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Separation of heat transfer components from impinging methane diffusion flames

Vinay C. Raj, Pramod Kuntikana, S. Sreedhara, S.V. Prabhu *

Department of Mechanical Engineering, Indian Institute of Technology, Bombay, India

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ABSTRACT

The high heat transfer rates from impinging flame jets and plumes are extensively used in many industrial applications. Comprehensive literature review suggests that the characterization of flame impingement is done primarily by the measurement of heat flux onto the target surface. The use of in-situ probes limits the spatial resolution of the measurement. For a diffusion flame, radiation cannot be neglected and it is therefore necessary to determine the convective and radiative heat flux components to quantify the thermal boundary condition to the impingement surface.

For determining the heat transfer characteristics of impinging diffusion flames, the target surface is impinged by a methane diffusion flame from the bottom and is simultaneously cooled from the top by air jets of different Reynolds number. At steady state, one dimensional energy balance across the impingement surface provides an equation with the three unknowns being the heat transfer coefficient of the flame jet, the reference temperature and the emissivity of the gas/flame. By keeping the flame jet impingement conditions same and varying the air jet impingement on the top surface, five different forms of the energy balance equation is obtained. A minimization technique, that makes use of the Nelder-Mead algorithm, is developed to solve for the over-determined system of equations. The obtained results are compared with the slope method that determines the effective heat transfer coefficient and the reference temperature.

The impingement surface is modeled in FLUENT and the experimentally obtained heat transfer coefficient of the flame jet, the reference temperature and the emissivity of the gas/flame is provided as the boundary condition to numerically determine the surface temperature. For validation purpose, the impingement surface material and thickness is changed and the experimentally obtained and numerically determined wall temperatures are compared. It is demonstrated that the minimization technique is capable of separating the convective and radiative heat transfer components from impinging diffusion flames.

1. Introduction

Jet impingement heat transfer is a well established technique for achieving locally high heat transfer rates [1–8]. Impinging flame jets are extensively used in many industrial applications to enhance the heat transfer to the impingement surface. Premixed and diffusion flames are used for shaping of glasses, heating water walls in a boiler furnace, heating metal bars, blooms, ingots and billets, melting of scrap materials and heat treatment of metals [9–12]. Traditional industrial combustion systems such as the stoker fired boilers make use of diffusion flame for steam generation. Due to its varied applications, jet impingement heat transfer is extensively studied to determine the spatial heat transfer distribution [11]. Diffusion flame impingement is studied as part of the fire safety research to simulate large-scale fires impinging on walls and ceilings caused by ruptured piping in chemical process industries [13,14]. Comprehensive reviews on the state-of-the-art experimental, empirical, semi-analytical and numerical studies on jet and flame impingement are presented by Livingood [1], Martin [3], Downs [8], Viskanta [11], Jambunathan [15], Baukal [12,16–18] and Chander and Ray [19].

The flow regions of an impinging axisymmetric diffusion flame/plume are as shown in Fig. 1. The flow structures are subdivided into three characteristic regions:

(a) In the *free jet* region, the shear driven interaction of the flame jet/hot plume entrains the ambient air. Entrainment of the surrounding air results in the decrease in the axial

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* Corresponding author at: Department of Mechanical Engineering, Indian Institute of Technology, Bombay, Powai, Mumbai 400 076, India.

E-mail address: svprabhu@iitb.ac.in (S.V. Prabhu).

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Nomenclature

A	impingement surface [m^2]
d	burner tube diameter [m]
D	pipe nozzle diameter [m]
h	heat transfer coefficient [W/m^2 K]
I	current [A]
k	thermal conductivity [W/m K]
$\dot{m}$	mass flow rate [kg/s]
$\dot{q}''$	heat flux [W/m^2]
T	temperature [K]
v	velocity [m/s]
V	voltage [V]

Greek symbols

ε	emissivity
ρ	density [kg/m]^3
μ	dynamic viscosity [Pa s]
σ	Stefan Boltzmann constant [W/m^2 K^4]

Non-dimensional numbers

$Re = \frac{\rho VD}{\mu}$	Reynolds number
$Nu = \frac{hD}{k}$	Nusselt number

Subscripts

∞	ambient
aj	air jet
b	bottom
bs	back side
conv	convective
eff	effective
f	flame
fj	flame jet
fs	front side
m	mean film
NC	natural convection
p	plate
rad	radiative
ref	reference
t	top
w	wall

velocity component. The radial velocity profile changes from a top hat profile to a Gaussian curve. Entrainment also results in a decrease in the jet temperature.

(b) In the *stagnation* region, the local flow velocity becomes zero and the jet turns in the radial direction. The stagnation zone of an impinging jet is characterized by an extremely thin thermal boundary layer [20].

(c) In the *wall jet* region, the flow moves laterally outwards parallel to the wall. Heat transfer in the wall jet region is greater than that during the parallel flow. This is due to the turbulence/mixing generated due to the shear between the wall jet and the ambient air [11,15].

The local convective heat transfer coefficient, defined as in Eq. (1), is determined by measuring the convective heat flux ($\dot{q}''_{conv}$), the impingement plate temperature (T_w) and the reference temperature (T_{ref}).

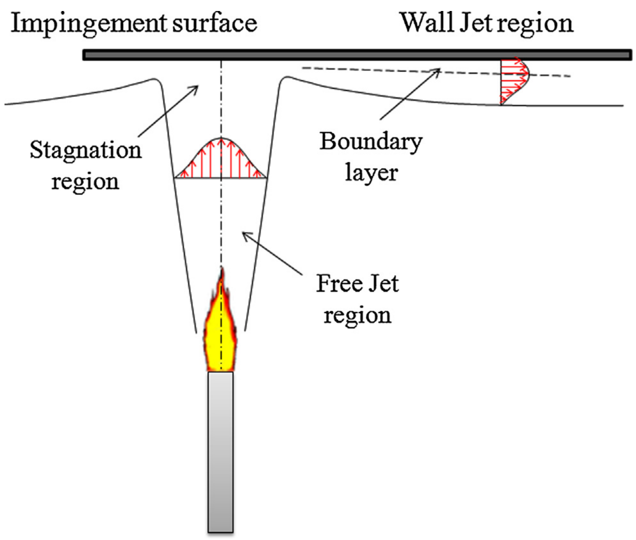

Fig. 1. Flow regions in an impinging diffusion flame/plume.

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

It is non-dimensionalized in terms of Nusselt number, which is the ratio of the convective to the conductive heat transfer at the boundary layer within the fluid, as follows:

$$Nu = \frac{hD}{k} \tag{2}$$

where h is the convective heat transfer coefficient; D is the characteristic length and k is the thermal conductivity of the fluid. Extensive literature review for measurement of impingement surface temperature, heat flux and the reference temperature is presented below with the aim to update the researchers.

1.1. Measurement of temperature of the impingement surface

Surface temperature measurement is crucial for the determination of heat transfer from flames to impingement surfaces. Temperature of a surface is conventionally measured by means of thermocouples embedded on the target surface. Recently, non-intrusive thermometric techniques like thermographic phosphors and infrared thermography have been used to determine the surface temperature. A brief review on measurement of temperature of impingement surface is presented below:

(a) Thermocouple: The impingement surface temperature is measured on the flame side of the impingement plate with the help of thermocouples embedded in a small hole drilled from the rear side of the impingement surface within 1 mm of the impingement side. Kwok [21] and Zhao et al. [22] made use of a single thermocouple located at the center of the impingement surface to measure the plate temperature. Due to the use of a circular nozzle, the surface temperatures are measured by traversing either the flame or the plate along only one radial direction. Dong et al. [23-28], Huang et al. [29] and Chander and Ray [30] measured the plate temperature by means of an array of thermocouples embedded onto the surface of the impingement plate.

(b) Thermographic phosphors: Phosphor thermometry utilizes the physical properties of the phosphor particles such as intensity,