論 文 の 内 容 の 要 旨

Thesis Summary

Experimental Investigation on Water Film Characteristics and Droplets Formation around Cascade Blade

（翼列翼における液膜の特性と液滴形成に関する実験的研究）

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Global energy demands have been increasing since the start of this century, especially in the emerging market economies. World's electricity demands are primarily fulfilled by the thermal power plants, and more commonly coal and gas are used as fuel. Among the thermal power systems, gas turbines (GT) systems are considered as one of the most important devices. It is commonly known that the thermal efficiency of GT deteriorates with an increase in the ambient atmospheric temperature. One approach to overcome the loss of GT power output during hot seasons is to cool the inlet air. The cooled dense air provides high mass flow rates, resulting in an increase in GT power output. Different techniques have been utilized to increase the overall efficiency of GT systems, however, fogging has gained more interest among the gas turbine manufacturers because of being the simplest, cost effective and highly efficient technique. In fogging, water droplets are directly sprayed into the inlet plenum duct of the GT system through a rack of nozzles which results in an increase in the density of working fluid. Potential benefits of water ingestion from the thermodynamic point of view have been identified by many researchers and almost all of them concluding that the presence of water droplets ingestion due to fogging in GT systems can significantly improve their performances. Despite the extensive thermodynamic study about the two-phase phenomena in GT systems, the fundamental kinematics of two-phase flow have not been understood in detail to fully utilize the potentials of the fogging technology. Therefore, the main aim of the present experimental study is to understand the characteristics of the liquid film formation on the blade's surface and to determine the droplet size distribution aft the trailing edge (T.E.) of the cascade blade.

In order to obtain the fundamental knowledge of the two-phase phenomenon, geometrically simple blade configuration was used, namely, elliptical profile blade. Such simple blade configuration allows understanding the kinematics of the characteristics of liquid film formation on the blade surface with ease and simplification. In the real fogging systems, water is ingested from arrays of nozzles, leading to the formation of the liquid film on the blade's surface. To simplify this phenomenon, in this study, water ingestion holes were made at the leading edge (L.E.) of the blade to grasp the influences of the shape and size of the striking droplets in the real systems. Further, simplifications were made by using a single blade. The main parameters of this thesis are the water mass flow rate, the angle of attack (AOA) of the blade, water ingestion hole geometry, the air flow momentum, T.E. thickness and the surface tension of the liquid. The prime objectives of this study are to understand the characteristics of;

- Liquid film formation on the blade's surface,

- Water accumulation, ligament and its breakup from the T.E. of the blade, and
- Droplets size distribution aft the T.E. of the blade.

Firstly, results showed that the liquid formed on the blade's surface was a function of aerodynamic forces (air velocity), liquid's surface tension property and its mass flow rate. From the extensive visualization, it was observed that if the aerodynamic forces exceed the liquid's surface tension forces, an instability appears on the surface of the liquid film. On the other hand, if the liquid's surface tension forces exceed the corresponding aerodynamic forces, the liquid's surface appears smooth. A theoretical model has been proposed by assuming the Couette flow and linear velocity profile assumption to estimate the thickness of the liquid film. Based on the proposed model the liquid film thickness is estimated to decrease inversely to the square of the air velocity increase. Moreover, greater the liquid's viscosity is, thicker is the liquid film formed and vice versa. Based on the minimum energy principle, the shape and motion of the liquid film become stable under the condition at which the total energy gained by the liquid from the air become minimum. And thus, the liquid film thickness to width ratio remains identical under the similar conditions of air momentum due to similar properties of aerodynamic and surface tension forces. Liquid film instability criterion was understood based on the Craik's model. Based on this model, it was shown that the normal pressure forces applied on the liquid – air interface played a dominant role in destabilizing the interface by displacing the liquid towards the crests and away from the troughs. The shear pressure forces further destabilize the interface by accelerating the crests in the windward direction and de-accelerating the troughs in the leeward direction.

Secondly, to understand the characteristics of water accumulation and ligament formation, high-speed images were captured. Due to airflow separation at the T.E., the local concentration of the water at the T.E. was observed. The extent of the amount of water accumulation was observed to be a function of the blade's geometry and AOA, and the surrounding air momentum ratio. In the case of the elliptical profile blade, at high momentum ratio, a large amount of water accumulation was observed, which is thought to be due to the relatively large velocity difference between the gaseous and liquid phase, whereas, at low momentum ratio small amount of water gets accumulated. The accumulated water for high momentum air and weber number resulted in the smaller ligament length and droplets size distribution formation (due to the vibrational mode of droplets breakup). However, for low air velocity and weber number, a large amount of ligament remained attached at the T.E due to the dominant effect of liquid's surface tension, with a low frequency of breakup. This ultimately resulted in an increase in liquid's ligament length and was observed to oscillate up and down excursions at the T.E. of the blade. When this ligament segment get exposed to the incoming air flow, which was almost perpendicular to the exposed ligament, it penetrates into the ligament segment resulting in the formation of the elongated bag and ultimately leads to the disintegration of the water segment due to the bag mode of a breakup. From the visualization results, due to different breakup mode of the ligament from the T.E. the droplets distribution angle aft the T.E. was found to be inversely proportional to the air velocity. Theoretical models have been proposed to predict the droplets shedding frequency, ligament's wavelength and the primary droplet size formed at different momentum ratio. In the case of droplet's shedding frequency, it was derived that the shedding frequency increases with an increase in the aerodynamic forces (i.e., air velocity). Additionally, if the liquid used is denser, then the shedding frequency decreases. The shedding frequency remains almost constant for a particular air momentum under varying liquid mass flow rate, due to nearly stationary state of the accumulated water at the T.E. in contrast to the surrounding air velocity. Therefore, whatever the liquid mass flow rate is, the shedding frequency remained the same. The experimental measure frequency shows a fairly good agreement with the theoretical models. In case of ligament's wavelength prediction, it was derived that the wavelength of the ligament(s) attached at the T.E. is inversely proportional to the square root of the gaseous phase velocity. Thus, with an incrementing the aerodynamic forces, the ligament length will decrease and vice versa. The ligament length was found to increase with an increase in the liquid's (mass) flow rate. In order to predict the primary droplets size formed, it was found theoretically that the primary droplets formed is inversely proportional to the aerodynamic forces, whereas, larger surface tension forces results in coarse droplets formation and vice versa. At high air momentum and weber number, the primary droplets produced were smaller compared to that of the low air momentum and weber number cases. Lastly, the theoretical expression of the effects of Weber number (based on T.E.) was derived, and it was proven experimentally that for the two different blades thickness with an identical Weber number, then the one with greater T.E. thickness would results in coarse droplets formation and vice versa. In the context of the derivation of this model, it was also theoretically proven that the primary coarse droplets formed aft the T.E. was also directly proportional to the liquid property of surface tension and was inversely proportional to the square of the air velocity.

Thirdly, to understand the characteristics of droplets size distribution aft the T.E. of the blade. An image processing code based on canny edge method was developed to convert the grey scale images to the binary scale images. Droplets size distribution was measured at 0.25-, 0.5-, 0.75- and 1- chord length (C) aft the T.E. of the blade at different liquid's flow rate and air momentum cases. Experimental results show that the liquid's mass flow rate did not influence droplets size distribution and was only limited to the number of droplets formed i.e., greater the liquid's flow rate is, a greater number of the droplets formed and vice versa. The droplets formed at a particular position aft the T.E. of the blade remained identical for a particular air momentum case. This is primarily due to the fact that the slip velocity between the droplets and the surrounding air velocity remains the same. In the case of high air momentum ratio, stripping of droplets from the T.E. of the blade was observed, due to the dominant effect of the aerodynamic forces. Moreover, the gradient of droplets change underwent small change as the distance aft the T.E. increases due to the vibrational mode of droplets breakup and smaller oscillating amplitude of the ligaments. On the other hand, the ligament breakup phenomenon completely changes for the low air momentum conditions were seen to be dominated by the liquid's property of surface tension, resulting in the formation of thick and highly elongated ligaments. The droplets produced from the disintegration of these ligaments were relatively coarse. Overall, the gradient of droplets size change for low momentum is comparatively large due to the bag mode of droplets breakup and high amplitude of the ligaments oscillation.

With an increase in the AOA, the liquid film thickness to width ratio and the droplets size distribution remains the same at a particular position for a particular momentum ratio. However, greater the AOA was, larger is the liquid film thickness to width ratio is and the droplets formed were also coarser in size compared to the 0 – AOA case, due to the reduce velocity effect on and aft the T.E. region.

Summing up, from all the experimental results conducted so far, it can be concluded that

- The liquid film thickness is a governed by the blade profile, mass flow rate, surface tension and the air velocity only and is almost independent of the size of the ingestion hole geometry. An increase in air velocity, a decrease in the mass flow rate and surface tension causes the film thickness to decrease and vice versa.
- Primary droplets formed aft the T.E. region is a function of the T.E. profile and the air momentum only, and is independent of the mass flow rate and the geometry of the ingestion hole.
- For the same T.E. profile, the primary droplet size decreases with an increase in the air momentum and vice versa.
- The droplet size distribution aft the T.E. region remains the same irrespective of the mass flow rate as the slip velocity between the droplets and the surrounding air remains identical.
- Droplet size decreases as its distance aft the T.E. increases.
- The momentum ratio plays an important role in the distribution of the droplets aft the T.E. region of the cascade blade. For high momentum ratio the droplets size distribution is at narrow area whereas for low momentum ratio the droplets size distribution is at the relatively wider region.
- The primary droplets size form due to the breakup of the ligaments is inversely proportional to the square of the air velocity.
- Droplets shedding increases with an increase in the air momentum and decrease for high density liquid and vice versa.
- Primary droplets formed are larger in size for liquids having higher surface tension as well as low surrounding air velocity and vice versa.
- Droplets size, liquid film thickness increases with an increase in AOA.
- For identical Weber number (based on the T.E. thickness) the droplets formed from the thicker T.E. is larger than that formed from the thinner T.E. profile.