International Journal of Heat and Mass Transfer 124 (2018) 90–108

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Heat transfer and fluid flow characteristics of a pair of interacting dual swirling flame jets impinging on a flat surface

Parampreet Singh, Subhash Chander *

Department of Mechanical Engineering, Dr. B. R. Ambedkar National Institute of Technology Jalandhar, Punjab 144011, India

ARTICLE INFO

Article history:
Received 29 December 2017
Received in revised form 2 March 2018
Accepted 9 March 2018

Keywords:
Swirling flames
Impingement heat fluxes
Interactions
Cross-flow
Thermal imaging

ABSTRACT

Experimental and numerical studies have been conducted to investigate the flow field and heat transfer characteristics of a pair of dual interacting swirling flames impinging on a flat surface. Commercial computational fluid dynamics (CFD) code (FLUENT®) has been used to simulate the interacting isothermal swirling impinging jets. Inverse heat conduction procedure (IHCP) has been used to calculate the impingement heat fluxes from the surface temperatures captured by Infra-red camera. Effect of separation distance (H/D_h = 2.5, 4, 6 and 8) and inter-jet spacings (S/D_h = 4, 6, 8 and 10) have been studied at various Reynolds numbers (*Re*(o) = 7000, 9000, 11000, 13,000 and *Re*(i) = 700, 1000, 1300) under stoichiometric conditions. Strong interactions between adjacent dual swirling flames result in high heat transfer due to increased mixing and turbulence in the interaction region. The inner non-swirling flames are seen to deflect towards interacting side due to asymmetric interactions. Numerical simulation predicted this deflection to be primarily due to large recirculation bubble developed from asymmetric interactions. Tilted cross-flow, emerging from interaction region has been observed due to momentum exchange taking place between cross-flow and swirling flames (jets). Area weighted average of local heat flux and relative deviation from averaged value has been calculated at various H/D_h and S/D_h. High average heat fluxes are obtained at smallest H/D_h and S/D_h. It has been concluded that for a system of burners considered for the present study, H/D_h = 2.5 and S/D_h = 8 is the optimum configuration on the basis of minimum relative deviation.

1. Introduction

In industrial applications like metal shaping and melting, glass processing, gas turbine cooling, cooling of micro-electronic chips, preservation of tissues in medical science, etc., high heat and mass transfer coefficients are required. Jet impingement heat transfer (*JIHT*) has emerged as an effective technique as turbulent impinging jets are well known to possess high potential for rapid heating or cooling of the target surface. The elevated heat transfer rates associated with impinging jets are well documented in past reviews [1–4]. Direct flame impingement heating has extensively been used in many industrial applications where impinging flame jets are employed as an advanced rapid heating technology to melt scrap metal and to give shape to glass and metal bars. Baukal and Gebhart [5] reviewed the effect of experimental conditions and measurement techniques those are of significant importance for impinging flames in rapid heating furnaces. The major demerit concerned with conventional impinging flame jets is highly non-uniform heat transfer at the target surface [6]. More recently, Zuckerman and Lior [7] have explored the physics of single and multiple impinging jets. Different correlations developed for impingement heat transfer have also been reviewed and it has been reported that cross-flow causes nearly 25% degradation in averaged Nusselt's number values.

Impinging swirling jets flourished as an improved version of jet impingement heat transfer causing more uniform heat transfer on the target surface [8–12]. Impinging swirling flames have also been explored for higher and more uniform spatial distribution of heat fluxes [13–16]. Swirling flames exhibit wider flammability limits and possibility to sustain combustion under lean premixed conditions. This results in lesser average flame temperatures and hence lesser pollutant emissions. Improved combustion characteristics of swirling flames lead to one-fifth reduction in flame length due to better mixing [17–19]. Improved stability of swirling flames through recirculation of hot combustion gases [19] inevitably favor their use in impingement heating applications [13].

* Corresponding author.
E-mail address: chanders@nitj.ac.in (S. Chander).

https://doi.org/10.1016/j.ijheatmasstransfer.2018.03.034
0017-9310/

Nomenclature

A/F	air-to-fuel ratio
T	temperature (K)
t	time (s)
Δt	time interval (s)
x, y	coordinate axis on the impingement plate
x/D_h, y/D_h	non-dimensional distances in x and y direction
z	thickness (mm)
Z	downstream distance from burner exit (mm)
r	radial distance from mid-point of two burners (mm)
r/D_h	non-dimensional radial distance
p	pressure
q''	heat flux (kW/m^2)
Re	Reynolds number
Re(o)	Reynolds number of outer flame
Re(i)	Reynolds number of inner flame
H	separation distance between burner exit and impingement plate (mm)
H/D_h	non-dimensional separation distance
D_h	hydraulic diameter (mm)
d	diameter of inner pipe (mm)
S	inter-jet spacing (mm)
S/D_h	non-dimensional inter-jet spacing
u, v, w	velocity components in x, y and z direction
u_m	average velocity at burner exit (m/s)
M	molecular mass (kg/kmol)
X	mole fraction
k	turbulent kinetic energy (m^2/s^2)
MCIJ	multiple conventional impinging jets
MSIJ	multiple swirling impinging jets
IFOV	instantaneous field of view
FPA	focal plane array
IHCP	inverse heat conduction procedure
RNG	renormalization group theory
RANS	Reynolds averaged Navier Stokes
RCZ	recirculation zone

Greek symbols

Φ	equivalence ratio
α	thermal diffusivity (m^2/s)
μ	dynamic viscosity (kg/m s)
ε	dissipation rate (m^2/s^3)
ρ	density (kg/m^3)
λ	thermal conductivity (W/m K)

Subscripts

avg	area-weighted average
atm	atmospheric
dev	deviation from averaged value
dev, rms	root mean square deviation
∞	ambient
i	initial time
j	index for chemical species
wf	front side of impingement plate
wr	rear side of impingement plate
s	surface

A number of studies pertaining to heat transfer characteristics of impinging swirling flames have been conducted. Swirling motion causes heat flux peak to occur at radial location away from the centre directly confirming to either the hydrodynamics of jet or maximum flame temperature location [20]. Stagnation region is marked with relatively lower heat flux values [13–15,21]. Effect of swirl persists only upto certain separation distances beyond which the peak heat fluxes shift to the stagnation point [15,20]. Effect of Reynolds number (firing rate), swirl number, equivalence ratio on heat transfer characteristics have been established in number of studies [13–16,20–22]. Swirling flames entrain a lot of ambient air due to the nature of flow itself causing increased thermal dilution. This shift in flame chemistry causes peak heat fluxes to be realized at slightly fuel rich conditions [14,21]. Despite of the stated advantages, the heat transfer distribution resulting from a swirling flame is still non-uniform. More recently, Singh and Chander [23] introduced the concept of a dual flame burner comprising of outer swirling and inner non-swirling flame. Use of inner flame in dual flame burner led to reliable stabilization of outer swirling flame at higher flow rates and also under fuel lean conditions. This aided in heating of the stagnation region thus alleviating the non-uniformity aspect to some extent.

Viskanta [4] identified array of impinging flames as an important research area from the comprehensive review of studies pertaining to isothermal and flame jets impinging on a surface. Malikov et al. [24] stated that the impact of array configuration on direct flame impingement (*DFI*) heating must be carefully investigated in future studies so as to achieve uniformity in heating performance. Bulk of the studies on impingement heat transfer are mainly related to single axisymmetric round jets, slot jets and arrays of round and slot jets. While single impinging flame is used for heating a smaller target surface, an array of suitable configuration employing multiple impinging flames is used for impingement heating of a larger surface. Multiple impinging flames also assist in uniform heat exchange as the mechanism of heat transfer in an array is significantly different from that of a single flame. Presence of several impingement zones, interactions among adjacent flames both prior to and post impingement, cross-flow of spent gas are some of the additional variables affecting heat transfer in an array employing multiple flames. Thus thermo-fluid dynamics of an array is incoherent with that in a single impinging flame and mere extension of information pertaining to single impinging flame in forecasting the behaviour of multiple-jet system is illegit. A few number of studies have been conducted for multiple conventional (non-swirling) flames predicting the effect of interactions and cross-flow on resulting heat transfer [24–30].

Many configurations of array of impinging flames have been explored in the literature. This includes inline and staggered arrangements with different number of flame jets. In most of the studies three flame jets (round and slot) have been used [27–30]. The purpose of these studies was to understand the effect of interactions on heat transfer characteristics of the impinging flames. Wu et al. [26] inferred that interactions taking place among flame jets issuing from *RJRC* nozzle strongly affect the heat transfer distribution at impingement surface. Dong et al. [27] studied three in-line laminar flame jets as a subset of larger in-line array and deduced that interacting flame jets resulted in reduction of heat transfer rate in the interacting zone due to the depressed combustion. At smaller inter-jet spacings, a positive pressure is produced at the interaction region leading to flow reversal and thus decreased heat transfer coefficients. Chander and Ray [28] investigated an array of three methane-air flame jets arranged in shape of equilateral triangle forming subset of staggered array. It was stated that at smaller inter-jet spacings, strong interactions took place