A comparative study of laminar burning velocities of methane, methanol and ethanol using the Heat Flux method

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Abstract

The Heat Flux method is one of the most recent experimental methods, which allow measuring laminar burning velocity. In order to improve the accuracy of the measurements and to determine possible systematic uncertainties, several sets of experiments have been carried out and their results have been compared. In this study the Heat Flux method has been applied to measure laminar burning velocities of methane, methanol and ethanol mixtures with air. The measurements have been performed by four different laboratories from Eindhoven University of Technology, Lund University, OWI Oel-Waerme Institut GmbH and TU Bergakademie Freiberg.

Introduction

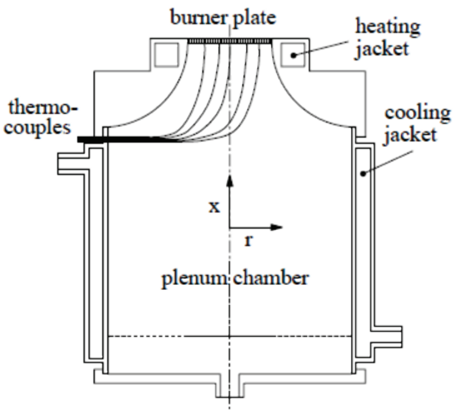
The laminar burning velocity is a fundamental property of a reactive fuel-oxidizer mixture, depending on a mixture composition, ambient pressure and initial temperature. Reliable experimental data on laminar burning velocities are essential for validation of chemical reaction mechanisms. These data are also often needed in designing of different industrial and domestic burners. There are several experimental methods to measure laminar burning velocity: the Bunsen flame method, the spherically expanding flame method, the stagnation flame method and the flat flame burner method, including the Heat Flux method. A detailed overview of different methods can be found in [1] and [2].

In this study the Heat Flux method has been applied to measure laminar burning velocities of methane, methanol and ethanol mixtures with air at atmospheric pressure. In order to improve the measurements, check their reproducibility and determine possible systematic uncertainties, several sets of experiments have been carried out. The measurements have been performed by four different laboratories from Eindhoven University of Technology (TUE), Lund University (LU), OWI Oel-Waerme Institut GmbH (OWI) and TU Bergakademie Freiberg (TUBaF).

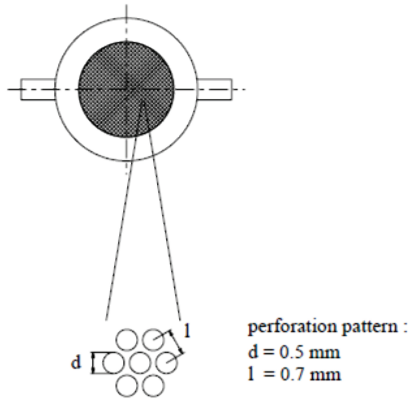
Experimental Method

The Heat Flux method was proposed in 1993 by de Goey, van Maaren and Quax [3]. This method of measuring laminar burning velocities is based on the earlier work of Botha and Spalding [4]. The main advantage of this method is that it deals with an unstretched one-dimensional flame at close to adiabatic conditions. The stabilization of this one-dimensional adiabatic flame has been proved by van Maaren et al. [5] and Bosschaart and de Goey [6]. More details about the Heat Flux method can be found in [7].

The Heat Flux burners used by four different labs are almost identical (except some small differences in design and operation). However, the other parts of the test rigs (like fuel preparation, thermal conditioning, control and measurement sections) are quite different. For a better understanding, first a typical experimental setup and measurement procedure are explained and then the differences between the experimental setups are presented.



a)



b)

Figure 1 – Schematic view of the Heat Flux burner [6]: a) cross-section and b) top view

The main parts of the Heat Flux burner are shown in Figure 1. One of the main burner elements is a 2-mm thick brass burner plate with an effective diameter of

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approximately 30 mm and a uniform perforation (see Figure 1b). A conditioned heating jacket operates at a constant temperature, which is set to keep a temperature difference between unburnt gas and the heating jacket between $\Delta T = 60$ K and $\Delta T = 75$ K. A plenum chamber is surrounded by a cooling jacket, which maintains the temperature of the plenum chamber at a temperature equal to that of the unburnt gas mixture.

In order to measure a radial temperature profile in the burner plate, eight thermocouples are attached to the burner plate. To stabilize an adiabatic flame on top of the burner plate the net heat flux, which is defined as a sum of the heat flux from the flame front to the burner plate and the heat flux from the burner plate to the fuel-air mixture, should be equal to zero. For gas velocities u_g lower than the laminar burning velocity S_L the net heat flux is positive and the burner plate has a higher temperature than the heating circuit. This results in a radial heat flux from the burner plate centre to the edge and the burner plate centre achieves the highest temperature (Figure 2a). The net heat flux is negative, when the gas velocity is higher than the laminar burning velocity. In this case the temperature at the centre of the burner plate is the lowest measured temperature, due to the reverse direction of the radial heat flux (Figure 2b). For a flat temperature profile, the net heat flux is zero, which means that all the heat transferred from the flame to the burner plate is transferred then to the unburnt gas mixture. This situation corresponds to adiabatic flame conditions and the corresponding gas velocity u_g equals to the laminar burning velocity S_L.

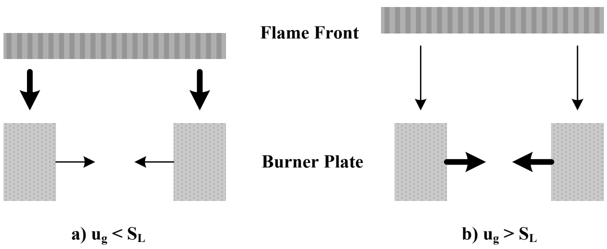

Figure 2 – Working Principle of the Heat Flux method

The flowchart of a typical Heat Flux burner test rig is presented in Figure 3**.** All test rigs consist of four sections: a fuel preparation section, a thermal conditioning section, a burner and a control and measurement unit.

The differences and specific features of the experimental setups are listed below for each lab/setup. Mainly different methods of vaporization of liquid fuels have been applied.

Eindhoven University of Technology (TUE)

- Thermocouples: type T.
- Temperature difference was set to 60 K.
- Effective diameter: 3 cm.

Lund University (LU)

- Thermocouples: type T, unshielded, made of 0.13 mm wires.
- Temperature difference was set to 70 and 50 K for the unburned temperatures of 298 and 318 K, respectively.
- Effective diameter: 2.93 cm.
- The evaporation system was based on a controlled evaporator mixer with carrier gas (CEM Bronkhorst B.V.).
- Liquid flow was controlled via a Coriolis based mass flow controller.

OWI Oel-Waerme-Institut (OWI)

- Thermocouples: type E.
- Temperature difference was set to 75 K.
- Effective diameter: 2.93 cm.
- Liquid flow was controlled via high-performance liquid chromatography pump (HPLC).
- The evaporation was carried out with a porous plate vaporizer.
- Both heating jacket and cooling jacket were operated with oil.

TU Bergakademie Freiberg (TUBaF)

- Thermocouples: type E.
- Temperature difference was set to 70 K.
- Effective diameter: 2.93 cm.
- The evaporation system was based on an adapted direct evaporator, this setup is described in detail in [8].
- Liquid flow was controlled via a Coriolis based mass flow controller.

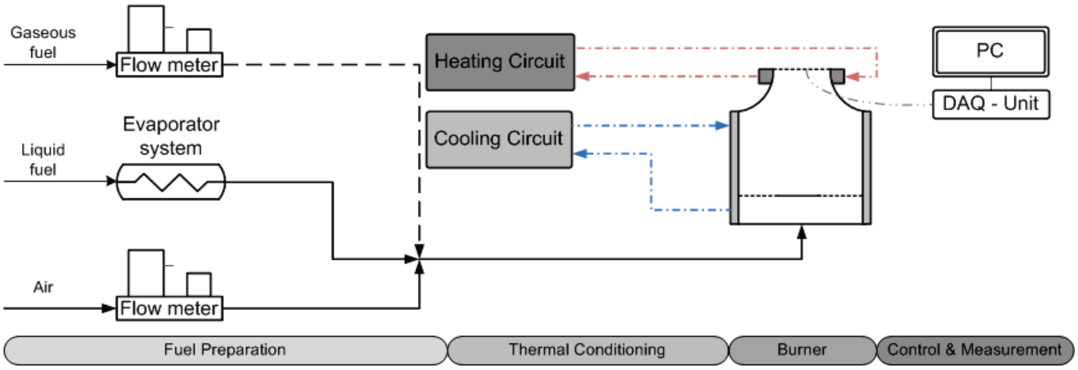

Figure 3 – Schematic flowchart of a Heat Flux burner test rig

Results

To evaluate the performance of the Heat Flux method, several sets of experiments have been carried out and their results have been compared. Three different fuels have been investigated at atmospheric conditions – one gaseous fuel (methane) and two liquid fuels (ethanol and methanol). The initial temperature was equal to 298 K for methane, 318 K for ethanol and 298 and 318 K for methanol.

I. Methane (CH_4)/air mixtures

In Figure 4 the laminar burning velocities of methane/air mixtures for equivalence ratios from 0.7 to 1.3 at 298 K and 1 atm are presented. The mean values together with the corresponding mean and standard deviations are given in Table 1. Among equivalence ratios used the maximum mean burning velocity (38.1 ± 0.7 cm/s) was measured at an equivalence ratio of 1.1. The figure shows that the experimental results of OWI and TUBaF are very close to each other and only small deviations can be detected. At equivalence ratios of 0.7 and 0.8 the results of all labs agree quite well with each other. At equivalence ratios of 0.9 and 1.0 the results of TUE are higher by about 1 cm/s compared to other results. The results of LU agree well with those of OWI and TUBaF for lean and stoichiometric flames, but for rich flames they show noticeably lower burning velocities compared to three other labs. As a result, the mean and standard deviations from the mean values increase at higher equivalence ratios (see Table 1).

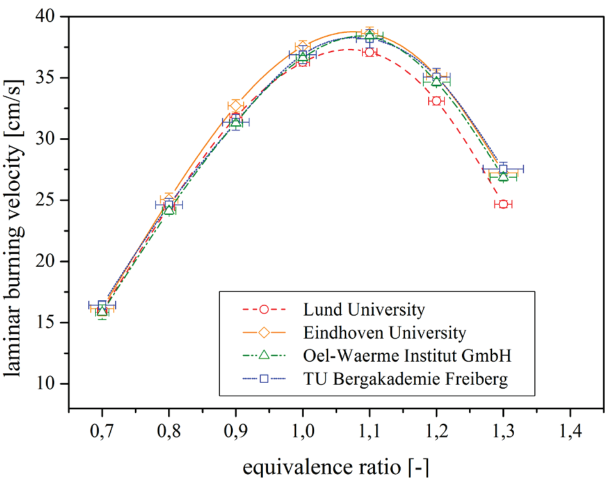

Figure 4 – Laminar burning velocity of methane/air flames at 298 K

To quantify the agreement (or disagreement) between the results of the different labs, for every measured value of the burning velocity the difference with a corresponding value measured by another lab has been calculated. The absolute values of those differences have been then averaged over all equivalence ratios. The obtained average differences are presented in Table 2. The burning velocities measured, for example, by TUBaF and OWI labs differ from each other on average only by 0.4 cm/s (see also Figure 4). The results of TUBaF, OWI and TUE differ from each other on average not more than by 0.7 cm/s, while the results of LU differ on average by 1.1 cm/s from those of other labs. The average difference between every two single measurements for methane/air flame is 0.8 cm/s.

Table 1 – Mean values of measured burning velocities for methane/air mixtures at 298 K

φ	Mean value, cm/s	Mean deviation, cm/s	Standard deviation, cm/s
0.7	16.1	0.2	0.3
0.8	24.6	0.3	0.4
0.9	31.8	0.5	0.7
1	36.8	0.4	0.5
1.1	38.1	0.5	0.7
1.2	34.5	0.7	0.9
1.3	26.6	1	1.3

Table 2 – Average differences between the results of different labs for methane/air mixtures at 298 K

Average difference [cm/s]			
	TUBaF	OWI	TUE
LU	1.1	0.9	1.3
TUBaF	-	0.4	0.5
OWI	-	-	0.7

II. Ethanol (C_2H_5OH)/air mixtures

For ethanol/air mixtures the laminar burning velocities have been measured at an initial temperature of 318 K. The results of LU, OWI and TUBaF labs are compared in Figure 5 over an equivalence ratio range of 0.7–1.4. The mean values of measured burning velocities are given in Table 3. The maximum mean laminar burning velocity of 48.8 ± 0.6 cm/s has been measured at an equivalence ratio of 1.1.

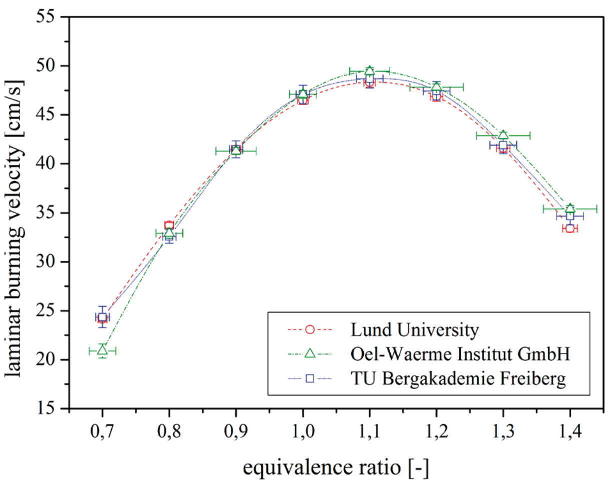

Figure 5 – Laminar burning velocity of ethanol/air flames at 318 K

Overall, the results are in a good agreement with each other. Only at $\varphi = 0.7$ the results of OWI are noticeably lower compared to those of LU and TUBaF, which leads to rather high values for the mean and standard deviations at this equivalence ratio (see Table 3).

The average differences between the experimental results of the different labs for ethanol/air mixtures at an initial temperature of 318 K are given in Table 4. The average difference between every two single measurements for ethanol/air flame is 0.9 cm/s.

Table 3 – Mean values of measured burning velocities for ethanol/air mixtures at 318 K

φ	**Mean value, cm/s**	**Mean deviation, cm/s**	**Standard deviation, cm/s**
0.7	23.1	1.5	1.9
0.8	33.1	0.4	0.6
0.9	41.4	0.1	0.1
1.0	46.9	0.3	0.3
1.1	48.8	0.4	0.6
1.2	47.4	0.3	0.5
1.3	42.1	0.5	0.7
1.4	34.5	0.7	1.0

Table 4 – Average differences between the results of different labs for ethanol/air mixtures at 318 K

Average difference [cm/s]		
	TUBaF	OWI
LU	0.6	1.3
TUBaF	-	0.9

III. Methanol (CH_3OH)/air mixtures

The laminar burning velocities for methanol/air mixtures at initial temperatures of 298 and 318 K have been measured by LU and TUBaF labs. Figure 6 shows the experimental results obtained at 298 K. The mean values of burning velocities for an equivalence ratio range of 0.7–1.0 are given in Table 5. The agreement between the measured data by both labs is very good. The average difference between the two test series is only 0.2 cm/s. The maximum difference between the test series is 0.35 cm/s. Both mean and standard deviations do not exceed 0.2 cm/s (see Table 5).

Table 5 – Mean values of measured burning velocities for methanol/air mixtures at 298 K

φ	**Mean value, cm/s**	**Mean deviation, cm/s**	**Standard deviation, cm/s**
0.7	18.5	0.1	0.1
0.8	28.1	0.2	0.2
0.9	36.4	0.0	0.0
1.0	42.3	0.1	0.2

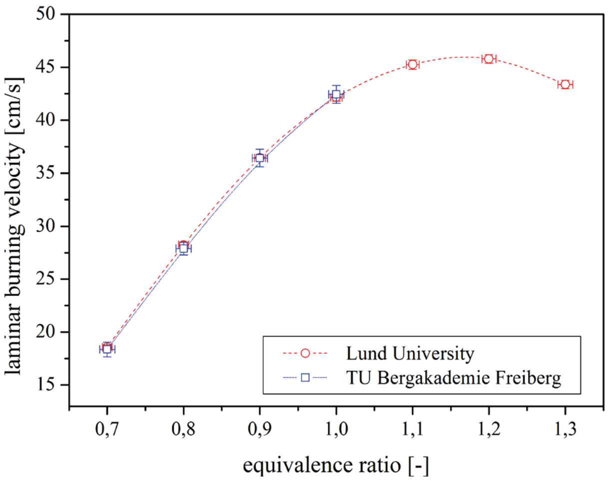

Figure 6 – Laminar burning velocity of methanol/air flames at 298 K

The laminar burning velocities for methanol/air mixtures at 318 K are presented in Figure 7. The mean values of burning velocities for an equivalence ratio range of 0.7–1.0 are given in Table 6. The agreement between measured values of burning velocities at 318 K is a bit poorer compared to the results at 298 K, but it is still good. The average difference between the two test series is 0.6 cm/s. The maximum difference between the test series is 0.8 cm/s.

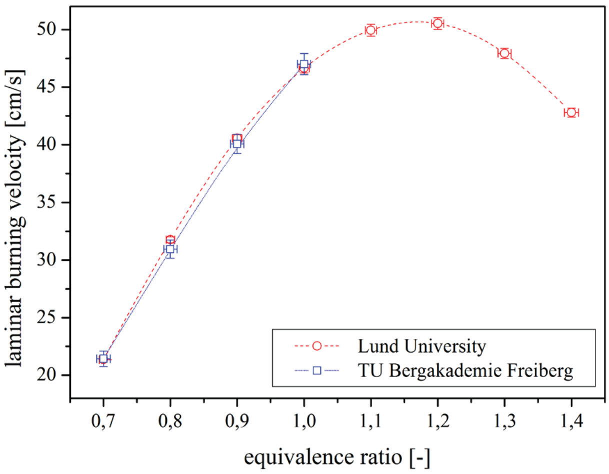

Figure 7 – Laminar burning velocity of methanol/air flames at 318 K

Table 6 – Mean values of measured burning velocities for methanol/air mixtures at 318 K

φ	**Mean value, cm/s**	**Mean deviation, cm/s**	**Standard deviation, cm/s**
0.7	21.4	0.0	0.0
0.8	31.4	0.4	0.6
0.9	40.3	0.3	0.4
1.0	46.8	0.2	0.2

Discussion of Results

The results obtained for different fuels have a different number of points to compare. The best agreement has been observed for methanol/air flames, though only results of two labs at four equivalence ratios were available for comparison. The agreement itself is very good – the mean deviation did not exceed 0.4 cm/s for methanol flames. For ethanol/air flames the measurements have been performed by three labs for an equivalence ratio range of 0.7-1.4 and only one point at an equivalence ratio of 0.7 significantly differs from other results. For other equivalence ratios the mean deviation did not exceed 0.7 cm/s and the standard deviation did not exceed 1.0 cm/s. For methane/flames the most number of data points have been obtained. In general, the agreement is good, though it is a bit poorer than the comparison using the other fuel/air mixtures. It still has to be clarified why the results of LU lab for rich methane/air flames are significantly lower than those of the other labs. There is no big difference in laminar burning velocity at fuel rich ethanol flames, so most likely this is not related to some systematic difference between the setups. Other differences in the results also cannot be ascribed to some big systematic differences. There can be, however, still be some systematic differences between the setups (or in the measurement procedures used). To be able to find them, the measured values of burning velocities should be compared together their uncertainties. Every lab has evaluated its measurement uncertainty according to its own procedure and, for example, for methanol flames the observed differences in burning velocities (for both initial temperatures) are within the estimated measurement uncertainty. It is also the case for some measurement points obtained for ethanol and methane flames. However, before making any general conclusions, it is necessary to first evaluate the measurement uncertainties of the different labs using exactly the same procedure, which is going to be the next step of this research.

Conclusions and Outlook

In this study the heat flux method has been used to measure the laminar burning velocities of three different fuels (using up to four different test rigs at four different labs). It has been confirmed that this method can produce reliable and comparable data on laminar burning velocities. The measured trends are found to be consistent for all measurements. Moreover, in more than 70% of the cases the difference between two single points measured by different labs did not exceed 1 cm/s. It should be noted, however, that there are still some unknown phenomena, which resulted in differences between the measured laminar burning velocities. Therefore, as a further step, a detailed validation of the individual test rigs (together with a harmonised uncertainty evaluation) will follow.

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