CH4/AIR-FLAME IMPINGEMENT HEAT TRANSFER TO A CYLINDRICAL SURFACE

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Abstract
The heat flux of methane/air flames, impinging normal to a cylindrical surface was determined experimentally. Light induced phosphorescence from thermographic phosphors, was used to investigate surface temperatures at the stagnation point from nearly one-dimensional laminar premixed flame burning against a water cooled ceramic tube. The flame heated surface of the ceramic tube was coated with chromium-doped alumina and excited with a green light-emitting diode (LED) to measure the surface temperature. Experiments on the effects of variations in the cold gas velocity (0.1m/s-0.5m/s), equivalence ratio (Φ = 0.85-1.2), separation distance, H (15 – 30 mm) are reported. Stagnation point heat fluxes increased with the increase of the cold gas velocity. At cold gas velocities less than 0.2 m/s, maximum heat fluxes were obtained for fuel-rich mixture conditions, possibly due to air entrainment from the surrounding. While for cold gas velocities greater than 0.2 m/s higher heat fluxes for stoichiometric mixtures were observed, probably due to higher adiabatic flame temperature. Further investigations are under way to study the effects of variation of the separation distance on heat transfer characteristics at different equivalence ratios.

Introduction
The situation of flame impingement heating is majorly encountered in technical applications due to its high heat fluxes. A substantial number of studies have reported the possibility of impinging non-reacting jets to enhance heat transfer in applications ranging from drying of textiles to the cooling of gas turbines blades and combustor walls [1]. The focus of these studies mostly being on jet impingement on flat surfaces. More reviews on the subject may be found in Refs. [2, 3]. Flame impingement on curved surfaces is quite often encountered in industrial applications such as heating and melting of metals and glass. However, reported studies that cover the cylindrical case are limited, most of them concentrate on impingement cooling heat transfer on either concave or convex surfaces and mostly for turbulent flows [4]. The present work extends the investigation on flame impingement heating on curved surfaces for laminar flows. The heat transfer characteristics is investigated for flame impinging normal to a cylindrical surface. This is carried out by measuring the temperatures on the inner and outer surface at the stagnation point of a water cooled ceramic
tube heated by premixed laminar methane/air flame. The inner temperature is measured with a Pt100 thermal resistor while, the outer surface temperature is measured with phosphor thermometry, which depend on luminescence of doped ceramics after exposition to light from a LED [5]. The heat fluxes are calculated using Fourier’s law. Effects of variation in the cold gas velocities (0.1 m/s-0.5 m/s), equivalence ratio (0.85-1.2) and separation distance (15 mm-60 mm) are investigated.

Methods
The ceramic tube coated with 1.1 % chromium doped alumina was calibrated in a furnace from room temperature up to 750 K as shown in figure 1. Pflitsch et al. [6] reported that ruby films doped with 1.1 % chromium are most promising for temperature sensor applications, because they show high phosphorescence intensities and long phosphorescence lifetimes.

![Figure 1. Temperature calibration.](image)

For each temperature, the emission signal of the phosphorescence was recorded and the decay time evaluated by fitting an analytical waveform to the decay curve signal using an algorithm suggested by Brübach et al. [7]. The temperature-dependence of the phosphorescence lifetime was determined only for the outer surface of the ceramic pipe. Figure 3, shows the obtained calibration curve for the phosphorescence lifetime as a function of temperature. To investigate the heat transfer from different flames to the cylindrical surface, another setup, shown in figure 2, was designed, where temperature measurements are only aimed at the stagnation point. A homemade sintered bronzed burner of 30 mm diameter is used to establish a one-dimensional premixed laminar flame, if no cylinder is present. The flame impinges on a water cooled alumina cylinder. For the measurement of the temperature on the flame side, the phosphor coating is excited with a LED array at a wavelength of 532 nm. A fast pulse generator is used to provide the current input for the LED and to control the temporal excitation intensity shape.
The emitted phosphorescence signals from the measurement area are focused with lenses through a band pass filter onto a photomultiplier (PM) tube. The signals are recorded by a digital oscilloscope and then transferred to a personal computer after averaging for 128 pulses.

**Figure 2.** Single flame jet impingement.

A first set of experiments have been conducted to study the effects of variation of cold gas velocity (0.1 m/s–0.5 m/s) on stagnation point heat flux for three equivalence ratios, lean (Φ = 0.85), stoichiometric (Φ = 1.0) and rich (Φ = 1.2) at a separation distance, \( H = 15\) mm. This distance is denoted as the axial distance along the burner axis measured from the exit plane of the burner to the target point on the ceramic tube. The second set of experiments is currently underway to investigate the effect of varying, \( H \) (15 mm-60 mm) at \( Φ = 1.0\). The flow of the cooling water is kept constant at 20 L/h for all experiments. Methane with 99.5% purity is burnt with synthetic air. Two mass flow controllers (MFC) for volumetric flow rates of 10 and 50 litters/min are used to control the flows of methane and synthetic air respectively.

**Results**

**Temperature dependent lifetime**

Figure 3 shows the phosphorescence lifetime as a function of temperature ranging from 2.8 ms at 298 K to 74 µs at 723 K. For the temperature range selected in this study, Seat and Sharp [8] showed that a resolution of 1 K is possible. The lifetimes are decreasing with an increase in temperature. Pflitsch et al. [6] also reported that the lifetimes are decreasing linearly on a logarithmic scale between 290 and 623 K and with a stronger gradient between 623 and 833 K. It was found out that below
623 K, the temperature dependence of the radiative transition is dominating the phosphorescence, while above 623 K the non-radiating energy transfer is rate limiting.

![Figure 3](image1.png)

**Figure 3.** Lifetime of Cr: Al₂O₃ at different temperatures.

A curve was fitted to the calibration curve and used to determine the surface temperatures on the flame side of the ceramic tube.

**Effects of equivalence ratio on stagnation point heat fluxes**

Heat fluxes at the stagnation point were evaluated with the Fourier’s law for one-dimensional steady state conditions.

![Figure 4](image2.png)

**Figure 4.** Stagnation heat fluxes at $H = 15$ mm.

Figure 4 shows the experimental heat fluxes calculated for the equivalence ratios, $\Phi = 0.85$, 1.0 and 1.2 at a separation distance of 15 mm. In all cases heat fluxes increased with increase of cold gas velocity. This increase resulted to increase in convective heating. At cold gas velocities below 0.2 m/s, $\Phi = 1.2$ had the highest
heat flux compared to $\Phi = 0.85$ and 1.0. This was possibly due to the low burning velocity resulting in a larger separation of the flame front from the burner, thus lower heat losses to the burner for $\Phi = 1.2$. Also, the initially rich mixtures for $\Phi = 1.2$ possibly becomes nearly stoichiometric due to entrainment of surrounding air. Salem et al. [9] also reported maximum heat fluxes for fuel-rich conditions for mass flux less than 0.3 kg/(sm)$^2$ for methane/air flames impinging on a flat surface at $H = 15$ mm. At cold gas velocities above 0.2 m/s, the effects of air entrainment is probably minimal resulting in higher heat fluxes for stoichiometric as compared to rich and lean conditions. This was attributed to higher adiabatic flame temperature for stoichiometric as compared to rich and lean conditions.

**Effects of separation distance on stagnation point heat fluxes**

The distance between the burner and the target surface is important from the perspective of flame stability and heat transfer, more especially when the other operation conditions are fixed or cannot be altered easily. Results are shown in figure 5 for separation distance of 15 mm-30 mm for $\Phi = 1.0$

![Figure 5. Stagnation heat fluxes at $\Phi = 1.0$](image)

The heat flux for the smallest distance is highest, while it is lowest for larger distance. The small separation distance provides very high wall heat fluxes, because of their close proximity to the ceramic tube. Further investigations are being carried out for separation distance larger than 30 mm.

**Conclusion**

Heat fluxes for laminar premixed methane/air flame impinging on a ceramic tube has been investigated. The surface temperature on the flame side at the stagnation point has been measured with thermographic phosphors. Phosphor thermometry was suitable for these flame measurements, but reduced optical accessibility hindered measurements at separation distances less than 15 mm. The stagnation point heat fluxes increases with increase of cold gas velocity for all the equivalence
ratios and decreases with the increase of the separation distance. For gas velocities below 0.2 m/s fuel-rich conditions has the highest heat fluxes than for stoichiometric and lean, but at gas velocities above 0.2 m/s stoichiometric conditions shows maximal heat fluxes. Throughout the experiments, it is seen that the mechanism of flame stabilization changes from burner to plate stabilized, when the fresh gas velocity approaches the free flame velocity \(u_{\text{FF}}\). The heat flux curves tend to increase first quite fast with changing cold gas velocity, which is reduced when approaching \(u_{\text{FF}}\).

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References


