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An experimental and numerical investigation of heat transfer distribution of perforated plate burner flames impinging on a flat plate

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A B S T R A C T

Heat transfer from perforated plate burner flame impinging on a flat plate finds importance in industrial (gas fired boiler) and domestic heating (household gas burner and commercial hotel gas burners) applications. A limited study on heat transfer distribution of this kind of burner plate is found in the literature. In the present work, high resolution heat flux is estimated by the inverse heat conduction (IHCP) technique based on use of analytical solution for semi-infinite medium for the impingement plate. Inline, star and staggered holes patterns with three different inter-hole distances (pitch) are considered in the present study. Methane–air premixed flame of Reynolds number varying from 50 to 600 and an equivalence ratio varying from 0.6 to 1.2 is considered. The hole to impingement plate distance is varied from 3 to 7. From the experimental results, it is found that the inline and staggered patterns have the same heat flux averaged over an area of 50 mm × 50 mm for different Reynolds number. The intermediate pitch of 7 mm is the optimal pitch over the entire mixture flow range considered in the present study. The specific fuel consumption for the star pattern is less by 40–60% as compared with the inline pattern for $p/d = 1.67$, $Re = 50$–300 and $z/d = 3$–7. A numerical simulation is carried out using CFD software to explain the shift in the peak heat flux away from the geometric intended location.

1. Introduction

Heat transfer from perforated plate burner flame impinging on a flat plate finds importance in industrial and domestic heating applications. In a domestic perforated plate burner, the impingement is usually done on an object that is representative of a flat plate. In case of this application in a gas fired boiler in an industry, the holes are located on the convex surface of a cylindrical drum. Due to the large number, small size and closeness of the holes, this class of impingement study is a different problem as compared to the multiple tube flame jet impingement study. Furthermore, the tube burners have sufficient length ($l/d = 40$) and hence the flow pattern and the associated combustion would be different from that of the perforated plate burners whose developing length is of the order of the hole diameter itself.

The perforated plate burner flame has been characterized by few researchers. Kedia and Ghoniem [1] studied the flame stability conditions leading to the blow off of a laminar premixed methane–air flame stabilized on a heat-conducting perforated-plate/multi-hole burner. An unsteady, fully resolved, two dimensional simulations are carried out with detailed chemical kinetics for methane–air species combustion. The combined effect of heat loss and flame stretch is attributed for the flame blow off criterion. Jatoliya et al. [2] investigated the flame characteristics of premixed LPG–air mixture for varying fuel richness. The species concentration is measured by a gas analyzer. The concentration of CO is found to decrease, while the concentration of NO increases, with the increase in the mass flow rate of the mixture. Timmermans et al. [3] studied the thermo-acoustic instability in the near wake of a perforated plate using hot wire anemometry and particle image velocimetry. They found that the low frequency instability occurs in transition region (laminar to turbulent) of the flow.

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Nomenclature

A	area (m^2)
A/F	air to fuel ratio
Cp	specific heat (J/kg K)
d	hydraulic diameter (m)
k	thermal conductivity (W/m K)
M	molecular weight
Pe	Peclet Number
Pr	Prandtl number
q''	heat flux (W/m^2K)
r	arbitrary radius (m)
R	maximum radius of the burner tube (m)
Re	Reynolds number
t	time (s)
T	temperature (K)
u_m	average velocity of fuel–air mixture (m/s)
w	square burner width (m)
X	mole fraction
Y	mass fraction
z	burner tip to target plate distance (m)
Z	quartz plate thickness/depth (m)

Greek symbols

α	thermal diffusivity (m/s^2)
μ	absolute viscosity (Pa-s)
ρ	density (kg/m^3)
ϕ	equivalence ratio

Subscripts/superscripts

eq	equivalent
i	initial
j	component of the mixture
f	flame
m	mixture
stoich	stoichiometric
w	wall

Heat transfer characteristics of impinging flame jets from perforated plate are of great importance and needs to be investigated. Substantial information on the flame jet impingement heat transfer characteristics from tube burners is reported in the literature. Reviews by Viskanta [4], Baukal and Gebhart [5,6] and Chander and Ray [7] summarize the flame jet impingement studies done so far. However, the heat transfer characteristic of perforated plate type of flame jet impinging on an object is limited in the literature [8–10]. Ko and Lin [8] studied the thermal efficiency and emissions characteristics of two grades (low and high heating values) of natural gas fired domestic gas stove. They found that when higher heating value natural gas is used for the burner designed for low heating value, the thermal efficiency decreases and the CO emissions increase. Li et al. [9] have studied the thermal efficiency and emissions characteristics of LPG fired burner stove for varying Reynolds number, equivalence ratio, inter-hole spacing and heating heights. They found that the thermal efficiency decreases continuously, in a constant manner, with the increase in the Reynolds number while the emissions peak up at the intermediate Reynolds number. Boggavarapu et al. [10] have studied the thermal efficiency of LPG and PNG fired domestic gas stove burner. They have suggested the use of circular strip in the flow path within the burner and radiant sheet as a design modification. This modification increased the thermal efficiency by 2.5%.

The studies reported in the literature give averaged heat flux distribution over the heating area and fail to capture sufficient spatial resolution. Due to the small size and closeness of the holes, the use of heat flux sensor/calorimeter generally used in literature [9,11–13] lacks sufficient resolution. In the present study, an analytical IHCP method is employed using an infrared thermal camera to get high spatial resolution in a short time with good accuracy. Inline, staggered and star patterns with three different inter-hole pitch distances (p/d = 1.67, 2.33 and 3.33) are considered in the present study. Methane–air premixed flame of Reynolds number varying from 50 to 600 and equivalence ratio varying from 0.6 to 1.2 is considered. The non-dimensional perforated plate to impingement plate distance (z/d) is varied from 3 to 7. Following are the objectives of the present work –

i) To compare the heat transfer distribution for inline, staggered and star pattern burners
ii) To study the effect of mixture Reynolds number (Re), equivalence ratio (ϕ), non-dimensional perforated plate to impingement plate distance (z/d), inter-hole pitch distance (p/d) on the heat transfer distribution
iii) To study the effect of operating flow parameters (Re, ϕ) and geometric conditions (z/d, p/d)
iv) To understand the fluid flow and heat transfer distribution by numerical simulations carried out using a CFD software

2. Experimental details

2.1. Description of experimental setup

2.1.1. Flow control and measurement

Fig. 1 is the schematic of the experimental setup used in studying the flame jet impingement heat transfer.

The flow controls and instrumentation are shown in Fig. 1. Mass Flow controllers (MFC) of accuracy 1.5% of full scale are used to meter the flow of methane gas (99.5% purity) and air from compressed air storage tank. The mass flow controllers used are of Aalborg make, USA. The air mass flow controller is calibrated with DryCal (DCLITE H) calibrator, BIOS International make whose accuracy is 1% of the reading traceable to NIST standards. The methane mass flow controller is calibrated by Soap bubble meter of PCI Analytics make, India whose accuracy is 2% of reading traceable to national standards (Fluid Control Research Institute, India). Methane and air are mixed in a mixing tube containing stainless steel balls which ensure that the two fluids find enough time for proper mixing and reduce the flow fluctuations.

2.1.2. The perforated plate burner construction

The schematic of the perforated plate burner is shown in Fig. 2. The fuel–air mixture enters from the bottom and is then made to pass through SS balls and wire mesh. This would ensure uniform flow. A 150 mm × 150 mm aluminum plate with holes drilled at a fixed pitch (p) on an area of 50 mm × 50 mm is fitted on the top of the cylindrical tube. The different configurations of the burners used in the present study are shown in Fig. 2. Three configurations – inline, staggered and star with three inter-hole