International Journal of Heat and Mass Transfer 101 (2016) 133–146

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Heat transfer characteristics of premixed methane–air flame jet impinging obliquely onto a flat surface

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ARTICLE INFO

Article history:
Received 2 February 2016
Received in revised form 7 April 2016
Accepted 2 May 2016
Available online 26 May 2016

Keywords:
Flame impingement
Oblique
Nusselt number
Effectiveness
Thermal efficiency

ABSTRACT

Oblique flame jet impingement finds a wide range of domestic and industrial applications. An experimental investigation is carried out to study the effect of oblique flame jet impingement on the heat transfer characteristics. An asymmetric boundary layer is formed on the impingement surface due to oblique impingement. Steady state technique using one dimensional energy balance across the target plate is employed to determine the local heat transfer coefficient and the reference temperature of the impinging flame jet. The effect of the mixture Reynolds number (400–1200), mixture equivalence ratio (0.8–1.5), burner or plate inclination (0–45°) and burner to plate distance (2–6 times the burner diameter) on the heat transfer characteristics are investigated. It is found that stoichiometric mixture provides optimum Nusselt number distribution and lower burner to plate spacing provides maximum effectiveness for impinging premixed cone flames. Normal impingement resulted smooth heat flux distribution and better thermal performance. Correlations are developed for stagnation point Nusselt number and effectiveness.

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1. Introduction

Research on flame jet impingement over last four decades contributed better designs of direct heating equipment with respect to both heat transfer [1–4] and combustion aspects [5–7]. These researches are aimed to improve the industrial direct flame heating methods to have higher effectiveness, lesser fuel consumption with lower emissions. Flame jet heating has a wide range of industrial and domestic applications because of rapid and high heat transfer rates [8]. The experimental studies describing the effect of flame jet parameters such as mixture Reynolds number, equivalence ratio and plate separation distance on the local or average heat transfer characteristics are reported [9–11]. Viskanta [12], Baukal and Gebhart [13,14] have reported some analytical and semi-analytical solutions for flame jet impingement heat transfer. Remie et al. [15,16] reported the analytical solutions based on the inviscid assumptions for two-dimensional axisymmetric cases for flame jet impingement. Van der Meer [17] compared the heat transfer characteristics of the isothermal gas jets and the reacting flame jets. Chander and Ray [18] contributed a most extensive review on flame jet impingement heat transfer. It revealed that the rate of heat transfer from the flame jet to a target solid surface depends on the structure of the flame, convective and radiative properties of the constituent gas species of the flame and the temperature of the gas within the boundary layer in vicinity of the plate. The flame temperature field is highly influenced by the combustion mechanism which is very sensitive to the flow field. Tuttle et al. [19,20] studied the convective flame heat transfer characteristics along with the flame structure and stability for a partially premixed methane–air flame jet impinging on a target plate. Researchers have used direct measurement with heat flux sensor [18], calorimeter [21,22] and inverse heat transfer techniques [8] to determine the flame heat flux onto the target plate.

Hou and Ko [23] reported the experimental studies on the effect of burner inclination along with plate separation distance on the flame structure and temperature field for obliquely impinging flame jets. The effect of the burner inclination on temperature field was strong for lower burner to plate separation distances. Dong et al. [10] presented the heat transfer characteristics of impinging butane–air premixed flame jet on an inclined flat surface. Decreasing the incident angle enhanced the maximum local heat flux and reduced the average heat transfer. Agrawal et al. [24] have reported the numerical simulations of the methane–air premixed flame jet impinging on an oblique plane surface. The oxidation mechanism was modeled with global two-step irreversible reaction kinetics; turbulence was modeled with RNG k–ε model and

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.05.004
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Nomenclature

a, b	length and width of target plate (m)
A	surface area (m^2)
d	inner diameter of tube burner (m)
h	heat transfer coefficient (W/m^2-K)
HHV	higher heating value (J/kg)
k	thermal conductivity (W/m-K)
L_f	flame height (mm)
l	length of burner (m)
M	molecular weight (kg/kmol)
$\dot{m}$	mass flow rate (kg/s)
Nu	Nusselt number
$\dot{Q}$	rate of heat (W)
q''	heat flux (W/m^2)
$\bar{q}''$	spatial averaged heat flux (W/m^2)
r	radial distance (m)
Re	Reynolds number
T	temperature (K)
T_f	flame temperature (K)
v	velocity (m/s)
X	mole fraction
x, y	rectangular co-ordinates (m)
Z	spacing between burner or nozzle and target plate (m)
z	axial distance (m)

Greek symbols

ε	emissivity
η	effectiveness
η_{th}	thermal efficiency (%)
θ_b	burner inclination with respect to vertical (°)
θ_p	plate inclination with respect to horizontal (°)
μ	absolute viscosity (Pa-s)
ρ	density (kg/m^3)
σ	Stefan–Boltzmann constant ($5.67 \times 10^{-8} W/m^4 - K$)
ϕ	equivalence ratio

Subscripts/superscripts

0	stagnation
∞	ambient
act	actual
conv	convection
f	fuel
ht	heat transfer
m	mean film
max	maximum
mix	mixture
ref	reference
stoic	stoichiometric
w	wall

Abbreviations

CBL	compression boundary layer
EBL	expansion boundary layer

radiative heat mechanisms with Discrete Ordinate Methods. Oblique impingement resulted in asymmetric heat flux profile with higher value of average heat flux in the uphill side compared with the down hillside. Fig. 1 shows the schematic of oblique jet impingement on a plane target surface. The obliqueness is obtained either by inclining the plate while the burner is held vertical or by inclining the burner while the plate is mounted horizontal [23]. Direction towards which the burner is inclined (forms acute angle with the impingement plate) is defined as the uphill side and the other direction is defined as the downhill side. Moreover, the uphill and downhill sides are also termed as compression and expansion regions respectively based on the nature of boundary layer formed. The impingement surface is divided equally by '*x*' and '*y*' co-ordinate axes and '*z*' is the vertical axis. The '*y*' axis is the axis of symmetry of the impingement plate. The burner is mounted in the '*x*' plane such that its axis always passes through the geometric center of the plate. The negative values of *y*-coordinate indicate the uphill region and the positive values as downhill region of the impingement plate.

The data reported in the literature has certain limitations in terms of usage as it reports the heat flux, wall temperature and averaged Nusselt number data for obliquely impinging premixed methane–air flame jets. Due to the ambient air entrainment, the process of impingement is not at all adiabatic. Thus, the assumption of adiabatic flame temperature as the reference temperature is inappropriate. The temperature of combustion gas in the vicinity of the boundary layer over the impingement surface is to be treated as the reference temperature. The reference temperature shows radial variation because of thermal dilution.

The present work emphasizes the heat transfer characterization (spatial heat flux distribution, Nu and η distribution along the axis of symmetry) and thermal efficiency determination for obliquely impinging flame jets. A steady state technique considering two surface conditions of impingement surface [25] is employed for thermal characterization. The major parameters of study are:

- mixture Reynolds numbers, $Re = 400$–1200 in steps of 200,
- mixture equivalence ratios, $\phi = 0.8$, 0.9, 1.0, 1.2 and 1.5,
- angle subtended by the plate normal or burner axis with the vertical direction (i.e., inclination angle), θ_p or $\theta_b = 0°$, 15°, 30° and 45°,
- non-dimensional plate separation distance from burner tip, $Z/d = 2$, 4 and 6.

2. Experimental setup and procedure

Fig. 2 shows the schematic of the experimental setup used in the present study. The methane gas having 99.5% purity and the compressed air from the air storage tank are metered through mass flow controllers (MFC's) at 2 bar pressure. The MFC's used are Aalborg (USA) make, and have an accuracy of 1.5% of full scale. The air and methane MFC's are calibrated respectively with BIOS International make DryCal Defender 530H (Range: 300–30,000 cm^3) and 530 M (Range: 50–5000 cm^3).The gas flow calibrators have an accuracy of 1% of the reading traceable to NIST standards. The metered air and methane is then passed through a mixing cup. The mixing cup consists of packed bed of steel balls to ensure the proper mixing of the fuel and air, and to reduce the flow fluctuations. The mixture is then supplied to a tube burner having inner diameter of 10 mm and length to diameter ratio (l/d) of 50 to ensure fully developed flow at the burner exit. The burner is mounted on a holder which is capable of inclining the burner axis to desired angle with the arrangement for aligning the burner with respect to the plate. The flame jet of the tube burner is made to imping upon a 1 mm thick quartz target plate having dimensions of 150 mm × 150 mm. The quartz surface has an emissivity of 0.93 [26].The plate is mounted on a platform which can be tilted to the desired inclination.

Infrared thermal camera (Thermoteknix make VisIR® 640 s) is used to capture steady state temperature of the impinging surface. The camera has a spectral range of 7.5–13.5 μm and temperature

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