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Experimental and numerical study on heat transfer characteristics for methane/air flame impinging on a flat surface

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ABSTRACT

Heat flux from a premixed methane/air slot laminar flame jet impinging upward to a horizontal target plate is studied experimentally and numerically. Mach-Zehnder interferometer is used to obtain the overall temperature field. The flame jet is produced by a slot nozzle with length of $L = 25$ mm and width of $W = 3$ mm. The slot nozzle is parallel to the target plate which has the dimensions of $250 \times 130 \times 10$ mm. The experimentally obtained heat flux distributions were compared for different firing rates and nozzle to plate spacing. A second peak in heat flux to the target surface (an off-center peak with respect to the axis of the nozzle) was observed for the shortest spacing and highest firing rate in the present study. The heat flux distribution and the second peak in it could be successfully simulated using numerical computations. With the help of numerical results and analyzing the velocity components, it was found that the position of the second peak along the plate is in accordance with a second stagnation point caused by the present configuration of the confined flame between the two parallel plates, namely the target plate and the base plate of the two-dimensional nozzle. The results show that the onset of the presence of the second stagnation point could be controlled by the spacing and firing rate.

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1. Introduction

Impinging flame jets are widely used in heating, cooking, drying, power generation, metal annealing, and glass production industries. They are efficient due to their high ability to increase the rate of heat and mass transfer [6]. Heat release characteristics from a flame jet is strongly dependent to the temperature distribution around the receiving medium. Comparisons between impinging flame jets and isothermal gas jets have shown that Nusselt number distribution is similar at same Reynolds numbers for circular nozzles [18,30]. For flame jets, many studies have been conducted to investigate the effect of operating conditions on heat transfer characteristics including Reynolds number, equivalence ratio and plate to nozzle spacing. Part of these studies have used Butane/air as the fuel and oxidizer to characterize the effects of flame spacing [11], Nuslet number [20], local heat flux [10], the material of the plate [36], and flow parameters such as Reynolds number and equivalence ratio [23]. Most of the studies have investigated point heating rather than line spread heating [33], and limited studies have also considered the effect of non-circular slot using butane [24].

A number of investigations have been focused on using methane with circular burner. It is reported that the local heat flux corresponding to the stagnation point increases with the Reynolds number when the jet-to-plate distance is larger than the length of the inner reaction zone [8]. For triangular configuration of three interacting methane/air flame jets, the local heat flux distribution became more non-uniform when inner jet spacing is increased considerably [7,22] performed experiments to investigate heat transfer features of methane-diffusion and premixed methane-air flame impinged on a cold steel plate. They observed eddies in the wall-jet region for diffusion flame. Comparative study is performed on heat transfer distribution between impinging flame jet and impinging air jet at different Reynolds numbers as well as non-dimensional nozzle to plate spacing, reporting that there is a good agreement between the Nusselt numbers for higher spacing near stagnation region [16]. Nusselt number is also computed for methane circular impinging flame based on an estimation of the adiabatic wall temperature through theoretical description and

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Nomenclature

C	Goldstone-Dale equation constant
D	diameter (m)
L	target surface length (m)
M	molecular weight (g/mol)
N_f	fringe number
Nu	Nusselt number
P_w	wetted perimeter (m)
P	pressure (pa)
R	constant gases (J/K)
Re	Reynolds number
T	temperature (K)
u	velocity (m/s)
Y	mole fraction
c	Speed of light (m/s)
h	heat transfer coefficient $(W/m^2 \quad K)$
k	thermal conductivity (W/mK)
n	refractive index
q	heat flux (W/m^2)
FR	firing rate (kW)
A	sectional area (m^2)
F	fuel rate
Lo	Loschmidt number
N	number density

Greek symbols

ε	fringes displacement (m)
ϕ	equivalence ratio
φ	phase displacement
λ	wavelength (m)
μ	dynamic viscosity $(N.s/m^2)$
θ	phase difference
ρ	density (kg/m^3)
τ	time (s)
υ	kinematic viscosity (m^2/s)
η	effectiveness

Subscripts/Superscripts

act	actual
ad	adiabatic temperature
f	flame
h	hydraulic
mix	mixture
ref	reference
sto	stoichiometric
∞	ambient
m	molecules
e	electron
w	wall

experimental data [14]. Recently, an investigation is performed on a dual impinging flame of natural gas on a flat plate using circular nozzles [27].

Although circular nozzle has been used extensively in many industrial as well as academic applications, however, there are a number of challenges in using circular nozzles that have made researches study the effect of nozzle geometry. For impinging jets, it is found that the heat flux to the target plate becomes uniform when a slot nozzle is used instead of a circular nozzle [32]. This is reported to be a result of greater impingement zone when using a slot nozzle [6,9]. Improvement of the heat flux due to switching to slot nozzles has been measured to be up to 25% [19]. General heat transfer characteristics made by a slot nozzle have been observed to be improved even compared to circular multiple jets. For instance, in cooling of a multichip module, circular multiple jets generated a blockage in vicinity of the jets leading to a complicate fluid distribution downstream of the impinging location [34]. A comparison between circular, square, and rectangular nozzles have also shown that the Nusselt Number for rectangular nozzles in various Reynolds numbers and spacings is 10–20% more than that of circular and square nozzles [12]. Therefore, it is known that the advantages of having an impinging flame jet are to improve the heat transfer significantly, to lower the fuel consumption, and to increase the productivity. Most of the previous studies on slot nozzle belong to non-reacting jets and limited studies have been conducted on impinging flames through slot nozzles.

The present study is different from all the others since it characterizes the heat transfer as a result of a two-dimensional methane/air premixed impinging flame from a slot burner to a flat plate. The configuration is also unique since there are two parallel walls that partially confine a two-dimensional flame presently. The present configuration leads to different heat flux characteristics comparing to heat flux due to circular flame impingement which is already reported. A second peak in heat flux is obtained experimentally along the target plate. The temperature of the flat plate is not kept constant and Non-intrusive interferometry is used to experimentally visualize the impinging flame at different flow conditions, which is already employed for flames of methane and LNG in two-dimensional and axi-symmetric non-impinging burners [2,3,15]. The isotherms are presented in the vicinity of the slot and the plate and heat transfer coefficient is obtained along the plate. A numerical simulation is finally presented for the same configuration and flow conditions for an equivalence ratio of 1. The numerical simulation can predict a second peak in heat flux along the target plate successfully.

2. Material and methods

2.1. Experimental facility

Fig. 1 shows the schematic representation of the experimental setup. Metered methane and air are fully mixed in a brass cylinder before entering to a plenum chamber. After mixing of air and methane, the mixture enters from the bottom side of a cubic chamber of 220 mm each side with 6 mm thickness. The top surface is covered by a square plate of 240 mm with 7 mm thickness. The top plate is screwed to the chamber. The plenum chamber is half filled with very small stainless steel beads (4 mm in diameter) in order to produce uniform flow. A honeycomb structure is also installed to dissipate possible eddies of the flow. The remaining vacant height is sufficiently enough to eliminate small eddies. The screwed top plate of the chamber is where the slot nozzle has been machined with dimensions of 25 mm long and 3 mm wide. The target plate holder is fixed to a 3D-positioner used to adjust the distance between the target plate and the slot nozzle. The copper target plate has the dimensions of 250 mm long, 130 mm wide and 10 mm thick and is horizontally held parallel to the slot nozzle. Ten calibrated K-type thermocouples with 6 mm spacing from the stagnation point extending to the wall jet region are utilized to measure the copper plate temperature (see Fig. 2). Thermocouples

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