International Journal of Thermal Sciences 111 (2017) 409–422

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

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

Effect of mixture composition on heat transfer characteristics of impinging methane-air flame jets of tube burners equipped with twisted tapes

Pramod Kuntikana, S.V. Prabhu*

Department of Mechanical Engineering, Indian Institute of Technology Bombay, Powai, Mumbai, 400 076, India

A R T I C L E I N F O

Article history:
Received 28 April 2016
Received in revised form
14 September 2016
Accepted 19 September 2016

Keywords:
Flame impingement
Twisted tape
Nusselt number
Effectiveness
Thermal efficiency

A B S T R A C T

Present study investigates the effect of the mixture equivalence ratio on the heat transfer characteristics of impinging premixed methane-air flame jets of tube burners equipped with twisted tape inserts. The induced swirl flow enhances the mixing process and improves the flame stability limits. The flame jet with mixture Reynolds number of 800 and burner to plate spacing of four times burner diameter is chosen based on the flame stability range. The heat transfer characteristics of non-swirling flame jet are compared with the swirling flame jets for various mixture compositions. Swirl flow is achieved with twisted tape inserts having twist ratios of 2, 3.2, 4.5 and 7.5. Twisted tape inserts resulted asymmetric flame. The flame shape is found to be highly influencing the heat transfer from the flame jet to the target surface. Better heat transfer distribution is achieved with stoichiometric mixture. However, the rich mixture produces more uniform heat flux distribution. Best thermal performance is observed for twisted tape with twist ratio of 7.5. The present study helps in better understanding and optimum design of the flame jet impingement heat transfer equipment.

1. Introduction

Industrial direct heating processes and domestic gas burners employ impinging flame jets of hydrocarbon fuels due to their higher heat transfer coefficients compared with other heating techniques. Considerable knowledge on flame jet impingement is provided by Viskanta [1], Baukal and Gebhart [2,3] and Chander and Ray [4] in the form of review. Substantial data on heat transfer characteristics of impinging flame jets is reported in literature. Heat transfer analogy between impinging reacting jets and isothermal gas jets is reported by Viskanta [1] and Van der Meer [5]. Semi-empirical correlations for stagnation point and average heat transfer coefficient for impinging jets are reported in their studies. Analytical solution for heat flux distribution for impinging flame jets with inert gas jet approximation is presented by Remie et al. [6]. The heat transfer distribution for impinging flame jets of tube burner, orifice and nozzle are experimentally investigated by Chander and Ray [7]. They observed shift in peak heat flux location from stagnation point for low Reynolds number flame jets because of the influence of axial velocity. The burner geometry influenced the flame shape and hence the heat transfer characteristics. Hindasageri et al. [8] presented the heat transfer distributions for circular and rectangular tube burner impinging flames. Axis-switching phenomenon is noticed for non-circular burners. The act of impingement plate material and impingement surface temperature on heat transfer is presented respectively by Zhao et al. [9] and Li et al. [10]. Preheating of the mixture improved the thermal performance of the impinging flame jet [11]. The interaction of the flame jets from three tube burners placed in equilateral triangle fashion is presented by Dong et al. [12], Chander and Ray [13] and Hindasageri et al. [14]. Strong interaction between the jets with outward deflection was observed for smaller inter jet spacing.

Swirling flows are applied in engineering applications such as heat exchanger tube, vortex tube, vortex combustor, cyclone collector etc. for heat transfer augmentation [15]. The swirl flows are generated by the following methods:

(i) tangential entry of the fluid,
(ii) vane swirler,
(iii) twisted tape,

* Corresponding author.
E-mail addresses: pramodkuntikana@gmail.com (P. Kuntikana), svprabhu@iitb.ac.in (S.V. Prabhu).

http://dx.doi.org/10.1016/j.ijthermalsci.2016.09.024
1290-0729/

Nomenclature

a, b	length and width of target plate (m)
A	surface area (m^2)
d	Inner diameter of tube burner (m)
G	angular momentum (kg-m^2/s)
h	heat transfer coefficient (W/m^2-K)
HHV	higher heating value (J/kg)
k	thermal conductivity (W/m-K)
l	length of burner (m)
$\dot{m}$	mass flow rate (kg/s)
Nu	Nusselt number
p	pitch of twist (m)
$\dot{Q}$	rate of heat (W)
q''	heat flux (W/m^2)
$\overline{q''}$	spatial averaged heat flux (W/m^2)
r	radial distance (m)
R	radius (m)
Re	Reynolds number
S	swirl number
T	temperature (K)
TR	twist ratio
T_f	flame temperature (K)
w	width of tape (m)
x, y	rectangular co-ordinates of target plate (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	polar coordinate
ρ	density (kg/m^3)
σ	Stefan-Boltzmann constant (5.67×10^{-8} W/m^4-K)
σ_{std}	standard deviation of heat flux (W/m^2)
ϕ	equivalence ratio $\frac{(A/F)_{stioc}}{(A/F)_{actual}}$

Subscripts/ superscripts

∞	ambient
act	actual
b	bottom
$conv$	convection
f	fuel
fj	flame jet
ht	heat transfer
m	mean film
max	maximum
nc	natural convection
ns	no swirl
rad	radiation
ref	reference
s	swirl
t	top
w	wall

Abbreviations

COV	Coefficient of variance

(iv) physical rotation of the burner

Use of swirl flows in air jet impingement cooling is found to improve cooling performance for single and multiple jet impingements. A detailed review of swirl flow in combustion is presented by Syred and Beer [16]. Swirl flow help in improving the combustion process by

(i) the stabilization of high intensity flame jets as a result of formation of toroidal recirculation zones,
(ii) high rate of ambient air entrainment and fast mixing especially on the boundaries of recirculation zones

The swirl results in reduced flame lengths. Luo et al. [17] compared the heat transfer behaviors of swirling premixed flame with non-swirling premixed flame for the same operating condition. Non-swirling premixed flame produced large heating area and more uniform heat flux because of faster radial spreading rates. Because of complete combustion, higher flame temperature is observed for premixed flames with induced swirl [18]. Zhao et al. [19] developed an array of three induced swirl flame jets. Under low pressure, low Reynolds number operating conditions, the swirling flame jets achieved more complete combustion for lower burner to plate spacing. Singh et al. [20] investigated the effect of swirl angle on heat transfer characteristics of impinging natural gas-air flames. More uniform heat flux distribution is observed for moderate burner to plate spacing with larger vane swirl angle. Hindasageri et al. [21] observed an improvement in heat flux distribution by 40–140% with tube burners equipped with twisted tape inserts. The transient temperature history with semi-infinite body assumption is used for flame heat flux determination. The initial heat flux to the target plate is higher compared to the steady state heat flux. Hence, the reported data is limited to the initial time frames.

For better understanding of swirl burners, there is a need to investigate the effect of mixture composition on heat transfer characteristics of impinging swirl flames. Present study focuses the characterisation of impinging flame jets issuing from tube burners equipped with twisted tapes. The mixture Reynolds number ($Re = 800$) and burner to plate spacing ($Z = 4d$) are fixed based on the flame stability limits and flame height such that maximum number of equivalence ratios (0.8–1.5) does not result in central cool flames. The heat flux distribution is analysed for uniformity and thermal efficiency. The Nusselt number and effectiveness are determined with two equation technique proposed in our previous work [22].

2. Experimental technique

2.1. Flow metering and instrumentation

Fig. 1 shows the schematic of the experimental set up. The fuel (from methane cylinder) and the oxidiser (from air receiver) are metered through mass flow controllers (MFC). The Aalborg made MFC for air and methane have ranges of 0–10 SLPM and 0 to 1 SLPM respectively. The MFC's are calibrated with BIOS make gas flow calibrator with an accuracy of 1% reading attributable to NIST standards. The mixing cup is a packed bed of steel balls, ensures the proper mixing of fuel and air and dampens the flow fluctuations. The premixed mixture is supplied to the tube burner mounted on the holder.