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# Heat transfer investigations on methane-air premixed flame jet exiting from a circular nozzle and impinging over semi-cylindrical surfaces

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ABSTRACT

The flame jet impingement on curved surfaces finds applications in various direct flame heating situations. The design of heating equipment demands the estimation of the surface temperature and of the convective heat flux to the target surface at steady state for various impingement parameters. The characterisation of flame jets in terms of Nusselt number and effectiveness aids the designer to numerically estimate the steady state surface temperature and heat flux by specifying the convective boundary condition with spatial distribution of reference temperature. The present study reports the heat transfer characteristics of single flame jet impinging on convex and concave surfaces of a semi-cylindrical target plate. The effects of mixture Reynolds number, equivalence ratio, curvature ratio and burner to plate spacing on the heat transfer behavior are investigated. The uniformity of the heat flux distribution and the overall thermal efficiency are determined from the local heat flux distributions. The flow fields along the curvilinear axes influence the overall thermal performance. The concave surface produces higher thermal efficiency and better uniformity of heat flux over the impingement surface as compared with the convex surface.

## 1. Introduction

The flame jet impingement over curved surfaces is a commonly encountered circumstance in industrial and domestic heating equipment. The applications include conventional processes such as heating of cylindrical metal billets, heating cylinders for surface treatment of polymers, textile, fires impinging on pipes in chemical industries [1] and fires impinging on saj (a large concave or convex disc-shaped frying pan) griddles. The key role of the direct heating equipment is to extract and transfer heat to the impingement surface optimally with lesser environmental impacts. The designs of burners and furnaces have evolved over the time with improvements in the performances. The normal jet impingement over a flat surface is axisymmetric and the flow field is axial before impingement and radial post impingement. The problem of jet impingement over cylindrically curved surface is fundamentally three dimensional and asymmetric in nature. Thus, the heat transfer characteristics are highly influenced by the flow fields along the axial and angular directions [2]. The buoyancy and the inertia forces of the combustion products govern the flow field features. Therefore, basic knowledge of heat transfer characteristics of impinging jets is necessary for a proper design of direct heating equipment. Most of the studies on jet impingement over curved surfaces are associated with the isothermal air jets. Only a few studies are available on flame jets. In literature, two types of curved surfaces are investigated, namely concave and convex.

Viskanta [3] reported an extensive review of studies on impingement heat transfer of isothermal air jets and flame jets. Various studies on two dimensional slot jets and circular jets and the heat transfer correlations are presented. The effect of cross flow in multi-hole orifices is also summarised. Martin [4] comprehensively reviewed the literature on heat and mass transfer of gas jet impingement on solid surfaces. A large number of empirical correlations are congregated for the prediction of heat and mass transfer coefficients within a wide range of impingement and geometric parameters. The illustration of utilizing the correlations for optimizing the heat transfer performance of dryer and heat exchanger is presented.

Few studies in the literature have reported the heat transfer distributions for low Reynolds number (laminar) air jet impingement on hemi-cylindrical curved surfaces. Choi et al. [5] reported the measurements of impinging jet flow and heat transfer on a semi-circular concave surface for a two dimensional rectangular nozzle. The occurrence of secondary peak in the Nusselt number curve is associated with the jet flow characteristics in the impingement and evolving wall jet regions. Lee et al. [6] investigated experimentally the heat transfer characteristics of the laminar confined slot jet impinging on concave and convex surfaces. The flapping motion of jet column for the convex

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**Nomenclature**

| | |
|---|---|
| *a, b* | length and width of target plate (m) |
| $C_{HT}$ | heat flux correction factor |
| $C_T$ | temperature correction factor |
| *d* | Inner diameter of tube burner (m) |
| *D* | Diameter of semi-cylindrical target plate (m) |
| *h* | heat transfer coefficient (W/m$^2$-K) |
| *k* | thermal conductivity (W/m-K) |
| *l* | length of burner (m) |
| $\dot{m}$ | mass flow rate (kg/s) |
| *Nu* | Nusselt number |
| *q* | heating value (J/kg) |
| $\dot{Q}$ | rate of heat (W) |
| $q''$ | heat flux (W/m$^2$) |
| $\bar{q}''$ | spatial averaged heat flux (W/m$^2$) |
| *Re* | Reynolds number, $Re = \frac{\rho_{mix} v_j d}{\mu_{mix}}$ |
| *t* | thickness of target plate (mm) |
| *T* | temperature (K) |
| $T_f$ | flame temperature (K) |
| *x, y* | rectangular co-ordinates (m) |
| *y'* | co-ordinates along curved axis of the target plate (m) |
| *Z* | spacing between burner or nozzle and target plate (m) |
| *z* | axial distance (m) |

*Greek symbols*

| | |
|---|---|
| $\varepsilon$ | emissivity |
| $\eta$ | effectiveness |
| $\eta_{th}$ | thermal efficiency (%) |
| $\sigma$ | Stefan-Boltzmann constant (5.67 × 10$^{-8}$ W/m$^2$-K$^4$) |
| $\phi$ | equivalence ratio |

*Subscripts/ superscripts*

| | |
|---|---|
| $\infty$ | ambient |
| *ad* | adiabatic flame |
| *conv* | convection |
| *f* | fuel |
| *ht* | heat transfer |
| *m* | mean film |
| *max* | maximum |
| *ref* | reference |
| *std* | standard deviation |
| *stag* | stagnation point |
| *w* | wall |

surface than for the concave surface resulted in a larger heat transfer reduction for the convex surface. Poitras et al. [7] presented the aerodynamic and heat transfer characteristics of a jet impinging onto a concave surface. PIV measurements and the numerical simulations are performed in order to quantify the flow field characteristics. For a particular set of geometric configurations, the flow inside the concave cavity is observed to be oscillatory. Kim et al. [8] investigated the heat transfer characteristics of laminar confined slot jets impinging on to convex and concave shaped hemi-cylindrical surfaces. The Nusselt number peaked at the stagnation point and decreased monotonically. The local Nusselt number distributions for concave surface are observed to be 47% greater than those for the convex surface in the near stagnation regime for the same jet impingement configurations. The jet impingement over convex surface results in unsteady lateral distortions and flapping motion in jet column that considerably reduces the heat transfer.

The normal impingement of laminar flame jet on flat surface is investigated by various researchers across the globe [9–16]. Chander and Ray [17] reported a detailed review of literature on laminar flame jet impingement. The flame jet impingement over curved surface is not

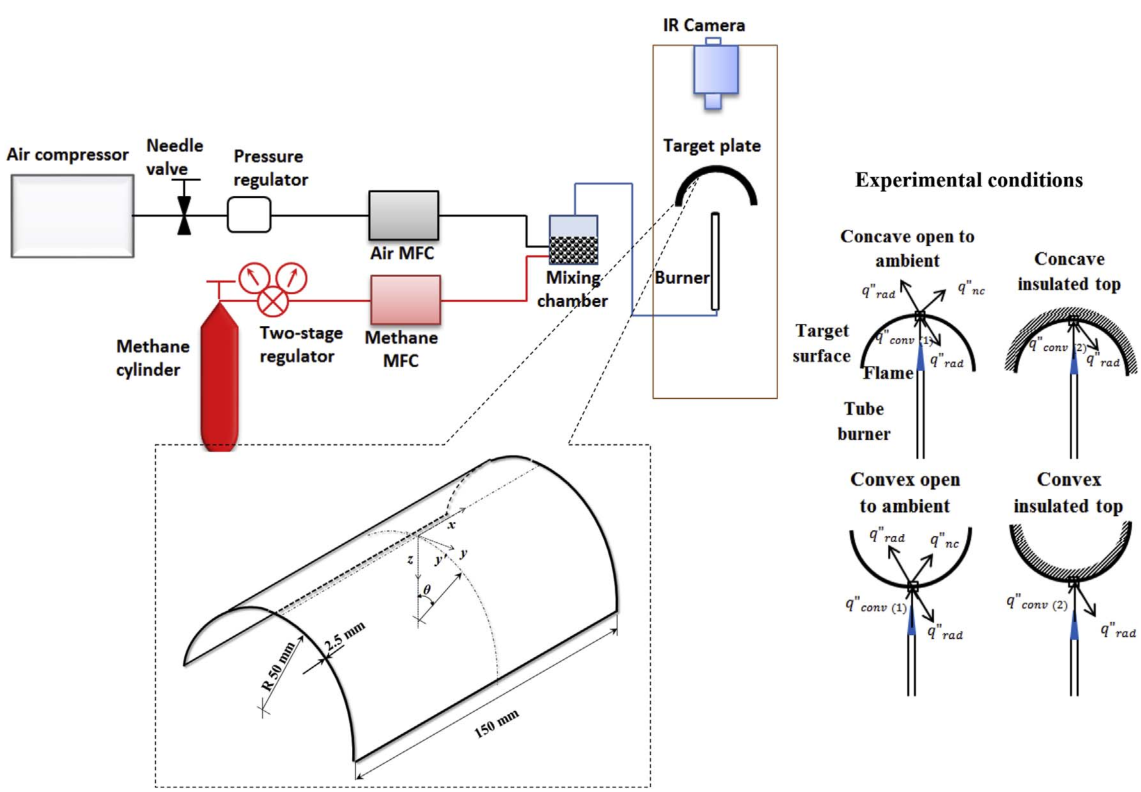


**Fig. 1.** Schematic of the experimental set up and experimental conditions.