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Simultaneous estimation of heat transfer coefficient and reference temperature from impinging flame jets

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ABSTRACT

Heat transfer from impinging flame jets to a flat plate has been assumed to be one-dimensional in most of the investigations and without radiation loss treatment. In the present work, the exact nature of diffusion of heat in the plate is investigated via solution to multidimensional heat conduction problem. Two procedures have been employed – Duhamel theorem and three dimensional transient analytical IHCP. The Duhamel theorem which is analytical model for transient one dimensional heat conduction is applied but its application failed the check of linearity requirement of the convection rate equation. From the solution by analytical IHCP for transient, three-dimensional heat conduction, the distribution of wall heat flux and the wall temperature is perfectly linear. This check confirmed that three dimensional approach has to be used. Experimental data is then analyzed by the three dimensional analytical IHCP for short and larger time intervals. It is found that for short time data, heat transfer coefficient and the reference temperature have oscillatory distribution along the radial direction on the impingement plate and for larger time data the oscillations die out. However, at larger time, radiation loss from the impingement plate becomes significant. The effect of variations in thermal conductivity of the impingement plate with the temperature on heat transfer coefficient and reference temperature is discussed. A novel method is developed to correct the heat transfer coefficient and reference temperature to incorporate radiation losses. The deviation in heat transfer coefficient and reference temperature estimated without considering variable thermal conductivity and radiation loss for large time interval is upto 50%.

1. Introduction

Flame jets find importance in industrial and household applications like metal and glass melting/forming and cook stoves respectively. It also has importance in scientific studies on cooling of combustor wall of a gas turbine/jet engine and reentry of a space vehicle in earth's atmosphere. Reviews by Viskanta [1], Baukal and Gebhart [2,3] and Chander and Ray [4] provide useful information on the heat transfer correlations and parametric studies reported in literature. Estimation of heat transfer from impinging flame jets has been extensively studied with techniques ranging from simple calorimeter [5–7], heat flux sensors [8,9] to application of inverse conduction problems [10–12]. While the former two methods would provide heat flux data, the latter is useful in obtaining the proper heat transfer coefficient and reference temperature required for any engineering purpose. The knowledge of reference temperature is essential to estimate the proper value of the heat transfer coefficient as per Eq. (1).

$$q'' = h(T_{ref} - T_w) \tag{1}$$

However, the estimation of reference temperature is not straightforward as the flame jet temperature is not same as that of the surroundings and further varies along the radial direction on the impingement plate. Loubat et al. [12] have estimated the heat transfer coefficient and the reference temperature simultaneously by applying numerical IHCP. Hindasageri et al. [13] have proposed an analytical-numerical method to determine the reference (adiabatic wall) temperature by applying analytical IHCP coupled with a numerical finite difference code for heat conduction. Application of IHCP solution to multi-dimensional heat conduction problem for impinging flame jets is presented in the work of Feng et al. [14,15].

Most of the reported experimental data assumes one-dimensional heat diffusion in the impingement plate citing the thinness of the plate used. A quantitative description of the one dimensional/multi-dimensional nature of heat diffusion in the impingement plate is not available in literature. Studies using semi-infinite medium concept [13] have been used for spatially varying heat transfer distribution while the analytical solution is that for spatially constant heat transfer boundary condition. For the reported transient three dimensional analytical and

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Nomenclature

d	burner diameter (m)
$F(t)$	time dependent temperature function
h	heat transfer coefficient (W/m^{2}K)
n	Number of possible values for which Eigen function is zero
Pr	Prandtl number
k	thermal conductivity of plate (W/mK)
q''	heat flux (W/m^2)
r	distance from stagnation point (m)
T	temperature (K)
t	time (Sec)
x, y, z	coordinate axes
u	average mixture velocity (m/s)
W	width of the plate (m)
H	thickness of the plate (m)
Z	location of the impingement plate from the burner tip (m)

Greek Symbols

μ	absolute viscosity (Pa-s)
Φ	Eigen function
θ^*	Kirchoff transformed temperature (K)
ν	kinematic viscosity (m^2/s)

Subscripts/ superscripts

∞	ambient air
f	flame
ref	reference
w	wall

Abbreviations

CFD	Computational fluid dynamics
IHCP	Inverse heat conduction problem

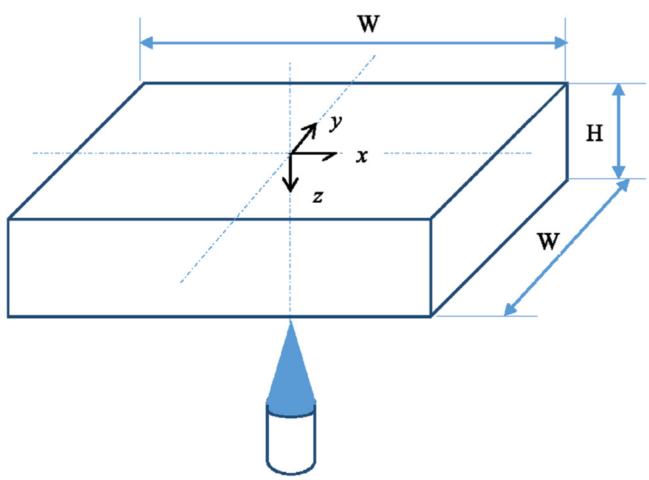

Fig. 1. Schematic diagram of the three dimensional plate impinged by a flame jet.

experimental studies mostly numerical IHCP procedure has been adopted [12]. In case of the recent analytical IHCP work of Feng et al. [15], transient three dimensional approach is employed but the validity of this method has been tested only with numerically simulated data. Experimental data is bound to have noise and hence can result in serious errors in the measured heat transfer parameters. Furthermore, the effect of radiation loss from the impingement plate has not been addressed in the literature. Coating the impingement plate with low emissivity paints or selecting material for the impingement plate itself with low surface emissivity is a well-considered option. However, thermal IR camera measurements are usually done with high emissivity paints so that error in measured temperature is less.

In the present study, analytical solutions to multi-dimensional conduction problem are used to estimate the heat transfer coefficient and the reference (adiabatic wall) temperature for impinging flame jets. Time dependent boundary condition for the impingement side has been considered. The one dimensional/multidimensional nature of heat diffusion is verified by two approaches- Duhamel theorem and method by Feng et al. [15]. Flame jets ensuing from circular burner with equivalence ratio of 1 is considered in the present study. A new procedure to correct the radiation loss from the impingement plate is presented. The effect of thermal conductivity variations with temperature for the impingement plate is also discussed.

2. Formulation of the heat conduction problem and solution methodologies

Fig. 1 is the schematic diagram of the three dimensional plate impinged by a flame jet.

The generalized multi-dimensional heat conduction problem with constant material properties (k, ρC) for flame jet impinging on a flat plate can be mathematically expressed as given in Eq. (2) along with boundary conditions.

$$\rho C\frac{\partial T}{\partial t} = k\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) \quad (2)$$

Location	Boundary condition	Description
At $t = 0$	$T(x, y, z, t) = T_\infty$	Initial
At x = 0, y = 0, z	$\frac{\partial T}{\partial n} = 0$	Symmetry
At x = $\frac{w}{2}$,y- = $\frac{w}{2}$, z	$\frac{\partial T}{\partial n} = 0$	Insulated
At x, y, z = H	$-k\frac{\partial T}{\partial n} = -\sigma\varepsilon(T^4 - T_\infty^4) + h(T_{ref} - T)$	Convective heat transfer + Radiation loss
At x, y, z = 0	$-k\frac{\partial T}{\partial n} = \sigma\varepsilon(T^4 - T_\infty^4)$	Radiation loss

*n is the direction along x, y and z axes.

At the sections (planes normal to x and y axes) passing through the impingement point, the symmetry condition is applied. The side surfaces of the plate are modeled as insulated boundary. The flame side surface is modeled as time dependent temperature boundary condition that addresses convective heating and radiation loss. The top side surface is modeled as time dependent temperature radiation boundary condition. For the transient heat conduction problem without radiation loss consideration, Duhamel theorem can be used for one-dimensional heat diffusion in the plate. Consideration of diffusion of heat in other directions requires more sophisticated method described by Feng et al. [15].

2.1. Duhamel theorem

As shown in Fig. 2, the flame side wall temperature varies with time and hence the temperature distribution solution for one dimensional