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An experimental and numerical study of stagnation point heat transfer for methane/air laminar flame impinging on a flat surface

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Abstract

A combined experimental and numerical study has been conducted to determine the stagnation point heat transfer for laminar methane/air flame impinging on a flat surface. Effects of Reynolds number, equivalence ratio and burner diameter on stagnation point heat flux were examined experimentally at different separation heights. Maximum stagnation point heat flux was obtained when the flat surface was closest to the tip of the inner premixed reaction zone. Heat flux decreased along the axial direction when the separation distance was further increased from the tip of inner reaction zone. There was a secondary rise in heat flux at the stagnation point at larger separation distances. Correlations were developed for stagnation point Nusselt number. Numerical simulations were carried out using a commercial CFD code (FLUENT) for laminar methane/air flame impinging on a flat surface for various separation distances. Results were compared with those found experimentally. The reason for conducting the simulations was to (a) gain more insight into how the presence of the plate affects the flame and the flow and temperature fields and (b) to explain the reason for high heat flux when the tip of the inner reaction zone was very close to the stagnation point.

Keywords: Premixed flame; Heat flux; Stagnation point; Flat plate; Flame tip

1. Introduction

It is well recognized that metal and glass processing industries require heating of solids of variety of shapes in controlled conditions. In general, rolling and shaping processes for metal and glass are carried out by heating in radiant or electric induction furnaces. The radiant furnaces are believed to have low heating cost but are inefficient and time consuming. The electric induction heating technique is relatively very fast but has problems with respect to adjusting magnetic fields according to shape and size of the job as compared to radiant furnaces. Looking at these difficulties the use of flame impingement heating of solids is becoming attractive even in conventional industries due to the scope of enhanced convective heat transfer rates due to direct contact. This technique has an advantage of increased productivity, reduced fuel consumption and lower pollutant emission from its furnace (Baukal and Gebhart [1]).

Sibulkin [2] investigated the rate of heat transfer at the forward stagnation point for a blunt-nosed body moving through the atmosphere. A semi-analytical relation was given for heat transfer near the forward stagnation point of the body of revolution assuming laminar, incompressible and low speed flow. An important parameter in that relation was the velocity gradient just outside the boundary layer which was a function of nozzle diameter and free stream velocity. Kilham and Purvis [3] studied experimentally the heat transfer to the forward stagnation point of the hemi-spherical nosed probe for premixed methane–oxygen and propane–oxygen flames of various equivalence ratios. Results were compared with those calculated, assuming that (a) recombination reaction of dissociated species are frozen in the boundary layer and the surface is non-catalytic; (b) equilibrium is maintained throughout

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Nomenclature

A/F	air fuel ratio
C_p	specific heat at constant pressure (kJ/kg K)
d	diameter of the circular nozzle (m)
D	diffusion coefficient
h	enthalpy (kJ/kg)
H	axial distance of the impingement plate from the burner exit plane (m)
H/d	dimensionless separation distance (m/s)
k	thermal conductivity (W/m K)
L_f	flame inner reaction zone length (m)
M	molecular weight (kg/kmol)
Nu	Nusselt number
p	pressure (Pa)
$\dot{q}''$	heat flux (kW/m^2)
r	radial distance (m)
Re	Reynolds number
T	temperature (K)
u	flow velocity (m/s)
υ	flow velocity in x or r direction (m/s)
Y	mass fraction
Z	axial distance between the burner exit plane and the impingement plate measured from stagnation point (m)

Greek symbols

μ	dynamic viscosity (kg-s/m)
ρ	density (kg/m^3)
ϕ	equivalence ratio
δ_f	axial distance between the stagnation point and the tip of the flame inner reaction zone (m)
β	radial velocity gradient in the vicinity of stagnation point

Subscripts

actual	actual state
b	burner rim
exit	at the exit position
i	mixture component including fuel and air
in	inlet mixture
mix	air/fuel mixture
p	plate
r	radial direction
stg	stagnation
stoic	stoichiometric state
x	axial direction

the boundary layer, but the Lewis number of all atoms and radicals is unity; and (c) energy transfer by diffusion and recombination of hydrogen atoms is more rapid than heat transfer by ordinary conduction. These comparisons show that method (a) seriously underestimates the heat transfer and that the experimental values are intermediate between those calculated on the basis of assumption (b) and (c). Conolly and Davies [4] experimentally determined convective heat transfer coefficients at the stagnation point of a blunt body immersed in flames of several common fuel gases burning with pure oxygen. Theoretical predictions of heat transfer were made for the range of conditions studied experimentally. Reasonable agreement between experiment and the numerical semi-empirical predictions was obtained. Fairweather et al. [5,6] presented mathematical models for the prediction of stagnation point heat flux in the chemical equilibrium region of turbulent flames. Experimental measurements of the stagnation point heat flux received by a hemisphere-cylinder probe placed in methane-air flames were included, and free stream temperatures, mean velocities and turbulence intensities were measured for comparisons between theory and experiment. Predictions of the mathematical models show that the influence of free stream turbulence on heat transfer from these flames is relatively small for the considered geometry. Hargrave et al. [7] measured stagnation point heat flux of a body of revolution and a circular cylinder for premixed methane-air flames. Unburnt gas equivalence ratios from 0.8 to 1.2 were examined, with burner exit Reynolds numbers ranging from 2000 to 12,000. Peak heat transfer rates occurred within or close to the flame reaction zone. Van der Meer [8] measured flow structure and heat transfer of impinging flame jets as well as impinging isothermal jets from two rapid-heating burners. The separation distance between burner and plate varied from 1 to 12 burner diameters. The Reynolds numbers of the examined isothermal jets were 3300–10,000. For flame jets, the Reynolds number range was 1700–4250. Stagnation points Nusselt numbers were determined in two ways: from heat flux density measurements and from measurements of the radial velocity gradient in the vicinity of the stagnation point. The results from flame jets agreed quantitatively with the results from isothermal jets if the fluid properties in the heat transfer correlation were taken at a temperature corresponding to the average enthalpy of the boundary layer along the plate.

Many other studies are available (for single flame jet impinging on a flat surface) in the literature (Dong et al. [9–11], Kwok et al. [12], Milson and Chigier [13], Rigby and Webb [14] and Chander and Ray [15]) where the focus was on heat flux measurements in the radial direction. Baukal and Gebhart [1], Viskanta [16,17] and Chander and Ray [18] mentioned in their review papers that flame impingement heat transfer needs further research because of its vast applications in industrial and domestic heating systems. Very recently, Remie et al. [19] have presented analytical relations for calculation of heat flux in the hot spot around the stagnation point for both two-dimensional and axi-symmetric situations of laminar fuel-oxygen flame