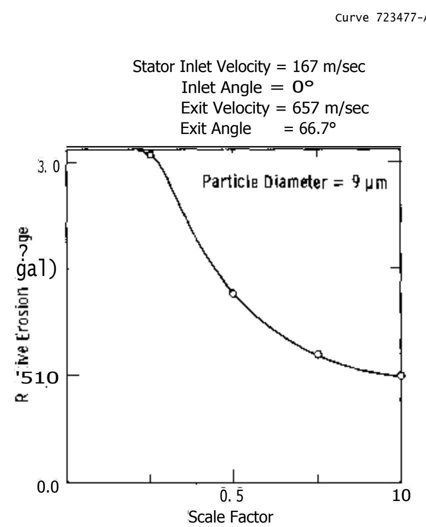

Fig. 9 - Total erosion rate in first stage stator as a function of scale factor.

vicinity of 20 . For this representative utility turbine vane passage, the combined effects of higher particle capture efficiencies and higher impact angles outweigh the effect of lower impact velocities for decreasing scale factors and erosion tends to increase with decreasing scale. Figure 9 indicates that the total erosion rate due to nine micron particles for the one-fourth scale vane is about three times that for the full-scale vane. Although results are shown in Figure 9 only down to one-fourth scale, for further decreasing scales a maximum in relative erosion might be expected followed by a fairly rapid drop in erosion. This corresponds to the particle impact angles over much of the surface reaching the angle of maximum damage for the ductile material after which larger impact angles result in decreased erosion.

Secondary Flows

The above scale effects are associated with the primary flow field in turbine passages. Erosion associated with secondary flows is also expected to be influenced by scale effects. Past small turbine tests have revealed high local erosion on vanes and blades due to highly localized particle concentrations caused by secondary flows. The larger dimensions of utility turbines enable greater secondary flow development compared to small cascades and test turbines but the boundary layers tend to occupy a smaller fraction of the flow areas for large turbines resulting in lower secondary flow intensities at any particular stage of development. Consequently, it is not obvious whether the net effect results in higher or lower local erosion in large utility turbines compared to small cascades or test turbines. Although effects of secondary flows on particle trajectories have been analyzed (6), apparently no evaluations have been conducted that quantify the effect of scale on localized erosion due to secondary flows.

ROTATION EFFECTS

Fixed Cascades

Substantial uncertainties can result in attempts to extrapolate erosion results measured in fixed cascade vane experiments to turbine rotors. The erosion environments produced in fixed vane passages (such as in cascade tests) are significantly different from the erosion environments produced in rotating blade passages. For erosion of rotor blades, particle motion depends on their absolute velocities and directions in a fixed reference frame (Newton's equations of motion are satisfied in an inertial reference frame) while damage due to the particle impacts depends on their relative velocities and directions with respect to the rotating blade. A fixed cascade vane experiment does not simultaneously produce both the absolute velocities and directions of particle flight and the relative impact velocities and directions that occur in rotating blade passages.

Figures 10 and 11 show results of applying the erosion damage models to the first stage stator and rotor of a large utility turbine for a particle loading and distribution representative of the carryover from a pressurized fluidized bed combustor after three stages of cyclone cleanup. These figures give representative erosion rates (for U-710 alloy and its oxide scale erosion response) versus axial position on the vane and blade measured in fraction of axial chord distance from the leading edge. The zero value of axial chord fraction corresponds to the leading edge and positive and negative values correspond to axial distances from the leading edge on the pressure surface and suction surface, respectively.

Even though the stator and rotor are of about the same scale and the stator exit gas velocity is several hundred feet per second higher than the exit gas velocity relative to the rotor, Figures 10 and 11 indicate that the greatest erosion rate on the rotor is about 10 times the greatest erosion rate on the stator. The higher rotor erosion rates mainly result

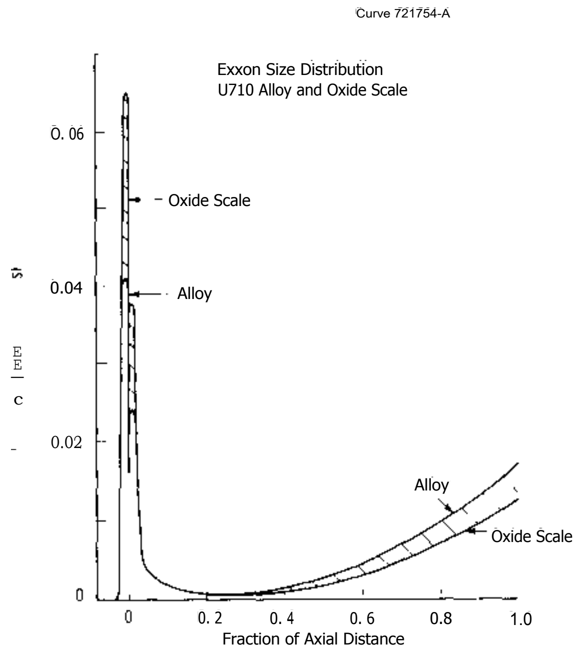

Fig. 10 - 10:1, 50 MW turbine stator erosion rates for 58 ppm (0.033 gr/scf) particle loading.

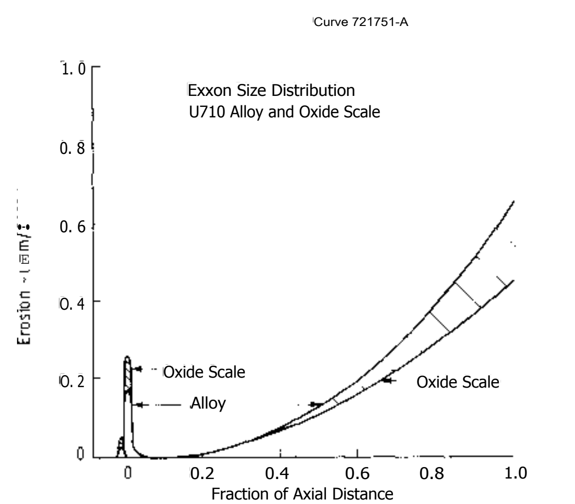

Fig. 11 - 10:1, 50 MW turbine rotor erosion rates for 58 ppm (0.033 gr/scf) particle loading.

from higher particle capture efficiencies and higher trailing edge impact angles which are closer to the angles of maximum impact damage for turbine materials. For example, Table 1 compares the stator and rotor capture efficiencies versus particle size. The rotor capture efficiencies for all particle diameters from 1 to 12 microns are about three times greater than the stator capture efficiencies.

Table 1

Comparison of Stator and Rotor Capture Efficiencies

Particle Size (Microns)	Stator Capture Efficiency	Rotor Capture Efficiency	Ratio of Rotor to Stator Capture Efficiency
1	0.02	0.07	3.5
3	0.07	0.21	3.0
6	0.16	0.53	3.3
9	0.25	0.98	3.9
12	0.35	1.00	2.9

Small Turbines

The following considers the use of measured rotor erosion rates in small turbine tests to assess erosion rates in large utility turbines. While cascade simulators can provide only stationary erosion environments, small turbines rotate at speeds up to 40,000 rpm or higher compared to 3000 to 4000 rpm for large utility turbines. The much higher rotation speeds for small turbines result in higher centrifugal forces on particles to cause migration of particles to tip regions and rebounds off end walls. The result can be a substantially different erosion environment from the first rotor through all downstream stages for a small machine compared to utility machines for which centrifugal effects are relatively small.

An approximate analysis has been used to evaluate centrifugal effects. Some of the results are given in Figure 12. In this figure, the percent of particles entering the first rotor that are centrifuged to the end wall before exiting the rotor is plotted against particle diameter for turbines of mass flow rates ranging from 611 lb/sec (3600 rpm) to 5 lb/sec (about 40,000 rpm). For the large utility turbine (611 lb/sec mass flow rate) only a few percent of the particles less than 15 microns in diameter are centrifuged to the end wall while for the smaller turbines over 209 of the larger particles are centrifuged to the end wall.

These results were obtained for conceptual turbines, all having the same design variables (rotor tip speed, velocity triangles, etc.) as those for the existing large utility turbine. However, it is important to note that the degree of centrifuging is substantially affected by axial gas velocity, blade axial chord and other turbine design variables in addition to rotation speed. For example, the amount of particle centrifuging is significantly affected by the ratio of rotor blade axial chord to average axial gas velocity in the rotor passage which approximates the time that particles are subjected to rotor centrifugal forces. Consequently, an assessment of centrifugal effects for any small machine requires an evaluation using its particular design variables.

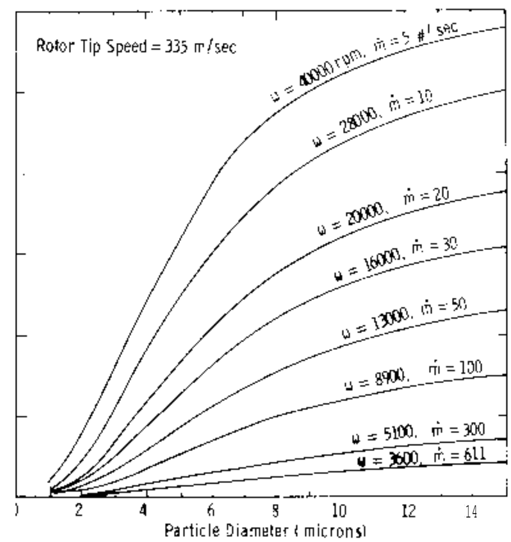

Fig. 12 - Particle centrifuging in first rotor versus turbine rotation speed.

INTERPRETATION OF CASCADE AND SMALL TURBINE TESTS

Some bases have been provided for evaluating small cascade and turbine tests to predict erosion performance of large utility turbines. Since velocity triangle effects can he significant, the following comments refer to extrapolation of small cascade or small turbine erosion results to large utility turbines with equivalent flow velocities and flow turning angles. For dissimilar velocity triangles, the turbine erosion modeling techniques applied to the specific cascade or small turbine and the utility turbine configurations can be used to extrapolate test results.

The above discussions indicate that cascade and small turbine experiments typically do not directly yield erosion rates and erosion tolerances of large utility turbines. Erosion rates measured in simulation tests could differ from utility turbine erosion rates by factors of three up to perhaps as much as an order of magnitude. Measured erosion rates from tests conducted at equivalent gas velocities and particle loadings (expressed in gr/scf or ppm) but at lower pressures than the utility turbine simulated should he scaled by the ratio of utility turbine to test pressure (usually gas temperatures are reproduced for corrosion evaluations).

The previously described results also indicate that erosion rates for large utility turbine stators may be less than erosion rates measured on small scale cascade vanes ingesting the same particle loadings. Because fixed cascades do not produce erosion conditions in rotors, erosion rates for utility turbine rotors may he much higher than erosion rates measured on small cascade vanes. The magnitude of the difference in erosion rates between a utility turbine and a cascade depends to a great extent on specific velocity triangles and scale differences.

Large utility turbine stators may experience lower erosion rates than small turbine stators due to scale effects. If centrifuging in a small turbine test is so great that a substantial percentage (perhaps above 201) of the most erosive large particles entering the first rotor passage migrate to the end wall before exiting the rotor, the erosion data may be so difficult to interpret as to be inferior to fixed cascade test data in terms of extrapolation to large utility turbines. For high centrifuging, particle rebounds from the end wall and three-dimensional effects such as particle flight through regions of changing velocity triangles and blade contours due to blade twist could produce erosion environments quite unrepresentative of those in large utility turbines. Since turbines of different designs, but with similar mass flow rates and rotation speeds could produce significantly different centrifuging effects, a careful choice of test turbines can facilitate obtaining interpretable data. Although a small turbine that minimizes centrifuging may have significantly different velocity triangles from the large utility turbine being simulated, the effect of velocity triangle differences on erosion may be more readily evaluated than high centrifuging effects.

Local erosion in large utility turbines due to secondary flows may possibly be higher than secondary flow erosion measured in either small cascade or small turbine tests. Of particular concern may be possible increased local concentration of particulates due to secondary flows and resulting local erosion through successive turbine stages since most small turbine tests to date have utilized single stage turbines. Since scale effects on erosion produced by secondary flows have apparently not been quantified, these effects are a major uncertainty in establishing erosion tolerances of utility turbines to PFB combustion gases and other coal derived fuels.

ACKNOWLEDGMENT

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REFERENCES

1. Hoy, H. R., and Roberts, A. G., "Investigations on the Leatherhead Pressurized Facility", Proceedings of the 6th International Conference on Fluidized Combustion, Atlanta, Georgia, April 9-11, 1980.

2. Moskowitz, S., "Pressurized Fluidized Bed Combined Cycle", Turbomachinery International, March 1980, pp. 36-39.

1. Sverdrup, E. F., Archer, D. H., and Menguturk, M., "The Tolerance of Large Gas Turbines to 'Rocks', 'Dusts', and Chemical Corrodants", Proceedings of the EPA/DOE Symposium on High Temperature Particulate Control, EPA-600/9-78-004, CONE-770970, Sept. 1977.

4. Menguturk, M. and Sverdrup, E. F., "Calculated Tolerance of a Large Utility Gas Turbine to Erosion Damage by Coal Ash Particles", from Erosion: Prevention and Useful Applications, edited by W. F. Adler, American Society for Testing and Materials Special Technical Publication 664, 1979.

5. Grant, G., "Model to Predict Erosion in Turbomachinery Due to Solid Particles in Particulated Flow", University of Cincinnati, Ph.D. Thesis, 1973.

6. Ulke, A., and Rouleau, W. T., "The Effects of Secondary Flows on Turbine Blade Erosion", ASME Paper 76-GT-74, 1976.