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Numerical Simulations on Droplet Coalescence in an L-shaped Duct for Inlet Fogging of Gas Turbine

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Abstract

Numerical model is developed in order to characterize the water droplet coalescence at the air intake duct of a gas turbine assumed under operation of Inlet Fogging System. Injected water fog is treated as distributed droplet size instead of a single size representative diameter. The numerical calculation is executed by ANSYS Fluent® v.14.5 in a simple rectangular duct and verified with experimental data. The calculated evaporation time of an isolated water droplet in an infinite room shows a good agreement with experimental data. With fogging amount below saturation condition injected water droplets with size distributions take a longer evaporation time and lead to a lower cooling efficiency than those with a single representative diameter. Then, the model is used to investigate droplet coalescence phenomena in an L-shaped duct geometry. It is shown that the L-shaped duct enhances coalescence due to drift after the corner of L-duct. This reproduces larger droplets and results in lower evaporation efficiency and increase of the water drainage.

Keywords: Inlet Fogging, CFD, droplet, coalescence, gas turbine

Introduction

In recent years, gas turbine power augmentation has drawn an attention of engineers and researchers. During the hot season, the power output and efficiency of gas turbine are reduced significantly by lower density air. In order to augment the power output and thermal efficiency, recovering intake air mass flow rate is needed. The power augmentation can be achieved by cooling air technologies (Han *et al.* 2012). Among the cooling air technologies, inlet fogging technology is widely used because of its simplicity and low installation cost.

(Utamura *et al.* 1998) reported that about 1% injection of normal temperature water by spray nozzles at inlet duct had a potential to increase the power output by several percent.

Some researchers had studied this system to characterize evaporative behaviour of water droplet and identified key operational parameters (Chaker *et al.* 2002). (Chaker *et a.l* 2002 and Jeanty *et al.* 2012) investigated synchronization distance where injected droplet velocity reaches becomes zero by numerical calculation and found slip velocity between injected droplet and air flow becomes quickly zero i.e. synchronization distance is the order of 0.1 m. Computational Fluid Dynamic (CFD) was used to predict flow behaviour for different condition and configurations. (Suryan *et al.* 2010) numerically investigated the suitable locations for spray nozzles within the air intake duct. However, those studies were executed in a single representative diameter, typically using Sauter Mean Diameter (D32) and droplet coalescence effect was not considered.

In this paper, both droplet size distributions and coalescence effect were investigated numerically in an L-shape duct. Validating the present method with experiment, the present study investigated the effect of distributed droplet size on evaporation efficiency and introduced the effect of droplets coalescence phenomenon in duct geometry.

Inlet Fogging System

The concept of gas turbine inlet fogging system is shown in Fig.1. Water fog is generated by spray nozzles upstream of inlet duct and mixed in the incoming ambient air. Fine water droplets with typical Sauter mean diameter of 20μm rapidly reach airflow velocity due to drag force. Droplets evaporate and can cool the air down to as much as wet bulb temperature where the air becomes saturated. A part of unevaporated water may attach duct wall to produce drain and the rest enters compressor. Thus, design issue of inlet fogging system is to minimize the loss of water due to the drain while attaining highest cooling efficiency.

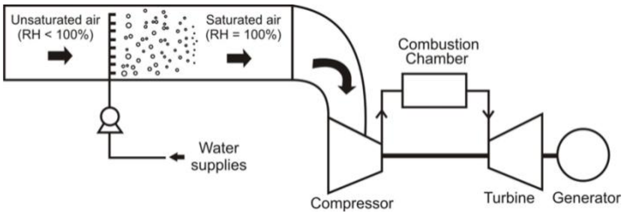


Figure 1. Concept of Inlet Fogging for a gas turbine

Numerical Model

Droplet evaporation model

The 1D model is no longer applicable where droplet interaction exists due to such causes as spatial inhomogeneity, existence of slip velocity, distributed droplet size, coalescence and so on. To deal with this problem of droplet interaction, commercial CFD, ANSYS Fluent® v.14.5 was used. An Euler-Lagrange dispersed particle model was used to compute the two phase flows. The air is the continuous phase and the water droplet is the dispersed phase. The velocity, turbulence parameters etc. were computed at first in Euler system, and then the traces of water droplets were obtained by integral in Lagrange framework after taking the turbulence diffusion and aerodynamic force from the continuous phase into account. Fluent adopts parcel approximation that treats a group of droplet with the same property instead of individual droplets to save computation resource.

Figure 2 shows the simple rectangular duct geometry and L-shape duct with 1m x 1m in cross section and 30m in length. Mesh in the plane perpendicular to the air flow direction was generated homogeneously. Twenty parcels were injected every time step at all elements at inlet plane with the speed same as inlet air velocity.

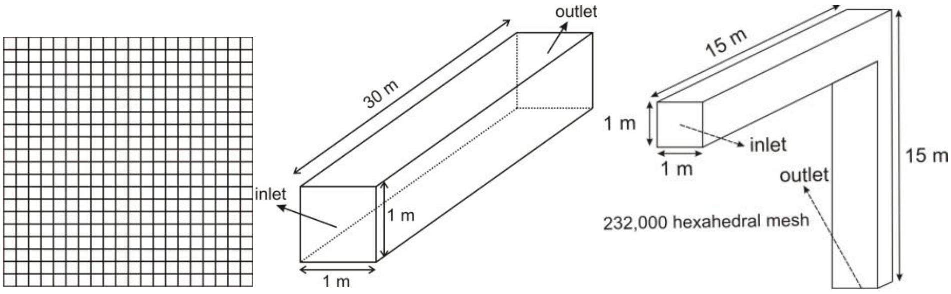


Figure 2. Model domain in simple duct geometry and L-shape duct

Simulation parameter

Boundary condition (BC) at inlet was inlet velocity and outlet was pressure outlet. Temperature initial conditions were set at inlet and outlet. Water droplets were injected as a form of the parcel at inlet surface (surface injection) with specific amount of mass flow rate. The symmetry boundary conditions (reflective BC) as well as no slip BC were applied to the side walls. In this condition, the droplets were assumed to rebound elastically once they reach the wall resulting in no loss of water at wall.

Transient calculation was executed and convergence was judged when the average value of ambient temperature (Ta) and Relative Humidity (RH) at outlet reached steady state condition. Simulations were carried out on Windows 7, Intel® Core™ i7 3.40 GHz with RAM memory 8 GB.

Model validation with single size droplet

The validation is needed in order to confirm the results with experimental data. (Ranz and Marshall 1952) experimental data for the evaporation of an isolated water drop in an infinite room was used.

Experimental condition is with droplet diameter of 0.10488 cm, droplet temperature (Td) of 9.11 °C, ambient temperature (Ta) of 24.9 °C and ambient pressure of 741 mmHg. The experiment was done with a water drop in still dry air. Therefore relative humidity (RH) was set to 0% RH in the simulation.

Figure 3 shows the comparison of time history of the diameter change of an isolated droplet in an almost infinite room. Excellent agreement is seen among calculations by Excel and Fluent and experiment. This implies that the evaporation model as well as the parameter setting of parcel approximation in Fluent is appropriate.

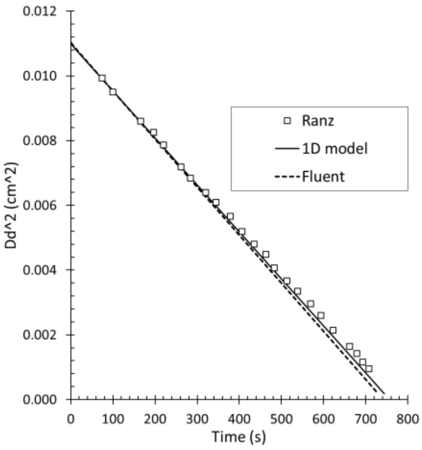


Figure 3. Comparison of droplet diameter with the experimental results by (Ranz and Marshall 1952)

Results and Discussion

The relative humidity and air temperature of non-inert droplets in every position of L duct is shown in Fig.4. It can be seen that the condition is saturated within 2 m from inlet or 0.13 seconds after injection. Air temperature reduced to 11.839 °C while wet bulb temperature taken from PROPATH was 11.549°C. Both values are very close, which is seen reasonable.

In Fig. 5 (a), the coalescence effect becomes significant from elbow at 16 m to outlet at 30 m although the mass of droplets is unchanged after 2 m. The reason is that there is drift flow around the corner and accelerating and decelerating flow field develops as shown in Fig.5 (b), which increases number density of droplets as well as relative velocity U_{rel} and average number of collisions μ. As a result, the number of collisions and volume fraction of larger droplets increase.

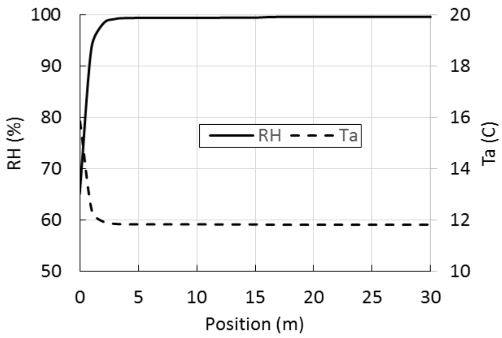
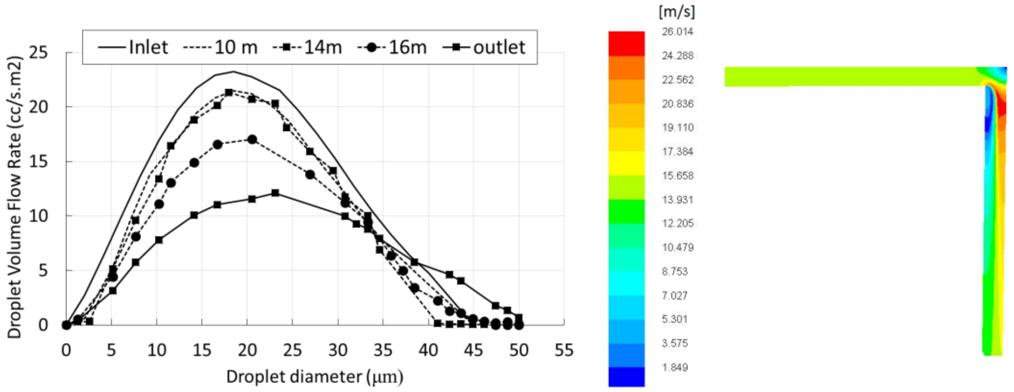


Figure 4. Relative humidity (RH) and air temperature (Ta)



(a). Droplet volume flow rate at different position (b). Velocity contour in L-duct

Figure 5. Droplet volume flow rate and velocity contour

Conclusions

Coalescence enhances in L-shape duct due to large velocity gradient around corner and larger droplets are generated. This may cause increased drainage and entrainment of larger droplets into compressor. The coalescence becomes enhanced under over fogging operation. To the contrary the deterioration of cooling efficiency is anticipated under moderate amount fogging operation. Hence avoidance of coalescence is suggested for an efficient operation of inlet fogging.

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