International Journal of Heat and Mass Transfer 86 (2015) 550–562

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Technical Note

Effect of preheated mixture on heat transfer characteristics of impinging methane–air premixed flame jet

Abdul Raouf Tajik [a], Pramod Kuntikana [b], Siddini V. Prabhu [b], Vijaykumar Hindasageri [a,*]

[a] Department of Mechanical Engineering, National Institute of Technology Karnataka, India
[b] Department of Mechanical Engineering, Indian Institute of Technology Bombay, India

ARTICLE INFO

Article history:
Received 1 December 2014
Received in revised form 2 March 2015
Accepted 11 March 2015
Available online 30 March 2015

Keywords:
Flame impingement
Nusselt number
Effectiveness
Preheat

ABSTRACT

Energy from spent flame or other low grade energy can be used to increase the temperature of the air before mixing with fuel. This would improve the heat transfer characteristics of the impinging flame jet. The studies on impinging flame jets reported in the literature are based on the fuel–air mixture at ambient temperature. In the present work, the inlet air for mixture is heated by an electrical heater. The heat flux distribution is estimated using an inverse heat conduction (IHCP) technique. The Nusselt number (Nu) and effectiveness (η) distributions are obtained by estimating the adiabatic wall temperature (T_{aw}) by the analytical–numerical method. A circular burner of 13.5 mm is used for impingement on quartz plate of 3 mm thickness. Reynolds number (Re) varying from 500 to 2000 for the non-dimensional burner tip to impingement plate spacing (Z/d) of 2–6 and stoichiometric condition ($\phi = 1.0$) is considered for varying preheated condition. The effect of equivalence ratio is studied for $\phi = 0.75$ to 1.5 for $Re = 1000$ and $Z/d = 4$. By increase in preheat temperature, the stagnation point heat flux increases from 20% to 50% unless the inner premixed zone touches the impingement plate. CFD simulations are carried out in FLUENT software to explain the distribution of heat flux.

1. Introduction

Impinging flame jets have found many domestic as well as industrial heating applications such as metal and glass processing industries. The study of heat transfer characteristics of impinging flame jets is therefore essential. Reviews on impinging flame jets by Chander and Ray [1], Viskanta [2] and Baukal and Gebhart [3,4] are reported. The effect of various parameters like Reynolds number, equivalence ratio, burner nozzle tip to impingement plate spacing, shape of target object and its orientation relative to burner nozzle, oxidizer and fuel compositions etc. on heat transfer characteristics of flame impinging flame jets have been explained in these review papers. For two-dimensional and axisymmetric case, analytical expressions have been derived by Remie et al. [5,6] for the heat flux distribution of a laminar flame impinging on a flat plate. Numerical studies of heat transfer characteristics of impinging flame jet are presented by Som et al. [7] and Conolly and Davies [8]. A numerical-analytical method has been proposed by Hindasageri et al. [9] for estimation of adiabatic wall temperature to estimate the Nusselt Number and effectiveness. Hindasageri et al. [10] have further presented a novel method for estimating the steady state heat flux distribution of impinging flame jets in an enclosure using IHCP technique. The stagnation point heat flux depends on the position of the inner premixed cone with respect to the target plate and maximum heat flux is obtained when the tip of the inner premixed cone just touches the impingement plate [11]. Chander and Ray [12] conducted a numerical and experimental study on the occurrence of off-stagnation peak in heat flux and explained that the shift in peak heat flux from stagnation point is due to corresponding peak in the axial velocity profile.

Hindasageri et al. [13] studied heat transfer distributions for non-circular burners and reported that axis switching happens for non-circular burners and it is more predominant with larger burner dimension. They also mentioned that the non-dimensional number, flame cone height to nozzle-plate separation distance (L_f/Z) is the sole parameter which correlates the Nusselt number and effectiveness distribution. Several experimental studies on heat transfer characteristics of impinging flame jets like inverse diffusion flame jet are reported by Dong et al. [14–16]. In an experimental study, Dong et al. [17] presented that heat flux profile by slot burner is more uniform than circular burner. Studies on heat transfer distributions of twin and three flame jets are presented by Dong et al. [18,19] and Chander and Ray [20] respectively. Chander and

* Corresponding author.
E-mail address: vkhnitk@gmail.com (V. Hindasageri).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.03.040
0017-9310/

Nomenclature

C_p	specific heat (J/kg K)
d	burner diameter (m)
h	heat transfer coefficient (W/m^2 K)
I	current (A)
k	thermal conductivity (W/m K)
L_f	flame cone height (m)
$\dot{m}$	mixture mass flow rate (kg/s)
Nu	Nusselt number
q''	heat flux (W/m^2)
Q	Electrical heat input (W)
r, z	coordinate axes
Re	Reynolds number
S_u	burning velocity (m/s)
t	time (s)
T	temperature (K)
u	mixture velocity (m/s)
V	voltage (V)
Z	location of the impingement plate from the burner tip (m)
Z_p	impingement plate thickness (m)

Greek symbols

α	thermal diffusivity (m^2/s)
δ	boundary layer thickness (m)
ΔT	$T_{mix} - T_\infty$ (K)
ϕ	equivalence ratio
η	effectiveness
μ	absolute viscosity (Pa s)
ν	kinematic viscosity (m^2/s)
ρ	density (kg/m^3)

Subscripts/superscripts

∞	ambient
adf	adiabatic flame
aw	adiabatic wall
el	electrical
i	initial
mix	mixture
o	stagnation point
ph	preheated
w	wall

Abbreviations

CFD	computational fluid dynamics
GRI	gas research institute
IHCP	inverse heat conduction problem

Ray [21] carried out experiments on effect of burner geometry on heat transfer characteristics of impinging jets. Thermal performance of impinging jets with induced swirl is demonstrated by Zhao et al. [22], Huang et al. [23] and Singh et al. [24]. Li et al. [25] have shown the effect of plate temperature on heat flux and emissions of impinging flame jets and presented that by increasing the plate temperature the heat flux is suppressed but the emission is reduced. Chander and Ray [26] conducted experiments on heat transfer characteristics of impinging flame jets on cylindrical surface and reported that cylindrical surface has higher stagnation region heat fluxes in comparison with flat plate.Studies on heat transfer of oxygen enhancement are done by Baukal [27] and Baukal and Gebhart [28]. Baukal and Gebhart [29] presented influence of surface conditions on impinging flame jet heat transfer, they have shown that heat flux for blackened surface is highest and for polished surface is the lowest. Studies on effect of surface inclination on heat transfer of impinging jets are presented by Dong et al. [30], Hou and Ko [31] and Agarwal et al. [32] and they reported that oblique angle significantly affect the heat transfer distribution of impinging flame jets. Zhen et al. [33] conducted experiments for annular impinging flame jet and concluded that annular flame jet is more desirable for uniform heating. Cremers et al. [34] reported that thermochemical heat release is significant for flame jets with oxygen as oxidiser and it can be ignored for methane–air flames.

All the studies in literature for heat transfer characteristics of impinging flame jets are based on air/fuel mixture at ambient temperature. Air can be heated by use of exhaust heat from the flame or other low grade energy source. By preheating the mixture, the thermal energy of the flame would increase and thereby would influence the output heat flux distribution on the impingement plate. In the present experimental and numerical study, the intake air is heated using an electrical heater. The Reynolds number range is 500–2000 for Z/d = 2 to 6 for three different preheated conditions ($\Delta T = (T_{mix} - T_\infty)$ = 0, 50 and 100 K). Experiments are also carried out for lean and rich mixtures at Re = 1000 and Z/d = 4 for different preheated conditions. The heat flux distribution is obtained using the initial transient IHCP technique presented in our previous work [9,13]. Nusselt number and effectiveness are estimated by obtaining the adiabatic wall temperature from analytical–numerical method presented in our previous work [9]. Numerical simulations are carried out using CFD software, FLUENT to bring out the physics of the problem.

2. Experimental setup

Fig. 1(a) shows the schematic of experimental set-up used for studying the effect of preheated air on heat transfer distribution of impinging flame jet similar to that our previous studies [9,13,35]. Circular steel burner of 13.5 mm diameter is used for impingement on a quartz plate (150 mm × 150 mm and 3 mm thickness). Thermal infrared camera (Thermoteknix make VisIR® Ti 200) is used for recording the transient temperature distribution on the top side of the quartz plate whose emissivity is 0.93 [9]. Venturimeters and orifice meters are used for measuring flow of air and methane. These venturimeters and orificemeters are calibrated with DryCal (DCLITE H) calibrator [9,13].

2.1. Preheating the air

An electrical heater of 800 W capacity is used for preheating the air (T_∞ = 300 K). The input heat is estimated using Eqs. (1) and (2) by noting the current and voltage measured using ammeter and voltmeter. For minimizing the heat loss, ceramic blanket is used for insulation of the heater and other intermediate parts up-to the burner exit. A mixing tube is connected to the exit of the heater for making the temperature more uniform. By increasing the temperature, thermal properties of air and methane will change. Therefore, the effect of temperature on mixture properties is also taken into consideration for mass flow rate and Reynolds number calculation for preheated mixture:

$$Q_{el} = VI \tag{1}$$

$$Q_{ph} = \dot{m} C_p \Delta T \tag{2}$$