MEASURING MICROPARTICLE IMPACT CHARACTERISTICS UNDER REALISTIC GAS TURBINE CONDITIONS

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Abstract

Gas turbines can be exposed to microparticle ingestion throughout their lifespan due to the harsh conditions, like deserts, in which many of them operate. Microparticles can wear out turbine blades and clog cooling holes which may result in the failure of the blade. To measure the interaction of microparticles with turbine components the Coefficient of Restitution (COR) is used. The objective of this research is to find the COR of these particle interactions at realistic gas turbine conditions using the VT Aerothermal Rig. The rig has recently been updated to be able to run safely up to 800°C. Test have been conducted at four different temperatures (25°C, 260°C, 600°C, and 800°C), using 10-20 µm and 20-40µm Arizona Road Dust on both stainless steel and Inconel coupons. Each of these tests were run at six different coupon angles (30°, 40°, 50°, 60°, 70° and 80°). These tests have shown that the COR decreases when the temperature and velocity increase.

Motivation

In aircraft and industrial gas turbines, environments contaminated with sand and other small particles are unavoidable, as shown in Figure 1. Even though there are filters to deal with this problem it is impossible to get rid of all the particles. These particles can wear down the turbine blades which can shorten the lifespan of the part. They also may clog the cooling holes which could cause the turbine blades to fail at high temperatures.

Figure 1. Example of a contaminated environment [1]

Modeling the trajectory of these particles can lead to a better understanding of the precise regions most susceptible to the effects of particle ingestion. The most common way to measure impact is using COR which is defined by equation 1.

\[ e = \frac{v_2}{v_1} \]  

Where \( e \) is COR, \( v_1 \) is the velocity of the particle before impact, and \( v_2 \) is the velocity of the particle after impact. Finding the COR for these particles will advance the development of accurate models of particle impact in gas turbines. Also, the techniques used in this project can be used for future projects that will also further the accuracy of these models.

The COR is dependent upon impact particle velocity, angle of impact, particle composition, temperature, and the material of the surface [2]. Due to all of these factors it is important to run many different tests in order to create a more universal model. The VT Aerothermal Rig is constantly being updated to accommodate for this diverse set of parameters.
Experimental Methodology

The VT Aerothermal Rig donated by Rolls Royce, shown in Figure 2, is being used to find the COR of sand particles on stainless steel and Inconel coupons. The operational specifications for this rig when installed at Rolls Royce were reported as 2.2kg/s at a maximum of 16atm and 1800°C. Currently the rig is run at atmospheric pressure with a mass flow rate of 0.15kg/s and a max temperature of 800°C. The temperature is being stepped up gradually and there are plans to soon run the rig at 1100°C. The original rig has been updated to allow for the injection of sand into the air flow. This update includes the sand injection nozzle and the equilibration section.

![Figure 2](image2.png)

To run tests the rig is supplied air by a compressor at a constant rate of 0.15kg/s. The air flow is regulated upstream with a globe valve where it then passes through a sudden step expansion and into the burner section. Methane, which is being used as fuel, flows through a fuel ring with up to 12 fuel nozzles. The fuel exiting these nozzles mixes with the air and is ignited using a hydrogen/air pilot light. At the exit downstream of the burner, the cross-section of the flow is reduced in diameter from 12” to 3”. Inside the contraction section, the sand particles are injected into the mainstream flow. These particles are entrained in a compressed air flow that is bled from the main flow upstream of the burner. This relatively cool flow of sand and air is then injected and mixed with the hot mainstream flow. The particles then enter the 6ft long equilibration tube. This enables the particles to accelerate to the same speed and temperature as the mainstream flow. The flow exits the equilibration tube as a free jet into the test section and impinges on the test coupon. The test section contains a test coupon, on which the impacts occur, and a support to allow for rotation of the coupon. The test section also has a laser access port as well as optical access for the camera to image the area in front of the coupon. The camera is actively cooled using a ventilation fan to ensure safe operation during heated testing. The interaction between the sand and the test coupon is photographed using particle tracking velocimetry (PTV), shown in Figure 3. PTV works by taking a pair of images very rapidly. By knowing the time difference between the two images and where the particles are in each image the velocity components for the particles can be found. The laser and camera that are being used to conduct these experiments are set up to take sixty pairs of images. A Matlab code is used to post-process the images which provides the velocity of the particles before and after impact. From these velocities the COR of the particle coupon interaction is found.

![Figure 3](image3.png)
Rig Updates

Blackout Cloth

The small size of the particles being photographed makes them difficult to capture. Any excess light that is captured by the camera can make the images unusable. This includes the lighting in the building and the natural light from the windows. Consequently it is very important to block out all light around the test area. Since the test area can become very hot the method used to block out the excess light must be able to endure high temperatures and also can’t trap in a lot of heat. To solve this problem a blackout cloth shield was developed. The material used is a high temperature and heat resistant fiber glass cloth produced by AB-Thermal which is specified to be able to withstand 537°C. The blackout cloth is 37.5” x 39” x 39” and is supported by a frame made from 80/20 extruded aluminum. At the top of the cloth there is a vent in order to let the trapped heat escape. This design successfully blocks out enough light so that the test images are usable while not trapping in enough heat to damage the camera.

Cooling and Insulation

Over the past year the VT Aerothermal Rig has gone from being run at ambient temperature to 800°C. Being able to run at such high temperatures was the result of a few different modifications to the rig. Overheating the camera is a large concern when performing tests at high temperatures. To monitor the camera temperature a thermocouple is being used near the lens of the camera. Also, to cool the camera a fan system that pulls cold air from outside the building and directs it at the camera was designed, shown in Figure 4. This system successfully keeps the camera at an acceptable temperature when running at 800°C. In the future when running higher temperature tests the fan may be replaced by a small air conditioner to further decrease the camera temperature.

A large amount of heat is lost in the equilibration section of the rig. In order to reduce the fuel required to run the rig, insulation was implemented from the outlet of the burner to the inlet of the test section. This greatly reduces the time that the rig takes to heat up and the amount of fuel required per run.

Automatic Sand injection

Since the VT Aerothermal Rig is run at high temperatures it is necessary to be able to run the rig from a separate control room. To do this there was a need for a computer controlled sand injection system, shown in Figure 5. The sand is injected using a portion of the mainstream air that was diverted into a secondary flow path. Along this flow path is a storage hopper with a butterfly valve at its outlet. The particles are released by partially opening the valve, allowing gravity and flow pressure difference to entrain the particles into the airstream. However, this system quickly becomes clogged with sand. In order to fix this and satisfy the need of a computer controlled injection system, a pneumatic vibrator spinning at +15,000rpm and applying +20lbf to the hopper was employed. The vibrator can be turned on remotely using a CompactDAQ current output module, solid state relay, and solenoid valve.
A large part of this year’s research has been to run tests at many different parameters. Tests were run at four different temperatures (25°C, 260°C, 600°C, and 800°C), using 10-20µm and 20-40µm Arizona Road Dust on both stainless and Inconel coupons. For each of these cases the tests were run at six different coupon angles (30°, 40°, 50°, 60°, 70° and 80°). Using six different angles enabled enough data collection to find the COR for any impact angle from about 15° to 85°.

To set up the tests the coupon is removed from the test section and polished, every run. This keeps the coupon surface at less than 50nm average roughness as measured by a surface profilometer. This is important because COR is dependent upon surface roughness. A smooth surface is achieved by sanding the coupons with 1500 grit sand paper until it has a mirror finish. After polishing, the coupons are reattached to the coupon support and put back into the rig.

Once the coupon is in, the sand injection system is set, and the methane, air, and hydrogen gas tanks are opened the rig is controlled by a LABVIEW program on a computer in the control room. From the control room ignition of the rig is started by turning on an igniter. Once there is a pilot flame the methane is turned on and a pneumatic valve controlled by the LABVIEW program is used to regulate the pressure of the methane which controls the temperature of the rig. When the desired temperature is reached and steadies the pneumatic vibrator on the sand hopper is activated to release the sand into the equilibration section of the rig. At this time the high speed camera begins to take pictures of the particles impacting the coupon. The images from these tests are then processed using a Matlab code.

Data Reduction

After the tests have been run, the images and a CFD file for the test section are used to find the COR. The first step to finding the COR is to take each image pair and determine particle velocities, this is done using a Matlab code. Once the particle velocities are found they are coupled with the CFD for the test section, as shown in Figure 6. With both the flow field from the CFD and the particle velocities another Matlab code is used to find the COR.

Figure 5. Sand injection system

Figure 6. Test section CFD and rebounding particle tracks
Results

After all the tests are run and the data is reduced the data can be compiled and plotted for COR versus coupon angle. This information is gathered for all the different particle sizes, temperatures, and coupon materials. An example of these results is shown in Figure 7. This plot includes the mean and standard deviation of the COR for the specific parameters.

![Figure 7. COR data for different impact angles with mean and standard deviation lines](image)

So far the mean COR data has shown some expected trends. The COR decreases with increased temperature and velocity conditions. The effects of increasing the temperature and velocity led to a 12% average reduction in COR at 260°C (47m/s), 15% average reduction in COR at 600°C (77m/s), and a 16% average reduction in COR at 800°C (102m/s) when compared with ambient results. The decrease in COR appeared to be almost entirely a result of increased velocity that resulted from heating the flow. Trends show that temperature plays a minor role in energy transfer between particle and impact surface below a critical temperature.

Conclusion

The objective of this research is to investigate the effect of sand on the erosion and deposition of gas turbine blades by finding the COR. The method that is used has not been done before, but would be practical for use in future experiments with similar goals. The results of the experiments discussed in the previous section will help reduce the unfavorable impact that particles have on gas turbines by providing information to more accurately model the interaction between microparticles and turbine components. Furthermore it will help lower the incidences of engine failure due to particle ingestion because the models created from these results can be used to improve turbine blade design.

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Literature Cited

