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EXPERIMENTAL INVESTIGATIONS OF LEAN STABILITY LIMITS OF A PROTOTYPE SYNGAS BURNER FOR LOW CALORIFIC VALUE GASES

Ivan R. Sigfrid
Department of Energy Sciences
Lund University
Sweden

Ronald Whiddon
Department of Combustion Physics
Lund University
Sweden

Marcus Aldén
Department of Combustion Physics
Lund University
Sweden

Jens Klingmann
Department of Energy Sciences
Lund University
Sweden

ABSTRACT

The lean stability limit of a prototype syngas burner is investigated. The burner is a three sector system, consisting of a separate igniter, stabilizer and Main burner. The ignition sector, Rich-Pilot-Lean (RPL), can be operated with both rich or lean equivalence values, and serves to ignite the Pilot sector which stabilizes the Main combustion sector. The RPL and Main sectors are fully premixed, while the Pilot sector is partially premixed. The complexity of this burner design, especially the ability to vary equivalence ratios in all three sectors, allows for the burner to be adapted to various gases and achieve optimal combustion. The gases examined are methane and a high H_2 model syngas (10% CH_4, 22.5% CO, 67.5% H_2). Both gases are combusted at their original compositions and the syngas was also diluted with N_2 to a low calorific value fuel with a Wobbe index of 15 MJ/m^3. The syngas is a typical product of gasification of biomass or coal. Gasification of biomass can be considered to be CO_2 neutral. The lean stability limit is localized by lowering the equivalence ratio from stable combustion until the limit is reached. To get a comparable blowout definition the CO emissions is measured using a non-dispersive infrared sensor analyzer. The stability limit is defined when the measured CO emissions exceed 200 ppm. The stability limit is measured for the 3 gas mixtures at atmospheric pressure. The RPL equivalence ratio is varied to investigate how this affected the lean blowout limit. A small decrease in stability limit can be observed when increasing the RPL equivalence ratio. The experimental values are compared with values from a perfectly stirred reactor modeled (PSR), under burner conditions, using the GRI 3.0 kinetic mechanism for methane and the San Diego mechanism for the syngas fuels.

INTRODUCTION

The demand for an environmentally friendly energy supply is pushing the gas turbine community to develop gas turbine systems that can handle a wide variety of fuels. Currently, a number of gas turbines are in use which are designed to run on specific fuels e.g., fuel oil, diesel and natural gas [1]. However, producing a gas turbine that can handle a wide range of fuels, without the down-time associated with refits, is difficult. Such a wide range operability hinges on the design of a combustor that functions properly irrespective of the fuel being used. Such an installation would offer the ability to alternate the fuel depending on availability and cost.

Table 1 Compositions of the gases examined

Gases	Gas compositions vol%				W* [MJ/m^3]	LHV [MJ/kg]	$Fuel/Air_{St}$
	CH_4	H_2	CO	N_2			
Ref.	100	0	0	0	55.30	50.01	0.0584
Syngas	10	67.5	22.5	0	27.70	33.14	0.104
Diluted Syngas	6.9	46.56	15.52	31.02	15.00	14.05	0.245

*Wobbe index based on the higher heating value (HHV).

This paper investigates the lean blowout limit (LBO) of a scaled 4th generation premixed dry low emission (DLE) burner supplied by Siemens, which was developed, in part, to be fuel flexible. The difficulty in handling different fuels lies in the large variance in fuel characteristics e.g., Wobbe index [2], laminar flame speed, ignition delay time and adiabatic flame temperature [3]. Wobbe index describes the ability of a fuel to transport energy into a system; a lower Wobbe index fuel requires larger volumes of fuel in order to maintain a desired power output. This added flow pushes the compressor towards the instable operating region close to the surge line [4]. Fuels that have a high laminar flame speed, for instance fuels with high hydrogen content, may cause flashback. The ignition delay time may cause the premixed fuel/air to auto-ignite prior to reaching the combustion zone. Variations in adiabatic flame temperature not only affect the NOx emissions by influencing the thermal NOx reaction pathway [5-7], but also, if too high, can reduce the combustor lifetime. The fuels investigated in this paper are methane (as a reference) and a high hydrogen content syngas mixture [1], which is also diluted with nitrogen, see Table 1. Noticeable is the large difference in the stoichiometric fuel to air ratio ($Fuel/Air_{St}$), which is four times larger for diluted syngas compared to methane. The diluted syngas is a type of gas that could be produced and combusted in an IGCC.

NOMENCLATURE

T	Temperature
Y	Mass fractions
W	Molecular weight
c_p	Specific heat at constant pressure
h	Species specific enthalpy
t	Time
$\dot{m}$	Mass flow
$\dot{w}$	Mass flow

Greek letters

ϕ	Equivalence ratio
ρ	Density
τ_{res}	Residence time
$\dot{\omega}$	Production rate

Subscripts

Main	Main burner section
Pilot	Pilot burner section
RPL	RPL burner section
i	Index
in	Inlet
tot	Total

EXPERIMENTAL SETUP

The experimental setup consists of an air and fuel supply system, the burner, a liner with an emissions probe at the end and an emission measurement system. The air and fuel supply, emissions system and the data sampling are only covered briefly in this paper.

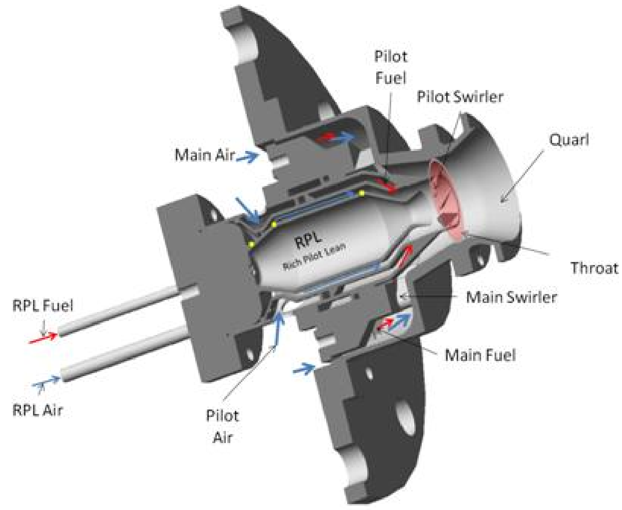


Figure 1 Scaled 4th generation DLE burner. The red arrows indicate fuel flow and blue arrows air flow. RPL thermocouple placements are indicated by yellow dots. The throat section of the burner is highlighted in red.

Burner

The burner used in the experiments is a scaled 4th generation DLE burner supplied by Siemens. It is has three concentric sections with separate fuel feeds. The sections are called RPL (Rich-Pilot-Lean), Pilot and Main (figure 1). All sections are in co-swirl arrangement.

The RPL is a central body stabilizer and can be set to run under both rich and lean conditions. The volume flow through the RPL can be controlled independently of the Pilot and the Main sections and is set to ~2.4% of the total volume flow. It is kept constant for all the tests in this investigation. The fuel and air is premixed before entering a swirler in the bottom of the RPL, after which the mixture is ignited. The position of the flame is monitored by three type N thermocouples placed on the outside wall of the RPL. These three thermocouples are placed at the RPL swirler, the conical expansion of the RPL and at the exit contraction of the RPL (yellow dots, Figure 1). The probe positions are Neck, Bottom and Top, designated, starting from the RPL entrance.

The fuel to the Pilot is injected perpendicularly to the oncoming airflow, at the exit contraction of the RPL, where it mixes with the air until combustion, just before the axial swirlers. As the fuel is injected close to the combustion zone, it is assumed that the mixing of fuel and air is not complete. The fuel to the Main is injected through circular pins positioned upstream of radial swirlers.

The combustion is stabilized in the conical section after the burner (figure 1). The conical section leads to an 85 mm x 700 mm cylindrical liner, which allows the necessary post combustion residence time (~15 ms), with a combustor loading below 10 kg/s $atm^{1.8}m^3$ as defined in [8].

$$Combustor\ Loading = \frac{\dot{m}}{VP_{in}^{1.8}10^{0.00145(T_{in}-400)}}$$

At the end of the combustion liner, there is a contraction to 50% of the liner cross-sectional area extending 15 cm. An emissions rake located in this extension, samples the exhaust gases at 8 equidistant points.

The air split between the Main and the Pilot is controlled by the pressure drop over their respective air paths. To determine the air split, effective areas are used [9]. The effective area is, theoretically, the area of the *vena contracta* after a step contraction that would give the same pressure drop as the air flow through an arbitrary air path.

The calculated air flow distribution is 21% through the Pilot and 79% through the Main burner pathway. The accuracy of the calculated effective areas are 5% for the Pilot and 2% for the Main, disregarding any effects from fuel injection.

Air and fuel supply

The air is supplied to the burner via two separate systems- one which supplies the Main and Pilot sections of the burner, and a second that supplies the RPL. Both systems preheat the air to 650 K. The fuel is supplied to the three burner sections separately, making it possible to vary the equivalence ratios in each section independently.

Emissions system

The emission system consists of a paramagnetic O_2 meter (Oxynos 100), an IR photometry CO/CO_2 meter (Binos 100) and a chemiluminescence NO_x meter (CLD 700). In this paper only values from the CO meter are considered.

Data sampling

For data sampling and control of the combustion system, an in-house computer program was used. It registers 30 measurements for each data point at a rate of 1 Hz. The standard deviations of these measurements are shown as error bars in the figures.

MODELLING

The blowout residence time and the adiabatic flame temperature (figure 2) was modeled using the free software package CANTERA [10]. The laminar flame speed calculations (figure 3) were done using the commercial software DARS v2.04 [11, 12]. The chemical kinetic mechanisms used were GRI 3.0 [13] for methane and the San Diego mechanism [14] for the syngas mixtures. The San Diego mechanism was used since it gives better agreement with results for syngas [12, 15].

Blowout residence time

The blowout residence time (figure 4) is calculated using an in-house perfectly stirred reactor (PSR) model which assumes non-isothermal adiabatic reaction [16]. A PSR qualitatively describes the chemical kinetic influence on the LBO. However the actual LBO is influenced on the burner geometry and function. The inlet temperature for the calculations is 650K.

The reactions occur in a reactor with one inlet and outlet, where the inlet flow is instantaneously mixed with the reacting flow. Thus the reacting flow and the outlet have the same state. The model solves the species conservation equation:

$$\frac{dY_i}{dt} = \frac{1}{\tau_{res}}\left(Y_{i,in} - Y_i\right) + \frac{\dot{w}_i W_i}{\rho}$$

and the energy equation:

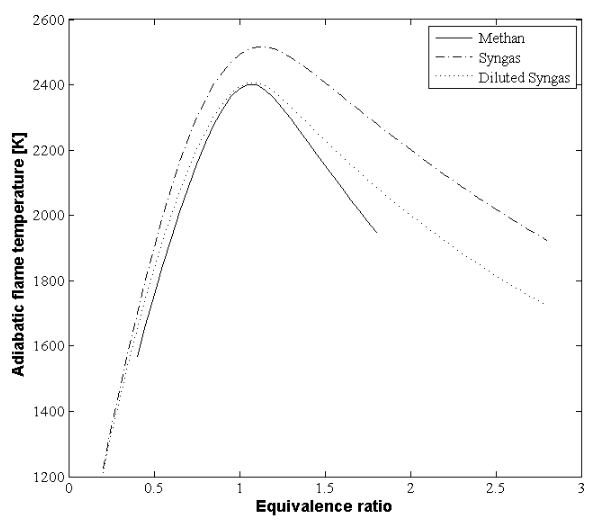


Figure 2 Adiabatic flame temperature for the examined fuels at inlet temperature 650 K

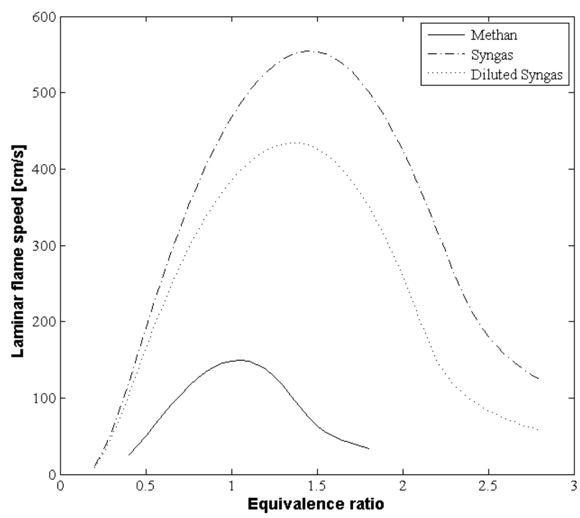


Figure 3 Laminar flame speeds for the examined fuels at inlet temperature 650 K

$$c_p \frac{dT}{dt} = \frac{1}{\tau_{res}} \sum Y_{i,in}\left(h_{i,in} - h_i\right) + \sum \frac{h_i \dot{w}_i W_i}{\rho}$$

where:

$$\tau_{res} = \frac{\rho V}{\dot{m}}$$

The continuity equation assumes the conservation of mass, which is true for a steady state solution. The equations above are solved for the residence time in question until steady state is achieved. The blowout residence time is defined as the minimum residence time acquired to maintain ignition in the reactor. The result of the calculations is illustrated in figure 4. The lean blowout equivalence ratio can be found where the gradient is large. It is harder to define a specific blowout equivalence ratio for the rich mixtures as the gradient is not as steep.

DEFINITION OF LEAN BLOWOUT

The lean blowout measurements were performed by lowering the total equivalence ratio of the burner until the combustion ceased or the CO emissions indicated that the flame was about to blowout. For this experiment, the blowout limit was defined as the equivalence ratio where CO concentration exceeded 200 ppm (figure 5). The 200 ppm limit was chosen both because it is high enough to indicate bad combustion and further the gradient $\frac{d[CO]}{d\emptyset}$ is large, thus reducing influence of the concentration measurement error.

EXPERIMENTAL RESULTS

All experiments were performed at atmospheric pressure with an inlet air temperature of 650 K. The metal temperature on the outside wall of the RPL was measured at three points to give an indication of the flame position inside the RPL. (Observing figure 8, equivalence rations 1.6 and 1.8, the measured RPL wall temperature is ~630 K, indicating some degree of heat loss between the preheater and the RPL wall.) The mean unburnt volume flow 0.12 m^3/s, 0.14 m^3/s and 0.16 m^3/s for methane. For syngas and diluted syngas it was 0.09 m^3/s and 0.13 m^3/s, respectively. This gives a variation of throat velocity (unburnt gas) between 49-86 m/s. The throat section is situated at the beginning of the quarl (figure 1). The RPL equivalence ratio was varied as part of the experiment, to determine its role in combustion. The total RPL flow was 0.0028 m^3/s the same for all experiments. The equivalence ratios of the Main and the Pilot sections of the burner were kept equal throughout the experiments. When performing the blow out tests the throat velocity and the RPL settings were held constant. It should be noted that accuracy of the total equivalence ratio is ±0.0025 for all measurements, limited by the standard deviation of the air flow supplied to the Main and Pilot.

Methane

The methane blowout test was performed with RPL equivalence ratios ranging from 0.8 to 1.8 (figure 6). When the tests are conducted at higher RPL equivalence ratios, the blowout occurs at progressively lower total equivalence ratios (figure 7). Additionally, the combustion is more stable at higher RPL equivalence ratios, as the smaller standard deviation in CO concentration indicates less fluctuation in the combustion. In most cases, the transition from stable combustion to flameout can be seen as a rapid increase in CO emission (figure 5); however, when the RPL equivalence ratio was set to 0.8, blowout occurred at total equivalence ratio 0.47, without onset of high CO values. The measured blowout limits were found to be in agreement with the range predicted by the PSR calculation: ~0.45

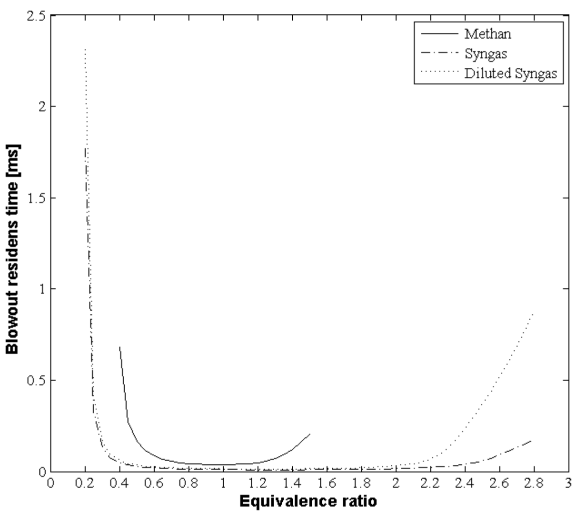


Figure 4 The blowout equivalence ratio is observed where the gradient of the blowout residence time is steep

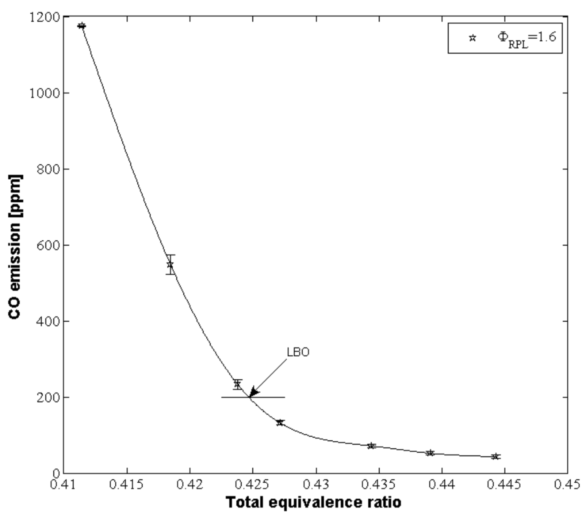
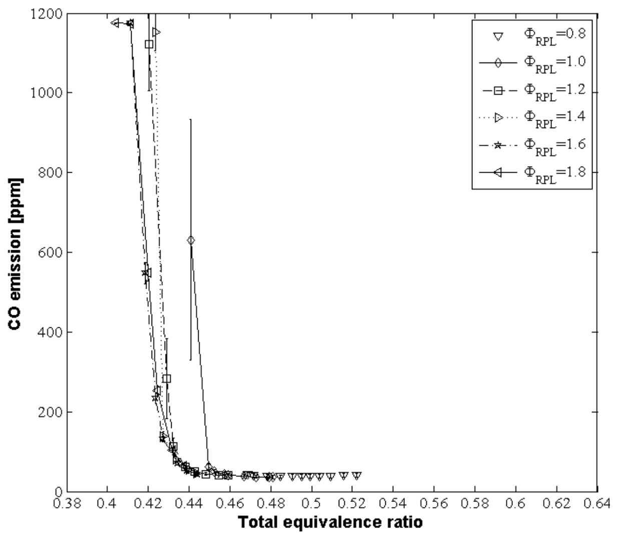


Figure 5 The lean blowout of methane at an RPL equivalence ratio of 1.6 were measured to be at a total equivalence ratio of 0.422. Volume flow 0.12 m3/s



Figre 6 CO emission from lean blowout measurement for methane. Volume flow 0.12 m^3/s

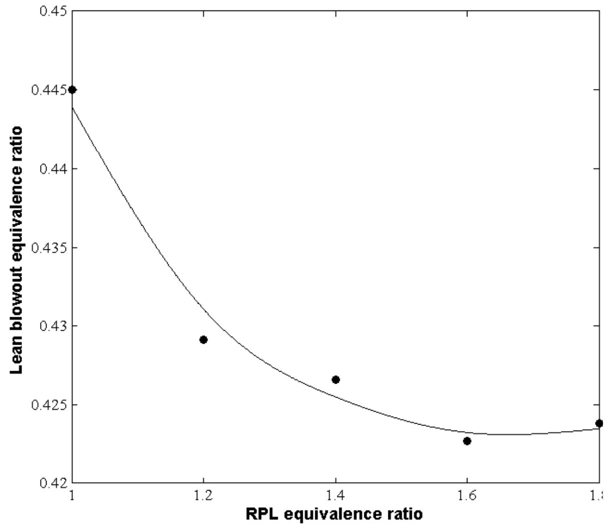


Figure 7 Change of blowout limit for methane when varying RPL equivalence ratio. Volume flow 0.12 m^3/s

depending on the specified cutoff blowout residence time (figure 4).

The temperature measurements from the RPL give some indication of the RPL flame behavior at the chosen equivalence ratios. A high temperature shows the presence of combustion heat release. For equivalence ratios 0.8-1.4 (figure 8), the temperature measurements show that the flame is positioned in the upper half of the RPL, as the Top temperature probe shows the highest temperature. At the RPL equivalence ratios 1.6 and 1.8 the temperatures indicate that no combustion takes place inside the RPL; thus, due to change in equivalence ratio the flame speed has dropped below a limit where the flame can be stabilized inside the burner.

An LBO test for the volume flows 0.14 m^3/s and 0.16 m^3/s (figure 9) indicate that increasing the flow through the burner slightly increases the lean blowout equivalence ratio. This is a typical behavior for most combustors [17]. The tests were done with the RPL equivalence ratio 1.6. The RPL temperature measurements for this test are ~800 K, indicating that the RPL combustion is within the RPL.

Syngas

The undiluted syngas blowout test was performed with RPL equivalence ratios ranging from 0 to 1.8. The lean blowout measurements for syngas show that the blowout limit is significantly lower than for methane, ranging from equivalence ratio 0.3-0.34 (figure 10).

With syngas combustion it was possible to run the burner without any combustion taking place in the RPL (figure 10). When increasing the RPL equivalence ratio the stability limit trend is the same as that for methane, i.e., lean blowout occurs at lower values (figure 11).

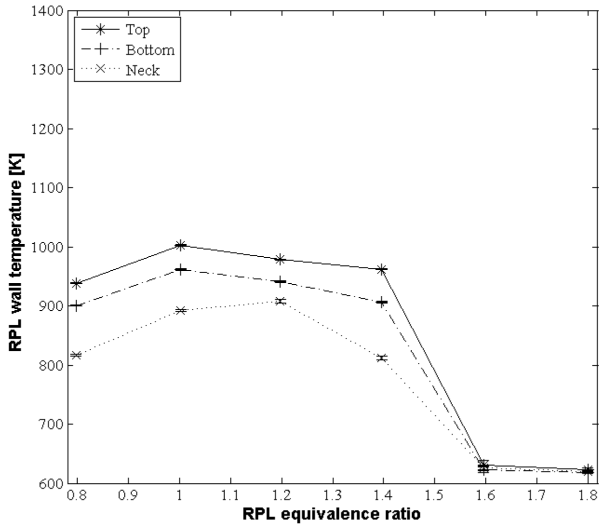


Figure 8 Temperature measurements for methane. Volume flow 0.12 m^3/s

Analysis of the temperature measurements indicate, because of the small temperature difference between the three thermocouples that at an RPL equivalence ratio of 0.4, combustion takes place in the centre of the burner, similar to stoichiometric methane. The laminar flame speeds in figure 2 show that the laminar flame speed for the syngas at an equivalence ratio of 0.4 is at the same level (approximately 100 cm/s) as for the methane measurements (excluding the two richer RPL equivalence ratios).

For RPL equivalence ratios from 0.8-1.8, the high neck temperature indicates that combustion occurs directly after entering the RPL, perhaps attached to the inlet ports. The high temperatures seen at the RPL exit for equivalence

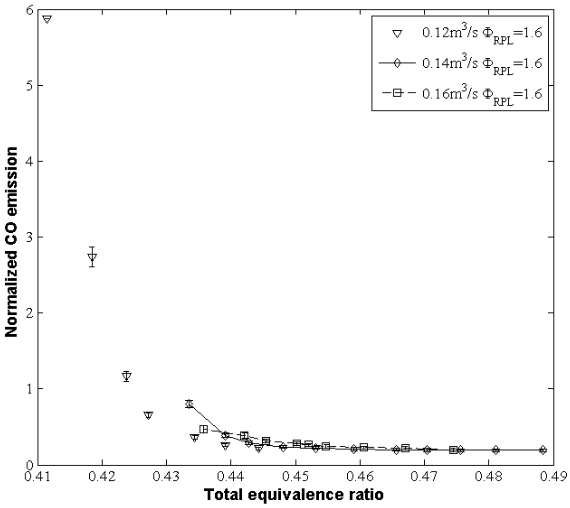


Figure 9 CO emission from lean blowout measurement for methane

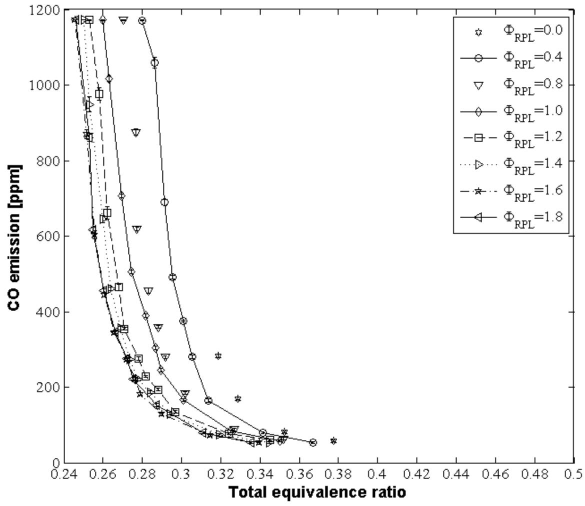


Figure 10 CO emission from lean blowout measurement for syngas. Volume flow 0.09 m^3/s

ratios of 1.2-1.6 suggest that there may be flash back in the Pilot burner section (figure 12). Removal of the liner showed that indeed the flame was attaching to the Pilot swirl vanes. The large standard deviations of these measurements are a result of a transient heating of the RPL from the beginning of measurement until the flame attaches to the Pilot vanes and the RPL lip had reached a steady state.

Diluted Syngas

The diluted syngas blowout test was performed with RPL equivalence ratios ranging from 0.4 to 1.8 (figure 13).

Again, the trend of lower blowout values for higher RPL equivalence ratios holds (figure 14), in this case extending the minimum stable total equivalence ratio from 0.325 to 0.31. This is a proportionately smaller influence of the RPL on stabilizing the combustion, as compared to methane and pure syngas.

The temperature profile for the different RPL equivalence ratios is similar to that of pure syngas (figure 15), with the exception that all equivalence ratios have their highest temperature at the RPL neck, i.e., combustion in vicinity of the inlet ports. No flashback at the Pilot region is observed.

DISCUSSION

Lean blow out limit

The RPL is shown to have an influence on the stability of the combustion in the burner. As the equivalence ratio of the RPL is increased the LBO is lowered. An increase in equivalence ratio, while the keeping the total flow constant, results in a higher fuel flow and subsequently increases the available chemical energy through the RPL. This together with the recirculated hot gases serves as the ignition source to Pilot and Main premixed flows. Observing the trends of

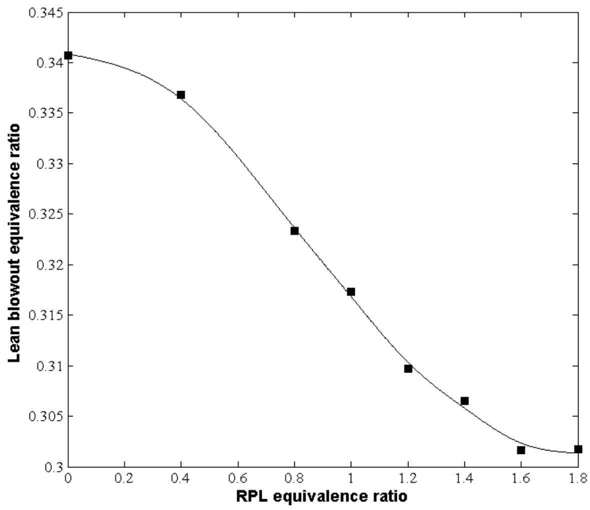


Figure 11 Change of blowout limit for syngas when varying RPL equivalence ratio. Volume flow 0.09 m^3/s

figures 7, 11 and 14, the influence of increasing the equivalence ratio is getting weaker with higher equivalence ratios. This is probably because, even though the chemical energy is increased as stated above, not enough of this energy is released as heat and active radicals at higher equivalence ratios to aid the stabilization of the combustion in the Pilot and Main.

Blow off

In the methane tests blow off was observed when the RPL combustion was pushed out of the RPL at higher equivalence ratios. The flame speed can be assumed to be proportional to the laminar flame speed. Observing figure 2

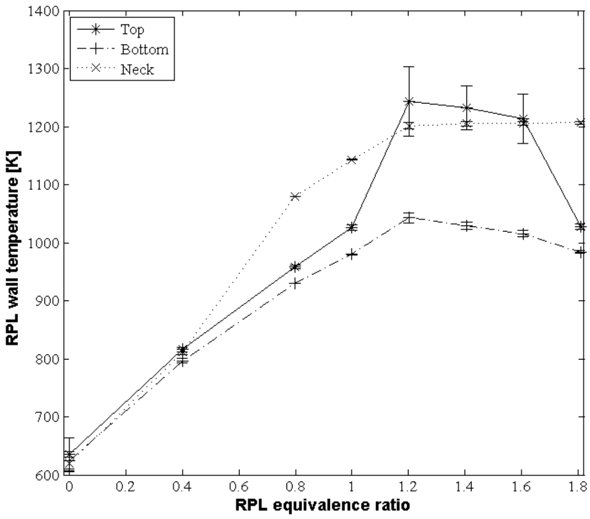


Figure 12 Temperature measurements for syngas. Volume flow 0.09 m^3/s

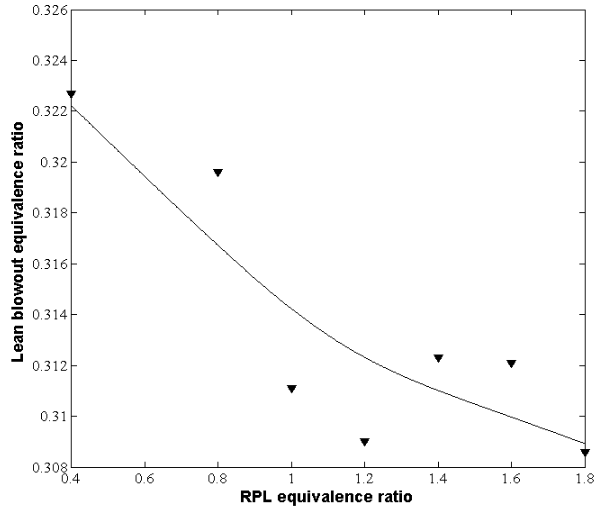


Figure 14 Change of blowout limit for diluted Syngas when varying RPL equivalence ratio Volume flow 0.13 m^3/s

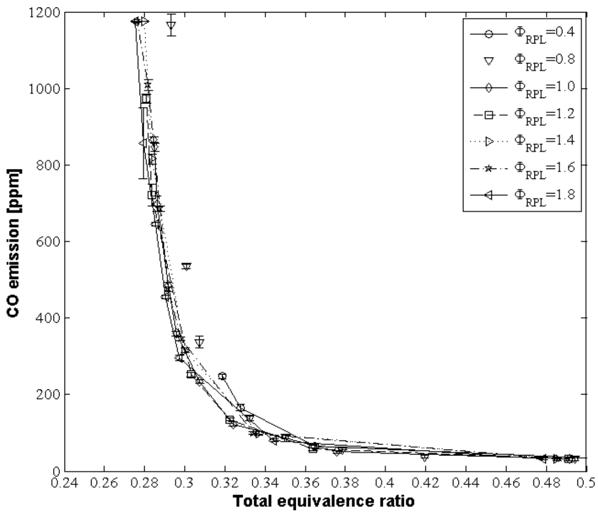


Figure 13 CO emission from lean blowout measurement for diluted syngas. Volume flow 0.13 m^3/s

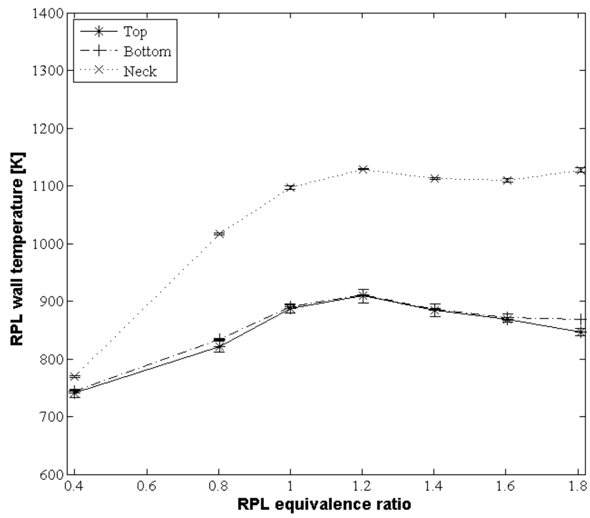


Figure 15 Temperature measurements for diluted Syngas Volume flow 0.13 m^3/s

it can be seen that the laminar flame speed is significantly lower for RPL equivalence ratios 1.6 and 1.8. It is likely, that the unburnt velocity inside the RPL, at these equivalence rations, is larger than the flame speed and as a result pushes the flame out of the RPL. This phenomenon was not observed for the methane tests at 0.14 m^3/s and 0.16 m^3/s. One explanation could be that the recirculation zone from the Pilot and Main is stronger which keeps the RPL combustion inside the RPL body. Another could be that the higher combustion loading [MW/m^3] radiates more heat down into the RPL and increase the reaction rates inside the RPL. This is an issue for further investigation.

Flash back

When the syngas test was performed at high equivalence ratio, flame attachment to the RPL exit lip and the Pilot swirlers where observed. This is considered to be flashback. The reason why it happened with the syngas, and not the other two gases, is that the flame speed is considerably higher for this mixture (figure 2). The flash back occurred at equivalence ratios higher than those that give the highest laminar flame speed. A reason for this could be that the rich combustion exhaust from the RPL diffuse/mix with the Pilot premixed stream. The intermediate mixture will consist of a range of equivalence ratios. Depending on the amount of mixing a different peak flame speed may be present.

CONCLUSIONS

The lean blowout limit of three fuels has been examined in a scaled DLE burner at different RPL equivalence ratios. The experiments were conducted at atmospheric pressure and a inlet temperature of 650 K.

Improvements on the lean stability limit can be achieved by increasing the equivalence ratio in the RPL. For methane this will, at high RPL equivalence ratios, force the flame out of the RPL. The syngas fuels did not show this behavior due to the high hydrogen content. For the syngas fuels, thermocouples indicated that the flame inside the RPL was close to the premixed inlet.

The blowout limit of the syngas mixtures was significantly lower than the methane mixture due to the high hydrogen contents and all blowout limits could be predicted using PSR model.

The higher flame speed of the undiluted syngas mixture caused the Pilot combustion to attach to the Pilot swirlers and the exit lip of the RPL for RPL equivalence ratios close to the peak laminar flame speeds.

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