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Coanda flames for development of flat burners

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Abstract

The Coanda effect is the tendency of a fluid to stay attached to a nearby surface. Since its discovery, several applications have been developed in aerodynamics, heat transfer and medical fields using this concept. A potential, and currently unexplored, application of the Coanda effect is its use in heating equipment. However, few research has been conducted on the behavior of flames under a Coanda flow pattern regime. Thus, the present study uses a generic swirl burner to analyze influence of the flow rate and fuel mixture on the flame stability. The objective is to identify differences in the behavior of a flame under an Open jet flow pattern and Coanda jet flow pattern that will lead to further development of novel flat burners. Changes in the burner configuration were made to induce one of the two flow patterns. Methane was used as a fuel and air as an oxidizer. Both gases were supplied to the burner at ~20°C and almost atmospheric pressure. Flow rates were regulated using variable area flowmeter. Gas flow was increased from 3 L/min to a maximum of 12 L/min with incremental steps of 1 L/min. For each gas flow rate, the oxidizer flow rate was increased, and the flame behavior recorded. It was found that a stable Coanda flame could only be induced when an Open jet flame existed. It is theorized that this behavior is due to a coherent structure that breaks down when a stable Open jet flame changes to Coanda flame. The concept is now presented as a novel option for development of novel, large industrial devices capable of stabilizing the flame while reducing size for their use in high temperature processes.

Keywords: Coanda; Swirling flow; Flat flame

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Nomenclature

CFJ	Coanda Jet Flow
D	Nozzle diameter
NTP	Normal temperature and pressure (1 atm & 20°C)
OJF	Open Jet Flow
PVC	Precessing Vortex Core
VAFM	Variable Area Flow Meters
ΔX	Distance between the flat plate and the tip of the nozzle outlet
ϕ	Equivalence ratio (fuel-air)

1. Introduction

The Coanda effect is the tendency of a fluid to stay attached to a nearby surface and remain attached even when the surface curves away from the initial jet direction. The first time it was observed was in 1800 by Thomas Young. The effect takes its name from Henri Coanda, who in 1910, used it in the first practical application by building the world's first jet propelled aircraft [1]. In the last 25 years, the Coanda effect has resurfaced in several applications. Some examples are: in aeronautics, where it has been used to increase the lift and thrust vectoring; in industry, where it has been used in reaction turbines, swirl atomizers, galvanizing techniques, cooling of cylinders and waste-gas flares; some applications in medicine also exist. A compilation of the applications has been made by Reba [2], with a more recent review made by Lubert [3]. The bulk of the available research was conducted in the 1960s. Ongoing research in the phenomena now focuses on noise levels [4], effect of wall temperature on the flow [5] and supersonic jets [6-7]. Energy related applications of the Coanda effect in industry seem to be limited to waste gas flares. As described by Desty [8] the advantages of having a Coanda effect on these type of flares is a smokeless combustion with increased combustion efficiency and decreased thermal radiation, when compared to other types of flare devices. Therefore, it is believed that potential applications exist that take advantage of the flat flow profile that the Coanda effect produces and are yet to be explored, especially on industrial processes that involve the heat treating of flat surfaces. One such application could be the use of this flat flame, wall attached, burners on annealing furnaces in the steel industry to substitute current technologies, i.e. radiant tubes. Expected benefits would include the reduction of volume furnace due to increased proximity of burner to strip, emission reduction and energy usage due to reduced fuel consumption.

However, to develop new industrial combustion applications that take advantage of the Coanda effect, a better understanding of the behavior of a Coanda flame is needed. Research has been conducted on the stability of an isothermal Coanda flow. Vanierschot [9] described a change in the flow pattern that was dependent on the inlet swirl as well as a hysteresis pattern when increasing and subsequently decreasing the swirl. Valera-Medina [10] conducted research on transition of a Coanda Jet Flame to/from an Open Jet Flame and found that it was dependent on the geometry and step size of a flat plate fitted to the nozzle. Therefore, the present study aims to increase the understanding of the stability of a Coanda flame by looking into different flow patterns that occur as the flow rate and equivalence ratio are varied during the experiment.

2. Experimental setup

A generic swirl burner was used to examine the flame stability under a Coanda Jet Flow (CJF) and an Open Jet Flow (OJF) pattern. The burner was fitted with a tangential swirl generator providing a geometrical swirl number of 1.04. The nozzle diameter was D=28mm and had an angle of 45 degrees. A schematic of the generic swirl burner is presented in Figure 1 and detailed elsewhere [11]. A flat plate was fitted to the nozzle. Two different normalized plate heights were chosen, $\Delta X/D=0.36$ and $\Delta X/D=0.00$, being ΔX the distance between the flat plate and the tip of the nozzle outlet. A set of experiments was performed for each normalized height. Previous isothermal studies have shown that a normalized plate height of the plate height ΔX/D=0.00 allowed the existence of a Coanda Jet Flow pattern, whereas a normalized height of ΔX/D=0.36 made it impossible to obtain [10].

Methane was used as fuel and air as oxidizer. Both gases were supplied to the system through flexible hoses. Inlet gas temperature was ~20°C and pressure was close to atmospheric. Three variable area flow meters (VAFM) with ranges of 1-12 L/min, 6-50 L/min and 40-440 L/min for air at NTP were used to regulate the air flow. Air was split between the VAFM in a way such that operating at the limits of each flow meter was avoided. A single VAFM with range of 1-18 L/min for methane at NTP was used to regulate the methane flow. After passing through the VAFM, methane and air combine into a single stream ~1 meter upstream from the burner inlet. The mixed flow then enters the burner and is furtherly mixed at the swirl chamber. The flow gains additional swirl by going through the swirl generator. Finally, the gas mixture goes out through the nozzle burner and is ignited by a pilot burner located ~0.3 m downstream the nozzle exit. A schematic of the experimental setup is presented in Figure 2.

Gas flow rate was varied from 3 L/min (~2 g/s) to a maximum of 12 L/min (~8 g/s) in incremental steps of 1 L/min (~0.7 g/s). For each incremental step of methane, the air flow rate was increased, and the flow pattern was recorded. All experiments where performed without confinement.

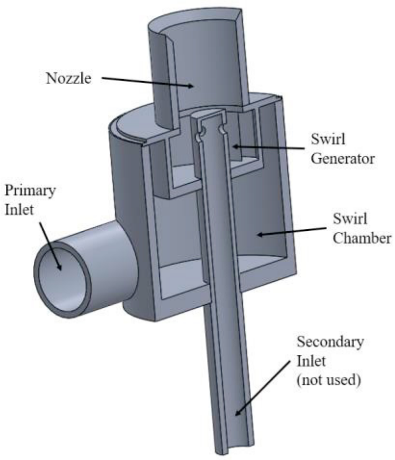

Fig. 1. Swirl burner

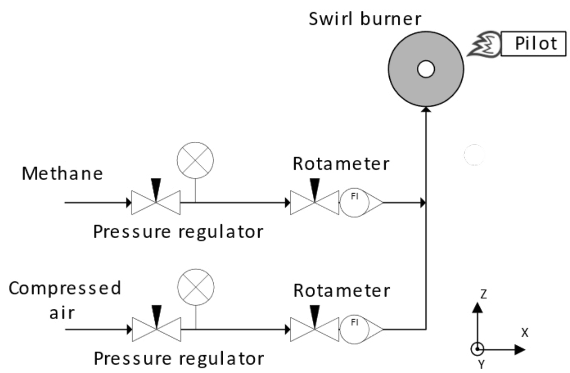

Fig. 2. Experimental setup

3. Results and discussion

With the flat plate set at position ΔX/D=0.36, four different states of the open jet flame were identified. For each gas flow rate with a low inlet air flow, the flame started as a stable, nozzle attached flame (Figure 3A). From this state, an increase in air flow could start the transition to one of two states: (1) flashback and (2) lifted flame.

The transition to flashback occurred when the total mass flow rate was less than ~0.75 g/s. In this situation, as the air flow was increased, the outer part of the flame continued attached to the nozzle but the central part of the flame started going into the nozzle. A point was reached when full flashback occurred, and combustion was taking place inside the burner (Figure 3D). This flashback behavior has been previously described in the literature as combustion induced vortex breakdown [12].

The transition to a lifted flame occurred when the total mass flow rate was more than ~0.75 g/s. An increase of the air flow detached the flame from the nozzle and went into a lifted flame state (Figure 3B). From this point, the lifted flame can take two paths as air flow is increased. The first one is flashback (Figure 3D). The second one being a lifted flame that ends up being blown off. Figure 5 shows the different transition points for each state. The overall behavior of the Open jet flame is known and widely reported in the literature [13-14].

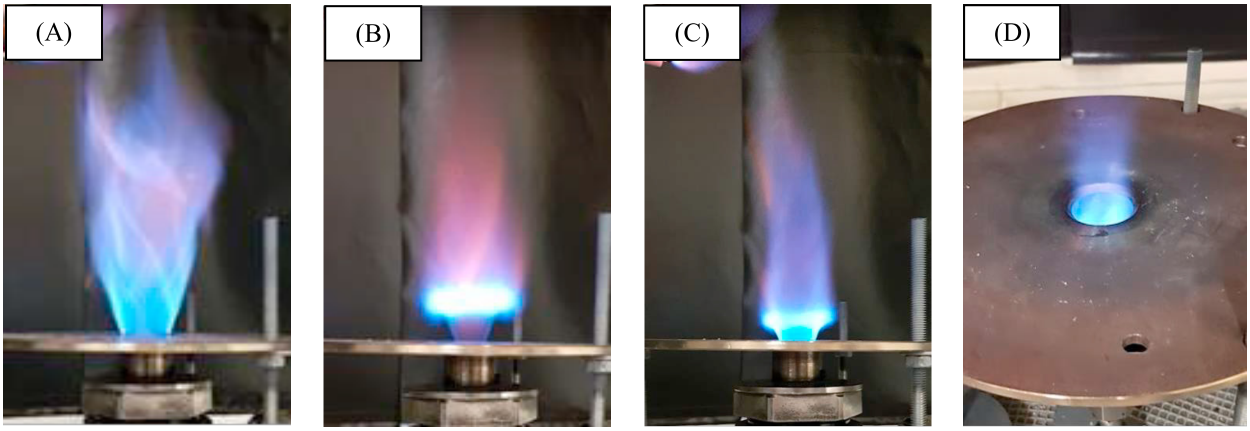

Fig. 3. Flow patterns in an Open Jet Flow flame.
A) Stable Open Jet Flame B) Lifted Flame C) Transition Lifted Flame – Flashback D) Flashback

With the flat plate at position $\Delta X/D=0.00$, the four previously described flame states were also possible. As with the previous configuration, the flame started as a stable, nozzle attached flame (Figure 3A), and transitioned to either a lifted flame or to flashback with an increase in the inlet air. By increasing gas and air flow, an attempt was made to induce the Coanda flame by using a steel rod to spread the flame. It was observed that a Coanda flame was possible when a lifted flame occurred. Thus, the lifted flame turned into a Coanda flame and remained like this until physically disturbed (Figure 4A and 4B). If the attempt was made to spread the OJF nozzle attached flame with the steel rod, the flame immediately returned to its nozzle attached state and the Coanda state could not be induced. This behavior was consistent at every combination of mass flow rates and equivalence ratios. Once the Coanda flame was established, and when the air flow rate was increased, the flame gradually retreated to the nozzle and the combustion zone became smaller (Figure 4C and 4D). This behavior continued until a point where the Coanda flame spontaneously detached from the plate and turned into a lifted flame that was close to a flashback condition (Figure 3C). Figure 6 shows the different transition point for each flame state.

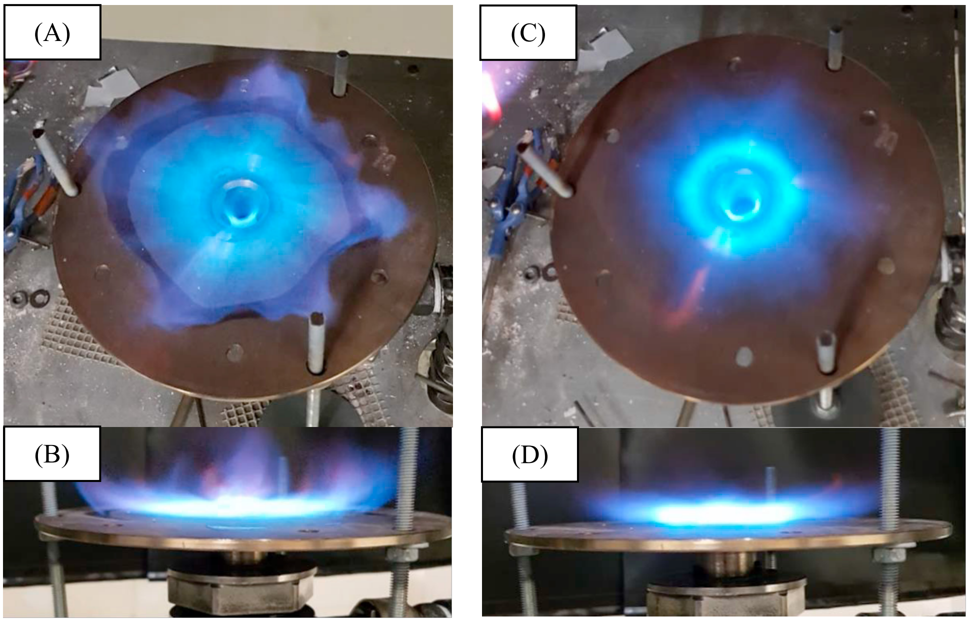

Fig. 4. Flow patterns in a Coanda Jet Flow flame. A) Stable Coanda Flame B) Stable Coanda Flame side view
C) Transition Coanda Flame – Flashback D) Transition Coanda Flame – Flashback side view

By comparing the set of measurements with the flat plate at position ΔX/D=0.36 (Figure 5) and with the plate at position ΔX/D=0.00 (Figure 6) it can be observed that the flame stability patterns follow a close resemblance between each case. Moreover, the operating region corresponding to a lifted flame in Figure 5 is practically a mirror image to the region in Figure 6 where the Coanda flame existed. Previous experiments on this swirl burner suggest the presence of a Precessing Vortex Core (PVC) on an OJF regime [9]. It has been shown that the PVC plays an important part on the stability of swirling flames by anchoring the flame [15-16]. It is speculated that the reason that the transition to a Coanda flame is only possible when the flame detaches is because once the flame detaches from the nozzle, the PVC breaks down and can no longer contribute to the flame stabilization, allowing the possibility for the Coanda flame to exist. Additional evidence from new results (unpublished) on isothermal experiments performed in this same burner seem to confirm this hypothesis, where a PVC was observed on the Open Jet cold flow [17] and another similar structure was observed in the Coanda Jet cold flow in the region between the nozzle and the jet. This suggests that this structure is responsible for anchoring the jet to the flat plate. However further experimentation is needed to confirm the presence of this structure in a reacting flow.

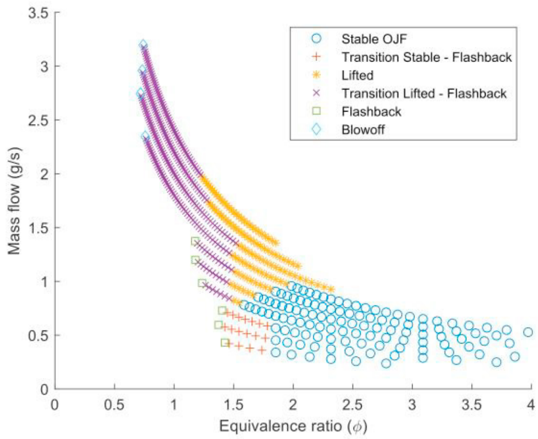

Fig. 5. Burner flow patterns with plate set to ΔX/D=0.36.

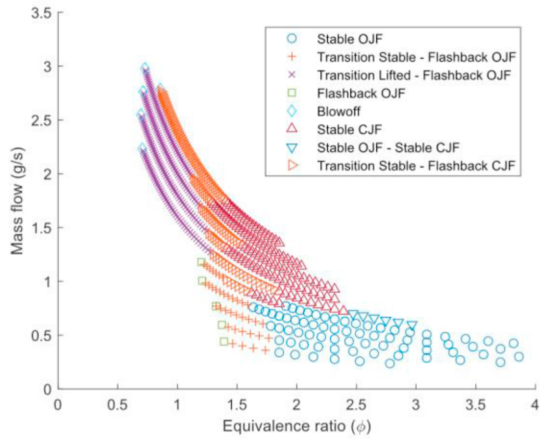

Fig. 6. Burner flow patterns with plate set to ΔX/D=0.00.

4. Conclusion

The flame stability under two flow patterns, Open Jet Flow and Coanda Jet Flow, were investigated using a generic swirl burner. The swirl burner was fitted with a flat plate and the distance between the plate and the tip of the nozzle was changed to induce one of the two flow patterns. It was found that a stable Coanda flame could only be induced when the flame was previously in a lifted condition. It is theorized that this behavior is due to the breakdown of the PVC when the stable Open jet flame transitions to a lifted flame. The breakdown of the PVC allows the change to a Coanda flame. The results denote the need of reaching this lifted state before the flame can be flatted up by the Coanda effect, thus suggesting that further development to create new flat burners will need to consider this aspect.

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