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Experimental study of impact of swirl number as well as oxygen and carbon dioxide content in natural gas combustion air on flame flashback and blow-off

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A B S T R A C T

In this paper, experiments involving the combustion of natural gas in a quartz tube using a burner with three swirl generators were conducted to determine ranges of stable combustion limited by flame flashback and blow-off. The swirl generators with a tangential supply of substrates were described using the geometric swirl numbers: 0.69, 1.16, and 1.35. Effects on combustion atmospheres such as air, air enriched with up to 25 vol. % of oxygen, and oxygen-enriched air with addition of 15 vol. % of CO_2 per stable combustion range were tested. The findings of the experiments proved that enriching air with oxygen leads to an expansion of the stable combustion range because the curve of flame blow-off progresses quicker than that of flashback. In terms of flame flashback, the burner with swirl generator $S_g = 1.35$ turned out to be the most favorable for the combustion atmospheres under consideration. The highest resistance of the flame against flashback was recorded for air. Addition of CO_2 to oxygen-enriched air improved the flashback limits. The most favorable stable combustion range was calculated for the atmosphere of air enriched with up to 25 vol. % of oxygen when $S_g = 1.35$ and that of air when $S_g = 0.69$. The smallest stable combustion range, which was 26% smaller than the best result, was recorded for the mixture of oxygen-enriched air and 15 vol. % of CO_2 when $Sg = 0.69$.

1. Introduction

One of the easiest and most efficient methods to stabilize the flame is to use the swirl flow of a combustible mixture (Durox et al., 2013; Jerzak, 2015) or an oxidizer (Merlo et al., 2013; Palies et al., 2011). There are various ways of generating a swirl: tangential supply of a stream to the burner (Scarano et al., 2015; Syred et al., 2012, 2014), use of an axial-annular swirl generator (Ishak et al., 2015; Palies et al., 2011), a swirler with helicoidal vanes (Choi and Kim, 2012; Singh et al., 2012), or a mechanical spinner (Freitag and Janicka, 2007; Hoffmann et al., 1994) – the latter is used least often. In addition to mixing the combustion substrates and stabilizing the flame, swirl generators reduce fuel consumption and the emission of pollutants (Merlo et al., 2013; Sayad et al., 2013). By increasing the swirl of the stream, a critical condition can be reached where the flow of reagents along the axis of the flame is reversed. An area created inside the stream, which causes the outer limits of the flame to expand, is called Central or Internal Recirculation Zone (CRZ or IRZ). In addition, an External Recirculation Zone (ERZ) is formed near the burner. One of the criterion for the presence of a CRZ is the swirl degree of the stream, expressed with the swirl number (Harris et al., 1949):

$$S = \frac{G_\varphi}{G_x \cdot R} \tag{1}$$

Referred to in the literature, the standard parameters needed to obtain a fully developed reverse flow are $S > 0.6$ and $Re > 18{,}000$ (Syred and Beér, 1974). Typical values of the swirl number for the combustion of gaseous and liquid fuels fall within a range of 0.2–2 (Syred, 2006). The following three types of stream swirl (Harris et al., 1949) can be distinguished:

1. Weak swirl $S < 0.6$,
2. Critical swirl $S = 0.6$,
3. Strong swirl $S > 0.6$.

The reverse flow of hot gases in the CRZ intensifies the mixing of

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non-combusted reagents, acts as a reservoir of heat, and creates an “aerodynamic flame holder” while extending the combustibility limits. A phenomenon of distorting the swirl, which is understood as a sudden change in the structure of the swirling core that causes it to fall apart, may from time to time occur in the flame. Then the flame loses its stability, e.g. due to variations in the speed with which the combustion heat is released while causing noise and pulsations. These undesirable vibrations may cause wear and damage to parts of the combustion chamber, and in some extreme cases, breakage of parts of the turbines (Huang and Yang, 2009). By measuring the velocity fields of the swirl flame (PIV) (Scarano et al., 2015; Syred, 2006) and using OH chemiluminescence imaging (Schönborn et al., 2014), the existence of swirls called precessing vortex cores (PVCs) have been proven that move eccentrically around the central axis of the burner. The latest research confirms the occurrence of PVCs when $S > 0.4$ (Scarano et al., 2015) and $S > 0.45$ (Durox et al., 2013), although there are also experimental studies where no evidence for the presence of PVCs has been found (Huang and Yang, 2009). The occurrence of a too strong reverse flow of hot gases in the CRZ is one of the reasons why the flame may flow back to the burner, as demonstrated by (Schönborn et al., 2014), when conducting research on hydrogen combustion. The occurrence of PVCs (Syred et al., 2014) and thermoacoustic oscillations (Durox et al., 2013) increases the propensity of the flame to flashback. Another reason for flashback is the propagation of the flame within the boundary layer depending on a critical velocity gradient (Harris et al., 1949).

$$g_F = \frac{4 \cdot \dot{V}}{\pi \cdot R^3} \tag{2}$$

Such flashback is predominant for flows with low turbulence levels, where low flow rates occur within the boundary layer. The critical velocity gradient grows rapidly, when the oxygen content of the oxidizer increases (Baukal, 2013). Flame flashback also occurs when the turbulent combustion velocity exceeds the local velocity of the combustible mixture. In particular, the problem of flashback applies for systems where the fuel is pre-mixed with an oxidizer (Zhiguang et al., 2014), promoting self-ignition. This is why perforated plates, which in the literature are called turbulence plates or flashback protectors, are installed in kinetic burners to prevent the flame from flashing back into the burner (Shelil, 2009; Johnson et al., 2005). Depending on the blockage ratio of the perforated plate, the flashback limits are shifted (Shelil, 2009).

The reasons why flames flash back in open space depending on the specified swirl number when a combustible mixture is supplied tangentially to the burner were sought, among others, by (Syred et al., 2012, 2014). He distinguished two flame flashback mechanisms for CH_4, H_2, $CH_4{-}H_2$, and coke-oven gas. The first mechanism that predetermines flashback for $S = 1.04$ and 0.8 is too low flow rates in the boundary layer, whereas the second one is an increased volume of the CRZ for $S = 1.47$. More favorable conditions in terms of flame flashback during methane combustion occur for $S = 1.08$ at an equivalence ratio of $0.5<\Phi < 1.0$ to be defined using equation (3). For rich flames ($\Phi > 1.3$), it is difficult to clearly specify for which swirl number ($S = 0.8$ or $S = 1.47$) flames show a weaker tendency to flash back.

$$\Phi = \frac{m_F/m_O}{(m_F/m_O)_{stoich}} \tag{3}$$

By interpreting the findings of experimental and numerical studies on methane combustion (Shelil, 2009) conducted in open space for the same type of swirl generators with $S = 1.47$ and $S = 1.54$, it was found that the mass flow rate needed to overcome flashback grows with increase in pressure and the temperature of substrates. Furthermore, addition of CO_2 to CH_4 with a 30 vol. % share of CO_2 expressed as $(CO_2/CO_2{+}CH_4)$ significantly extends the stable combustion range in terms of equivalence ratios in a range of $0.6<\Phi < 1.2$. An increased propensity to flashback along with increases in pressure and adiabatic temperatures of flames have also been confirmed by (Beerer et al., 2014). For the swirl hydrogen flame, it has been found that the higher the swirl number, the smaller the stable combustion range (Schönborn et al., 2014). The broadest stable combustion range falling within a range of $0.12<\Phi < 0.46$ was obtained for $S = 0.52$. Apart from flame flashback, the parameters that limit the efficiency of the swirl burner include flame blow-off, which is also referred to as blow-out (Merlo et al., 2013). Blow-off may occur due to the combustion of very lean mixtures, strong combustion instability, or a too short hold-up time of reagents as compared to the time corresponding to characteristic time for chemical reaction (chemical kinetic time) according to the Damköhler number (Hoffmann et al., 1994):

$$Da = \frac{\tau_{res}}{\tau_{chem}} \tag{4}$$

A small Damköhler number ($Da<<1$) refers to a very slow chemical reactions. If, $Da>>1$ the chemical reaction rates are high compared with the turbulent mixing rates.

(Abdulsada, 2011) researched the limits of flame blow-off in open space using cylindrical and conical metal burner caps and swirl generators with a tangential supply of combustible mixtures such as methane. Burner caps, which are heated up during tests to prevent cool air from being drawn into the flame and the CRZ, considerably improve the blow-off limits. A conical fitting seems to be even better in terms of flame blow-off, regardless of the swirl numbers $S = 0.8$ and $S = 1.04$ and the type of fuel under examination. If burners are fitted with caps, the blow-off limits vary for $S = 0.8$ and $S = 1.04$ insignificantly. The limits of flame blow-off in open space are worsened when CO_2 (Abdulsada, 2011) or N_2 (Sayad et al., 2013) are added and the swirl number is lowered. Experimental studies of methane pre-mixed with air in the combustion chamber using an axial-annular swirl generator were conducted by (Cavaliere et al., 2013). A loss of flame stability, and consequently a blow-off, was observed for swirl number $S = 1.25$ when the equivalence ratio was lowered to $\Phi = 0.57$. In each case, the blow-off was preceded by the flame extending over a low-swirl burner ($S < 0.6$). The maximum lift-off height of a pre-mixed flame was tested before the flame's blow-off numerically (Kang et al., 2008) and experimentally (Beerer et al., 2014). The recorded distance at which the methane flame is stable ranges from 6 to 9 mm (Beerer et al., 2014) and depends, among other things, on the fuel stream. Interesting experiments were conducted by (Amato et al., 2011), who reported that no effect of the length of a quartz tube on changes in adiabatic temperatures of the methane flames subject to blow-off could be observed.

It should be noted, however, that burners never operate within the efficiency range determined by flame flashback and blow-off as the NO_x and CO emission limits also pose a barrier (Amato et al., 2011).

Expressed with equation (1), the swirl number S is hardly usable. In 1974, (Syred and Beér, 1974) using certain simplifications, suggested an expression for the geometric swirl number S_g (5):

$$S_g \approx S = \frac{\pi \cdot r_e \cdot r_{eff}}{A_t} \tag{5}$$

For a swirl generator with a tangential supply of a combustible mixture, the individual parameters in equation (5) can be expressed as follows: