International Journal of Heat and Mass Transfer 77 (2014) 995–1007

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Heat transfer characteristics of dual flame with outer swirling and inner non-swirling flame impinging on a flat surface

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A R T I C L E I N F O

Article history:
Received 13 March 2014
Received in revised form 2 May 2014
Accepted 30 May 2014
Available online 5 July 2014

Keywords:
Dual flame
Impingement
Outer swirling flame
Heat flux
Heating uniformity

A B S T R A C T

An experimental study has been conducted to evaluate the heat transfer characteristics of CNG/air dual flame (outer swirling and inner non-swirling flame) impinging on a flat surface. Effects of variation of outer swirling flame Reynolds number ($\mathrm{Re}(o) = 3000–11{,}000$), inner non-swirling flame Reynolds number ($\mathrm{Re}(i) = 900–1700$), dimensionless separation distance ($H/D_h = 1–5$) and equivalence ratio of outer swirling flame ($\phi(o) = 0.8–1.2$) on heat transfer characteristics have been investigated at fixed inner flame equivalence ratio ($\phi(i) = 1.0$) and swirling insert helix angle of 40°. A significant effect on shape and size of the inner non-swirling flame has been observed due to central recirculation zone established by the outer swirling flame and vice versa. Impingement pressure distribution shows that the pressure peaks are the locations of peak heat fluxes on the impingement surface. Effect of presence of inner flame on heating characteristics is considerably less at larger separation distances ($H/D_h \geqslant 5$) due to dominating effect of recirculation zone over the central axial flow. Heating characteristics showed that the heat flux distribution lines corresponding to inner flame were pushed inward towards burner axis with increase in outer swirling flame Re(o) at fixed Re(i). On the other hand, the inner boundary of the outer flame had shifted outwards with increase in Re(i) at fixed Re(o). Average heat flux imparted to the target surface increases with decrease in separation distance and increase in Re(o). There has not been much gain in the average heat transfer to the impingement surface beyond certain value of Re(o) because the rate of increase of average heat flux decreases with increase in Re(o) due to entrainment effect. Relative deviation in heat flux distribution on the impingement surface decreases with increase in separation distance. In most of the cases it again starts increasing for $H/D_h > 2$. In many cases, with further increase in separation distance beyond H/D_h of 3, the deviation starts continuously decreasing. Thus, it is concluded that for a dual flame impinging on a flat surface, best operating conditions prevail at moderate Re(o) (7000–9000) and H/D_h of 2.

1. Introduction

Designing an efficient system for industrial and domestic heating remained an ever challenging topic for last many years. Many types of heating systems are in use in industry like radiant furnaces and induction furnaces, etc. Variety of fuels has been used like solid, liquid and gaseous in these heating systems. Direct flame impingement heating is one of the efficient heating systems that has been used in industrial and domestic applications. In this case, convective heat transfer is maximized by direct impingement of flames on the target surface. Impinging flame jets are employed as an advanced rapid heating technology to melt scrap metal and to give shape to glass and metal bars. Advantages like faster and efficient heating with very less pollutant emission can be achieved with direct flame impingement heating. In spite of numerous advantages, this heating technique is still used with some hesitation by the metal processing industry due to its inherent drawback of non-uniformity of heat transfer distribution on the impingement surface.

Many arrangements and modifications in burner designs have been recommended to enhance the uniformity in heat transfer to the impingement surface [1–3]. Forced convection is a dominant mode of heat transfer in impinging flames that contributes more than 70% of total heat transfer [4]. Luminous radiations can transmit up to 15% of total heat flux [5]. Thermo-chemical heat release can also contribute significantly along with forced convection (convection vivre [6]) for high temperature oxy-fuel impinging flames [7]. High heat transfer coefficients are observed particularly in the impingement region due to small wall boundary layer thickness resulting in large velocity and temperature gradients [4].

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2014.05.062
0017-9310/

Nomenclature

A	impingement area (m^2)
A/F	air fuel ratio
D_h	hydraulic diameter in m ($D_h = D_o - D_i$)
d	diameter of inner burner (m)
H/D_h	dimensionless separation distance
$\dot{q}''$	heat flux (kW/m^2)
r	radial distance in (m)
r/D_h	dimensionless radial dimension
$Re(o)$	outer swirling flame Reynolds number
$Re(i)$	inner non-swirling/swirling flame Reynolds number
V	velocity (m/s)

Greek symbols

μ	dynamic viscosity (kg/m-s)
ρ	density (kg/m^3)
$\phi(o)$	outer swirling flame equivalence ratio
$\phi(i)$	inner swirling/non-swirling flame equivalence ratio
$\theta(o)$	outer swirling insert helix angle in degree

Subscripts

dev	deviation
mix	mixture
rms	root mean square
stoic	stoichiometric

Numbers of studies are available for non-swirling premixed and diffusion flames impinging directly or intermittently on a flat surface [1,8–15]. A focused heating in the stagnation region was observed resulting in a bell-shaped heat flux distribution on the impingement surface. This localized heating results in creation of high temperature gradients within the material that may lead to production of thermal stresses and hence failure of material goods. This sets a huge challenge for this type of heating system to be recommended for industrial applications. At small separation distances when very high heat transfer rates are expected, the heating becomes increasingly non-uniform due to formation of inner cool central core [6,11]. Heat transfer characteristics of array of impinging flame jets are considerably different from single jet due interaction amongst the adjacent jets [3,16–18]. Extinction of the central flame jets and difficulty in release of the spent gases from the core of the array are few of the problems associated with the impinging arrays. Due to these limitations, the use of jet-array design for heat transfer becomes notably complicated.

Many studies are available on heat transfer characteristics of swirling jets impinging on flat surfaces [19–29]. A considerable amount of uniformity in heat flux distribution was attained using swirling impinging jets. Blein et al. [21] compared heat transfer distribution of conventional (without swirl) and swirling impinging jets. It was found that surface temperature and heat flux distribution were more uniform with swirling impinging jets. Heat transfer at stagnation point depends on swirl intensity of flow and at high swirl intensities; low stagnation point heat fluxes have been observed due to flow diversion and formation of a low velocity area at stagnation region [19,20,29]. Location of peak heat flux shifts away from the stagnation point with increase in swirler intensity due to displacement of maximum velocity away from the jet axis [21,22]. Abrantes and Azevedo [27] also observed the enhanced heat transfer for small nozzle to plate spacing with high heat fluxes at radial positions away from the jet axis. However at large impinging distances, the average Nusselt number decreases but heat flux distribution becomes more uniform. Thus, swirling impinging jets are capable of producing enhanced and uniform heat transfer though it often comes at the cost of lower stagnation point heat transfer coefficient [26,29].

Swirling motion in combustion systems reduces flame lengths by producing higher rates of entrainment of the ambient fluid and faster mixing close to the exit of the nozzle and on the boundaries of recirculation zones [30–32]. Tangential or azimuthal component of velocity in the swirling flow diverges the flow from pure axial to radial direction. Higher magnitudes of velocities were observed at some radial locations instead of nozzle's centerline [33,34]. At higher swirl number, a strong radial and axial pressure gradient are produced at the nozzle exit, which leads to reversal of flow and the formation of recirculation zone in the downstream direction [35]. This recirculation vortex plays an important role by supplying hot combustion products and active chemical species to the base of the flame along with providing low velocity region [36–38]. This leads to an effective aerodynamic that stabilizes the flame even at very high flow velocities.

Literature pertaining to heat transfer characteristics of swirling impinging flame is very scarce. Huang et al. [39] observed that circular laminar premixed flames with induced swirl had a larger impinging area than that of the similar flame jet without swirl. However the peak heat flux shifts to radial position away from stagnation point unlike premix non-swirling flames [40]. Zhen et al. [41] showed that the swirling motion affects the distribution of local heat flux by deteriorating the heating at stagnation point. The peak of local heat flux occurs at a radial distance away from the stagnation point where the vertical flame boundary actually strikes the impinging surface. Zhen et al. [42] also observed that the heat transfer at the stagnation point is severely suppressed by swirl and is the highest at a certain radial position, which coincides with the position of the maximum impinging flame temperature. Singh et al. [43] conducted an experimental study to investigate the heat transfer characteristics of compressed natural gas (CNG)/air swirling flames impinging on a flat surface. Again a dip in the heat flux at and around stagnation point was observed in almost all cases. This dip in heat flux becomes more pronounced at higher Reynolds number. It was further observed that the heat flux distribution was more uniform at moderate separation distance and at larger helical vane swirl angle. In a recent study on thermal and heat transfer behaviors of a multi-fuel-jet inverse diffusion flame with induced swirl, it is observed that radial heat flux distributions are M-shaped [44]. A low heat fluxes at the central stagnation region and high heat fluxes in certain radial positions were attained where intense combustion takes place.

It has been concluded from the reviewed literature that many studies have been carried out where emphasis is on imparting higher heat transfer rates along with maintaining uniformity of heat flux distribution on the impingement surface. Arrangements like arrays of burners, swirling flames were tested to maintain uniformity which is the primary requirement for recommending flame impingement heating for conventional metal processing industry. There are inherent drawbacks with the array of burners like performance deterioration due to interaction of flames and problem of exiting the spent flue gases from the array arrangement. In case of swirling flame, although there is better spread of the flame on