Determination of Laminar Burning Velocities of Nitro-methane using Heat Flux Method

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Master thesis

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Dedication

By the name of ALLAH

I lovingly dedicate this thesis to **Dildar Traders**

……………………………………………………………………………….

Abstract

In this paper the laminar burning velocities of nitromethane, ethanol and nitromethane-ethanol mixtures has been determined by using heat flux method. The laminar burning velocity of ethanol was measured at atmospheric pressure, initial temperatures range 298-358 K and equivalence ratio 0.7-1.6. The flame speed of ethanol shows a satisfactory agreement with previous available data.

The burning velocities of nitromethane and mixtures were determined at 338-358 K. The burning velocities of nitromethane and nitromethane-ethanol mixture have not been investigated before. Therefore a comparison between these results and ethanol results was performed at different temperatures. All the results for nitromethane have same curvature behavior and maximum velocity for each temperature found at $\varphi = 1.2$. The temperature dependence of ethanol and nitromethane with laminar flame speed has been studied.

This research gives new experimental data for the burning velocities of nitromethane. The results have good correlation between them but the further experiments and model development is required to validate the results.

Acknowledgement

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Chapter 1

Introduction

1.1 Background

Adiabatic burning velocity is a key parameter characterizing the combustion behavior of combustion mixture. This property depends upon temperature, fuel type and equivalence ratio. It is one of the input parameters for combustion models used to simulate mixture in an engine [3]. To measure the accurate value of adiabatic burning velocities of different fuels, several studies have been done with different methods. The counterflow method and closed vessel method was commonly used, and in recent research the heat flux method has been used to find the adiabatic burning velocities of fuels.

The heat flux method comes from the porous plug burner of Botha and Spalding [2] which is used to determine the heat loss for stabilizing the flame by measuring the temperature variation of the water used for cooling the burner. In 1993, Van Maaren et al. [3] presented the idea of perforated plate burner to stabilize the flame using a thin perforated brass plate. The burner plate perforated with hexagonal pattern was used to ensure the flatness of the stabilized flame. The small thermocouples were attached in different radial position on the burner plate to measure the temperature distribution due to heat loss from the flame to the burner. The heat flux method designed by Van Mareen et al.[3] can be used only to measure the adiabatic flame speed of gaseous fuels. Later In 2011 A.A.Konnov et al. [13] extended the heat flux method to determine the burning velocities of liquids fuels.

The current work aims to investigate the burning velocities of nitromethane and mixture of ethanol and nitromethane using the heat flux method at temperatures 338-358 K. Before burning the nitromethane, the burning velocities of ethanol/air will be estimated and compared with the previous data to make sure that the entire setup has good accuracy. As there is no relevant previous data available for burning velocity of nitromethane/air the results will be compared with recent ethanol data.

A biofuel is a type of fuel whose energy is derived from the conversion of inorganic carbon (carbon dioxide) to organic compound carried out by living organism. Biofuel can be obtained from biomass conversion, solid biomass, liquid fuels and various biogasses [16]. The interest in ethanol is because it is also a biofuel, which is considered more economical and environmentally friendly fuel. Ethanol is very common worldwide especially in Brazil as biofuel. Ethanol has higher octane number than gasoline, providing premium blending property. E85 is high level blend of ethanol used in flexible vehicles. More than 95% of the U.S gasoline contains ethanol at low level blend to oxygenate the fuel which may reduce the air pollution and Co_2 emission [17].

Nitro-methane is liquid at atmospheric pressure and room temperature and has the potential to be used for high performance and reduced replacement for hydrazine monopropellant [15]. Nitromethane has many applications, including solvent for chemical processing, liquid explosive and fuel additive [15].

Top fuel and nitro burning engines are the same, and they are designed to burn nitromethane rather than gasoline [20]. Nitromethane (CH_3NO_2) has its own oxygen atom and helps it to burn. The advantage of nitromethane is that the fuel gets more power inside the engine. Nitromethane is less energetic than gasoline but it can burn more and, as a result it increases more power per stock. To burn 1 kg of nitromethane 1.7 kg of air is needed as compared to gasoline where 15 kg of air needed to burn 1 kg of gasoline. It means that nitromethane can pump about 8-times more into cylinder of given volume and get complete combustion. Since nitromethane is less dense as compared to gasoline in terms of energy it cannot get 8-times improvements in terms of power, but it can double or triple engine power performance [20].

In 2009, R.J Meuwissen used the heat flux method to determine the adiabatic burning velocity of ethanol between 298K and 358 K for several equivalence ratios from 0.7 to 1.5. According to these results at ambient pressure of 0.1 Mpa and temperature of 358 K, the maximum burning velocity of ethanol/air flame appears to be around 56 cm/s at an equivalence ration of approximately 1.1 [4].

In 2010, J.P.J Van Lipzig investigated the flame speed of ethanol, n-heptane and iso-octane using the heat flux method. As compared to Meuwissen's work the most outer thermocouple is not used because it was placed outside the inner 20 mm of the burner plate. These experiments were carried out at two different temperatures 298 K and 338 K. The results of ethanol were showed a good match with the Konnov model and other literature value at 298 K and 338 K [5].

In 2011 A. A. Konnov estimated the adiabatic burning velocity of ethanol using the heat flux method at 298 to 358 K. The results show a good agreement with literature. The effects of initial temperature on the adiabatic burning velocity of ethanol were solved using the correlation $S_L=S_{L0}\ (T/T_0)^{\alpha}$. Uncertainties of the measurements were analyzed and overall accuracy of burning velocities was found to be $\pm 1\ cm/s$ [13].

In 1959, S.DE Jaegere and A.van Tiggelen measured the flame propogation velocities and temperatures for methyl nitrite, nitromethane and methane-nitrogen dioxide mixed with oxygen. The classical burner method was used to estimate the propagation velocities. Nitromethane/oxygen flames are characterized by low activation energy and they are much slower than what might be expected from theory [6].

In 2007, Eric Boyer and Kenneth K. Kue studied the modeling of nitromethane flame structure and burning behavior for higher performance and reduced toxicity monopropellant. A comprehensive detailed model for its flame structure and linear regression was developed and validated with experimental data. The predicted burning rates using the model have close agreement with measured rates over the pressure range of practical propulsion system up to 15 Mpa. Nitromethane showed three distinct zones based on the variation of species concentrations. The predicted temperature sensitivity of nitromethane burning rate is in the same magnitude as measured data [15].

Experimental and kinetic modeling was done in 2013 by Kuiwen Zhang. These experiments were taken for three premixed nitromethane /oxygen/argon flames at low pressure (4.655 kPa) with equivalence ratio 1.0, 1.5 and 2.0. More than 30 flame species were identified with tunable synchrotron vacuum ultraviolet photoionization mass spectroscopy with mole fraction as the function of height above burner. About 115 species and 730 reactions suggest and confirm against experimental results. The model results have satisfactory agreement with experimental results. These results show the reaction pathways that feature the combustion of nitromethane, including the primary decomposition of C-N bond fission, the oxidation of C2 and C1 hydrocarbons and formation of nitrogenous species [7].

1.2 Report overview

In this experimental work, to determine the laminar burning velocities of ethanol and nitromethane, the heat flux method is used. The report starts with general introduction, background and previous literature review of these fuels. In chapter 2, general concepts of Combustion Physics are given. Chapter 3 describes the experimental setup of the heat flux method and also described the partial pressure limitation. In chapter 4, for accurate flow of liquids and gases different calibrations of MFCs (mass flow controllers) have been done. In chapter 5, all measured data of ethanol and nitromethane with different temperatures (298-358 K) and equivalence ratio (0.7-1.6) are presented and compared with literature data. In the last chapter main conclusion are discussed and some recommendations are given.

Chapter 2

General Combustion Physics

2.1 Nitromethane

CH_3NO_2 is the simplest organic nitro compound and an important solvent for chemical processing and analysis. It is known as liquid explosive. It is also used as an additive to fuel for internal combustion engines. It is a slightly viscous and highly polar liquid mostly used as a solvent in many industrial applications (extractions, reaction medium, cleaning) [9]. It is used widely in the manufacture of pharmaceuticals, pesticides, explosives, fibers, and coatings.

The boiling point of nitromethane 100.8°C (213.4°F) and the melting point is -29°C (-20.2°F). The vapour pressure is 3.7 kPa at 20°C and it is highly flammable in the presence of open flames, sparks, heat, and oxidizing materials [8].

Nitro-methane is used as a fuel in motor racing, drag racing, rockets and radio controlled models. The nitromethane fuel comes with its own oxygen to burn in the engine [9].

The complete combust of nitromethane forms carbon oxides (CO, CO_2), nitrogen oxides (NO, NO_2) and water

$$4CH_3NO_2 + 3O_2 \rightarrow 4CO_2 + 6H_2O + 4NO \text{ ....Eq. (2.1)}$$

2.2 Ethanol

Ethanol is a volatile, flammable and colorless liquid used as fuel, solvent in thermometers, and spirits. It is also called ethyl alcohol, pure alcohol or drinking alcohol [19].

The boiling point of Ethanol is 79.58°C (175.2°F) and the melting point is -114.1°C (-173.4°F). Its vapour pressure is 5.95Kpa at 20°C and it is highly flammable in the presence of open flames, sparks, heat and slightly flammable in the presence of oxidants [10]. Complete combustion of ethanol forms products of carbon oxides (CO, CO_2) and water vapor.

$$C_2H_5OH + 6\ O_2 \rightarrow 2\ CO_2 + 3\ H_2O \text{ ....Eq. (2.2)}$$

2.3 Premixed Flames

A flame in which the oxidant (commonly air) is mixed with fuel before it reaches the flame front is called a premixed flame. To estimate the laminar flame speed, it generates a thin flame front with good possibility for complete combustion and these flames are mostly employed in laboratory work.

2.4 Temperature Dependence

The laminar burning velocity depends on the unburnt gas mixture temperature and pressure of the ethanol/air flame. The temperature dependence is calculated for several equivalence ratios in the temperature range of 298 K to 358 K and this temperature range is restricted to the limited values by the heat flux design. Water baths are used in this setup. A burner plate is fixed at 95 ℃ because the boiling temperature is 100 ℃ and a lower temperature can be assumed due to losses in water pipelines. The laminar flame speed propagation is a function of pressure and temperature of the unburnt gas mixture and it can be represented by power law relation:

$$S_L = S_{L,0}\left(\frac{T_u}{T_0}\right)^{\alpha_T}\left(\frac{P_u}{P_0}\right)^{\beta_P} \text{……………………………………………Eq. (2.3)}$$

Where T and P are the gas mixture temperature and pressure, respectively. The u denote the unburnt gas conditions and the 0 refers to the reference conditions ($T = 298\,K$ and $P = 1$ atm). $S_{L,0}$ is the unstretched laminar burning velocity at the reference conditions. The parameters α_T and β_P depend on φ, can be determined by fitting experimental data [1].

The Eq.2.3 can be approximated as

$$S_L = S_{L,0}\left(\frac{T_u}{T_0}\right)^{\alpha_T} \text{……………………………………………Eq. (2.4)}$$

Because in the current case we study only temperature dependence, the pressure factor is practically unity.

The equation can be simplified by dividing the laminar burning velocity over unstretched adiabatic burning velocity to obtain non-dimensional burning velocity as well as non-dimensional temperature.

$$S_L \sim {T_u}^{\alpha_T} \text{…………………………………………… Eq. (2.5)}$$

The linear relation between burning velocity and temperature on a log-log scale is obtained. The power exponent is determined by measuring the slope of each line at various equivalence ratios [1].

2.5 Flow Calculations and Equivalence ratio

To estimate the burning velocity of a fuel, the gas flow principal is important. A certain amount of liquid fuel and oxidant gas (air) are mixed together in mixing panel to get a required mixture composition. For the combustion reaction a balanced equation has to be written. In this study the following reactions will be used.

$$C_2H_5OH+3O_2 \rightarrow 2CO_2+3H_2O \text{ ……………………………………………… Eq. (2.6)}$$

$$4CH_3NO_2 + 6O_2 \rightarrow 4CO_2 + 6H_2O + 4NO \text{ ……………………………… Eq. (2.7)}$$

The molar stochiometric factor S_{molar} is the ratio of oxygen and fuel in the reaction.

$$S_{molar,ethanol} = \frac{3}{1} = 3$$

$$S_{molar,nitromethane} = \frac{6}{4} = 1.5$$

Molar fractions are converted to mass fraction using following the formula

$$S_{mass,fuel} = S_{molar} \times \frac{molecular\ weight\ of\ oxygen}{molecular\ weight\ of\ fuel} \text{ ………………. Eq. (2.8)}$$

The equivalence ratio defined as

$$\phi = S_{mas,fuel}(\frac{m_{fuel}}{m_{oxygen}}) \text{ ……………………… Eq. (2.9)}$$

where, m_{fuel} is the mass of fuel and m_{oxygen} is the mass of oxygen. If the equivalence ratio is $(\varphi = 1)$ its mean there enough amount of oxygen present in the mixture for fuel to completely be combusted. When $\varphi > 1$ there is not enough oxygen to burn all fuel and it is called rich mixture. If $\varphi < 1$ more air is present in the mixture than fuel and is called lean mixture. The gas velocity is calculated by the following equation and it is delivered by mass flow controllers [5].

$$v_g = \frac{R_0 T_u}{PA}(\frac{q_{air}}{M_{air}} + \frac{q_{fuel}}{M_{fuel}}) \text{ ……………………………… Eq. (2.10)}$$

where v_g is the desired unburned mixture velocity, R_0 is the universal constant, T_u is the temperature of unburned gas mixture, M_{air} is the molar mass of air, M_{fuel} is the molar mass of fuel, p is the actual pressure taken from [14], q_{air} and q_{fuel} are the mass flow for air and fuel respectively [5].

2.6 Laminar Burning Velocity

Laminar burning velocity is an important parameter in combustion physics and it contains basic information about reactivity, diffusivity and exothermicity. To determine the adiabatic burning velocity the flame should be flat and in the ideal case, one dimensional. The Heat flux method is used to determine the adiabatic burning velocity of the fuel.

2.7 The counter flow method

The counter flow method which is also called jet method was also used to estimate the burning velocities of fuels. It based on stabilization by conterflowing jets of fuel/oxidizer mixture [1]. In this method there is no interaction with burner, so the flame has no problem with heat loss. As from fig 2.1 the streamlines of the flow are not perpendicular to the flame front. The strain rate can be controlled by adjusting the distance between outlet nozzles [1].

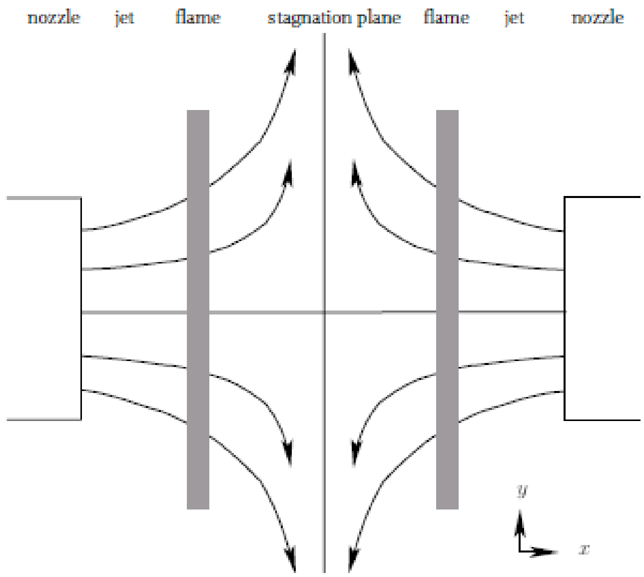

Figure 2.1: The counterflow method for measuring adiabatic burning velocities [1].

2.8 The closed vessel method

The closed vessel method or combustion bomb is also used to find the burning velocities. In this method the chamber is filled with a fuel/oxidizer mixture and ignited in the centre. The flame is not produced in a stationary mode like the conterflow method [1]. By burning the fuel a rotationally symmetric flame will be produced from the centre to the outside. To determine the burning velocities the whole process is recorded with camera and pressure probes and then analyzed [1].

2.9 Bunsen Burner Method

Bunsen burner is a simple apparatus for flame making connected to flammable gas (natural gas or liquefied petroleum gas) and air [18]. The Bunsen burner is used to heat, sterilize and burn. The flame surface area is measured and divided by the amount of consumed mixture per second. To obtain the burning velocity (V_b) the Eq 2.11 can be used

$$V_b = \frac{Input\ volumetric\ flow}{total\ flame\ area} \text{..............................Eq. (2.11)}$$

A few changes are made to modify a slot burner design to Bunsen burner. A pipe with specific diameter and length is oriented vertically directly above the regulator valve to control the flow in proper direction. The flow exists directly at the top of the steel pipe where the laminar flame forms. With this method it's also possible to test the effects of temperature and pressure.

The flow meter values are adjusted for the flame to become stable and flow meter settings show a desired mixture ratio. The several photos taken of the flame will be used to measure the canonical surface area of the Bunsen burner and is used later to calculate the laminar burning velocities [18].

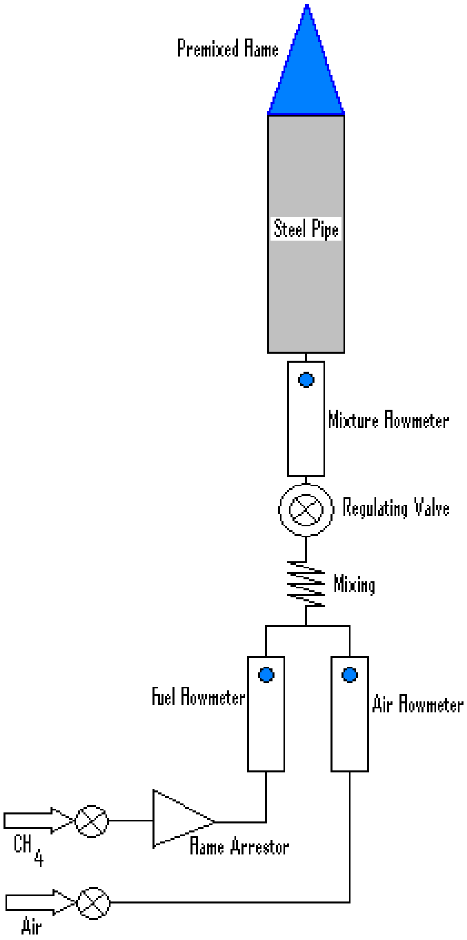

Figure 2.2: schematic picture of typical Bunsen burner [18].

2.8 Heat Flux Method

The heat flux method is the technique to measure the laminar burning velocity mostly used these days. It is based on measuring the temperature profile of the burner plate. The basic principle depends on the heat gained by an unburnt gas mixture from the burner plate equal to heat loss from the flame to the burner plate, which is necessary to stabilize the flame. Zero heat flux is obtained at adiabatic burning velocity condition. The Heat flux method is completely described in chapter 3.

Chapter 3

Heat Flux Method

3.1 Introduction

The heat flux method comes from the porous plug burner of Botha and Spalding [2] which is used to determine the heat loss for stabilizing the flame by measuring the temperature variation of the water used for cooling the burner.

In 1993, Van Maaren [3] gave the idea of perforated plate burner to stabilize the flame by using a thin perforated brass plate. The perforated burner plate with hexagonal was used to ensure that the stabilized flame remains flat. The small thermocouples were attached in different radial position on the burner plate to measure the temperature distribution due to heat loss from the flame to the burner. The heat flux method designed by Van Mareen can be used only to measure the adiabatic flame speed of gaseous fuels.

Meuwissen [4] improved the heat flux setup which possible to use to find the burning speeds of liquid fuels. An evaporator is used to mix liquid with oxidizer.

Later, van Lipzig [5] used an almost identical setup for liquid fuel designed by Meuwissen. The new setup had some improvements constructed and a new Labview program was designed.

3.2 Principal

The heat flux method is used to measure laminar burning velocity in the present project. The heat flux method is based on measuring the temperature profile of the the burner plate. The basic principle depends on the making heat gain by an unburnt gas mixture from the burner plate equal the heat loss from the flame to the burner plate, which is necessary to stabilize the flame and obtaining zero heat flux, defined as adiabatic burning velocity condition.

The adiabatic flame velocity can be found at constant temperature profile across the burner plate. The temperature profile depends on the burner plate temperature readings by thermocouples (T_p) in the axial direction. Because the thickness of the burner plate is very small compared to the plate radius, the temperature distribution depends only on the radius.

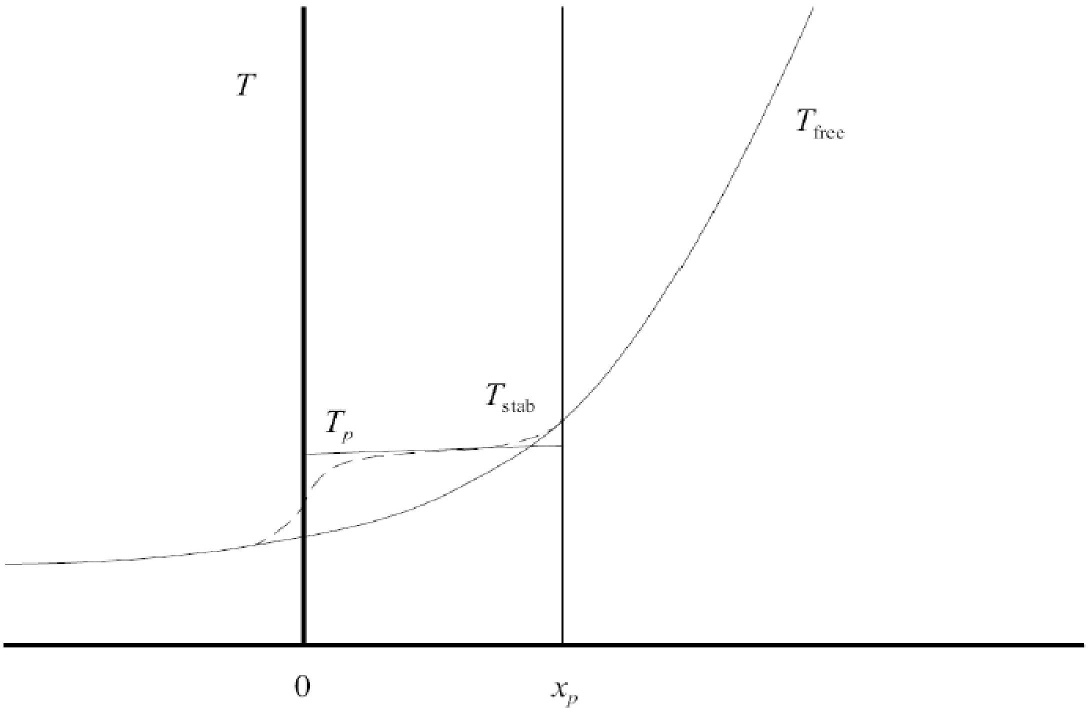

Figure3.1: The radial temperature profile of a free flame (line, T_{free}) compared to the temperature profile of a flame stabilized on the burner plate (dashed,T_{stable}). T_p Indicate the temperature of the burner plate [4].

The radial temperature profile of the burner plate is represented by

$$\overline{T_p} = T_{Centre} + \frac{q}{4\lambda_p h} r^2 \text{...Eq. (3.1)}$$

Where $\overline{T_p}$ is the mean temperature of the burner plate over the burner thickness at radial position. T_{Center} is the thickness averaged temperature of the burner plate at the center ($r = 0$). h is the burner plate thickness and the λ_p is the heat conductivity coefficient of the plate.

Using the temperatures measured by thermocouples, and fitting them to a second order polynomial form, parabolic shape can be obtained.

$$\overline{T_p} = T_{Cenetr} + \alpha^2 r^2 \text{ ....Eq. (3.2)}$$

Where, $\alpha^2 = -\frac{q}{4\lambda_p h}$

The laminar flame speed at adiabatic condition is estimated when experiments done for different unburnt gas velocities for each equivalence ratio and certain temperature. The α^2 will be calculated for each velocity. The α^2 coefficient take a positive value if the gas velocity is higher than the adiabatic burning velocity (S_L) and it will be a negative value if gas velocity smaller then adiabatic burning velocity (S_L) . When α^2 of the fit temperatures equals zero a flat temperature profile is achieved. To find adiabatic burning velocity (S_L), a flat temperature profile with approximately $\alpha^2 = 0$ should be achieved.

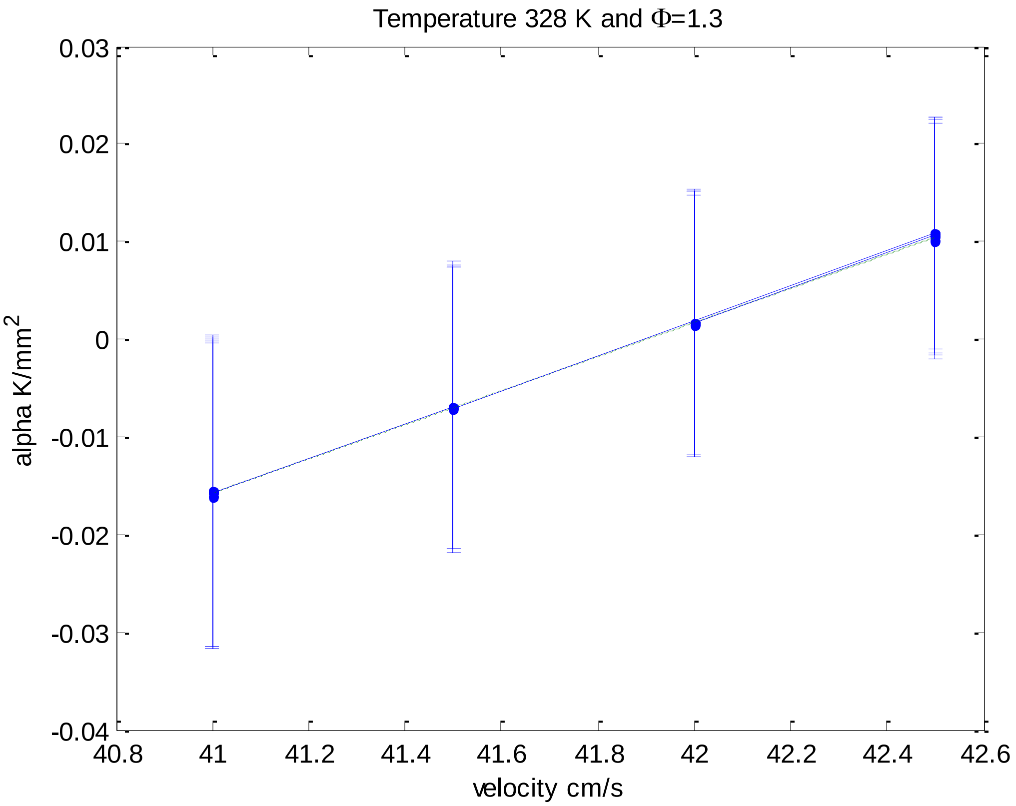

Figure3.2: Parabolic coefficient ethanol at 328 K and φ =1.3

Figure 3.2 shows a linear relation between the velocities of the unburned gas mixture and the parabolic coefficient. The error bars comes from different height of each thermocouple on the burner plate. The variation of thermocouples height creates standard deviation of the temperature gradient of each thermocouple reading. The measured temperature is fitted to a function T(r) =T (0) + αr^2. By applying a linear interpolation of this fit at $\alpha^2 = 0$ the burning velocity can be found. In this example the adiabatic burning velocity of Ethanol is equal to $42\ \mathrm{cm/s}$ at $\varphi = 1.3$ and the temperature of unburned gas mixture is equal to $T = 328\ K$

3.3 Experimental setup

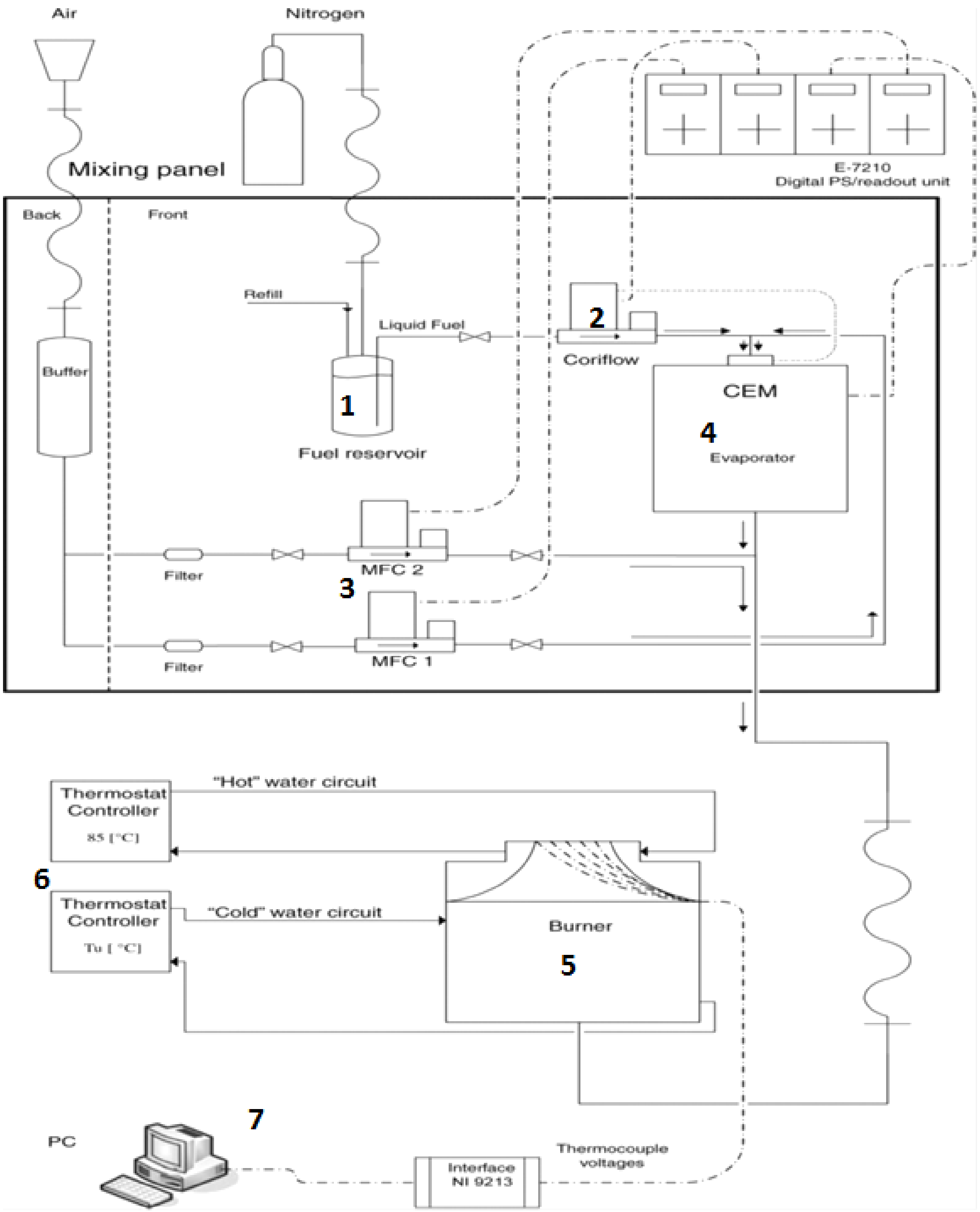

Figure 3.3: Schematic diagram of heat flux setup [11].

There are two types of setup of heat flux method, which are used in present project, heat flux method for liquids fuel and other gaseous fuel. These setups are quite similar but in gaseous setup more MFCs and bigger evaporator is used, which can handle larger flow rate (1200 g/h instead of 200 g/h).

The main parts of the setup are:

1. Fuel Reservoir

The fuel is stored in a fuel reservoir that is pressurized with nitrogen/Ar to imply a flow and protect the fuel from any moisture contamination [5].

2. Mass Flow Controller for fuel, Cori-flow

The flow is measured and controlled by mini CORI-FLOW mass flow meter which operating principal is based on coriolis forces. This Mass Flow Controller is connected to the controlled evaporator mixer.

3. Mass Flow Controllers for air and gases

The air flow is controlled by Mass Flow Controller (MFC). The working principle of these MFCs is based on the measurement of temperature difference of gas flows of two channels inside MFC. A buffering vessel is placed ahead of the MFCs to damp pressure oscillations caused by the compressor. Also, the MFC has reduces the pressure from 3 bar to atmospheric pressure when the air passing through it. The air exiting the buffering vessel is divided into two separate channels. The first MFC provides CEM directly with the required air. The second MFC is connected with the mixture line after the CEM output to provide the air needed to obtain the gas mixture composition. Table 3.1 shows the maximum flow rate of different mass flow controllers used in the present setup.

Table3.1: Different MFC's used in present setup

MFC's	Manufacture	Maximum flow rate
MFC76	Bronkhorst High-tech	15 (L/h)
MFC1c	Bronkhorst High-tech	4 (L/h)
MFC2c	Bronkhorst High-tech	30 (L/h)
MFC75(Cori-flow)	Bronkhorst High-tech	200 (g/h)

4. Controlled Evaporator Mixer (CEM)

To obtained a final gaseous mixture an evaporator is used .The liquid fuel (from Cori-Flow) enter into the Controlled Evaporator Mixer (CEM), and it converts the fuel into small droplets and mixes it with a carrier gas. The heating part of the CEM consists of a spiral which is placed in solid metal block and is externally heated. The mixture is heated up during flows through the high temperature spiral coil. The temperature should be sufficiently high to vaporize all liquid fuel droplets. The maximum temperature of the spiral coil is 483K. Table 3.2 shows the manufactures and maximum flow rate of the evaporators which used in present project.

Table3.2: Different evaporators used in the present project

Heat flux setup	Manufacture	Maximum flow rate(g/h)
Gaseous	Bronkhorst High-tech	1200
Liquid	Bronkhorst High-tech	120

5. Burner

This is the main part of the heat flux method and its goal is to determine the burning velocities of the fuel. The heat flux burner consists of a plenum chamber, a burner head and a burner plate with thermocouples attached.

The lower part of the plenum chamber is composed by a grid. The mixture of fuel and air enters from below through the plenum chamber where the velocity decreases. The combination of plenum chamber, its inner grid and orifice aims to stablize the flame and to carry thermocouples. The flow can be assumed to be uniform in the center of the burner head, approaching the edges however large deviations can occur. These are mainly created by flow divergence and mixing with the ambient air. Van Maaren [3], using Laser Doppler Velocimetry (LDV), found that a burner plate of 30 mm was able to generate a one-dimensional area of 20 mm. It is in this region that the flame can be assumed to be flat and the temperature distribution measured. The boundary layer effects can be minimized by reducing the heat transfer from the burner head to the unburned gas [4].

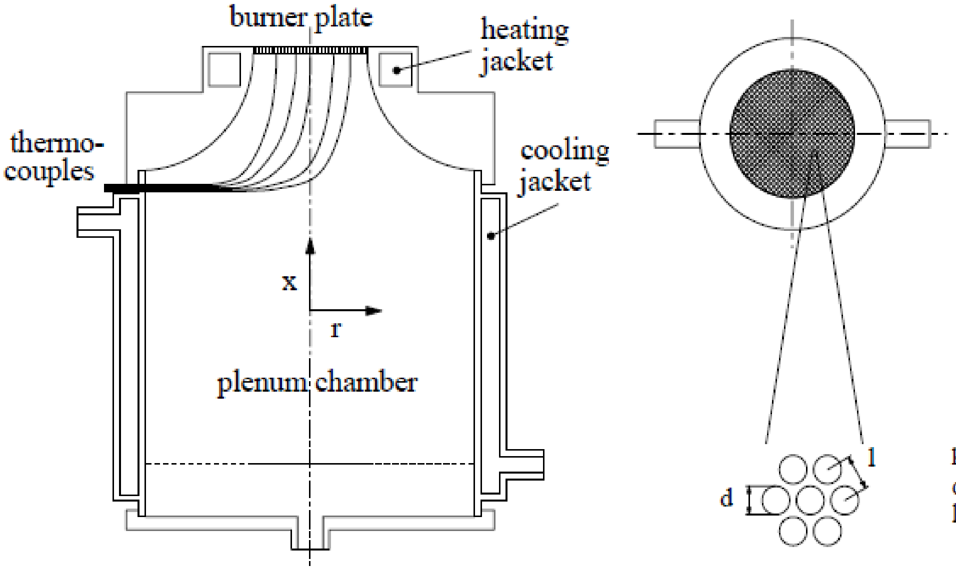

Figure 3.4: Schematic representation of the burner. Left, the perforated plate burner. Right, top view of the burner showing the perforated pattern of the burner plate [4].

5.1 Thermocouples

Thermocouples are used to measure the temperature profiles across the burner. The type of these thermocouples is T (copper-constantan) with a diameter of 0.1 mm. These are attached in a particular way across the burner. Each thermocouple is connected to the burner plate inside the small cylinder that is placed in a burner plate hole as shown in Fig 3.4. The small cylinder is made of brass and has the same diameter of a burner plate hole. This cylinder contains holes of the size of a thermocouple wire and each thermocouple can be placed in the burner plate at a nearly equal height.

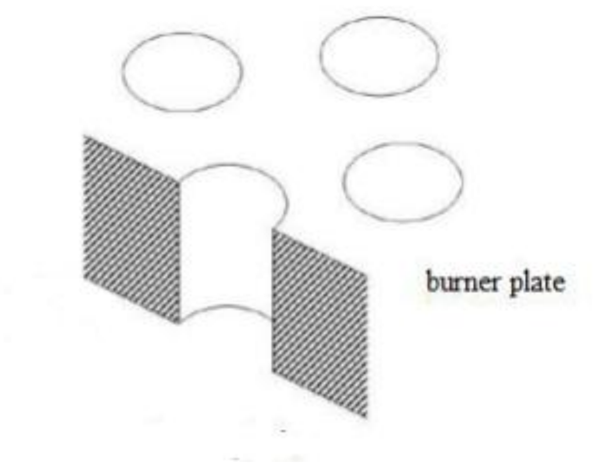

Figure 3.5: cross-section view of a burner plate hole [4].

6. Water baths

To keep the temperature difference between burner head and burner chamber, thermostat baths are used. Two thermostats baths are used to keep the required temperature of the jackets. One water bath keeping the burner plate hot at typically 85 C^0 or 95 C^0. The other water bath keeps the temperature of the plenum equal to the unburnt gas mixture temperature, so the temperature of thermostat bath change when higher temperature are to be measured.

7. Data acquisition unit

This is the last part of the setup. All the parameters which are related to calculate the burning velocities can be set manually in Labview program. Labview program is used to control the MFC'S flow and flow calculations are carried out.

3.4 Partial pressure limitations

For estimation of the adiabatic burning velocity of liquid fuels, control evaporator mixer (CEM) is used to convert liquid fuels to gas phase and mix it with gas carrier (air). Heat flux method faces some problems (especially when the unburned mixture is cooled down to room temperature) concerning mixture with high partial pressure of the fuels, high equivalence ratio and high molecular mass of the fuels. To resolve these problems maximum equivalence ratio of a mixture using partial pressure of fuel is calculated at room temperature. The fuel line and burner chamber operate at room temperature to get reliable results.

Partial pressure (p_{fuel}) of fuel is obtained from material safety data sheet for each fuel and mole fraction of the fuel can be calculated by using the following equation:

$$Mol\ fraction_{fuel} = \frac{p_{fuel}}{p_{mixture}} \text{ .... Eq. (3.3)}$$

The partial pressure limitation for mixtures in ϕ is calculated by

$$Mol\ fraction_{fuelmix} = \frac{p_{fuel1} * fraction_{fuel1} + p_{fuel2} * fraction_{fuel2}}{p_{mixture}} \text{...................Eq. (3.4)}$$

p_{fuel} is the partial pressure of the fuel, $p_{mixture}$ is 1 atm (760 mmHg) because we work at atmospheric pressure.

The limit in ϕ is calculated by

$$\Phi = \left(\frac{n_{O_2}}{n_{fuel}}\right)_{stochiometric} * \frac{Molfraction_{fuel}}{Molfraction_{O_2} * (1 - Molfraction_{fuel})} \text{ .... Eq. (3.5)}$$

$$\text{For 100\% nitromethane } \left(\frac{n_{O_2}}{n_{fuel}}\right)_{stochiometric} = 1{,}5/2 \text{.........................Eq. (3.6)}$$

$$\text{For 100\% ethanol } \left(\frac{n_{O_2}}{n_{fuel}}\right)_{stochiometric} = 3/1 \text{ .... Eq. (3.7)}$$

Table3.3: Partial pressure limitation for nitomethane, mixture of ethanol-nitromethane and ethanol at 20% and 35% of oxygen.

Nitromethane in ethanol [%]	T [°C]	Mol fraction Fuel	Limiting φ in air 20% O_2	Limiting φ in 35 mol% O_2
100	20	0.03	0.14	0.07
100	40	0.10	0.41	0.19
100	46.6	0.13	0.57	0.24
100	50	0.14	0.63	0.27
100	55	0.17	0.77	0.30
100	60	0.23	1.15	0.38
100	65	0.29	1.46	0.43
100	70	0.34	1.92	0.48
100	75	0.41	2.57	0.52
100	80	0.49	3.54	0.54
100	85	0.58	5.10	0.52
0	20	0.06	0.82	0.47

0	40	0.18	2.19	1.25
0	46.6	0.25	2.78	1.59
0	50	0.29	3.09	1.78
0	55	0.37	3.49	1.99
0	60	0.46	3.73	2.13
0	65	0.58	3.66	2.09
0	70	0.71	3.07	1.75
0	75	0.88	1.64	0.94
0	80	1.07	-1.07	-0.61
0	85	1.29	-5.69	-3.25

3.5 Error sources

In this part of the report the main sources of uncertainties in the heat flux method to determine laminar burning velocity are discussed. The uncertainties to estimate burning velocity can be due to flowing major reasons:

1. Thermocouples

   The different height of each thermocouple on the burner plate provides uncertainty of the flame speed. The variation of thermocouple height creates standard deviation of the temperature gradient of each thermocouple reading. The standard deviaton from the thermocouples by a least square fit on the spread of the temperature distribution. This error is calculated from the mean value of the standard deviation of the α coefficient in Eq.3.8 from each of the measured points and divide this with sensitivity derived from the α verses velocity interpolation.

   $T_p (r) = T_c + \alpha r^2$……………………………….Eq. (3.8)

   This is the error in the burning velocity due to thermocouple scatter. The total error in the burning velocity can be calculated by adding uncertainties due to thermocouples and MFCs flow uncertainties by using the relation Eq. 3.9

   $SL=\text{sqrt}(\Delta SL^2+\text{Error}_\alpha^2)*100$……………………… Eq. (3.9)

   Where ΔSL is the error due to MFC flow, Error_α is the error due to the thermocouple scattering and can be calculated using Eq 3.10 and 3.11

   $\Delta SL=\text{sqrt}(\Delta SL_{qori} + \Delta SL_{Air} + \Delta SL_{piston})/\text{area}$……………Eq. (3.10)

   $\text{Error}_{alpha}=(\text{std}(\text{alpha})/\text{sensitivity})/100$……………….Eq. (3.11)

2. Mass flow controller

   The accuracy of flow is directly related to flame speed. The uncertainty of the mass flow is a type of error burning velocity.

Table 3.4: Uncertainties of mass flow controllers

MFC1	Air	0.8% deviation of actual setpoint, including 0.2% deviation of max. flow
MFC2	Air	0.8% deviation of actual setpoint, including 0.2% deviation of max. flow
Cori-Flow	Liquid fuel	0.2 deviation of actual setpoint

It is recommended to be calibrate all MFCs before starting the experiments to obtain desired uncertainty estimated by manufacturer. The total equivalence ratio by combining air flow and fuel flow can be described by:

$$\Delta\varphi = \varphi\sqrt{(\frac{\Delta q_{MFC1+2}}{q_{MFC1+2}})^2 + (\frac{\Delta q_{Cori-Flow}}{q_{Cori-Flow}})^2} \quad \text{.......................................Eq. (3.12)}$$

3. Fuel purity

   Pressurized nitrogen is used to protect the ethanol from the surrounding air. To investigate the influence of nitrogen solubility, Meuwissen [4] did an experiment of burning ethanol. The conclusion was found nitrogen has no effect on burning velocity calculations.

4. Flame structure

   Flame structure also related to the burning velocity and depends on equivalence ratio, fuel and gas velocity. To estimate the laminar burner velocity flame should be flat so during experiments it is very important to take care of structure of flame. More detail about this can be found Van Lipzig thesis [5].

5. Preparation of solution

   To calculate the burning velocities of mixture of fuels, it is important to prepare the solution with accurate percentage of liquid.

6. Controlled evaporator mixer

   The controlled evaporator mixer can also affect the flame speed. The uncertainty depends on operating temperature of controlled evaporator mixer and it can affect the flame speed by ±0.05 cm/s. More detail about this effect can be find on Meuwissen [4].

Chapter 4

Calibration

4.1 Introduction and goal

As in heat flux method MFCs plays an important role for the accurate flow of air and gases, so to check the maximum accuracy of mass controllers it is recommended to calibrate them before starting the experiments. In this chapter is discussed the calibration for the mass controllers of liquid heat flux setup and for the mass controller employed in gaseous setup. Different types of apparatus can be used to calibrate MFCs like piston meter, rotor meter and compressed air. Here a piston meter and a computer program are used to operate air flow rate.

The calibration aim is to compare and verify the mass flow rate shown by the MFCs with certified real Mass flow rate. The flow rate accuracy of MFC`s are directly related to the mixture composition, equivalence ratio and flow velocity. All these factors affect the adiabatic burning velocity of the fuel.

MFC calibrations are also important to find the polynomial coefficients of the flow equations to set the corresponding and desired flow.

4.2 Experimental set up

4.2.1 Piston meter

The piston meter consists of a measuring cell, two junctions (suction fitting, pressure fitting) and display. The measuring cell, in turn, consists of a straight cylinder and piston. These two junctions are connected with two flow fluid pipes. The pressure fitting junction is connected with the inlet pipe while the suction fitting is connected with outlet pipe. Due to pressure in the cylinder, the piston will rise and gives a pressure reading [12].

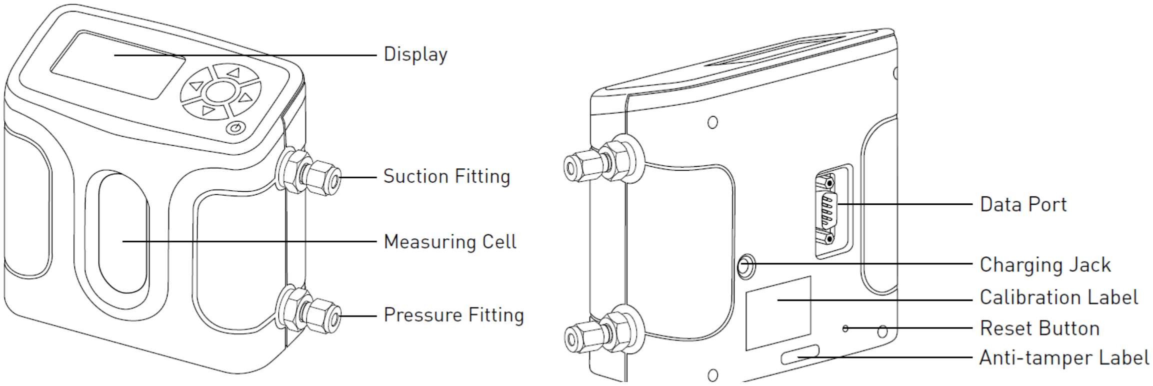

Figure 4.1: Schematic diagram of pistonmeter [12].

4.3 Procedure

- Flow view program(international instruments) is used to control the flow rate of MFCs
- Press the button on/off for 1 sec to turn on piston meter.
- Connect the tubing to outlet at top (suction fitting as shown in fig 4.1) when device draws air.
- Connect tubing to bottom inlet (pressure fitting) to push air in (pressure devices).
- Now on display select the reading type to Vol or Std.
- Chose the measurement type ''continuous'' and press enter.
- For each MFCs take the reading randomly (set point % for air/gas) from 10 to 100 as difference with 10 with each measurement.
- After press the ''continues'' on piston meter display, wait to complete adjusted measurement count.
- To terminate the current flow measurement but leave the average flow measurement press PAUSE.
- To terminate the flow and clear screen press RESET [12].

4.4 Results

Calibrations are carried at temperature 20 ^{0}C and standard atmospheric pressure; these conditions are defined normal conditions. The table 4.1 and 4.2 shows the measured piston meter reading against set flow of air.

Table 4.1: Measured data for calibration of MFC76 with air

Set point %	Litre/min(set point)	g/min	Average(Litre/min)
10	1.5	1.94	1.4160
20	3	3.88	2.9376
30	4.5	5.82	4.4492
40	6	7.76	5.9952
50	7.5	9.70	7.5103
60	9	11.64	9.0006
70	10.5	13.58	10.409
80	12	15.52	11.838
90	13.5	17.46	13.736
100	15	19.40	14.853

Table 4.2: Measured data for calibration of MFC1c with air

Set point %	Litre/min	Average(Litre/min)
10	0.40	0.5139
20	0.80	1.0284
30	1.20	1.5369
40	1.60	2.0548
50	2.00	2.5707
60	2.40	3.0847
70	2.80	3.6005
80	3.20	4.1081
90	3.60	4.6239
100	4.00	5.1255

Figures 4.2 and 4.3 below show the experimental points and polynomial fit between the set points of flow (MFCs) and measured points (pistonmeter). The linearity line shows that the polynomial fit is well with experimental data and set flow perfectly corresponding with measured flow.

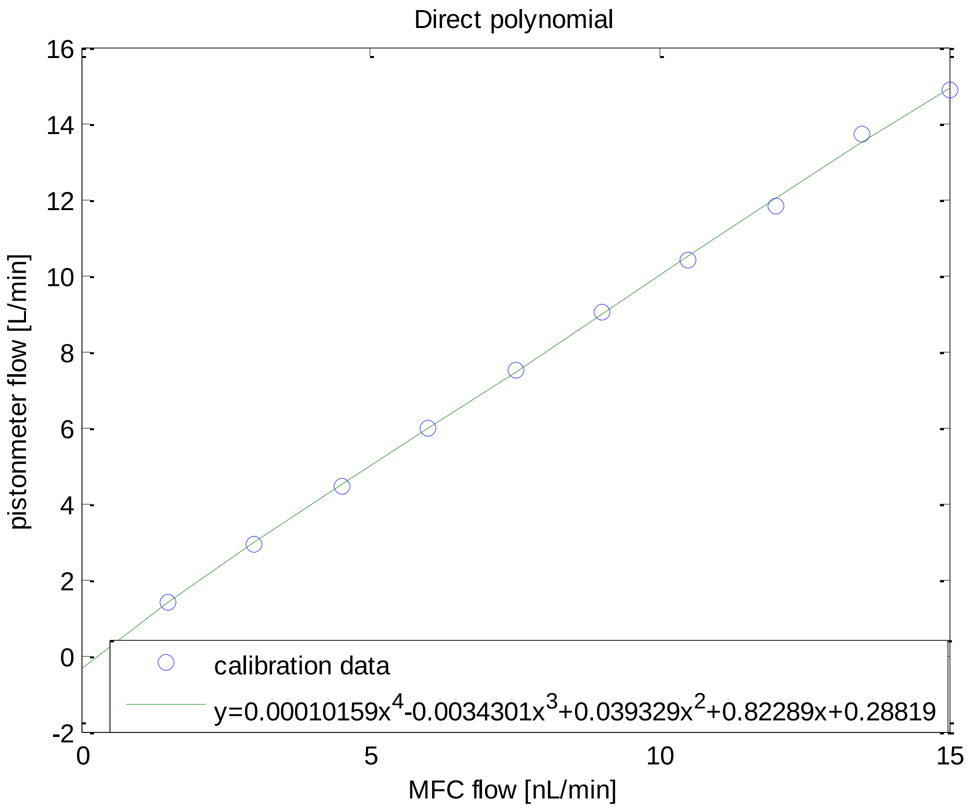

Figure 4.2: Air- MFC76 polynomial fit between the pistonmeter flow (*y*-axis) and set point flow (MFC) (*x*-axis)

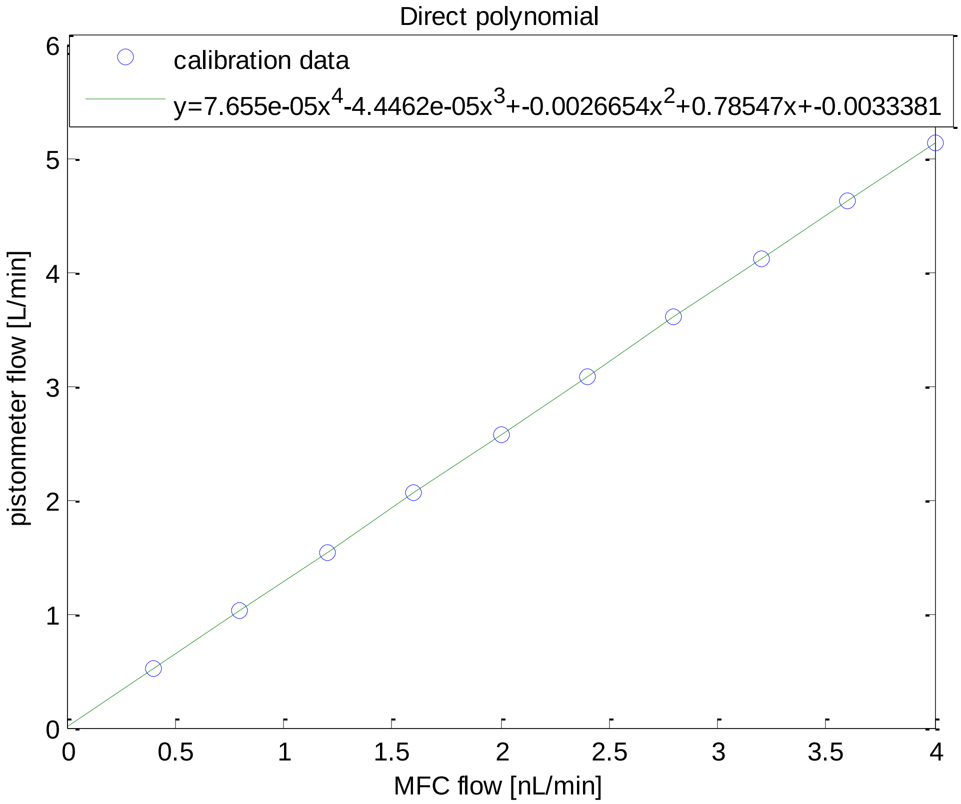

Figure 4.3: Air- MFC1c polynomial fit between the pistonmeter flow (*y*-axis) and set point flow (MFC) (*x*-axis)

To calculate the polynomial coefficient, a fourth order polynomial is used to fit these points. The polynomial equation obtained is reported below (Eq.4.1)

$\Phi_{set} = a_1\Phi_{measured}^4 + a_2\Phi_{measured}^3 + a_3\Phi_{measured}^2 + a_4\Phi_{measured} + a_5$ …….. Eq4.1[2]

where Φ_{set} is the set flow, $\Phi_{measured}$ is the measured flow and the coefficients from a_1 to a_5 are the calibration coefficients used and filled in the specialized program to obtain certain flow

The list of polynomial coefficients is given in table 4.3. Each MFC represents the direct and inverse coefficient of the pistonmeter. The fourth degree polynomial is used to fit these experimental data.

Table 4.3: List of direct and conversion polynomial coefficients for fourth polynomial fit

MFC	Date	Gas	X^4	X^3	X^2	X	C
MFC 76 dir(piston)	2013-03-20	Air	0.0000	-0.0000	0.0000	1.2933	0.0000
MFC76 Inv(piston)	2013-03-20	Air	-0.0000	0.0000	-0.0000	0.7732	-0.0000
MFC 1c dir(piston)	2013-03-20	Air	-0.0002	-0.0000	0.0060	1.2727	0.0044
MFC 1c inv(piston)	202013-03-20	Air	0.0001	-0.0000	-0.0027	0.7855	-0.0033
MFC76 dir(piston)	2013-03-25	Co_2	0.0000	-0.0000	0.0000	1.2933	0.0000
MFC76 inv(piston)	2013-03-25	Co_2	-0.0000	0.0000	-0.0000	0.7732	-0.0000
MFC1c dir(piston)	2013-03-25	O_2	0.0016	-0.0138	0.0407	1.2439	0.0238
MFC1c inv(piston)	2013-03-25	O_2	-0.0004	0.0049	-0.0187	0.8028	-0.0185
MFC2c dir(piston)	2013-04-01	Co_2	0.0000	-0.0002	0.0039	0.9865	0.0769
MFC2c inv(piston)	2013-04-01	Co_2	-0.0000	0.0002	-0.0037	1.0128	-0.0756

Chapter 5

Results and Discussion

In this section of report the results of experiments with ethanol, nitromethane, and mixture of ethanol and nitromethane are discussed. First the laminar burning velocity of ethanol/air is determined from 298 K to 358 K. After calculating the burning velocity of pure ethanol, the mixture of ethanol and nitromethane are created and the estimation of the laminar burning velocity is carried out in a range temperature comprised between 338 K and 358 K. At last the adiabatic velocity of nitromethane/air is calculated in a range of 338 K-358 K. The thermo bath of the burner plate is kept constant at 95 ^{0}C during all experiments. Both setups for heat flux method available in lab are used during the experiments.

5.1 Laminar burning velocity of ethanol/air at different temperatures from 298 K to 358 K

Adiabatic burning velocity of ethanol/air is determined using the heat flux method at different temperatures as function of the equivalence ratio. In this section all the results of pure ethanol are presented and compared with literature.

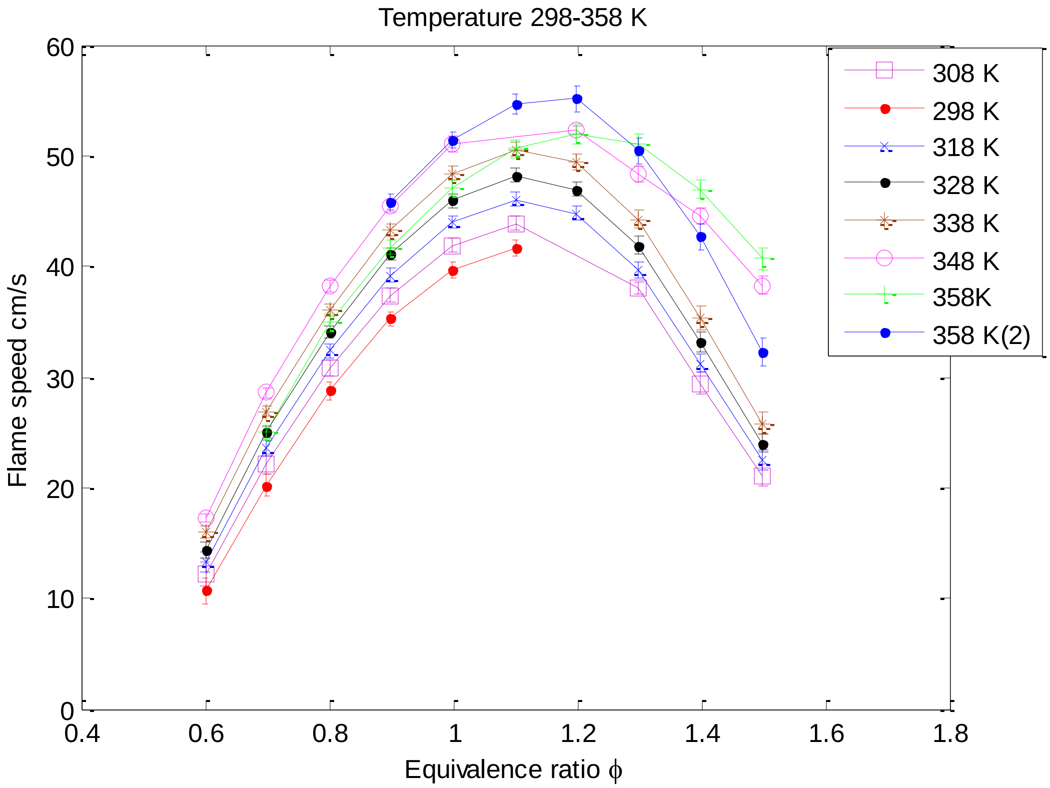

Figure 5.1: Adiabatic burning velocity of ethanol/air at 298 K-358 K

Fig 5.1 shows adiabatic velocities of ethanol/air at different temperatures. Different colours with symbols represent the different temperatures. As expected, increase of temperature corresponds to a flame speed growth. Furthermore, from the graph above it is possible to note that the curvatures are similar for different temperatures.

There are two measurements for temperature 358 K presented in this figure. The green plus signs represent the measurements taken on the same day with others temperatures and it shows some strange behavior as compared to other temperatures. It can be due to the fact that day on that day the program stopped many times and may be these measurements are taken with different calibration file. The other measurements show with blue dots are taken another day and show a good agreement between all measurements at different temperatures.

The maximum burning velocity is found at $\varphi = 1.1$ and temperature 298 K-338 K. For higher temperatures (348 K-358 K), the maximum burning velocity is found at $\varphi = 1.2$.

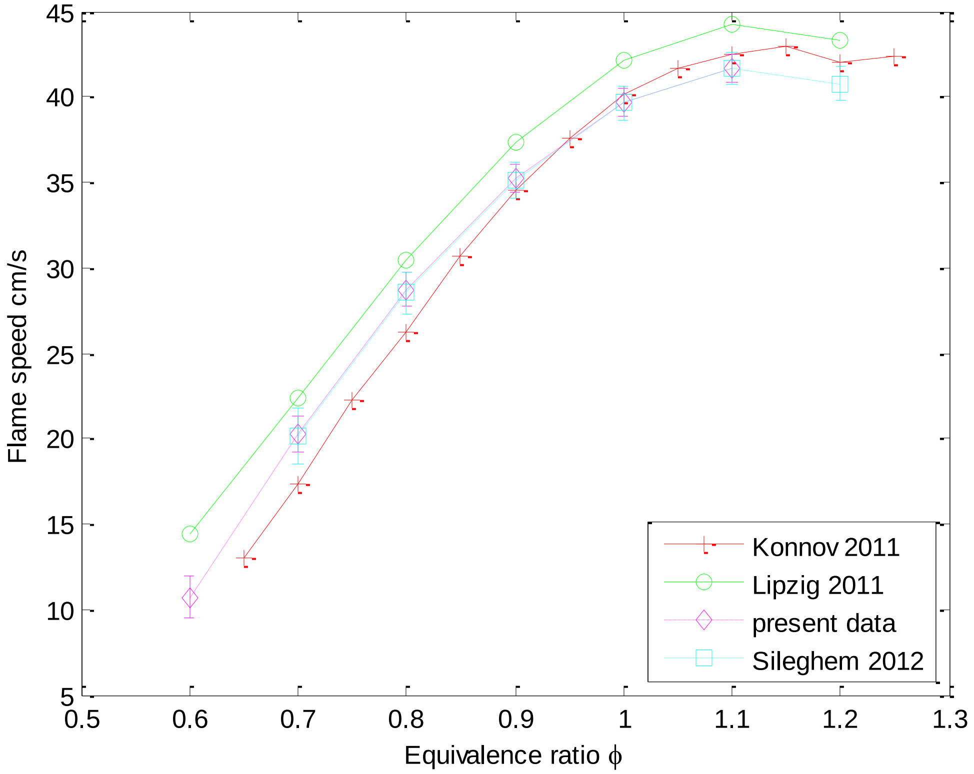

Figure 5.2: Adiabatic burning velocity ethanol at 298 K

In Fig 5.2 the results of the adiabatic burning velocity for ethanol is given and compared to some available literature data. The current work is represented with pink dashed line.

If this result is compared to the available literature data we can see it is similar to Sileghem et al. [21] result from equivalence ratio 0.7-1.1. It also can be seen that it also fits with the Konnov et al. [13] work from equivalence ratio 0.9-1.1. At last comparing our result with the Lipzig [5] result, it is evident that the result is lower but similar in shape.

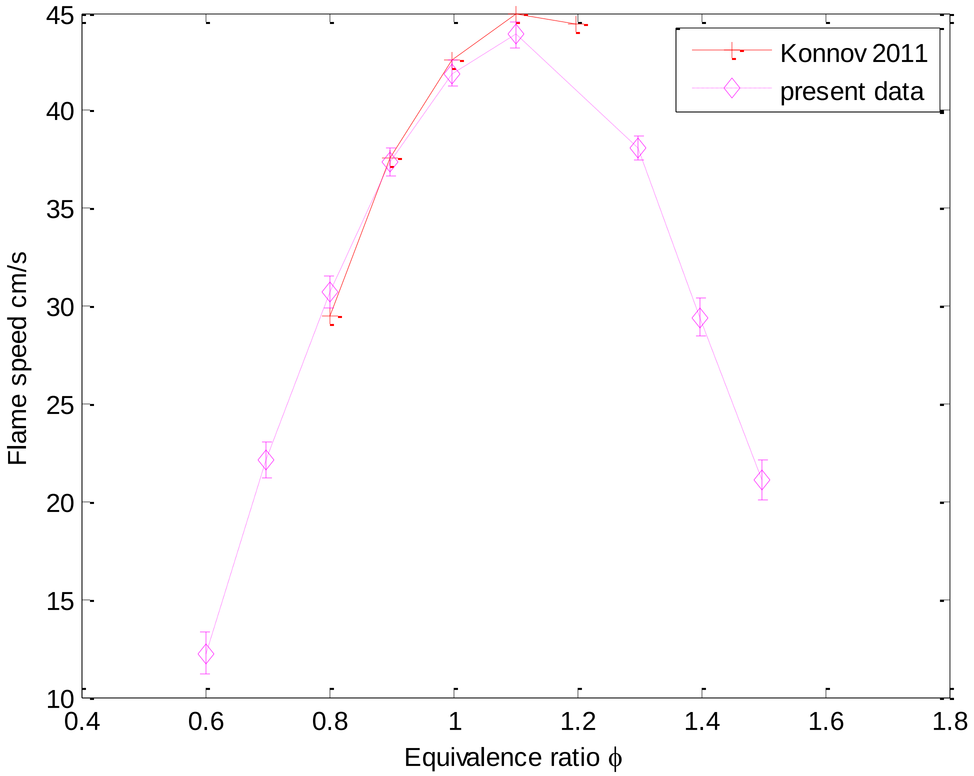

Figure 5.3: Adiabatic burning velocity of ethanol at 308 K

Fig 5.3 shows the results of ethanol at temperature 308 K and $\varphi = 0.6 - 1.5$. This results is compared with Konnov result and it shows good agreements in the lean region and the maximum burning velocities are found for both at φ =1.1. The Konnov et al. [13] result is a little higher at higher equivalence ratio.

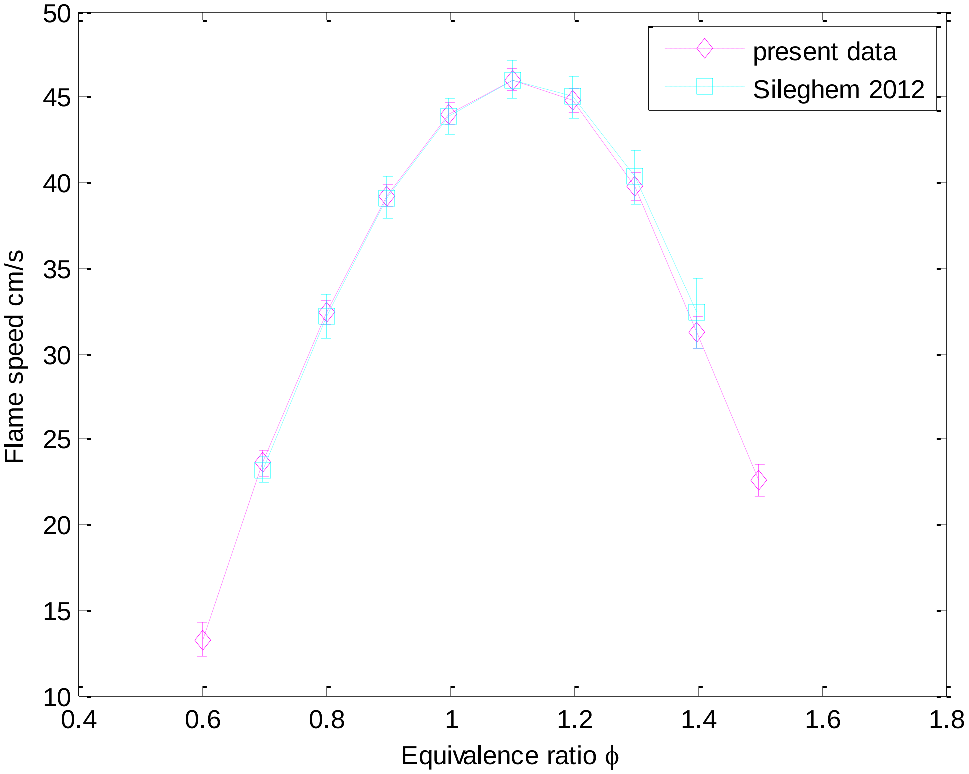

Fig 5.4: Adiabatic burning velocity of ethanol at 318 K

In fig 5.4 the result of estimation for ethanol at 318 K is given and compared with Sileghem et al. [21] experimental data for ethanol. The result gives a very good resemblance in the lean region as compared to the rich region where it has little big errors. The maximum velocities are found at $\varphi = 1.1$ for both results.

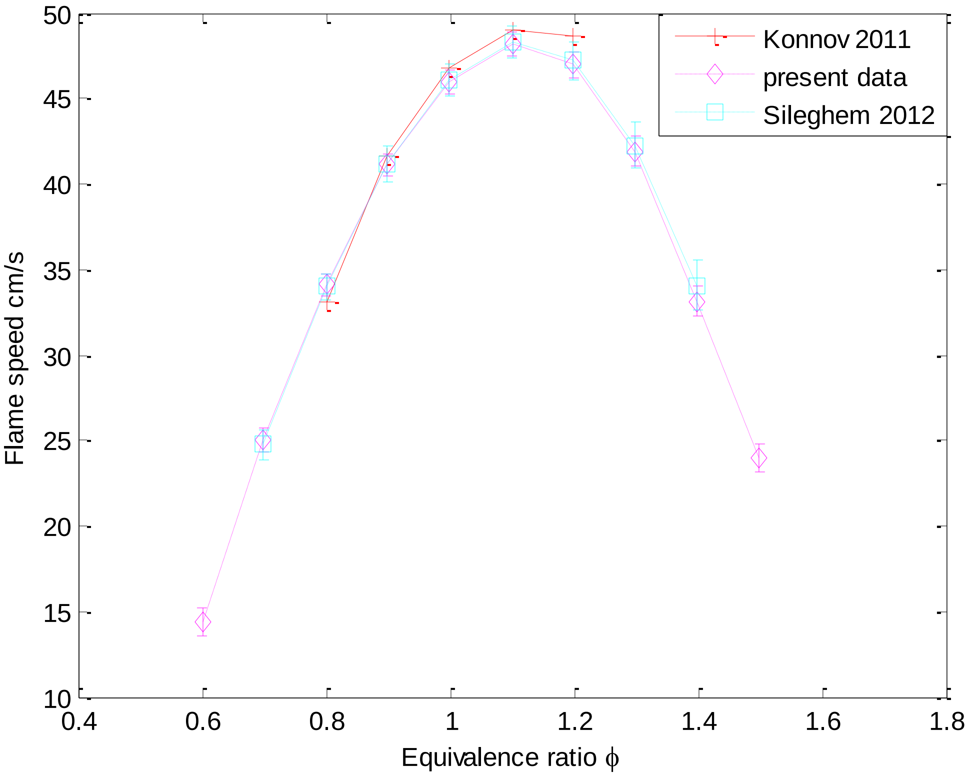

Figure 5.5: Adiabatic burning velocity of ethanol at 328 K

Fig 5.5 shows the result for ethanol at 328 K with equivalence ratio from 0.7 to 1.5.

The result is compared with the available data of Konnov et al. [13] and Sileghem et al. [21] and it possible to see that they show the same behavior of the curve. The present result is similar to the Sileghem et al. [21] result in lean and the rich region but is lower than the Konnov et al. [13] in the rich region.

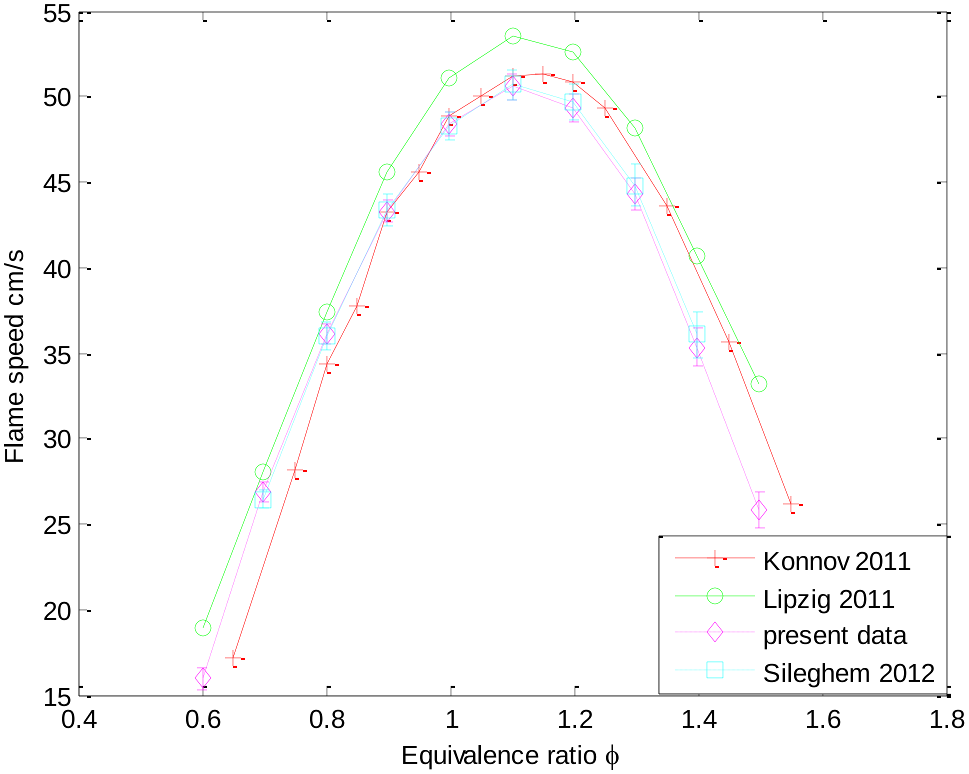

Figure 5.6: Adiabatic burning velocity of ethanol at 338 K

Fig 5.6 shows the experimentally determined flame speed of ethanol at 338 K and the result is compared with the previous available literature data at the same temperature. There is a satisfactory agreement between present data and Sileghem et al. [21] data. Present results are lower than Van Lipzig [5] experimental data. Present results fit with Konnov et al. [13] results at equivalence ration 1 and 1.1 but these results are above the Konnov results for $\varphi < 0.9$ and below from $\varphi = 1.2$.

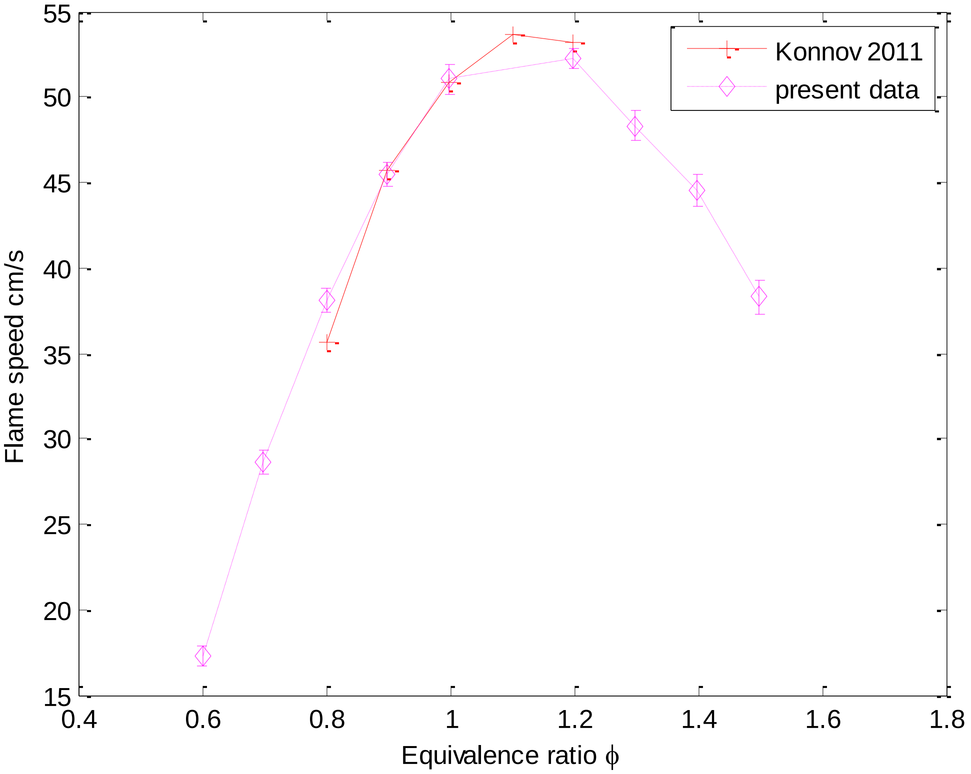

Figure 5.7: Adiabatic burning velocity of ethanol at 348 K

Fig 5.7 shows the experimental estimation of adiabatic burning velocity of ethanol using heat flux method at 348 K. The present experimental work is done from equivalence ratios from 0.6 to 1.5. The estimated burning velocities are compared with Konnov et al. [13] results. From fig 5.7 we can see the present results are fit with Konnov et al. [13] results at equivalence ratio 0.9 and 1.

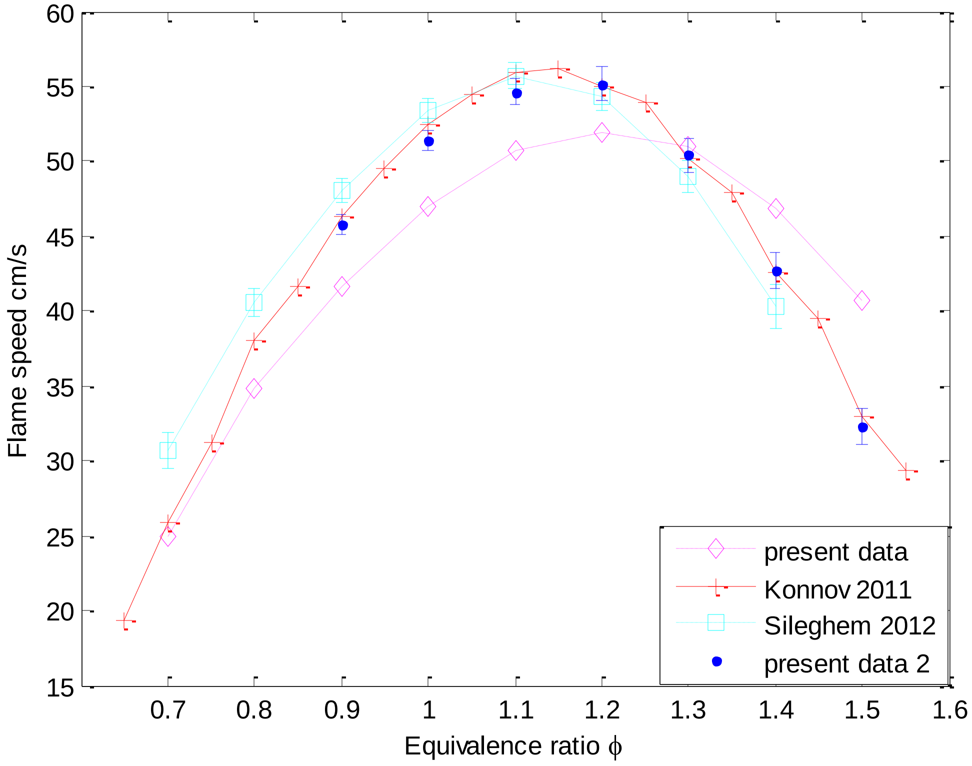

Figure 5.8: Adiabatic burning velocity of ethanol at 358 K

Fig 5.8 shows the adiabatic burning velocity estimation of ethanol at 358 K. Present results are represents with pink dashes line. The results are compared with the available literature data at 358 K. The curve show strange shape as compare to previous date.

There are two results for present data at that temperature which are also described in Fig 5.1. The results with pink dashed line represent the measurements which are taken in the same day with others temperatures. The results are not good and not have good agreement with previous data. The results with blue dots are the measurements which are taken another day which shows good agreement with Konnov et al. [13] data.

5.2 Laminar burning velocity of mixture of ethanol and nitromethane at different temperatures from 338 K to 358 K

To estimate the adiabatic burning velocity of ethanol and nitromethane mixture, at 50-50% volume mixture was prepared. Using the heat flux method at different temperatures as function of equivalence ratio, burning velocities are estimated from 338 K to 358 K. In this section all the results of nitromethane-ethanol mixture are presented.

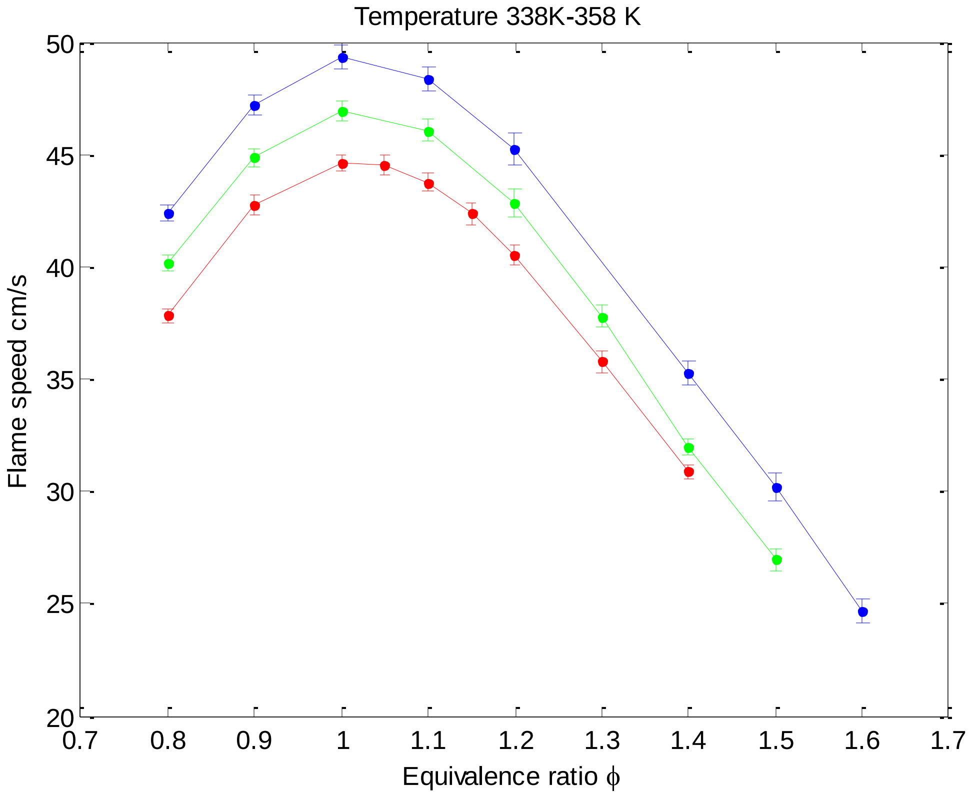

Figure 5.9: Adiabatic burning velocity mixture of ethanol and nitromethane at 338-348 K

In Fig 5.9 the results of the adiabatic burning velocity estimation for the ethanol/nitromethane mixture are presented. Ethanol and nitromethane are mixed to prepare a mixture with a percentage of 50 % volume of each.

After taking the measurements, it was observed that the equivalence ratio used in the program was wrong. There was a problem with the program to calculate the proper equivalence ratio. Using these measurements of flow from MFCs, equivalence ratio was calculated manually by the Eq. 5.1

$$\Phi = \left(\frac{n_{O_2}}{n_{fuel}}\right)_{stochiometric} * \left(\frac{Molfraction_{fuel}}{Molfraction_{O_2}}\right) \text{.........................Eq. (5.1)}$$

Table 5.1 show the manually calculated equivalence ratio of nitromethane+ethanol mixture at 338 K

Table 5.1: Manually calculated equivalence ratio for nitromethane+ethanol mixture at 338K

Equivalence ratio(φ)	Manually calculated Equivalence ratio(φ)	Laminar burning velocity (SL)
0.8	0.66	37.80
0.9	0.74	42.72
1	0.82	44.61
1.1	0.90	43.74
1.2	0.98	40.51
1.3	1.07	35.77
1.4	1.14	30.87

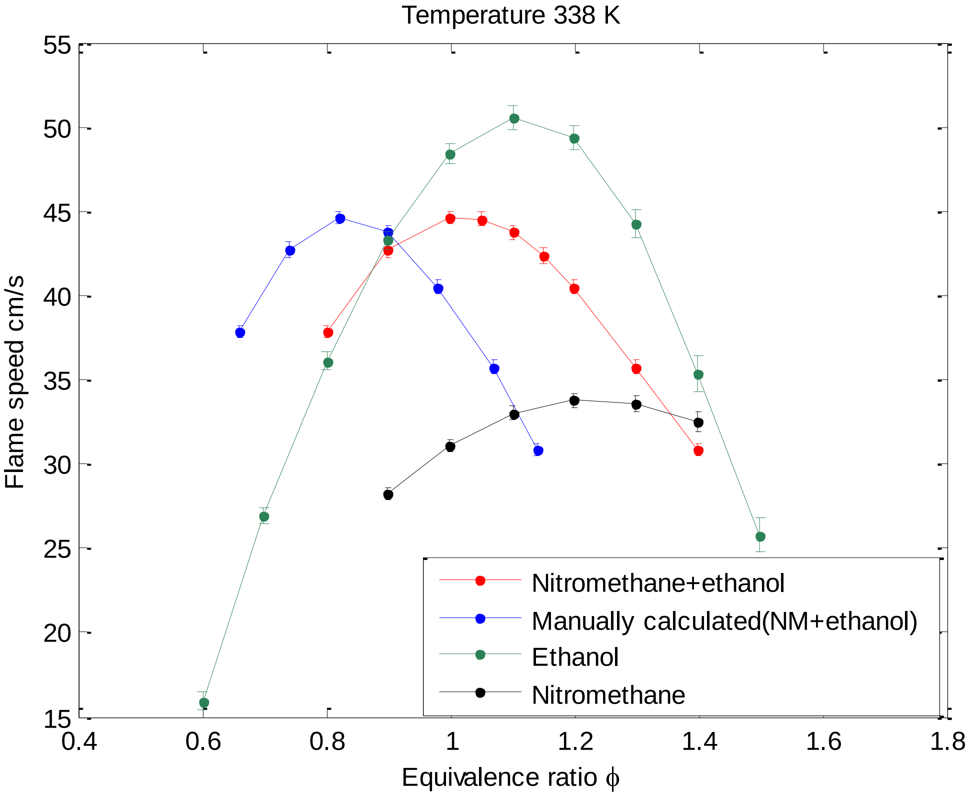

Fig 5.10: compression of burning velocity of nitromethane+ethanol mixture at 338 K

Fig 5.10 show the burning velocity of nitromethane+ethanol mixture at 338 K. The result compared with manually calculated result of the mixture,ethanol and nitromethane results at 338 K. It can be seen from the Fig 5.10 the manually calculated equivalence ratio does not give satisfactory results.

From figure 5.9 it can be seen that shape of the curves for all temperatures are similar. The maximum velocity for all temperatures is found at $\varphi = 1$ which is not the correct equivalence ratio. With an increase in temperatures the velocity also increases. When these results were plotted with nitromethane and ethanol results, a strange curve behavior is evident in Fig 5.10.

The results were shifted in the maximum equivalence ratio. It could have been a problem with separation of nitromethane and ethanol components.

5.3 Laminar burning velocity of nitromethane/air at different temperatures from 338 K to 358 K

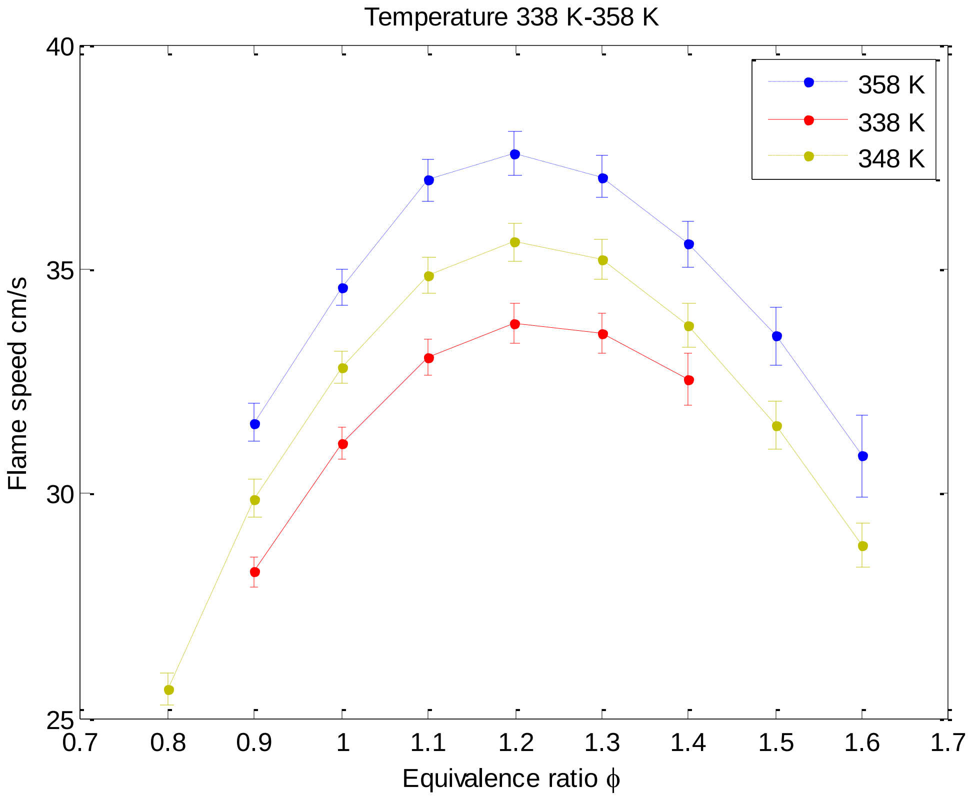

Figure 5.11: Adiabatic burning velocity of nitromethane at 338-358 K

Fig 5.11 shows the flame speed of nitromethane/air experimentally determined from 338-358 K. The maximum burning velocity was found at equivalence ratio 1.2. The velocities increase from 0.8-1.2 equivalence ratio and then decrease from φ =1.3-1.6. The curves shows a similar shape at all temperatures. From Figure 5.10 can be seen that with increase in temperature the burning velocities also increase. The measurements at temperature 358 K are taken twice and it was found the same result, which shows that results have good accuracy. As we have no old literature data about burning velocities of nitromethane we can compare these results with ethanol results of the present study.

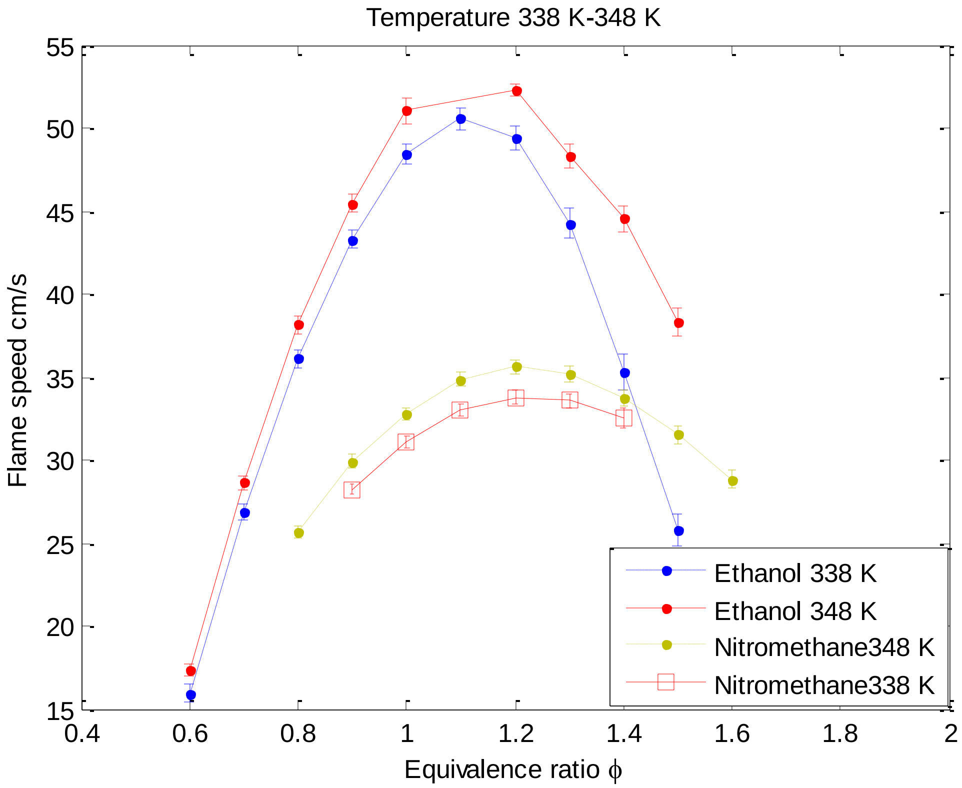

Figure 5.12: Adiabatic burning velocity of ethanol and nitromethane at 338-348 K

In Figure 5.12 the burning velocities of nitromethane and ethanol at 338-348 K are presented. The burning velocities for nitromethane are found less than there for ethanol. At temperature 348 K, the maximum burning velocities are found at $\varphi = 1.2$. The maximum velocity for ethanol is about 52 cm/s and for nitromethane is about 38 cm/s at 348 K.

5.4 Temperature correlation with laminar velocity

The adiabatic burning velocity depends on the unburnt gas mixture temperature and pressure of ethanol/air flame. The temperature dependence is calculated for several equivalence ratios in the temperature range between 298 K and 358 K, these temperature ranges is restricted to the limited values by the heat flux design. The water bath is used in the setup. The temperature dependence of ethanol/air flames was investigated by using the Eq. 2.4

The measured laminar speed of ethanol/air flames at atmospheric pressure and different tempratures from 298K up to 358K for several equivalence ratios are shown in Fig 5.11. The linear relation between burning velocity and temperature on a log-log scale is obtained.

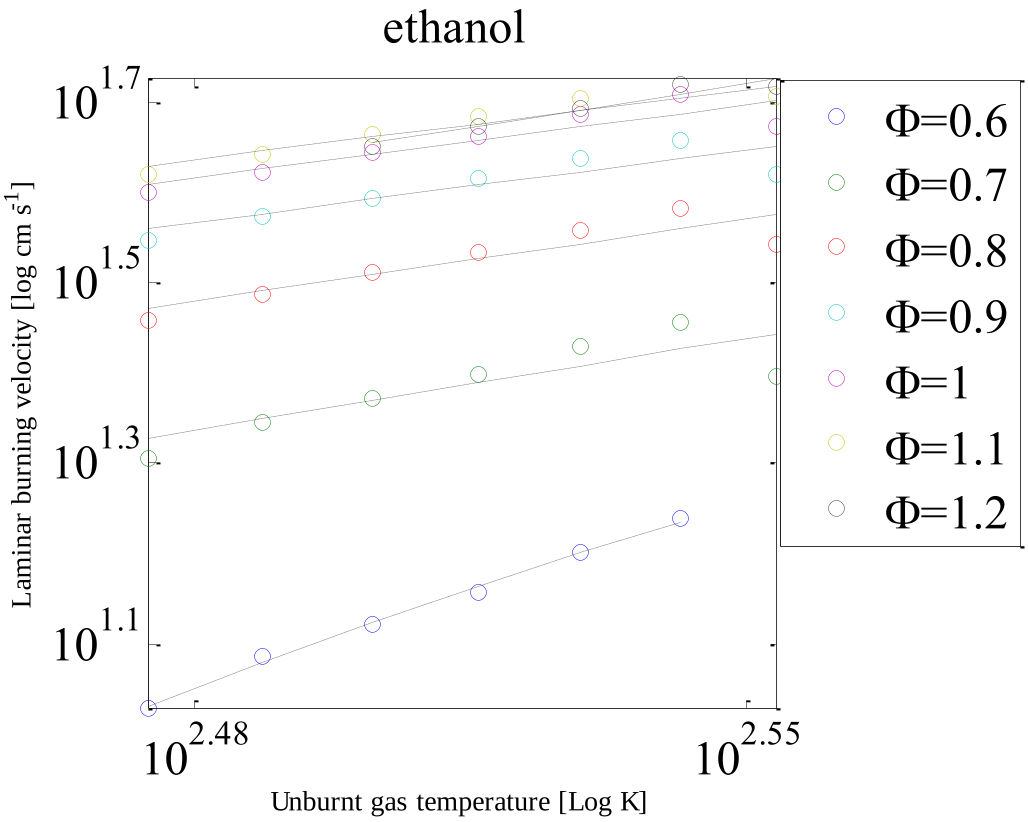

Figure 5.13: Temperature dependence of Ethanol/air flame speed in the temperature range 298-358K

Figure 5.13 shows the temperature dependence of ethanol laminar burning velocities for the range temperature 298-358 K. From the slop of the linear fit in Fig 5.11, the power exponent α was derived.

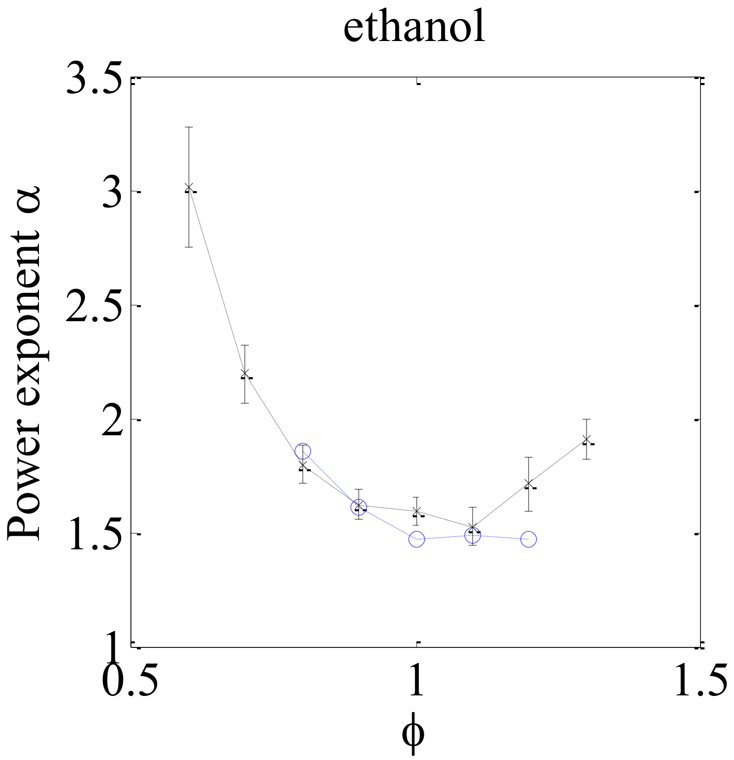

Fig 5.14: Power exponent α vs equivalence ratio for experimental ethanol flames.

The power exponent α of from the experiments of ethanol and compared with Konnov et al. [13] is presented in Fig 5.14. The black dashed line show recent experimental results and blue circle with dashed line is the Konnov et al. [13] results. According to experimental results, a non-linear relationship found between equivalence ratio and power exponent α. A minimum coefficient value is observed at $\varphi = 1.1$. At the same equivalence ratio the maximum burning velocity was found. The uncertainties of experimental value of α are large at lower equivalence ratio (0.6-0.7). The experimental exponent power α is compared with Konnov et al. [13] data. From Fig 5.14 it can be seen the experimental exponent power α has good agreement with Konnov at φ 0.8 and 0.9. At equivalence ratio 1.2 the difference in results due to less temperature readings at that φ in recent experimental data.

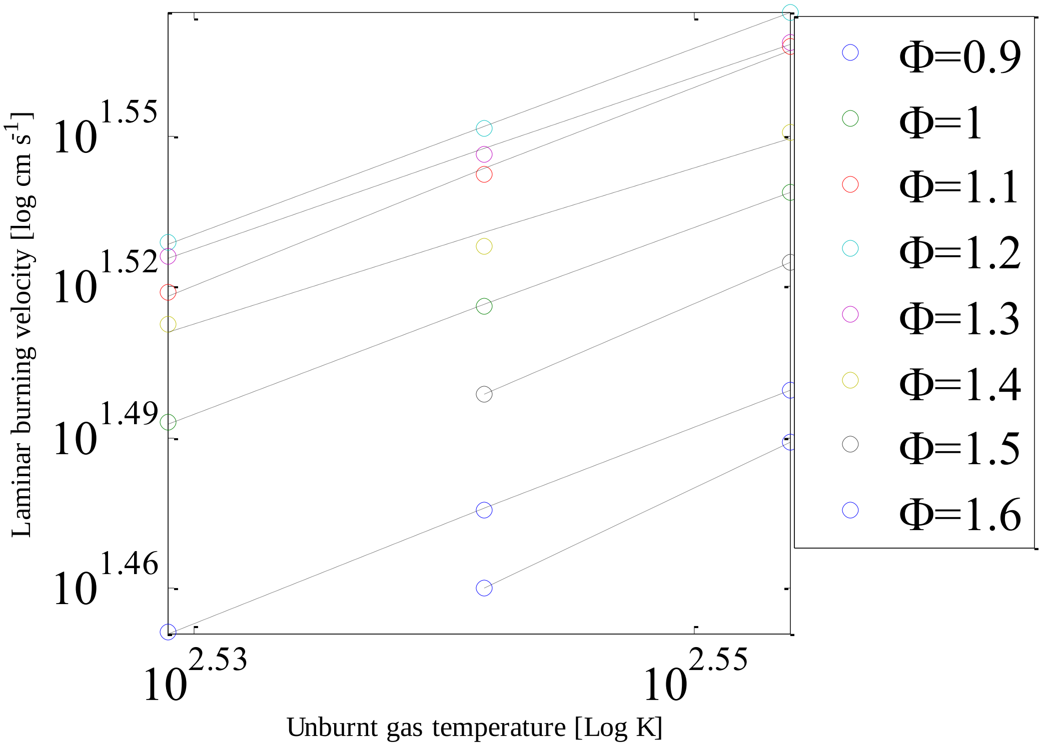

Figure 5.15: Temperature dependence of nitromethane/air flame speed in the temperature range 338-358 K

The measured laminar burning speed of nitromethane/air flames at atmospheric pressure in the temprature range 298 K-358 K for equivalence ratio 0.9-1.6 are shown in Fig 5.13. It can be seen from Fig 5.15 that the relation between the laminar burning velocity and the temperature is linear to a fair approximation as expected from theory.

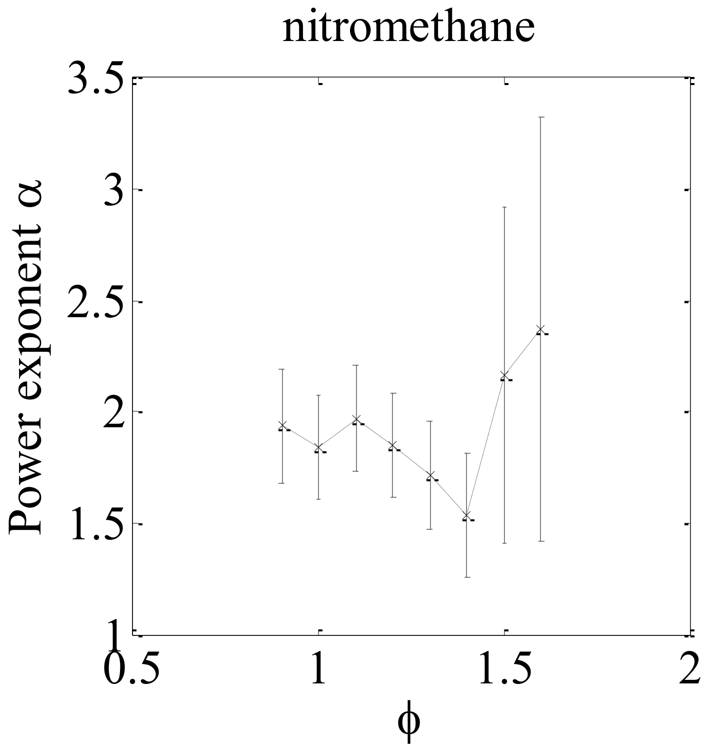

Fig 5.16: Power exponent α vs equivalence ratio for the experimental nitromethane/air flames.

The power exponent α from experiments of nitromethane for $\varphi = 0.9 - 1.6$ is presented in Fig 5.14. According to the experimental result the coefficient α show a non-linear behavior. A minimum coefficient value is observed at an equivalence ratio equal 1.4. The big error bar at $\varphi = 1.5 - 1.6$ could be due to the measurements was taken below than zero α coefficient to remove the corrugation in flame.

Chapter 6

Conclusion and Recommendation

6.1 Summary

The main goal of this project is to provide new and accurate measurements of laminar burning velocity of nitromethane/air and mixture of (ethanol+nitromethane)/air using the heat flux method. Before start of the experiments, mass flow controllers were calibrated with different gases. The aim of calibration is to obtain a high level of accuracy of flow and use calibration polynomial coefficients to correct flow equation. First, the burning velocity of pure ethanol has been determined at 298 K-358 K and compared with previous available data. Then the mixture of ethanol and nitromethane has been prepared and the flame speed determined at 338 K-358 K. At last the flame speed of nitromethane has been determined at 338 K-358 K. The numerical values of all laminar burning velocities determined in the present study are tabulated in Appendix.

6.2 Conclusion

The heat flux method is an efficient and useful technique to determine the burning velocity of liquid fuel. The flame speed of ethanol/air was determined at 298 K-358 K in the equivalence range 0.6-1.5. The results show that flame speed increases with higher temperature. The maximum burning velocity was found $\varphi = 1.1$ at 298 K-398 K and $\varphi = 1.2$ at 348 K-358 K. The measurements at 358 K were taken twice because the measurements that were taken in the same day were not good. The second measurement of ethanol at 358 K gives a good resemblance with previous data. The results at all temperatures were compared with old available data. The present result of ethanol gives a satisfactory agreement with previous available data. The overall accuracy of the burning velocities was estimated to be around $\pm 1 cm/s$. The temperature dependence of the unburned mixture on laminar burning velocity was studied.

The mixture of nitromethane and ethanol has been prepared with volume of 50% each. The burning velocities of ethanol-nitromethane were determined and the results are shown in fig 5.9. After taking the measurements it was observed that the equivalence ratio in the program was wrong. Using these measurements the equivalence ratio was calculated manually but it did not give satisfactory results.

The burning velocity of nitromethane is presented in fig 5.10. The measurements were taken at 338 K-358 K in the equivalence ratio range 0.9-1.6. The results of nitromethane show a similar shape at all temperatures. The maximum burning velocity was found at $\varphi = 1.2$ for all temperatures. The experiments were repeated at 358 K and it was found same results. The burning velocities of nitromethane are compared with the each other because there are no literature data available. The overall accuracy of the burning velocities was estimated to be around $\pm 1 cm/s$. Comparing the nitromethane burning velocity with ethanol burning velocity it was found that the first one is lower than the second one at all the temperatures.

6.3 Recommendations

Some recommendations can be considered to reach a high level of accurate results:

- More experiments and model developments are required to validate the results of nitromethane.
- Different mixtures could be created with ethanol or methanol and more experiments have to perform to investigate the reliability of burning velocities.
- The experiments could be extended with different temperature range (lower or higher).
- Extend the same work with another fuel or other types of fuel to compare it with the current results.
- Other research could be done with the same molecule using another combustion method such as closed vessel method. With closed vessel method variable pressure and higher temperature could be obtained.

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Appendix

Table1: Adiabatic burning velocities of Ethanol at temperature range 298-358K

Laminar burning velocity of ethanol at 298K	
Equivalence Ratio(φ)	Laminar Flame Velocity (SL) cm/s
0.6 ±0.00	10.71 ± 1.25
0.7 ±0.01	20.22 ± 1.25
0.8 ±0.01	28.73 ± 0.94
0.9 ±0.01	35.24 ± 0.82
1 ± 0.01	39.68 ± 0.82
1.1 ±0.01	41.68 ± 0.83
Laminar burning velocity of ethanol at 308K	
Equivalence Ratio(φ)	Laminar Flame Velocity (SL) cm/s
0.6 ±0.01	12.23 ± 1.07
0.7 ±0.01	22.13 ± 0.87
0.8 ±0.01	30.74 ± 0.78
0.9 ±0.01	37.37 ± 0.69
1.0 ±0.01	41.92 ± 0.70
1.1 ±0.02	43.88 ± 0.69
1.3 ±0.02	38.06 ± 0.60
1.4 ±0.02	29.44 ± 1.01
1.5 ± 0.02	
Laminar burning velocity of ethanol at 318K	
Equivalence Ratio(φ)	Laminar Flame Velocity (SL) cm/s
0.6 ± 0.01	13.25 ± 0.99
0.7 ± 0.01	23.58 ± 0.75
0.8 ± 0.01	32.39 ± 0.70
0.9 ± 0.01	39.21 ± 0.64
1 ± 0.01	43.99 ± 0.65
1.1 ± 0.02	46.01 ± 0.68
1.2 ± 0.02	44.76 ± 0.71
1.3 ± 0.02	39.73 ± 0.79
1.4 ± 0.02	31.25 ± 0.90
1.5 ± 0.02	22.52 ± 0.95
Laminar burning velocity of ethanol at 328K	
Equivalence Ratio(φ)	Laminar Flame Velocity (SL) cm/s
0.6 ± 0.01	14.36 ± 0.82
0.7 ± 0.01	25.02 ± 0.66

0.8 ± 0.01	34.09 ± 0.65
0.9 ± 0.01	41.12 ± 0.61
1 ± 0.01	45.91 ± 0.71
1.1 ± 0.02	48.19 ± 0.70
1.2 ± 0.02	46.96 ± 0.73
1.3 ± 0.02	41.90 ± 0.86
1.4 ± 0.02	33.13 ± 0.90
1.5 ± 0.02	23.96 ± 0.87
Laminar burning velocity of ethanol at 338K	
Equivalence Ratio(φ)	Laminar Flame Velocity (SL) cm/s
0.6 ± 0.01	15.94 ± 0.61
0.7 ± 0.01	26.92 ± 0.58
0.8 ± 0.01	36.11 ± 0.61
0.9 ± 0.01	43.28 ± 0.64
1.0 ± 0.01	48.39 ± 0.69
1.1 ± 0.02	50.57 ±0.75
1.2 ± 0.02	49.34 ± 0.78
1.3 ± 0.02	44.27 ±0.93
1.4 ± 0.02	35.32 ± 1.11
1.5 ± 0.02	25.79 ± 1.03
Laminar burning velocity of ethanol at 348K	
Equivalence Ratio(φ)	Laminar Flame Velocity (SL) cm/s
0.6 ±0.01	17.32 ±0.57
0.7 ±0.01	28.62 ±0.64
0.8 ±0.01	38.14 ±0.69
0.9 ±0.01	45.46 ±0.72
1.0 ±0.01	51.03 ±0.88
1.2 ±0.02	52.29 ±0.59
1.3 ±0.02	48.32 ±0.85
1.4 ±0.02	44.54 ±0.90
1.5 ±0.02	38.31 ±1
Laminar burning velocity of ethanol at 348K	
Equivalence Ratio(φ)	Laminar Flame Velocity (SL) cm/s
0.7 ±0.01	24.94 ±0.62
0.8 ±0.01	34.89 ±0.89
0.9 ±0.01	41.69 ±0.81
1.0 ±0.01	47.03 ±0.89
1.1 ±0.02	50.67 ±0.95

1.2 ±0.02	51.97 ±1.02
1.3 ±0.02	51.00 ±1.07
1.4 ±0.02	46.91 ±0.93
1.5 ±0.02	40.67 ±1.08

Table2: Adiabatic burning velocities of nitromethane at temperature range 338-358K

Laminar burning velocity of Nitromethane at 338K	
Equivalence Ratio(φ)	Laminar Flame Velocity (SL) cm/s
0.9 ±0.01	28.25 ±0.52
1.0 ±0.01	31.11 ±0.53
1.1 ± 0.02	33.02 ±0.56
1.2 ±0.02	33.79 ±0.57
1.3 ±0.02	33.57 ±0.60
1.4 ±0.02	32.54 ±0.70
Laminar burning velocity of Nitromethane at 348K	
Equivalence Ratio(φ)	Laminar Flame Velocity (SL) cm/s
0.9 ±0.01	29.89 ±0.55
1.0 ±0.01	32.81 ±0.50
1.1 ±0.02	34.87 ±0.53
1.2 ±0.02	35.61 ±0.54
1.3 ±0.02	35.21 ±0.57
1.4 ±0.02	33.74 ±0.60
1.5 ±0.02	31.51 ±0.64
1.6 ±0.02	28.84 ±0.60
Laminar burning velocity of Nitromethane at 358K	
Equivalence Ratio(φ)	Laminar Flame Velocity (SL) cm/s
0.9 ±0.01	31.57 ±0.56
1.0 ±0.01	34.59 ±0.56
1.1 ±0.01	36.98 ±0.61
1.2 ±0.02	37.58 ±0.61
1.3 ±0.02	37.05 0±.60
1.4 ±0.02	35.56 ±0.62
1.5 ±0.02	33.50 ± 0.75
1.6 ±0.02	30.85 ±0.99