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Research Paper

Air jet impingement technique for thermal characterisation of premixed methane–air impinging flame jets

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HIGHLIGHTS

- Steady state technique is proposed for thermal characterisation of flame jet.
- Effect of *Re*, ϕ and *Z* on *Nu* and η for impinging flame jets is investigated.
- Correlations are developed for local *Nu* and η in terms of flame jet parameters.
- Thermal efficiency of the burner varies with the flame jet parameters.

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ABSTRACT

A major part of the domestic and the industrial thermal energy requirement for the heating purpose is achieved by the combustion of hydrocarbon fuels using burners. The present study reveals that thermal characterisation of impinging flame jets can be performed with a steady state technique similar to thin metal foil technique used for impinging air jets. The target surface impinged by the premixed methane–air flame jet is simultaneously cooled from the rear side by impinging air jets at different Reynolds number. One dimensional energy balance across the thickness of the plate is performed. The Nusselt number and the effectiveness distributions for a tube burner with the present technique matched reasonably well with the two-equation technique proposed in our previous work. Maximum deviations of 12% and 15% are observed for *Nu* and η respectively. Correlations are developed for the local Nusselt number and effectiveness in terms of flame jet parameters. The burner is analysed for the thermal efficiency. For premixed cone flames, it is observed that the thermal efficiency increases with the Reynolds number and equivalence ratio and decreases with the burner tip to plate spacing.

1. Introduction

Impinging hydrocarbon–air flame jets are mainly employed to achieve higher rate of heat transfer. Industrial and domestic gas burners utilise these flame jets for direct heating processes. The extensive literature on methane–air impinging flame jets is reviewed and reported by Chander and Ray [1]. Viskanta [2] and Baukal and Ghebert [3,4] proposed analytical and semi-analytical solutions for impinging flame jets based on empirical analysis of experimental data. Van der Meer [5] identified the analogy of heat transfer in isothermal gas jets and reacting flame jets. Chander and Ray [6] studied the role of burner geometry on heat transfer characteristics. The flame structure and hence the heat transfer characteristics were observed to be changing with the burner geometry for the similar operating conditions. Hindasageri et al. [7] captured the transient surface temperature of the impingement surface with infrared thermal camera to predict the flame heat flux by inverse heat conduction technique. Heat transfer distributions of impinging laminar jet on flat surface for larger radial distances from hot spot are reported by Remie et al. [8]. Hou and Ko [9] observed the strong influence of oblique flame jet impingement on the flame structure for lower heating heights. The decrease in oblique angle resulted in a decrease in thermal efficiency. Agrawal et al. [10] developed a theoretical formulation of a premixed methane–air flame jet impinging on an inclined surface. The numerical solution to the theoretical model revealed the asymmetry in heat flux profile about the transverse axis of tilt. The impact of impinging methane–air flame jets on cold surface is reported by Milson and Chigier [11]. They observed a shift in the peak temperature location of central core flames to some distance away from the stagnation point. Studies on premixed butane–air impinging flame jet are reported by Dong et al. [12] and Zhao et al. [13]. Heat transfer characteristics of three interacting flame jets are reported by Dong et al. [14], Chander and Ray [15] and Hindasageri et al. [16]. Smaller inter jet spacing and

Abbreviations: BL, boundary layer; IR, infrared; MFC, mass flow controller; SLPM, standard litres per minute.

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separation distances caused the deflection of flame jets in outward direction from the centroid of triangular arrangement owing to the strong interaction between the jets. Dong et al. [17] and Kwok et al. [18] respectively characterised the single and array of impinging slot flame jets. Qi et al. [19,20] conducted the temperature field measurements of impinging butane–air flame jets with reference beam and Mach–Zehnder interferometry. Zhao et al. [21], Luo et al. [22], Singh et al. [23] and Hindasageri et al. [24] studied the effect of induced swirl on the heat transfer characteristics of impinging premixed flame jet. Inducing swirl flow prior to combustion resulted in improvement of thermal performance. Effects of target plate temperature and nozzle geometry on heat transfer and emissions of impinging premixed flame jets are reported by Li et al. [25,26]. Improvement in thermal performance is observed for preheated mixture [27]. Fu et al. [28] investigated the dynamics of turbulent flame jet impingement. They observed a crucial frequency corresponding to the combustion noise. Fénot et al. [29], Goldstein et al. [30] and Katti and Prabhu [31] characterised the impinging air jets using thin foil technique.

The studies reported in the literature assume different reference temperatures for impinging flame jet such as flame temperature at the edge of the boundary layer, adiabatic wall temperature and adiabatic flame temperature that limits the practical usage of the reported data. The present study features a simple technique similar to thin foil technique in impinging gas jet studies [31] that can be employed for impinging flame jets for heat transfer characterisation.

The objectives of the present work are:

i. Proposing a steady state technique involving simultaneous cooling of the flame jet impinged target surface by an impinging air jet for the heat transfer characterisation of premixed methane–air flame jet
ii. Determination of Nusselt number and effectiveness distributions of impinging premixed methane–air flame jets for various flame jet parameters ($Re = 500$ to 1500, $\phi = 0.8$ to 1.5 and $Z/d = 2$ to 6) for studying the effect of their variation on heat transfer
iii. Comparison of the Nu and η distributions obtained from present air jet impingement technique with that of the two-equation technique [32]
iv. Developing correlations for Nu and η in terms of flame jet parameters
v. Thermal efficiency determination and its variation with flame jet parameters

2. Experimental details

2.1. Details of setup for heat transfer characterisation of impinging air jet

The schematic of the experimental setup used for air jet impingement heat transfer characterisation is shown in Fig. 1. The compressed air is supplied by a screw compressor (ELGI make) through an air filter and pressure regulator. Air flow is metered using orificemeter through a flow control valve installed downstream. The metered air is then fed to a pipe nozzle of diameter 24 mm and length of 40D for ensuring fully developed flow at the nozzle exit. The nozzle tip to the impingement surface distance is kept fixed equal to six times the nozzle diameter for maximum cooling rate [31]. The pipe nozzle is held firmly by a nozzle holder with a threaded clamp. The air jet from the pipe nozzle is made to impinge over the target surface in the normal direction from the top side at the centre of the plate. A very thin (thickness = 0.05 mm) stainless steel foil having dimensions of 150 mm × 220 mm firmly clamped and stretched between two copper bus bars is used as impingement surface. The foil is sandwiched by 5 mm from either side between the flat copper bus bars bolted to a bakelite sheet for support. The impingement assembly is mounted on a mild steel frame for support. Electrical heating (resistance heating) is employed for heating the plate by using a step-down transformer. The power supply from the transformer is connected by copper power cables to the copper bus bars. The thin metal foil gets uniformly heated due to the higher thermal conductivity and lower thermal resistivity of copper bus bars. The electrical power input to the plate is varied by varying the voltage across the foil. The thinness of the foil ensures one dimensional heat conduction in the plate. Thus, the local temperature of the plate on the impingement surface and the rear surface of the foil is almost same with negligible temperature difference.

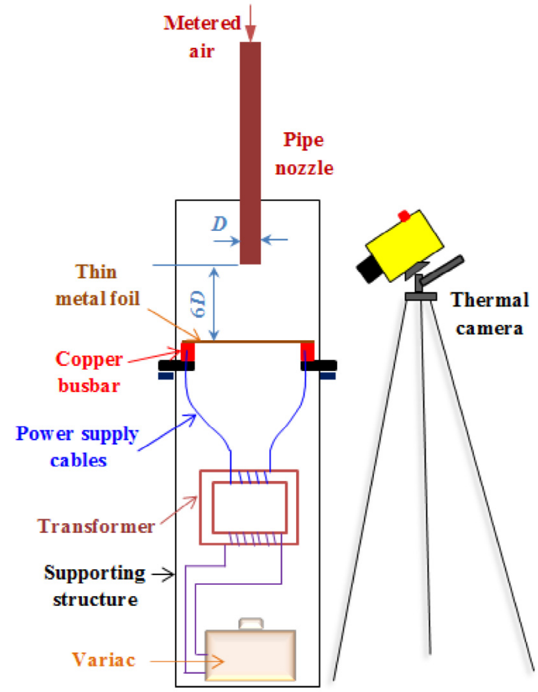

Fig. 1. Setup for in-house heat transfer characterisation of impinging air jet.

The impingement surface of the thin foil is painted with high temperature paint Pyromark for thermal imaging purpose. The surface emissivity of the spray painted surface and then cured by electrical heating (until a temperature of 200 °C) is 0.99 [33]. The thermal imaging of the impingement surface is done with Thermoteknix make VisIR® 640S infrared camera mounted on the impingement side of the foil to get the steady state surface temperature. The infrared thermal camera is calibrated in the operating temperature range with TEMPSENS Make, CALsys 1500BB model black body calibrator. A linear curve is fitted between actual temperature and measured temperature of the black body surface with an accuracy of 2%. The voltage and current across thin foil are measured with multi meter and clamp meter ('Meco' make) having an accuracy of 20 ± 0.5% V and 40 ± 0.5% A, respectively.

2.2. Details of setup for heat transfer characterisation of impinging flame jets

Fig. 2 shows the schematic of the experimental setup for heat transfer characterisation of impinging flame jets. The compressed air from the receiver of the air compressor is regulated to get sufficient air supply to the setup. The air is filtered by an inline air filter and then regulated through a pressure regulator to maintain a