Experimental Results of Laminar Burning Velocities of Adiabatic Syngas/H_2-Rich Fuel Gases – First Set

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Introduction

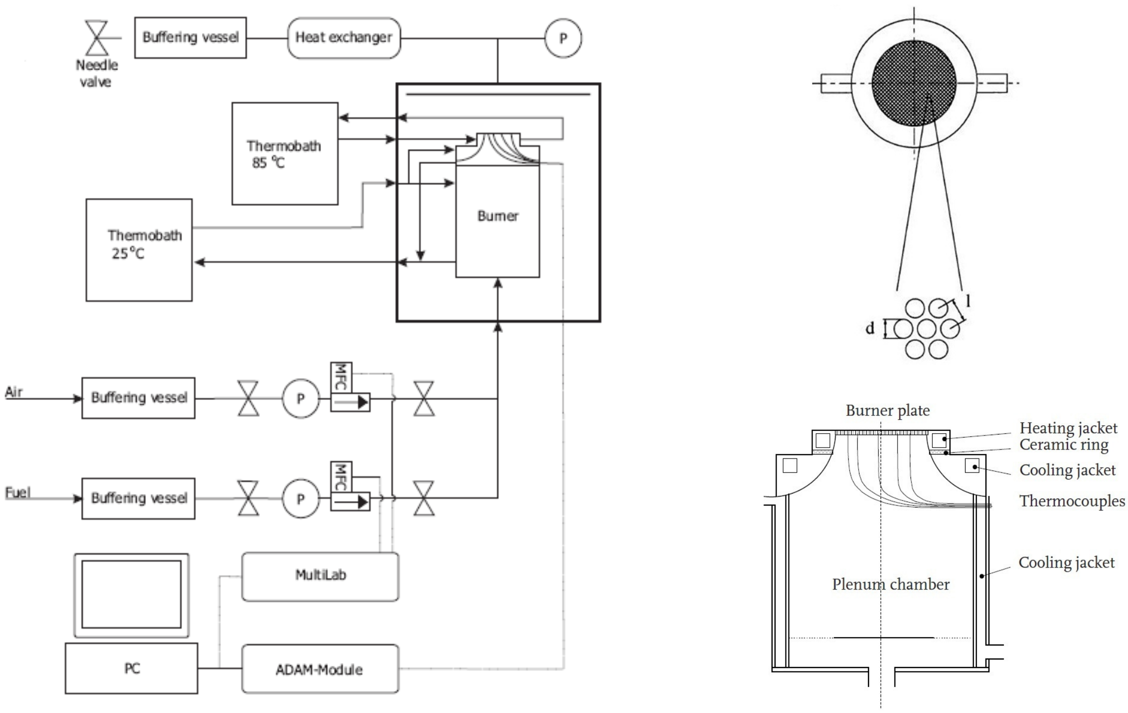
In the present project, SP1, WP1.1 is dedicated in providing experimental data on ignition delay and laminar burning velocity of syngas and High H_2 syngas. Laminar burning velocity defines the rate with which the unburnt mixture is consumed in the propagating laminar flame. This parameter is considered one of the most important entities in assessing many phenomena like ignition, flame quenching, flashback stabilization etc. in burners and combustors in the systems like mentioned above. Along with its importance in designing combustors, this parameter also holds its importance in validating chemical kinetic mechanisms. These mechanisms must be capable of predicting major combustion processes in numerical modeling.

There are a number of methods that can be employed in measuring this quantity. Some of them are counter flow flame method, spherically propagating flame method and conical flame method. In the present report it is intended to demonstrate a relatively new method called the ‘heat flux method’ for measuring this parameter. In the interest of the H_2-IGCC project it is the first attempt to operate this method at higher pressures for fuels like methane and syngas especially in the lean regime.

As decided among partners like DLR, PSI, NUI Galway and TU/e, the fuel that would be of utmost importance will be H_2:CO mixture of 50:50% and 85:15% by volume. Hence, these fuels will be tested along with CH_4 for conditions of elevated pressures. During the half yearly meeting at Genoa, TU/e demonstrated the high pressure heat flux method with methane as the fuel. On the same line, the system was upgraded to test syngas. The following sections summarize the method at high pressure, the upgrading of the system, the observations and the results.

Experimental Method

The main principle of the heat flux method is to stabilize a flat flame with unburnt gas velocity such that the heat loss by the flame is compensated by heat gain by the unburnt gases. A more detailed description of the concept and principle is available in the thesis of Bosschaart [1] and Hermanns [2]. A schematic representation of the experimental setup is shown in Fig. 1(a). A perforated plate is fitted on a burner head (Fig. 1(b)). The burner head is maintained at a temperature higher than the unburnt gas temperature. This gives a heat transport from the head to the burner plate and finally to the unburnt gas mixture. An increase in hot water temperature brings the flame closer to the plate.

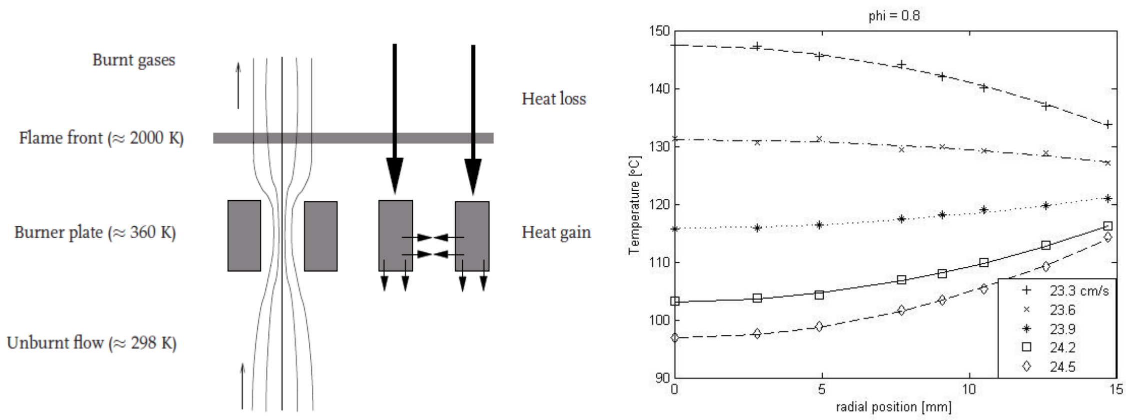


(a) (b)

Figure 1: (a) Schematic of the present experimental setup and (b) Burner plate (top) and Burner (bottom)

The unburnt gas mixture flows through the plenum chamber of the burner which is maintained at 298 K using a water thermal bath. The burner head is jacketed with a water thermal bath at 383 K. Eight Copper-Constantan thermocouples are soldered radially on the perforated burner plate with holes of 0.3 mm diameter and 0.4 mm pitch (Fig. 1(b)). The plate has a thickness of 1 mm. The burner is housed in a high pressure vessel made of C45 steel designed for pressures up to 10 bars. A chimney is placed on top through which burnt gases are guided out. A stainless steel connection pipe followed by a needle valve is connected to the exhaust of the chimney. The pressure in the vessel is controlled by this needle valve.

When the unburnt gas velocity is higher than the adiabatic burning velocity (super-adiabatic) the heat gain by the gas is larger than the heat loss from the flame. The situation is opposite in case of a sub-adiabatic flame. Fig. 2(a) illustrates a schematic of heat balance in the system. In practice, it is difficult to attain a strictly adiabatic flame. The only measurement required in this technique is temperature profile of the burner plate. The radial profile of temperature on the burner plate close to the adiabatic burning velocity is fitted by the method of least squares to a polynomial. The coefficients of such polynomials are plotted against sub and super adiabatic flow velocities. The adiabatic state is reached for zero value of the coefficient. The procedure and model calculation for measuring the temperature and evaluating the burning velocity is described by Hermanns [2]. Fig. 2(b) represents the measured temperatures along the burner plate for lean mixture of CH_4 and air at 3 atm and 298 K.



(a) (b)

Figure 2: (a) Heat balance (b) Radial temperature profiles across the burner plate at different gas velocities

H_2/CO Experiments

After the successful tests of CH_4 up to 5 bars, tests were planned for H_2/CO mixtures. In doing so a number of additions had to be done in order to ensure accurate and safe working environment. Since, these mixtures contained carbon monoxide, special attention was paid towards the safety aspects including a detection system and tested high pressure lines. Also, a special N_2-flushing line was introduced to keep the fuel line flushed when not in use. This ensured that no harmful gases could leak into laboratory where people are working. In addition to this, it was also observed that carbon monoxide when stored in iron or Ni based cylinders or stainless steel flow lines, some of the gas converts into compounds like carbonyls. When the mixture is lighted, the flame emits a pale, off-white color. This indicates that the mixture is not pure anymore. Hence, special care was taken to make all the lines with brass and copper. It was also ensured that all the components could withstand pressures as high as 30 bars. Mass flow controllers (MFC) from Bronkhorst were ordered and calibrated specially for high pressure.

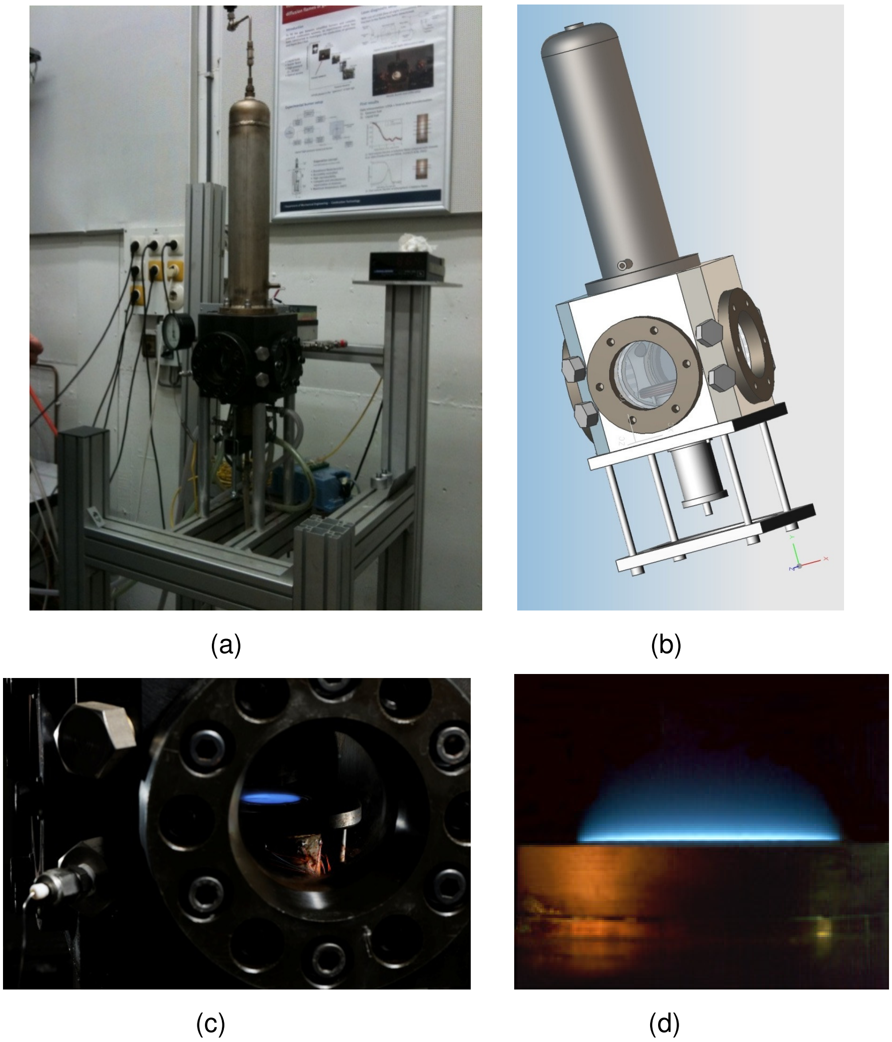


Fig 3. (a) Experimental setup (b) High pressure call (c) Flame in the high pressure environment (d) heat flux flame

Discussion

This section discusses the output obtained by the heat flux technique. The only measurement required in the heat flux technique is temperature of the burner plate. The radial profile of temperature on the burner plate close to the adiabatic burning velocity is fitted by the method of least squares to a polynomial. The coefficients of such polynomials are plotted against sub and super adiabatic burning velocities. The adiabatic state is reached for zero value of the coefficient. The procedure and model calculation for measuring the temperature and evaluating the burning velocity is described by Hermann [2]. Fig 4 represents the measured temperatures along the burner plate for lean mixture of CH_4 and air at 3 atm and 298 K.

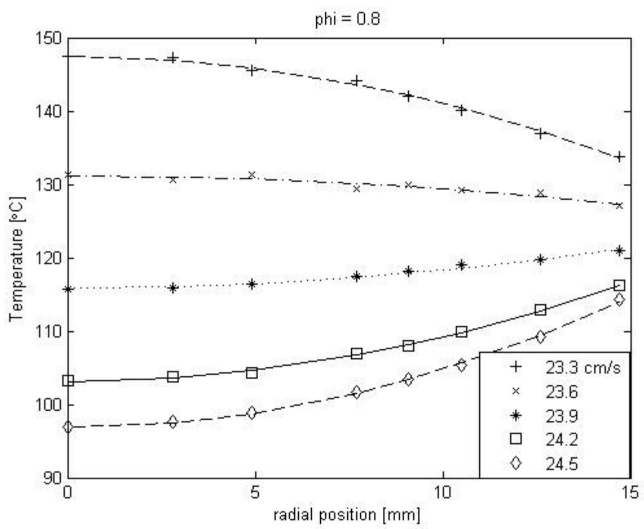


Fig 4: Temperature profile of the plate for CH_4/Air at 3 atm and 298 K.

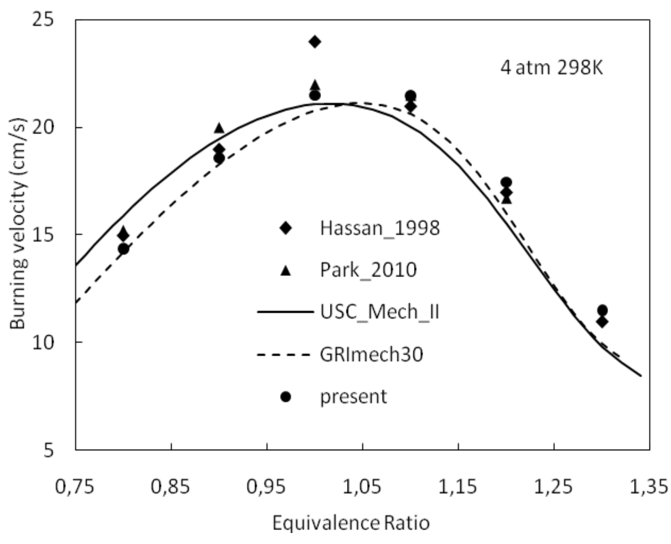


Fig 5: CH_4/Air at 4 atm and 298 K. Symbols are experimental results and lines are simulation results.

Heat flux flames are maintained flat for velocities close to the adiabatic range. At elevated pressures the flames are strained as the flow rates are higher. At too sub-adiabatic conditions the flows are low enough to pull the flame close to the burner plate and cause sudden increase in plate temperature. Hence, the range of velocity must lie within this region which is close to the adiabatic region. A prediction of the possible range of velocity is done using CHEM1D [3] which is an in-house 1-dimensional laminar flame code. After certain increase in pressure for certain equivalence ratio it is not possible to use this method as the adiabatic burning velocity falls lower than the velocity that the plate can take. This means the flow rate is lower enough to heat the plate rapidly. But this differs from mixture to mixture. Figure 5 represents a few measurements using this method.

Variation of laminar burning velocity with respect to equivalence ratio is represented in figure 5 for a mixture of CH_4 and air at 4 atm and 298 K. A comparison has been made with other experimental results [4,5] and simulations using two existing mechanisms [6,7]. This plot demonstrates the capability of the heat flux method at elevated pressure.

A major issue that may occur in future H_2/CO high pressure experiments for lean conditions is that these mixtures will experience very low lewis number. This results in unstable premix flame. For stoichiometric conditions the diffusive thermal effect stabilizes the flame. As pressure increases, hydrodynamic instability is significant enough to weaken diffusive thermal effects. Gases like He and Ar are employed instead of N_2 in the oxidizer [8,9].

Results

This section outlines the measurements that have been made so far using this technique for this project. The deliverable is expected to be the first set and hence the syngas measurements will be repeated for accuracy. It is also intended to extend the tests to 85:15% H_2:CO fuel. In case unstable flames are noticed due to reasons quoted above, oxidizers diluted with He will be tried. Table 1 represents all the experiments that are being reported from the present work.

Table 1 : Experimental results

Fuel	CH_4	H_2/CO (50/50%)
Oxidizer	Air	Air
		O_2/N_2 (15/85%)
		O_2/N_2 (10/90%)
ϕ	0.8 – 1.4	0.6 – 1.0
T (K)	298	298
P (atm)	1.5 – 5	1.5 - 4

Experiments for CH_4 were performed from P=1.5 to 5 atm for $0.8 < \phi < 1.4$ where ϕ is the equivalence ratio. This range of equivalence ratio was chosen to cover both lean and rich behavior of the flame at high pressure. The maximum error estimate for laminar burning velocity associated with this technique was 0.6 cm/s. Errors associated with equivalence ratio were less than 0.025 for all experiments. Fig 6 shows the dependence of laminar burning velocity for $0.6 < \phi < 1.4$ for pressures up to 5 atm.

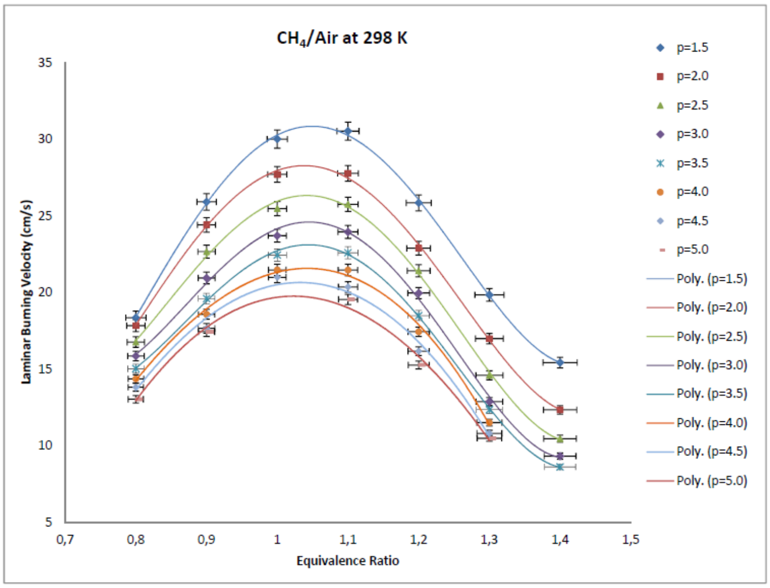


Fig 6: Results for CH_4/Air flames

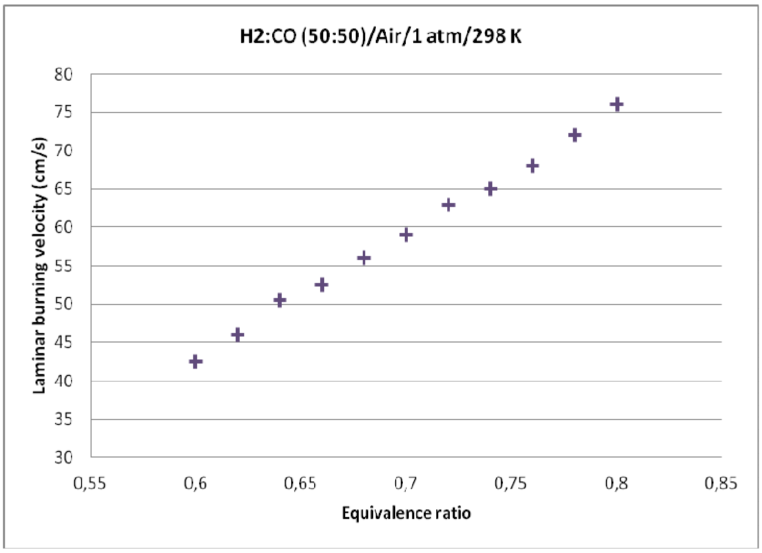


Fig 7: Results of atmospheric syngas/Air mixture

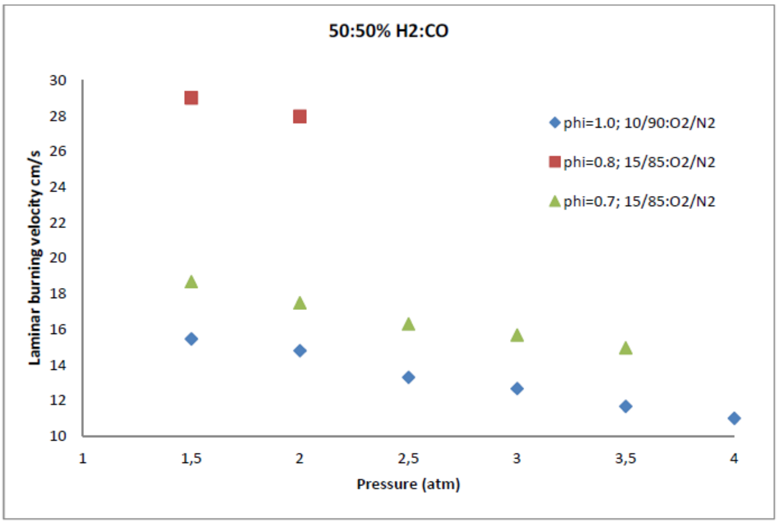


Fig 8: Results of high pressure 50:50 H_2/CO with diluted oxidizers

H_2/CO mixtures were introduced to the heat flux system first at atmospheric conditions. Since the burner is enclosed in a high pressure cell, the flame is always exposed to a pressure higher that atmospheric. Hence, these results cannot be treated most accurate. However, it is indicative that flat flames can be stabilized on such burner. The velocities are of the order of 40-80 cm/s in figure 7. As soon as the system was pressurized it was observed that the flame sweeped into an acoustical instability. After several trials it was decided to test the same fuel with diluted oxidizers so as to have lower velocities (10-30 cm/s). Figure 8 depicts the flames at pressures up to 4 atm with diluted oxidizers – 10:90% and 15:85% O_2:N_2 (by volume) at equivalence ratio, ϕ = 0.7, 0.8, 1.0.

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