International Communications in Heat and Mass Transfer 95 (2018) 33–41

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ichmt

A computational study of mist assisted film cooling

Mallikarjuna Rao P.[a], Pratibha Biswal[b], B.V.S.S.S. Prasad[a,*]

[a] Department of Mechanical Engineering, Indian Institute of Technology Madras, Chennai 600036, India
[b] Department of Chemical Engineering, School of Engineering, Shiv Nadar University, Gautam Buddh Nagar, Uttar Pradesh 201314, India

ARTICLE INFO

Keywords:
Mist
Evaporative cooling
Film cooling
Cooling effectiveness
Droplets

ABSTRACT

In the mist assisted film cooling, water droplets are injected along with the coolant air. The concentration difference between the water droplets and the coolant air results in the evaporation of the former leading to drop in temperature and enhancement of the cooling efficiency. In the present work, a new definition for mist-air film cooling effectiveness is proposed and the performance of mist assisted film cooling is investigated on the wall of straight channel in the presence of a film cooling hole. Detailed two dimensional computational studies are carried out for various droplet diameter, relative humidity of air and mist concentrations. Results show that the film cooling effectiveness is always larger for the case of mist-air compared to that of the dry air. Further, the film cooling effectiveness increases with the percentage of mist in the mist-air system. At a specified mass flow rate of dry air and various quantities of mist, the increase in droplet diameter results in the decrease of cooling effectiveness.The cooling effectiveness increases with the relative humidity of air at all percentages of mist.

1. Introduction

Film cooling of gas turbine blades is now a well-established practice for increased turbine inlet temperature and thermal efficiency. In the film cooling technique [1-5] coolant air is introduced through discrete holes located on the turbine blade. The coolant air then forms a thin film between the hot mainstream gas and the turbine blade. The film eventually mixes with the hot gas in the downstream flow. In order to increase the film cooling effectiveness, small water droplets in the form of mist are injected into the coolant air. Each water droplet remains suspended in the coolant air for some time before it completely vaporizes and thus acts as a discrete heat sink. During the course of evaporation, heat is transferred to the droplets causing further cooling of the mainstream air. The relatively colder air cools the turbine blade to a larger extent and hence an increase in the film cooling effectiveness when mist-air is used as coolant. The main factors affecting the film cooling effectiveness are the size of droplets, mass flow rate of mist, temperature and relative humidity of air. If the droplets are larger in size they may travel longer and take longer time while evaporating farther into the downstream region.

A number of research publications reported enhancement of film cooling when mist is added to air. Guo et. al. [6-8] investigated various numerical and experimental studies for mist based cooling of straight tube involving highly super heated wall temperatures. Li et al. [9] investigated the transient behavior of heat flow to a spherical cap involving air-mist impingement. Air-mist cooling of a flat surface involving jet impingement was also studied by Li et al. [10]. Wang et al. [11] carried out a series of experiments to investigate the cooling of hot solid surface using mist for different initial surface temperatures, droplet size and droplet velocity. Li and Wang [12-14] also numerically simulated air/mist film cooling. A theoretical analysis of heat and mass transfer to/from a spherical water droplet moving in humid air has been carried out by Barrow and Pope [15]. Yamada et al. [16] presented evaporation of droplets in mist-air mixtures. Wang et al. [17] investigated gas turbine inlet air-cooling technique involving fog cooling for different fundamental geometries such as a straight tunnel, a diffuser, a contraction, and a 90° bend. Wang and Li [18] numerically studied the enhancement of the cooling effectiveness with water mist injection involving various hole geometries on a flat surface. Pakhomov and Terekhov [19] performed a numerical simulation to study the flow structure and heat transfer of impact mist jet with low (liquid mass flow 1%) concentration of droplets. Kim et al. [20] presented evaporative cooling process involving moisture of air and small amount of water droplets using various simultaneous heat and mass transfer models. Dhanasekaran and Wang [21] performed computational simulations to investigate the mist cooling technique in a 180-degree tube bend at gas turbine working conditions. Computational study on the cooling enhancement of smooth and ribbed channels with various mist concentrations is also carried out by Dhanasekaran and Wang [22]. Jiang et al. [23] presented numerical simulations to understand film cooling enhancement on turbine vane involving injected mist along with the coolant air. Flow and heat transfer characteristics are reported during

* Corresponding author.
E-mail addresses: mallikarjuna.mec@gmail.com (P. Mallikarjuna Rao), pratibha.biswal@snu.edu.in (P. Biswal), prasad@iitm.ac.in (B.V.S.S.S. Prasad).

https://doi.org/10.1016/j.icheatmasstransfer.2018.03.028

Nomenclature, SI unit

D	diameter of coolant hole/slot width
C_p	specific heat at constant pressure
d_p	droplet diameter
g	acceleration due to gravity
P	pressure
T	temperature
T_{in}	temperature at the inlet of coolant hole
T_{min}	minimum temperature reached after evaporation
T_m	mainstream temperature
T_w	wall temperature
u	velocity vector
x	position vector

Greek symbols

η	cooling effectiveness based on minimum temperature
η_i	cooling effectiveness based on coolant inlet temperature
ρ	density
μ	dynamic viscosity
Φ	viscous dissipation
ν	kinematic viscosity, $m^2 s^{-1}$

mist-steam cooling in a square channel at elevated gas turbine operating conditions in [24]. Zhao and Wang [25] experimentally investigated the utility of mist/air cooling on the film cooling. They reported that the cooling effectiveness was enhanced with addition of fine water droplets of the order of 5 μm in the coolant air without changing the cooling pattern. They also reported that liquid droplets in the film provided a more extended film cooling coverage effect compared to the air film cooling. The main observation from the earlier works is the enhancement of the cooling effectiveness of gas turbine blades with the addition of mist to the coolant fluid.

In all the previous studies,the film cooling effectiveness is defined as

$$\eta_i = \frac{T_m - T_w}{T_m - T_{in}} \quad (1)$$

Here, T_m, T_w and T_{in} correspond to the mainstream temperature, wall temperature and coolant inlet temperature, respectively. When the coolant is dry air, the value of T_{in} is minimum, $T_w > T_{in}$ and η_i is therefore always less than unity. However, for the mist-air film cooling, as the air and mist travel together along the hole, evaporation takes place. As the water droplets vaporize to form water vapor, it results in the drop of coolant air temperature. As a result, the coolant acquires a temperature lower than the value of T_{in} and consequently T_w may become lower than T_{in}. The effectiveness, as per Eq. (1), may then take a value larger than unity. Such behavior of effectiveness is mildly evident from Li and Wang [12], near the hole. In order to keep the effectiveness value not to exceed unity by definition, even for mist-air cooling, a new definition is necessary. The present paper therefore proposes a new generic definition of mist-air cooling effectiveness where the temperature drop due to the evaporation process is also taken into account. In addition to the dry air, the injection of humid air may also exhibit interesting trends of the temperature contours and cooling effectiveness. In order to bring out these features, computations are carried out in the present work and comparisons of the cooling effectiveness, with the dry and humid air with the mist, are presented. The effects of various mist concentrations and droplet diameters on the film cooling effectiveness are brought out.The effect of temperature and relative humidity of coolant air on the mist-air film cooling effectiveness is presented. The visual representations of the fluid temperature and droplet tracking are also shown to gain better understanding of evaporation and film cooling.

2. Physical system and governing equations

Fig. 1 illustrates the schematic diagram of geometric model and computational domain. The geometry, the physical model and the computational domain is taken from Li and Wang [12] so that specific results from the present study can be compared with them [12]. As per Li and Wang [12], the diameter of the coolant hole is 5 mm, inclined at an angle of 35° with the mainstream direction. The mainstream, with a Reynolds number of $Re \approx 3.42 \times 10^4$, flows over the flat plate. The dry coolant air flows with a Reynolds number of $Re \approx 3.42 \times 10^3$, flows through the coolant hole forming a film over the plate. The water droplets are injected at the inlet of the coolant hole along with the coolant air as shown in Fig. 1.

The computational simulation is carried out based on the Euler-Lagrangian approach. The mainstream air and dry coolant air and water vapor are considered as element of the continuous (Eulerian) phase and the injected water droplets correspond to the dispersed or discrete (Lagrangian) phase. The Navier-Stokes equations are solved in the continuous phase whereas, each particles in the dispersed phase are tracked through the continuous flow field. The calculation for continuous and dispersed phases is coupled as exchange of mass, momentum and energy that occurs between the continuous and dispersed phases (Fig. 2).

The governing equations for the continuous phase are solved for certain number of iterations before solving the discrete phase equations. Taking this continuous phase variables as the base, one droplet per cell is injected (Fig. 2) and the droplet trajectories are calculated by applying discrete phase equations. Thus, the source terms for the continuous phase are estimated. The governing equations for continuous phase are again solved for another set of iterations with updated source terms. Thus the process of alternate solving of continuous and discrete phases continues till a converged solution is obtained. The governing equations are described in the following sections.

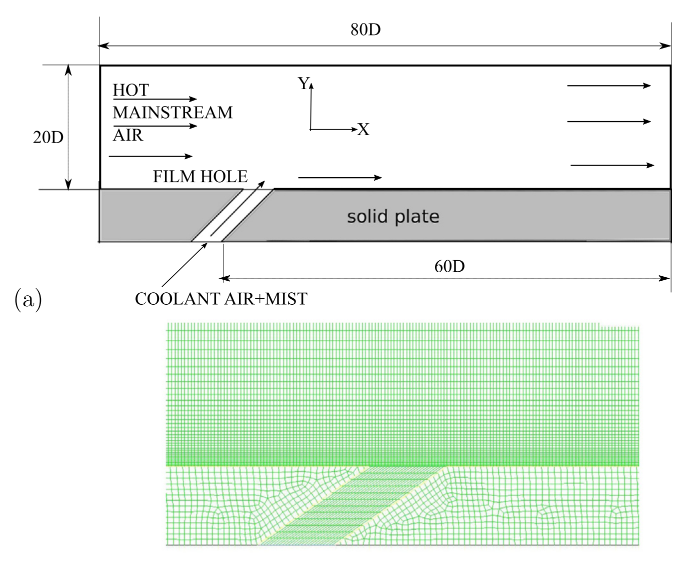

Fig. 1. The schematic representation of (a) the physical system and (b) mesh the for flat plate and film hole.