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EROSION STUDY IN TURBOMACHINERY AFFECTED BY COAL AND ASH PARTICLES

Phase 1

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ABSTRACT

Turbomachinery operating with coal particles or using pulverized coal as fuel are exposed to erosion. The problem of predicting erosion in rotating machinery is very complex. A review study of turbomachinery erosion research performed by the "Australian Coal-Burning Gas Turbine Project" is completed.

OBJECTIVE AND SCOPE OF THE WORK

The objective of this research is to perform an experimental and theoretical study of the erosion of potential turbine materials caused by coal and ash particles. Attempts will be made to determine the factors which are significant in such erosion, and a computer model will be developed which will facilitate the prediction of potential for erosion in future turbomachinery design.

SUMMARY OF PROGRESS TO DATE

In the first quarterly report a historical review of the erosion literature in regard to turbomachinery erosion was reported. The present report deals with the Australian research progress in the same area. The preparations for testing in the cold erosion wind tunnel are completed. Turbine blade materials will be tested in the coming weeks. The results of the tests will be reported in the next progress report.

REVIEW OF THE AUSTRALIAN COAL-BURNING GAS TURBINE PROJECT

Introduction

Australian research on the burning of coal in a gas turbine [1], conducted between 1948 and 1970, was intended to develop a combustion and turbomachinery system that would operate efficiently and economically on the abundant coal fuel. Several problem areas were investigated, including coal combustion processes, methods of feeding and pulverizing coal, erosion and deposition on the turbine blading, solids separation, and blade materials. Extensive experimental studies were carried out to determine the characteristics influencing blade erosion, as this was recognized to be a limiting factor in the gas turbine operation. In addition to controlled experiments with small laboratory rigs, data was collected from tests on a 1 MW gas turbine to enhance the understanding of erosion phenomena as it occurs in turbomachinery. The technical feasibility of operating a directly-fired open cycle gas turbine on pulverized coal was demonstrated. Therefore, the results of the Australian project should be carefully reviewed to identify those which may be applicable to our current research.

Coal Types Used

Composition of the coal, particularly its ash content, must be known so that the sizes, shapes, and concentrations of the unburned particles entering the turbine can be determined. Three types of coals were used in the erosion studies, and their pertinent characteristics are noted. Victorian brown coal contained a high percentage of volatile matter, and it was low in both ash content (1.5% to 3%) and mineral matter found in the ash. Bituminous (black) coal from the Greta Seam was higher (5% to 8%) in ash content, and the mineral matter (primarily silica and alumina) constituted about 80% of the ash composition. A Queensland black coal from the Callide area was comparatively low in volatile matter and very high in ash content (14%) and moisture. A complete chemical analysis of all coal types is given in Appendix B of reference [1]. Note that the composition of these coals in terms of ash content and particle size is quite similar to the coal ash provided for our research.

The importance of knowing the coal composition was graphically illustrated in the Australian research. With each of the three types of coals tested, different erosive characteristics were observed. Also, different methods of pulverization, combustion, and separation were associated with each type.

Initial Laboratory Tests

Prior to the gas turbine tests, the possibility of blade erosion caused by coal ash passing through the turbine was anticipated. So a laboratory rig was built to impact heated ash particles of less than 10 microns in diameter on a small target made of the blade material. No erosion damage to the specimen was observed with brown coal, although substantial ash deposition occurred. Further tests using a small aircraft turbo-supercharger produced the same results, again using the brown coal. Ash deposition appeared to be the major problem, so considerable effort was made to determine the effects of gas temperature, gas velocity, and specimen size on its occurrence. At high gas velocities, the deposition of hard ash was observed to decrease, presumably due to its erosion by ash particles. This led to the thought of adding erosive particles to the turbine inlet flow in order to remove large ash deposits, while being careful not to cause blade metal erosion at the same time.

Ruston & Hornsby Gas Turbine Tests with Brown Coal

A 1MW Ruston and Hornsby "TA" Gas Turbine was purchased, and its combustion chamber was replaced with one that had been developed to burn coal. It had a two stage high pressure axial turbine used to drive a 13 stage axial compressor, followed by a two stage low pressure turbine connected through a reduction gear box to the load. Initial tests were conducted with the brown coal, but unlike the laboratory controlled tests, the mean size of the ash particles entering the turbine was 36 microns.

Severe erosion of both rotors and stators in the high pressure turbine resulted. Heavy erosion occurred on the pressure (concave) surfaces, especially near the trailing edges, along with pitting of the second stage leading edges and notching of the rotor blade roots. An ash separator was installed between the combustor and turbine to reduce the mean particle size to about 6 microns, with the largest particles less than 25 microns. This substantially reduced erosion rates by 30 to 70 times the initial values, but the erosion was still considered high enough to limit industrial application. At this point, several observations were noted which seemed to have some correlation with the erosion phenomena: (a) the weight of ash particles greater than 16 microns had been reduced by the separator in the same proportion as had been the erosion, thus indicating that particles larger than 16 microns are significant in the erosion process; (b) blade cleaning methods used to remove ash deposits did not significantly add to the blade metal loss; (c) turbine gas velocities approach 1100 fps in the high pressure turbine where erosion is severe, while they only reach 800 fps in the low pressure turbine where erosion levels are low enough to be acceptable. It was concluded that operation of a gas turbine on pulverized brown coal was technically feasible and could be put to commercial use, provided that adequate ash separation was possible and that the turbine could be redesigned for lower gas velocities.

Initial Work with Black Coal

Preliminary experiments in the laboratory rig using the bituminous (black) coal were conducted concurrently with the Ruston and Hornsby gas turbine brown coal tests. Their main purpose was to accumulate data on which to base a combustor design for future tests with the gas turbine using black coal. A smaller gas turbine (Rover 1S/60) was modified with a solid fuel combustor, and it was operated on both brown coal and black coal to obtain comparative data on blade erosion and ash deposition. Erosion patterns were similar for both coal types, but the results did not correlate with the brown coal tests on the Ruston and Hornsby gas turbine. In addition, it was observed that despite a tenfold increase in the amount of black coal solids passing through the Rover turbine, the rate of erosion was lower than that of the less concentrated brown coal solids. At this point, it was concluded that these preliminary Rover gas turbine tests could not be used to predict the erosion characteristics of the Ruston and Hornsby gas turbine fueled by the Greta-seam coal.

Ruston and Hornsby Gas Turbine Tests with Black Coal

Subsequently the Ruston and Hornsby gas turbine was run using the black coal of higher ash and mineral content. Initial tests experienced severe blade erosion, primarily due to an ineffective ash separation system which allowed mean particle sizes of 20 to 30 microns to enter the turbine. Later tests, using a finer coal feed, reduced these mean sizes to 6 to 8 microns, with the largest sizes not exceeding 20 microns. These sizes were then comparable to those of the brown coal tests, but the measured erosion rate of the high pressure turbine blades was nearly four times larger with the Greta-seam coal. As in the brown coal tests, the wear rate in the power (L.P.) turbine was commercially acceptable, about one-tenth that of the compressor (H.P.) turbine.

Erosion was expressed as milligrams of metal eroded from the blade per square centimeter of wetted area per kilogram of solids fed to the turbine inlet. Its accuracy was thus dependent upon the accurate measurement of solids loading, which could only be determined within a ±15 percent error. Due to the considerable variation in particle size from test to test, it was possible to note the size effect upon the erosion rate. As particle size was increased, erosion continued to increase as expected, but the erosion rate showed no signs of leveling off (as was observed in subsequent tests with the Rover gas turbine and in tests of particle impingement on a flat plate specimen). Although data scatter was considerable, the erosion for each blade row could be extrapolated to zero at a mean particle size of slightly less than 5 microns. The effect of the blade exit gas velocity on erosion was noted to be similar to that observed during the brown coal tests, the erosion being proportional to gas velocity raised to a power between 3 and 5. However, neither the effect of particle velocity nor impingement angle was considered at this time. Another general observation of these black coal tests was that engine performance significantly decreased as blade erosion progressed. In fact, the reduction in power output of the turbine due solely to the blade profile effects after testing with the larger (20-30 microns) particles was measured as 29 percent. It was clearly established that the blade life in this gas turbine was governed by the loss of aerodynamic performance due to erosion of the H.P. turbine blade surfaces.

Erosion Tests on Modified Rover Gas Turbine

To confirm the erosion results observed on the Ruston and Hornsby gas turbine, further experiments were conducted on the Rover 1S/60 gas turbine [2]. The Rover was modified to operate on "clean" fuel using an externally controlled air supply, permitting known quantities of silica and coal particles to be injected into the turbine at temperatures (1150-1250°F) and velocities (900-1200 ft/sec) typical of the Ruston and Hornsby engine. Although the range of conditions tested was not large, sufficient data was obtained to determine the effects of particle size, gas velocity, particle velocity, and to a lesser degree the angle of impingement and centrifugal forces upon the blade erosion rate. Tests were run with three grades of silica particle sizes; a fine grade containing particles from 0 to 7.5 microns, a medium grade of sizes from 0 to 15 microns, and a coarse grade containing a range of 0 to 22.5 microns, in concentrations similar to those measured during the Ruston and Hornsby turbine tests. These particle size ranges collectively represented 90 percent of the overall size range of coal ash particles measured at the inlet to the Ruston and Hornsby gas turbine. When inspected under a microscope, the silica particles were found to be sharp and jagged, which indicated a highly erosive nature. In fact, test results showed severe erosion on the rotor blades at the trailing edge tip on the pressure surface and also to some extent on the suction surface. Stator blades were eroded on the pressure surface near the trailing edge, more severely near the inner diameter than at the outer diameter. Qualitative observations indicated that the particles experienced centrifugal accelerating forces as they moved through the stator blade row, tending to concentrate them near the pressure surfaces. Upon leaving the blade row, the imparted exit swirl resulted in a radial force which centrifuged the particles outward toward the shroud.

The effect of particle size on erosion rate, defined here as milligrams of metal eroded from the blade per kilogram of silica injected, was observed to agree with results obtained by other researchers [3]. Increasing particle size increased the erosion (at a given gas velocity) but at a diminishing rate as size was further increased. The maximum mean particle size necessary for zero erosion was experimentally found to be 5 to 7 microns, which compared favorably with the estimate of 5 microns from the Ruston and Hornsby turbine tests with black coal. In addition, an analytical expression, developed by M.C.G. Smith [4] to identify the proportion of particles entering a blade passage which eventually hit the blade surface, was used to predict the particle sizes necessary for total (100%) impact. Silica particle sizes of 6 to 7 microns were calculated as being the minimum that would experience total impact, i.e. not be significantly deflected by the airstream so as to miss the blade surface. It was in this particle size range that erosion rates were observed to change rapidly with changes in mean particle diameters, indicating a large influence of the flow pattern. Interestingly, as gas velocities (and, indirectly, particle velocities) were increased, the maximum particle size allowable for zero erosion decreased, which indicated that a particle of a given size would produce no erosion at a low velocity but would erode the blade at a higher velocity.

The effect of velocity on erosion was determined by observing the relationship of erosion rate with both particle velocity and gas stream velocity measured only at the exit of each blade row. Erosion increased as gas exit velocity increased, but its rate of increase was positive on the shroud, negative on the stators, and either positive or constant on the rotors. Likewise the correlation of particle exit velocity to the observed erosion rate yielded similar inconclusive results. Assumptions were made to simplify the calculation of particle velocities such as ignoring the velocity components in the direction of the rotor inlet relative flow and normal to the stator outlet flow. Actual particle velocities may have been higher, particularly in the rotor where the particles entered the blade passage at large negative incidence angles and experienced multiple impacts through the blade row. Such complex trajectories cannot be defined simply in terms of the exit velocity, as was discovered.

Laboratory Erosion Rig with Flat Specimen

Further attempts were made to isolate and evaluate the various factors influencing erosion rate under conditions simulating the gas turbine environment. A laboratory rig was built which would inject particles into an air stream and direct them upon a tilted plane specimen. Both silica and coal ash particles were used, the coal being the black type from Queensland (Callide). Among the parameters which could be controlled were particle velocity, angle of incidence, specimen material, gas stream velocity and temperature, and particle size. An extensive literature survey conducted at this time revealed little data obtained by other researchers with particles of the very small sizes typical of coal ash.

The most significant effect measured with this apparatus was that of angle of incidence of the specimen; 90 degrees being normal to the air-particle stream, and 0 degrees being aligned tangent to the stream. The results obtained were qualitatively similar to those of other researchers; that erosion increased as the angle of incidence was increased from zero degrees, reach a maximum level at some intermediate angle, and then decreased as the angle was further increased to 90 degrees (normal impact). However, unlike the results of many others using larger sizes particles, (Neilson and Gilchrist, Wood and Espenschade, Bitter, Sheldon and Finnie, and Tabakoff and Grant) the angle of incidence at which maximum erosion occurred was measured to be larger than 30 degrees. This maximum erosion angle was also observed to be a weak function of target material and particle size, generally decreasing as particle size was increased. One possible explanation for this apparent disagreement with other researchers, who found the angle of impact for maximum erosion to be nearer 20 degrees, is that the influence of the deflecting gas stream upon the small particles approaching the specimen becomes significant. It is erroneous to report the angle of incidence of the specimen in this rig to be equivalent to the angle of impact of the particles upon its surface, since the particle sizes tested were small enough to be affected by the local flow field around the flat plate specimen. As the particle size was increased, the angle of incidence for maximum erosion tended to decrease, which indicated the lessening influence of the airstream upon the particles trajectories. For quantitatively correct results, the aerodynamics of the flow in the vicinity of the specimen should have been evaluated if erosion was to be correlated with the true angle of particle impact. As an incidental result, the ratio of maximum erosion to that at an angle of 90° was about 2 for tests at atmospheric temperature; however this value was not a common result for small particle sizes below 7 microns at elevated temperatures.

Temperature was observed to affect the erosion rate, but insufficient data was reported to allow formulation of any distinct relationships. Tests were conducted at both atmospheric temperatures and at elevated temperatures where the gas stream temperature of 1238°F heated the specimen to just over 1000°F. In general, the erosion rate of the two temperature environments was very similar over the range of incidence angles where maximum vlaues of erosion were attained. However, the erosion was significantly lower at the larger impact angles (above 50 degrees) for the elevated temperature tests. It was postulated that perhaps the higher temperatures caused softening of the coal ash and secondary hardening of the target material, both tending to reduce the erosion rate.

As was observed in the modified 1S/60 Rover gas turbine tests, erosion increased rapidly as mean particle size was increased from its "zero" erosion value up to about 7 microns. As the mean particle sizes were further increased, the rate of increase of erosion was considerably reduced, and appeared to approach a constant value at very large mean particle sizes. However, these results must again be examined for possible influence of aerodynamic effects. A lesser proportion of the smaller particles struck the target due to the deflection of the gas stream, and as the mean particle size was increased, the corresponding increase in the proportion of particles which hit the specimen caused the resulting increase in the erosion rate.

Erosion could not be correlated with the calculated blade row exit velocity in the Rover gas turbine, but the laboratory rig did achieve a velocity dependence consistent with those of other researchers. With the targets set at a 45° angle of incidence, silica particles of 9 microns mean size and Callide coal ash particles of 6 microns mean size produced erosion (milligrams of metal eroded per gram of abrasive fed) rates proportional to velocity raised to the powers 3.4 and 2.3 respectively. Whether the velocity reported was the gas stream velocity or the particle velocity was not clear, although in either case the values would be practically identical. What is significant is that the velocity was associated with the incoming particle kinetic energy, and not with values of the discharge flow.

Even differences between erosion rates observed during initial testing on new specimens and those attained in subsequent tests were noted. The materials tested in this rig suffered an initially high erosion rate which dropped off to lower and more stable values after several hours of operation. These same characteristics were later observed in the gas turbine tests, and were thought to be related to the surface conditions of the target material as protective oxide layers formed.

Ruston and Hornsby Gas Turbine Tests with Callide Coal [5]

Additional erosion data was obtained with the Ruston and Hornsby gas turbine operated on Queensland black coal from the Callide area. The high ash content and low volatility of this coal caused difficulties in providing adequate combustion and particle separation. However, a combustion chamber was developed which operated at 98% efficiency, and the particle separator was able to deliver ash particle size distributions at the turbine inlet that were similar to the smallest achieved in the Greta seam black coal tests. The measured mean particle sizes were between 4 and 8 microns, so it was not surprising to find that the specific erosion rate produced by the Callide coal was no different from that of the Greta coal. Significantly different, however, was the overall blade metal loss which was four times greater for Callide coal ash ingestion than for the Greta seam black coal. Due to its higher ash content, Callide coal ash solids loading to the turbine (determined within a ±13 percent error) was four times greater, which corresponded to an equivalent reduction in blade life.

Erosion patterns observed on rotors and stators were similar to those measured in the Greta tests; again, the greatest erosion rates occurred in the first stage rotor blades of the high pressure turbine. As before, the stators eroded most severely in the trailing edge tip region on the pressure surface. The low pressure turbine blading continued to experience insignificant erosion. Different blade materials were used to investigate their effects upon the wear rates, and the findings showed that suitable surface treatments would extend blade life. Although difficulties were experienced in making accurate measurements of mean particle sizes and solids loading, and although variations in turbine gas velocities were experienced from test to test, the qualitative results indicated that the blade erosion produced by the Callide coal ash was the prime factor in limiting engine operation.

Redesign of the Ruston and Hornsby Gas Turbine to Reduce Erosion

The logical conclusion to the Australian coal-burning gas turbine research effort was to apply the results obtained in all tests of the Ruston and Hornsby engine, the Rover gas turbine, and the laboratory rig to the design of a turbine that would have commercially acceptable blade life. A large reduction in the erosion rates of the high pressure turbine was necessary to achieve the goal.

Ash separation had been developed to a practical limit such that the sizes of particles entering the turbine could not be reduced below a range of 4 to 8 microns. Similarly, the combustion processes for the various coal types could not be improved to sufficiently reduce the rate of solids loading to the turbine. Within these constraints, a reduction in gas (or particle) velocity was chosen as the means for a substantial decrease in blade erosion. In all previous tests, the low pressure turbine had suffered negligible erosion, even though samples taken at the inlet indicated that the mean particle sizes ingested were similar to those of the high pressure turbine. The main reason for this lower erosion rate was attributed to the lower velocities (800 feet per second) as compared to those of the h.p. turbine (1100 feet per second). It was also recognized that at the lower velocities, more annulus area (and thus large blades) was required to pass the same mass flow, thus resulting in a smaller number of particles impinging on a unit area of the blade surface. To create these conditions in the high pressure turbine required the addition of the third stage to the original two-stage design if the same power output was to be achieved.

A thermodynamic analysis based upon one-dimensional flow characteristics and free-vortex criteria was used to design the three-stage turbine [6]. Work output was distributed evenly among the three stages to equalize velocities (and thus erosion rates) throughout the turbine. Design velocities were chosen to be slightly higher in the stators where it was felt that more erosion could be tolerated. Recognition of secondary and cross channel flows [7] resulted in additional features being incorporated into the blade designs. Particles tended to concentrate on the pressure face of the blades near the trailing edge, so the trailing edge thicknesses of both rotors and stators were increased beyond standard design values to provide more metal to be eroded before performance would significantly deteriorate. Radial migrations of ash particles towards both outer and inner diameters created localized areas of severe erosion, so mid-span stator "wake fences" were employed to redistribute this ash into the main gas stream. Regions of low momentum flow, such as in blade wakes and in separated zones on the blade surface, were noted as being particularly vulnerable to small particle movements inward due to the radial static pressure gradients, but rather than attempt to reduce the extent of these regions (which would require thinner trailing edges) the stator fences were considered adequate in limiting radial flows. To further insure that the ash reaching the inner boundary would not severely erode the rotor blade root sections, the cantilevered stator free ends were recessed into the ID surface.

Prior to initiating tests with solid coal fuel, the redesigned three-state turbine was operated on liquid fuel to compare its performance with that of the original two-stage high pressure turbine. The results were very similar, and measurements indicated that the outlet gas velocities from each blade row were between 760 and 865 feet per second.

Subsequently the redesigned turbine was operated with black coal from the Greta seam which had produced significant erosion in earlier tests [8]. Ash samples taken at both the turbine inlet and exhaust showed mean particle sizes similar to those recorded in the earlier black coal tests using both Greta seam and Callide types. Interestingly, this same particle size distribution was demonstrated in the Bureau of Mines redesigned turbine. As in the previous tests, ash deposition was very slight and was confined to the leading edge region of the first stage stators. Initial blade erosion rates were high for the first 50 hours of testing, but afterwards stabilized to nearly constant values for the remainder of the test. As observed in earlier tests, the first stage rotor blade erosion rates (expressed as milligrams of metal eroded per square centimeter per kilogram of ingested ash) were higher than those of the following rotors, while the second and third stage stators experienced more than double the erosion rate of the first stage stator. Evidence of particle centrifuging was implied by the areas of heavier blade erosion in the outer annulus region, particularly along the pressure surface. The stator fences limited the transport of small particles towards the inner diameter since the fences themselves experienced some erosion, as did the sections of the rotor blades opposite them.

Although the blades and vanes in the redesigned turbine were manufactured from a more erosion-resistent material than were those of the original two-stage high pressure turbine, the measured erosion was adjusted to what would have occurred with the original material. This adjustment was made on the basis of tests with the Ruston and Hornsby gas turbine operated on Callide coal using both blade materials. A comparison of erosion rates between the original and redesigned turbines (assuming use of the same blade material) indicated that the metal loss per kilogram of ash in the three stage turbine was reduced by factors of 6.6 and 8.2 in the first and second rotor rows respectively, and by 4.7 in the first and second stator rows. These reductions may increase the estimated blade life.

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