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Heat transfer characteristics of natural gas/air swirling flame impinging on a flat surface

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ABSTRACT

An experimental study has been conducted to investigate the heat transfer characteristics of compressed natural gas (CNG)/air swirling flames impinging on a flat surface. Qualitative flame structures have been studied by taking direct photographs of impinging flames. The radial temperature distribution of swirling free and impinging flames is presented at different axial heights under fixed operating conditions. Effects of dimensionless separation distance (1–6), Reynolds number (3500–6000), equivalence ratio (1–1.5) and helical vane swirler angle (0–60°) on heat transfer characteristics have been investigated. The heat transfer characteristics of swirling and non-swirling flames have been compared under similar operating conditions. A dip in the heat flux at and around stagnation point was observed in almost all cases which could be the main cause of non-uniformity even in case of heating with swirling impinging flames. The dip in heat flux becomes more pronounced at higher Reynolds number. The heat flux distribution on the impingement plate was more uniform with swirl as compared to without swirl. Also, heat flux distribution was observed to be more uniform at moderate separation distance and at larger helical vane swirl angle. Stagnation point heat flux variation remains almost constant at higher separation distances for different values of Reynolds number and equivalence ratios. There was significant decrease in average heat flux with increase in separation distance. It was further observed that average heat flux increases sharply with Reynolds number whereas the variation was not that steep with change in equivalence ratio.

1. Introduction

Heating, cooling and drying processes are often used in industry. In many of the applications, high and uniform heat transfer rates are required in order to have increased productivity and high product quality. Radiant and induction furnaces are commonly used in industry for heating of metal and glass products. There is inherent drawback with the radiant furnaces of low heat fluxes (~50 kW/m^2) and with induction furnaces in adjusting the magnetic field with different sizes of the products. Keeping in view these limitations, impinging flame jets are ideal substitute for heating the materials in industry due to enhanced heat transfer rates. Heat transfer rates of the order of 500 kW/m^2 can be achieved because of direct contact of the hot fluid with the target surface. The major drawbacks in utilizing the impinging flame jets are non-uniformity in the heat flux distribution and limited range of flame stability at high flow rates. Swirl has been successfully introduced to enhance the flame stability in many large scale industrial applications using turbulent diffusion flames.

Literature reviewed revealed that majority of studies pertaining to swirling flames are for open free flames. Yilmaz et al. [1] classified swirling flows into three groups, namely curved, rotating and vortex flows. Vortex swirling flow can be generated by the addition of tangential entry or a guide vane. Swirling flows are commonly used to improve and control the mixing process between fuel and oxidizer to achieve flame stabilization and enhanced heat release [2]. Excellent research work has been carried out in this direction by various researchers who published state-of-the-art research papers and revealed the hidden facts in swirling flows [3–17]. The swirling flow field governs the main flow structure; its match-up with fuel distribution is the key for achieving homogeneity of fuel/air mixture and consequently low NO$_x$ emission. Combustion intensity is greatly enhanced in swirling flow because of the higher shear stresses resulting from the rotating movement of the flow [18]. The main effect of swirl is to improve flame stability because of the formation of toroidal recirculation zones above the nozzle exit. Introduction of swirl reduces the combustion flame lengths by producing high rates of entrainment of ambient fluid and fast mixing particularly near the boundaries of recirculation zone. Due to central toroidal vortex, the overall fuel–air mixing rate within a swirl-stabilized flame is found to be five times greater

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Nomenclature

d	burner exit diameter (mm)
H/d	non-dimensional nozzle to plate distance
n	number of samples
$\dot{q}''$	heat flux ($\mathrm{kW/m^2}$)
r	radial distance (mm)
Re	Reynolds number of the air/fuel mixture flow
Se	swirl number

Greek symbols

ϕ	equivalence ratio
θ	helical vane swirler angle (degree)

Subscripts

avg	average
dev	deviation
rms	root mean square

than that of a simple jet resulting in five-fold shortening of the flame length [9,10]. The shape of recirculation zone and the turbulence intensity is affected by combustion (heat release) in swirling flame jets compared to non-reacting swirling jets [5,10]. Syred et al. [3] showed that combustion induces comparatively small change in the aerodynamics of swirling flow fields. Another advantage of swirl was that it makes overall fuel-lean operation possible. Syred and Beer [2] carried out exhaustive review on swirling flows and described various methods to produce swirling flow. Feikema et al. [11] applied swirling flow to enhance the blow-out limits of non-premixed flame jet, where swirling flow was induced with the help of four tangential inlets.

In order to improve the heat transfer characteristics of an impinging jet and to realize more uniform heating or cooling for heat transfer equipment, a number of experimental studies have been carried out on swirling isothermal impinging jets [19–23,25]. Ward and Mahmood [19] mentioned that a swirling impinging jet had potential to have more uniform heat transfer on the surface. It was observed that as swirl number was increased, heat transfer coefficient at stagnation point and in wall-jet region decreased. Ichimiya and Tukamoto [23] investigated experimentally the heat transfer characteristics of a circular swirling impinging jet with two tangential entries at a constant distance from nozzle exit. Effect of change in entry angle of tangential flow was observed. Blein et al. [21] compared the heat transfer characteristics of conventional (without swirl), multi-channel conventional and swirling impinging jets. Surface temperature distribution was more uniform with swirling impinging jet and uniformity was increased with increase in swirl angle. Bakrici and Blein [24] observed decrease in Nusselt number at stagnation point with increase in swirl number due to reduction in the jet arrival velocity at the impinging surface. Huang and El-Genk [20] used a swirl generator made of cylindrical plug with four narrow channels to provide swirl to single and multiple air impinging jets. It has been observed that swirling jet impingement (SIJ) demonstrated large increase in Nusselt number and significant improvement in radial uniformity of heat transfer compared to multi-channel impinging jets (MCIJs) and conventional impinging jet (CIJ) which is contrary to results observed by Ward and Mahmood [19] and Lee et al. [25]. This could be attributed to the fact that turbulence generated due to sudden enlargement and contraction caused higher heat transfer rate for SIJ. Yuan et al. [22] observed that Nusselt number at stagnation point of swirling jet is about 5% lower than that of conventional impinging jet. It is because the swirling promotes the centrifugal force of the fluid, and causes more fluid to flow apart from the center. This weakened central impinging jet which further deteriorates the stagnation region heat transfer.

Very few studies are available on heat transfer characteristics of single and multiple impinging swirling flame jets. Huang et al. [26] showed that a circular laminar pre-mixed flame jet with induced-swirl has more uniform heat flux distribution and higher temperatures compared to without swirl flame jet. Zhao et al. [27] developed an array of three identical laminar pre-mixed flames with induced-swirl and suggested that under low-pressure and low-Reynolds-number conditions; a swirling flame jet array can achieve more complete combustion at shorter nozzle-to-surface distance and provides more uniform heat transfer on the target surface. Heating efficiency was enhanced when induced-swirl was applied. Zhen et al. [28,29] studied the heat transfer from a turbulent swirling inverse diffusion flame (IDF) to a flat surface. Value of maximum convective heat transfer coefficient increased monotonically as swirl number was increased from 4.56 to 9.l2. Further, it was observed that impinging swirling IDF achieved complete and intense combustion at smaller nozzle-to-surface distances compared to impinging non-swirling IDF. This was due to better mixing between the fuel and air induced by the swirl. Luo et al. [30] studied the heat transfer characteristics of a swirling premixed flame impinging vertically normal to a horizontal plate. It was concluded that swirling flame provides a larger heating area and produces a more uniform radial heat flux distribution compared to non-swirling flame.

Comprehensive literature review revealed that there is a great potential of overcoming the major drawbacks of flame impingement heat transfer like non-uniformity of the heating on the target surface with use of swirling flames. Lean combustion with better flame stability can conveniently be attained with induction of swirl in the flame. Most of the studies on swirling jet impingement heat transfer are carried out on gas jets or pre-mixed flame jets with low swirl intensities. The application of high-swirl in a flame jet has many advantages such as rapid mixing of fuel and oxidizer, high flame stability, broader operational limits and reduced soot formation. Present work investigates the heat transfer characteristics of compressed natural gas (CNG)/air swirling flame impinging on a flat surface using helical vane swirler insert. Effects of different operating parameters like, Reynolds number (3500–6000), equivalence ratio (1.0–1.5), and nozzle-to-surface distance (1–6) and helical swirler vane angle (0–60°) on the heat flux distribution on impingement surface have been studied. Here it is pertinent to mention that the swirl intensity/swirl number for the type of vane swirler used is not only the function of helical vane swirler angle but also depends upon the length of swirler insert, depth of groove, and location of the swirler with respect to the burner exit. Therefore authors felt it more appropriate to express the swirl intensity in terms of helical vane swirler angle. The other parameters like length of swirler, depth of groove, and location of the swirler with respect to the burner exit are kept constant. It was concluded that the main drawback of the direct flame impingement heating could be partially taken care-of using swirling impinging flames.

2. Experimental setup and procedure

Fig. 1 shows the schematic diagram of swirling flame impingement experimental setup. The experimental setup comprises of