Burning Rate Characteristics of Turbulent Rich Premixed Flames

A dissertation submitted in partial fulfillment of
The requirements for the degree of
MSc in Sustainable Energy and Environment

By

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September 2007
ABSTRACT

The challenges associated with a sustainable future in terms of energy utilisation will require the utilisation of non-traditional fuels and operating conditions for power generators such as gas turbines and reciprocating engines. Cardiff School of Engineering is undertaking a detailed programme of work to study and analyse the fundamental turbulent burning characteristics of alternative fuels under a range of ambient conditions. This thesis provides the first studies of a new atmospheric experimental facility, which forms part of the overall programme of work.

The Cardiff atmospheric combustion rig was designed and developed at the Cardiff University to investigate burning velocities for different types of fuels. However, it is known that due to the installation of different types of turbulence plates (in some references turbulence plates are referred to as turbulence discs) raises the turbulence intensity which results in changes on the flame parameters on the Borghi chart. The focus of the research concerns the turbulent burning velocity and the effects of turbulence plates on the flame burning rates and the flame stretch. As such, the main aim of this study was to undertake a first benchmarking study for this rig using methane-air mixtures, compare the recorded data with others that have used atmospheric combustion facilities, and hence determine a protocol for the interpretation of results from the Cardiff atmospheric combustion rig. This study found that the diameter of the holes in the turbulence discs, the discharge coefficient and holes layout has a great impact on the burning velocity. On the other hand, the disc thickness, the number of holes also has an effect on the burning velocity. The rise of pressure and its profile distribution on the turbulence plate surface has a great impact on increasing burning velocities. The work also pointed out where the turbulence plates are situated on the Borghi/Peters chart.
Acknowledgments

This case study is an effect of my research during a 3-month period at Cardiff school of engineering in Wales where I did my daily work in doing my literature review modeling taking notes and getting an in depth understanding of the field of combustion which I had no back ground in before.

I’d like to thank my mother, father and brother for their help, prayers, support and scientific guidance all my life and till now.

I thank Dr. Peter Kay who was my actual every-day boss at Cardiff school of engineering for his professional supervision, discussions and generous scientific support. I would also like to thank PhD student Audrius Bagdanavicius, for his follow up and kind help in setting up and taking samples .I thank the man in charge of our Combustion Research Laboratory, Professor Phil Bowen for his expertise and feedback. For the financial support I am grateful to Cardiff School of Engineering, especially to professor Phil Bowen.
DECLARATION

This work has not previously been accepted in substance for any degree and is not being concurrently submitted in candidature for any degree.

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Statement 1

This thesis is the result of my own investigations, except where otherwise stated.

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1. Introduction:

1.1. The environmental issue connected with combustion:
Due to the rise in fuel prices which has been the result of the growing demanding economies of the countries of the world especially China India, global warming, depletion of oil sources (the ones which are reachable and easy to get) and the race for space tourism has meant that more research is to be invested in the field of combustion. This research covers all aspects of the flame which include products of combustion the reactants, the type of oxidizer (air or oxygen) the fluid dynamics and the thermodynamics side of the process. A large portion of $CO_2$ emissions are emitted by the energy production sector and the Kyoto protocol has restricted countries in how much $CO_2$ they should emit (this has been one of the main drive for countries) and due to the $CO_2$ taxation on the $CO_2$ emissions exceeding there limits for each country countries has its own limits which it should not exceed, European countries have been trying to cut down on there $CO_2$ emissions either by $CO_2$ sequestration, scrubbers, capturing $CO_2$ and later pumping it back into run out oil wells.

1.2. Design modifications on automotive engines:
On the motor vehicle side, installing emissions filters on there gas exhaust on cars has been one of the methods in tackling the problem. of the process Car companies have also been trying to solve the emissions problem either by improving the efficiency of the combustion process such as using the better efficiency atomizers (fuel sprays) or piston surface design modification. Accurate control of the spray timing of the fuel air mixture and controlling this process electronically results in better combustion efficiency not forgetting that having different running modes in a car (sport or economic mode) also improves the fuel economy. Due to the fast response that electronic equipment have, less weight and also is much easy to replace and upgrade they have an advantage on mechanical mechanisms that means better burning.
1.3. Designers provided with accurate Data gives improved designs:
Knowing the conditions of the fuel that can make it burn at its best can speed up the design control modification up grade estimation of costs process. Turbulence in a combustion process is needed but the type of turbulence should be controlled, turbulence is used for flame stabilization because the creation of a circulation zone provides the gaseous mixture the appropriate time to burn completely (that’s the purpose of what is called flame holders in jet engines).

Figure 1-1: Range of burnable fuel-air ratios versus combustor gas velocity.

Knowing the combustion flame temperature and pressure for a certain fuel helps out in the selection of combustors material. Having background info on fuel air ratio leads the designer to making the correct selection of flow rates volumes and size of the combustors as can be seen in the figure 1-1.
Figure 1-2: a gas turbine used to generate electricity with all its components excluding the Alternator shows how difficult it is for a designer to get all the components to work at its best [11].

The velocity profile in the combustion chamber helps out in knowing the residence time for the fuel charge as can be seen from the following figure 1-1, for the fuel charge to spend less time in the combustor means incomplete combustion and increasing the residence time means this will cause blow out of the flame and that can be hazardous for a jet plane and would cause severe knocking effect and vibrations in internal combustion engines. This is the case for a gaseous fuel air mixture in some other cases like in internal combustion engines droplets of the fuel need time to evaporate to turn into gas and then oxidize this will increase.
From figure 1-3, for a jet engine fuel droplets need to be atomized from the fuel nozzle to small particles so that the oxidize straight away then additional air is provided for dilution which means for the unburnt fuel. Cooling air is provided so that would prevent $No_x$ from being produced and to cool the combustor surface and for reducing high gas temperature reaching the turbine blades.

\[\text{Figure 1-3: A cross section in a combustor of an early model jet engine and how complicated it is for the designer to get every component running at its best [24].} \]

1.4. Aims and objectives:

The objectives required to achieve the goal are:

1. The aim of the research is to provide understanding and interpretation of new data generated on a new stationary turbulent burning rate rig at Cardiff school of engineering, and the burn and interpretation of data from a new high pressure temperature optical rig at the new gas turbine research centre (The Centre, at Port Talbot South Wales).

2. To provide understanding of turbulent combustion.

3. Apply theory and practical methods to new data.

4. Analyse new data and the predict consequences and elevating ambient parameters.
2. Theory and Literature Overview

2.1. Fuel Chemistry:

2.1.1. Some basic info:

The various hydrocarbon families are differentiated by whether the fuel molecules consist entirely of single carbon-carbon bonds (c-c) or contain one double (c=c) or contain one triple (c≡c) bond, and whether the molecules are open chains (all chain ends are unconnected) or form rings.

The Alkanes, Alkenes, and Alkynes are all open-chain structures, while the Cyclanes and Aromatic exhibit ring structures.

For the open-chain families (Alkanes, Alkenes, and Alkynes), the following nomenclature is used to denote the number of carbon atoms contained in a particular family member:

<table>
<thead>
<tr>
<th>Carbon Number</th>
<th>Alkane</th>
<th>Alkene</th>
<th>Alkyne</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1-meth</td>
<td>2-eth</td>
<td>3-prop</td>
</tr>
<tr>
<td>2</td>
<td>2-meth</td>
<td>2-eth</td>
<td>4-but</td>
</tr>
<tr>
<td>3</td>
<td>3-meth</td>
<td>3-eth</td>
<td>5-prop</td>
</tr>
<tr>
<td>4</td>
<td>4-meth</td>
<td>4-eth</td>
<td>6-prop</td>
</tr>
</tbody>
</table>

Table 2-1: A summary of hydro-carbons [3]:

<table>
<thead>
<tr>
<th>Family Name</th>
<th>Other Designations</th>
<th>Molecular Formula</th>
<th>Carbon-Carbon Bonding</th>
<th>Primary Molecular Structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alkanes</td>
<td>Paraffines</td>
<td>$C_nH_{2n+2}$</td>
<td>Single bonds only</td>
<td>Straight or branched open chains</td>
</tr>
<tr>
<td>Alkenes</td>
<td>Olefines</td>
<td>$C_nH_{2n}$</td>
<td>One double bond, remainder single</td>
<td>Straight or branched open chains</td>
</tr>
<tr>
<td>Alkynes</td>
<td>Acetylene</td>
<td>$C_nH_{2n-2}$</td>
<td>One triple bond, remainder single</td>
<td>Straight or branched open chains</td>
</tr>
<tr>
<td>Cyclanes</td>
<td>Cyclolkanes,Cyclopentanes,Naphthenes</td>
<td>$C_2H_{2n}or(CH_2)_n$</td>
<td>Single bonds only</td>
<td>Closed rings</td>
</tr>
<tr>
<td>Aromatics</td>
<td>Benzene family</td>
<td>$C_nH_{2n-6}$</td>
<td>Resonance hybrid bonds (Aromatic bonds)</td>
<td>closed rings</td>
</tr>
</tbody>
</table>

2.1.2. Methane Properties:

Methane is the major component of a natural gas, typically 97% by volume. At room temperature and standard pressure, Methane is a colourless, odourless gas; the smell characteristic of natural gas is an artificial safety measure caused by the addition of an odorant, often Methanethiol or Ethanethiol. It melts at –183°C and boils at –164°C. It is not very soluble in water. Methane is combustible, and mixtures of about 5 to 15 percent
in air are explosive. Methane is not toxic when inhaled, but it can produce suffocation by reducing the concentration of oxygen inhaled. Liquid methane does not burn unless subjected to high pressure (normally 4–5 atmospheres.)[12, 22].

Figure 2-1: Methane 3d balls.

Because it contains a carbon atom, when methane burns it creates carbon dioxide, which is a greenhouse gas. Therefore methane is not the perfect fuel [23].

2.1.3. The combustion of Methane:

In the combustion of methane, several steps are involved:
a-Methane is believed to form a formaldehyde (HCHO or H2CO). The formaldehyde gives a formyl radical (HCO), which then forms carbon monoxide (CO). The process is called oxidative pyrolysis:

\[ CH_4 + O_2 \rightarrow CO + H_2 + H_2O \]

b-Following oxidative pyrolysis, the H₂ oxidizes, forming H₂O, replenishing the active species, and releasing heat. This occurs very quickly, usually in significantly less than a millisecond.

\[ 2H_2 + O_2 \rightarrow 2H_2O \]

c-Finally, the CO oxidizes, forming CO₂ and releasing more heat. This process is generally slower than the other chemical steps, and typically requires a few to several milliseconds to occur [18].

\[ 2CO + O_2 \rightarrow 2CO \]

2.1.4. The Oxidation of Methane:

The oxidation process of Methane either occurs at low temperature or at high temperature due to conducting the lab tests at \( \phi = 1.43 \) this has the result of low flame temperature as shown on figure, so the description of low temperature oxidation has only been described in this paragraph.
Figure 2-3: variation of flame temperature with the increase of equivalence ratio.

So in conclusion the flame temperature at the Stochiometric condition is 2210 K which is taken from table on figure for methane air condition so this is the maximum burning temperature.

Table 2-2: Approximate flame temperatures of various Stochiometric mixtures critical temperature 298(K).

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Oxidizer</th>
<th>Pressure(atm)</th>
<th>Temperature (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acetylene</td>
<td>Air</td>
<td>1</td>
<td>2600</td>
</tr>
<tr>
<td>Acetylene</td>
<td>Oxygen</td>
<td>1</td>
<td>3410</td>
</tr>
<tr>
<td>Carbon monoxide</td>
<td>Air</td>
<td>1</td>
<td>2400</td>
</tr>
<tr>
<td>Carbon monoxide</td>
<td>Oxygen</td>
<td>1</td>
<td>3220</td>
</tr>
<tr>
<td>Heptane</td>
<td>Air</td>
<td>1</td>
<td>2290</td>
</tr>
<tr>
<td>Heptane</td>
<td>Oxygen</td>
<td>1</td>
<td>3100</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>Air</td>
<td>1</td>
<td>2400</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>Oxygen</td>
<td>1</td>
<td>3080</td>
</tr>
<tr>
<td>Methane</td>
<td>Air</td>
<td>1</td>
<td>2210</td>
</tr>
<tr>
<td>Methane</td>
<td>Air</td>
<td>20</td>
<td>2270</td>
</tr>
<tr>
<td>Methane</td>
<td>Oxygen</td>
<td>1</td>
<td>3030</td>
</tr>
<tr>
<td>Methane</td>
<td>Oxygen</td>
<td>20</td>
<td>3460</td>
</tr>
</tbody>
</table>

a: This maximum exists at $\phi = 1.3$.

b: This maximum exists at $\phi = 1.7$. 
Methane has certain oxidation characteristics that differentiate it from other hydrocarbons. The first bond \((C - H)\) in Methane needs the largest portion of energy to break it in comparison with the other three bonds [12]. This is the reason why the ignition of methane at lower temperatures is harder to achieve in comparison with other hydrocarbons due to the fact the oxygen molecule attack would be slower at lower temperature than at high temperatures where it will have low kinetic energy. The simplest scheme that will explain the lower-temperature results of methane oxidation is the following:

\[
CH_4 + O_2 \rightarrow \cdot C H_3 + HO_2 \ldots \ldots (1) \quad \text{(Chain initiating)}
\]

\[
\cdot C H_3 + O_2 \rightarrow \cdot C H_2 O + OH \ldots \ldots (2)
\]

\[
OH + C H_4 \rightarrow H_2 O + \cdot C H_3 \ldots \ldots (3) \quad \text{(Chain propagating)}
\]

\[
\cdot O H + C H_2 O \rightarrow H_2 O + H \cdot C O \ldots \ldots (4)
\]

\[
CH_2 O + O_2 \rightarrow H \cdot O_2 + H \cdot C O \ldots \ldots (5) \quad \text{(Chain branching)}
\]

\[
H \cdot C O + O_2 \rightarrow CO + H \cdot O_2 \ldots \ldots (6)
\]

\[
H O_2 + CH_4 \rightarrow H_2 O_2 + CH_3 \ldots \ldots (7) \quad \text{(Chain propagating)}
\]

\[
H O_2 + CH_2 O \rightarrow H_2 O_2 + H \cdot C O \ldots \ldots (8)
\]

There is no \(H_2 O_2\) dissociation to \(OH\) radicals at low temperatures. \(H_2 O_2\) dissociation dose not become effective until temperature reaches about 900K. As before, reaction 1 is slow. Reaction 2 and 3 are faster since they involve a radical and one of the initial reactants. The same is true for reactions 5, 6 and 7. Reaction 5 represents the necessary chain branching step. Reaction 4 and 8 introduce the formyl radical known to exist in the low temperature combustion scheme. Carbon monoxide is formed by reaction 6, and
water by reaction 3 and the subsequent decay of the peroxides formed. A conversion step of \( CO \) to \( CO_2 \) is not considered because the rate of conversion by reaction:

\[
CO + OH \rightarrow CO_2 + H
\]

is too slow at the temperatures of concern here. It is important to examine more closely reaction 2, which proceeds through a metastable intermediate complex-the methyl peroxy radical-in the following manner:

\[
\begin{align*}
\text{CH}_3 + \text{O}_2 & \rightleftharpoons \text{H} - \text{C} = \text{O} \rightleftharpoons \text{H} - \text{C} - \text{O} + \text{OH} \\
\end{align*}
\]

\[\ldots\ldots(12)\]

At lower temperatures the equilibrium step is shifted strongly toward the complex, allowing the formaldehyde and hydroxyl radical formation. The structure of the complex represented in reaction 12 is well established. Recall that when \( \text{O}_2 \) adds to the carbon atom in a hydrocarbon radical, it forms about a 90deg bond angle.

Perhaps more important, however, is the suggestion Benson that at temperatures of the order of 1000K and above the equilibrium step in reaction 12 shifts strongly toward the reactants so that the overall reaction to form formaldehyde and hydroxyl cannot proceed[1].
2. 2. Combustion Fundamentals:

2.2.1. Introduction:

This section will give the reader good background info on the fundamentals needed in this project study. Getting the equivalence ratio correctly will pave the way to make a comparison of the work that was found in the lab with other researchers work. Usually researchers illustrate the burning velocities as a function of the equivalence ratio. That’s why this chapter has been given so much attention.

2.2.2. The combustion equation of an arbitrary hydrocarbon:

Here is the general equation [13] used for an arbitrary hydrocarbon by substituting the constants in x and y which are known once you know what fuel is used this will lead us to evaluate the constant (a), (a) is easy to evaluate due to our knowledge of the equivalence ratio while conducting our experiment and x and y are known due to their relation with the fuel molecular formula.

\[ C_x H_y + a(O_2 + 3.76N_2) \rightarrow bCO_2 + fO_2 + cCO + dH_2O + eH_2 + 3.76aN_2 \] \hspace{1cm} (13)

\[ \phi = \frac{x + 0.25y}{a} \] \hspace{1cm} (14)

The coefficients \( b \), \( d \) and \( f \) can be found by \( C \), \( H \) and \( O \) atom balances,

\[ b = x \]
\[ c = 0 \]
\[ d = y/2 \]
\[ e = 0 \]
\[ b = \frac{(1-\phi)}{\phi} (x + y/4) \]
During Lab tests with the change of the air fuel ratio the constants change that’s why for each given case to find the constants you have to solve the set of equations which can take a number of six equations with six unknowns.

2.2.3. There are cases which are fundamental for conducting the lab-work:

a-The Stochiometric case:
Is the quantity of oxidizer which is just the amount needed to completely burn a quantity of fuel.

![Figure 2-4](image)

**Figure 2-4:** This shows the exact volume of oxidizer equals the exact volume of fuel which refers to the Stochiometric, but due to difference in density they don’t have the same volume.

b- The Fuel Lean case:
If more than a Stochiometric quantity of air is provided to the fuel.

\[
\phi \leq 1 \quad \text{..........................(15)}
\]

\[
C_xH_y + a(O_2 + 3.76N_2) \rightarrow bCO_2 + dH_2O + fO_2 + 3.76aN_2 \quad \text{................. (16)}
\]
c- The Fuel Rich case:
Supplying less of the oxidizer to the fuel results in a fuel rich mixture.

\[ \phi > 1 \]  
\[ C_{x}H_{y} + a(O_{2} + 3.76N_{2}) \rightarrow bCO_{2} + cCO + dH_{2}O + eH_{2} + 3.76aN_{2} \ldots \]  

Figure 2-5: This shows the exact amount of fuel equals the excess amount of oxidizer which refers to the fuel lean case.

Figure 2-6: This shows the exact amount of oxidizer equals the exact amount of fuel in addition to it excess fuel this refers to the fuel rich case.
d- The Fuel Air Ratio:

Is the division of the mass of fuel over the mass of air in a certain condition
Where $F$ is the mass of fuel ($kg_{fuel}$) and $A$ is the mass of air ($kg_{air}$).

\[
\alpha = \frac{F}{A} \quad \text{................ (19)}
\]

So $\alpha$ unit should be ($kg_{fuel} / kg_{air}$).

e- The Stochiometric Fuel Air Ratio:

Is the division of the exact mass of fuel over the exact amount of air needed for a the combustion of a fuel.

\[
\alpha_{stoic} = \frac{F}{A}_{stoic} \quad \text{................ (20)}
\]

So $\alpha$ unit should be ($kg_{fuel} / kg_{air}$)$_{stoic}$.

f- The Equivalence Ratio:

Is used to indicate quantitatively whether a fuel-oxidizer mixture is rich, lean, or Stochiometric.

\[
\phi = \frac{(A/F)_{stoic}}{(A/F)} = \frac{(F/A)}{(F/A)_{stoic}} = \frac{\alpha}{\alpha_{stoic}} \quad \text{................ (21)}
\]

\[
\% \text{ The Stochiometric Air} = \frac{100\%}{\phi} \quad \text{................. (22)}
\]

\[
\% \text{ The Percent of Excess Air} = \frac{(1-\phi)}{\phi} \cdot 100\% \quad \text{......... (23)}
\]
2.2.4. The implementation of the fundamentals on a lab methane case:

The use of methane leads us to substitute $x = 1$ and $y = 4$ in the molecular form equation

$$CH_4 + a(O_2 + 3.76N_2) \rightarrow bCO_2 + dH_2O + fO_2 + 3.76aN_2$$

$$\phi = \frac{1+0.25\times 4}{a} = \frac{2}{a}$$

So that means once a reading is made from the flow meters of the fuel ($m_{fuel}$) and the air ($m_{air}$) the value of $a$ can be calculated starting from the fuel air ratio:

$$\alpha = (A/F) = \frac{m_{air}}{m_{fuel}}$$

Then using the equivalence ratio that is a function of the fuel air ratio for both the lab case and the Stochiometric case:

$$\phi = \frac{(A/F)_{stoc}}{(A/F)} = \frac{(F/A)}{(F/A)_{stoc}}$$

The problem has two unknowns for one equation that leads to the following step of finding the Stochiometric fuel air ratio.

For a Stochiometric case and ease of calculation we assume the simplified composition for air is 21% $O_2$ and 79% $N_2$ (by volume) i.e., that for each mole of $O_2$ in air, there are 3.76 moles of $N_2$.

$$\alpha_{stoc} = (F/A)_{stoc} = \frac{4.76a}{M_{air}} \frac{M_{fuel}}{1}$$

Where $M_{air}$ and $M_{fuel}$ are the molecular weights of the air and fuel.

So for our case Methane is $CH_4$ so for a hydrocarbon given by the following equation

$$C_xH_y + a(O_2 + 3.76N_2) \rightarrow xCO_2 + \left(\frac{y}{2}\right)H_2O + 3.76aN_2$$

Where:

$$a = x + \frac{y}{4} = 2$$

And:
\[ MW_{\text{air}} = 29 \]
\[ MW_{\text{fuel}} = 16 \]
\[ (F / A)_{\text{stoic}} = \frac{4.76a}{1} \frac{MW_{\text{air}}}{MW_{\text{fuel}}} = \frac{9.52 \times 29}{16} \]
\[ (F / A)_{\text{stoic}} = 17.255 \left( \frac{\text{kg}_{\text{fuel}}}{\text{kg}_{\text{air}}} \right) \]
\[ \phi = \frac{2}{a} = \frac{(F / A)}{(F / A)_{\text{stoic}}} \]
\[ a = \frac{(F / A)_{\text{stoic}}}{2(F / A)} \]

So for the studied case the final equation should be:

\[ CH_4 + \frac{17.255}{2(m_{\text{fuel}}/m_{\text{air}})} (O_2 + 3.76N_2) \rightarrow bCO_2 + dH_2O + fO_2 + 3.76aN_2 \]

By solving the four equations with the four unknown the studied case chemical equation can be found:

\[ \frac{17.255}{2(m_{\text{fuel}}/m_{\text{air}})} = 2b + d + f \]
\[ 17.255 \frac{3.76}{2(m_{\text{fuel}}/m_{\text{air}})} = 2 \times 3.76a \]
\[ 1 = b \]
\[ 4 = 2d \]

Then we would substitute them into the equation:

\[ CH_4 + \frac{17.255}{2(m_{\text{fuel}}/m_{\text{air}})} (O_2 + 3.76N_2) \rightarrow bCO_2 + dH_2O + fO_2 + 3.76aN_2 \]
2.2.5. The heat of combustion for Methane:

The heat of combustion is the difference in enthalpy. The method used to measure it is measured by pressurizing a strong metal reaction vessel (called a bomb) with a mixture of methane and oxygen gas.

\[ CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O(l) \ldots \ldots (24) \]

The vessel is immersed in a calorimeter filled with water. An ignition source is used, which is an electrical wire. A current is passed through the wire (a fine iron wire), which ignites the wire and the fuel air mixture.

The heat balance for the experiment is as follows:

\[ 0 = q_{\text{cal}} + q_{\text{wire}} + q_{\text{comb}} \ldots \ldots (25) \]

The heat flow through the calorimeter \( q_{\text{cal}} \) can be calculated by multiplying the heat capacity of the calorimeter with temperature difference between the initial and the final temperature after the experiment had been conducted and the whole fuel mixture has been burnt. The amount of water in the calorimeter stays the same; that means that \( C_{\text{cal}} \) is the combination of the heat capacities of the calorimeter, the water, and the bomb itself.

The ignition wire burns and releases heat; this heat should not be neglected in the calculations. Note: this heat is treated separately for each time the experiment is conducted due to the fact that the amount of wire used changes from each experiment.

The heat released by the combustion reaction is \( q_{\text{comb}} \) which is also connected to the molar internal energy of the combustion process:

\[ \Delta E_{\text{comb}} = \frac{q_{\text{comb}}}{n_{\text{methane}}} \]

Large amounts of oxygen are used in the Combustion experiments, because methane is the limiting reactant. Once the methane is finished there is no more heat release not forgetting that the whole process occurs at constant pressure.
The molar enthalpy of combustion \( (\Delta H_{\text{comb}}) \) is related to the molar internal energy of combustion \( (\Delta E_{\text{comb}}) \) by the equation 26. (Note: that \( H = E + PV \) and the volume is constant when the experiment is conducted.)

\[
\Delta H_{\text{comb}} = \Delta E_{\text{comb}} + V\Delta P = \Delta E_{\text{comb}} + R\Delta(nT) \quad \ldots \quad (26)
\]

The total moles of gas-phase species is \( n \). (The assumption implicit in this analysis is that the volume occupied by solids and liquids is negligible compared to the volume of the bomb and thus condensed phases do not contribute significantly to changes in pressure.) The term \( R\Delta(nT) \) is small compared with \( \Delta E_{\text{comb}} \), and that’s why \( \Delta H_{\text{comb}} \) is usually very close to \( \Delta E_{\text{comb}} \).

For example, "suppose the bomb has a volume of 271 mL and initially contains 10. mmole of methane and excess oxygen at 25.0 °C. Further suppose that after combustion the system reaches a temperature of 27.0 °C, at which time 10.0 mmole of methane and 20.0 mmole oxygen have reacted to form 10.0 mmole of carbon dioxide and 20.0 mmole of liquid water. The initial \( nT \) for gaseous species is 8.94 K mole and the final value is 3.00 K mole. The term \( R\Delta(nT) \) is thus \(-49.4 \text{ J per 10.0 mmole methane or } -4.94 \text{ kJ mole}^{-1} \) \[20\]. Compare this quantity with the molar heat of combustion as determined in the experiment described below.

Combustion reactions are often used to calculate the molar enthalpies of formation. For the methane case, the standard molar enthalpy of combustion for methane can be expressed in terms of the standard molar enthalpies of formation of the reactants and products equation 27:

\[
\Delta H_{\text{comb}}^0 = 2\Delta H_{\text{water}}^0 + \Delta H_{\text{methane}}^0 - 2\Delta H_{\text{oxygen}}^0 \quad \ldots \quad (27)
\]

\( \Delta H_{\text{comb}}^0 \) : is measured experimentally.

\( \Delta H_{\text{oxygen}}^0 = 0 \), because oxygen is a pure element.
2.3. The Study of Turbulence:

2.3.1. Basics of Turbulent Flow:
Whether a flow is laminar or turbulent depends on the relative importance of fluid friction (Viscosity) and flow inertia. The ratio of inertial to viscous forces is the Reynolds number. Given the characteristic velocity scale, \( U \), and length scale, \( L \), for a system, the Reynolds number is \( Re = \frac{uL}{\nu} \), where \( \nu \) is the kinematic viscosity of the fluid.

![Figure 2-7: Tracer transport in laminar flow.](image)

From figure we can see the straight, parallel blue arrows which are streamlines, which are everywhere parallel to the mean flow. In laminar flow the fluid particles follow the streamlines, as shown by the linear white dye trace in the laminar tube region injected by the white tube on the write hand side.
Figure 2-8: Tracer transport in turbulent flow.

Figure 2-8 shows the velocity vectors for velocity fluctuations for an eddie in a turbulent flow. In turbulent flow eddies of many sizes are superimposed onto the mean flow. When dye enters the turbulent region it traces a path dictated by both the mean flow (streamlines) and the eddies. Larger eddies carry the dye laterally across streamlines. Smaller eddies create smaller scale stirring that causes the dye filament to spread (diffuse) [10, 25].

The turbulent flow can be characterized qualitatively by

1- Irregularity in space and time (chaotic behavior with coherent structures)
2- Continuous spectrum of time and length scales
3- Large Reynolds numbers
4- Three-dimensionality
5- Domination of vortical motion
6- Intermittency
7- Enhanced mass and heat transfer
2.3.2. Turbulent flows are commonly characterized using statistical methods:

Characterizing Turbulence:

Turbulent eddies create fluctuations in velocity. As an example, the longitudinal (u) and vertical (v) velocity measured at point A in figure 2-8. Both velocities varying in time due to turbulent fluctuations. If the flow were steady \( u' = v' = 0 \) and laminar then \( u(t) = \bar{u} \) and \( v(t) = \bar{v} \) for all time \( t \), where the over-bar denotes a time average. For turbulent flow, however the velocity record includes both mean and turbulent component.

\[
\begin{align*}
\bar{u} + u' & = u(t) \\
\bar{v} + v' & = v(t)
\end{align*}
\]

Figure 2-9: Velocity recorded at random point in figure 2-8.

The flow is decomposed as follows.

\[ u(t) = \bar{u} + u'(t) \]
\[ v(t) = \bar{v} + v'(t) \]  

\[ \text{Figure 2-9: Velocity recorded at random point in figure 2-8.} \]

Where \( \bar{u}, \bar{v} \) are the mean velocity value and \( u'(t), v'(t) \) are the turbulent fluctuation.
This is commonly called a Reynolds decomposition.

**Figure 2-10:** Velocity recorded at random point which has turbulence effects on both the x and y axis.

Because the turbulent motions associated with the eddies are approximately random, it is characterized using statistical concepts. In theory the velocity record is continuous and the mean can be evaluated through integration. However, in practice the measured velocity records are a series of discrete points, $u_i$. Below an over bar is used to denote a time average over the time interval $t$ to $(t + T)$ as shown on figure 2-9, where $T$ is much longer than any turbulence time scale, but much shorter than the time-scale for mean flow unsteadiness, e.g. water hammer.

**Mean velocity:**
The mean velocity is given using equation (29).

$$
\overline{u} = \frac{1}{t^+} \int_{t}^{t^+} u(t) \, dt = \frac{1}{N} \sum_{i=1}^{N} u_{(i)} \tag{29}
$$
Where: \( \int_{t_1}^{t_2} u(t) dt \) is a continuous record and \( U = \frac{1}{N} \sum_{i=1}^{N} u_i \) is a discrete, equally-spaced parts.

**Figure 2-11:** The transfer of data from a none uniform structure (graph shown on the left) to a uniform structure (graph on the left).

**Turbulent Fluctuation:**
Turbulence fluctuation is given by equation (28) where \( u'(t) \) is a continuous record is.

\[
u'(t) = u(t) - \bar{u} \quad \ldots \ldots \ldots \ldots (30)\]

**Turbulence Strength:**
Turbulence strength is given by equation (2-4):

\[
U_{rms} = \sqrt{(u'(t))^2} = \left[ \frac{1}{N-1} \sum_{i=1}^{N} (u_i')^2 \right]^{\frac{1}{2}} \quad \ldots \ldots \ldots (31)
\]

The turbulence strength is obtained using the equation above.

**Turbulence Intensity:**
Turbulent flow is often described in terms of intensity, which is a measure of the importance of the fluctuating velocity relative to the mean velocity.
For parallel flow intensity, or level of turbulence, is defined quantitatively by the expression:

\[ T = \sqrt{\frac{1}{3} (u_x'')^2 + (u_y'')^2 + (u_z'')^2} \]  
\[ \frac{u_x}{2} \]  
\[ \text{…….. (32)} \]

In the special case called isotropic turbulence, the three mean-fluctuating velocities are equal so that the equation is simplified to:

\[ T = \frac{\sqrt{(u_x'')^2}}{u_x} \]  
\[ \text{…………… (34)} \]

Is the ratio between the turbulence strength and the mean velocity.

\[ T = \frac{u_{\text{rms}}}{u} \]  
\[ \text{………….. (35)} \]

The subscript .rms. stands for .root-mean-square... You should recognize the definition of \( u_{\text{rms}} \) given in (31) as the standard deviation of the set of random velocity fluctuations, \( u'\text{t} \). Similar definitions apply to the lateral and vertical velocities, \( v(t) \) and \( w(t) \). A larger \( u_{\text{rms}} \) indicates a higher level of turbulence. In the figure (2-12), both records have the same mean velocity, but the record on the left has a higher level of turbulence [6].
Figure 2-12: The effects of turbulence intensity and how it is shown graphically. The study of turbulence has been given a priority due to the need to understand the lab data measurements were fluid dynamics data is provided.

Figure 2-13: The turbulence fluctuating plays a vital role in the Borghi/Peters chart.
2.4.1. Flames:
Since the time man was on earth fire has been something that interested humans due to his motivation to satisfy his daily needs such as for cooking, heating, etc., by time his knowledge and understanding of flames grew more and more when the industrial revolution happened and the use of steam engines came into use scientists became more aware of the need to quantify parameters related to fuel and burning. It is important due to that flames burn all in a very similar way once we can understand one we can understand the rest as can be shown the similarity of the flames.

Figure 2-14: The image of a number of flames which illustrate the similarity of flames in the way they burn and there flame structure similarity [19].

Due to the importance and relationship of the laminar burning velocity with the Borghi chart it is crucial to know what parameters have an effect on the laminar burning velocity. Not forgetting having the basic knowledge and understanding of the flame structure.
2.4.2. Premixed Flames:

Premixing air and fuel and providing an ignition source will result in an exothermic flame (exothermic describes a process or reaction that releases energy in the form of heat), this flame will burn continuously on the condition (self-propagate) of providing it with the right conditions of temperature and temperature and a continues source of air-fuel mixture.

2.4.3. Mass and energy conservation in premixed flames:

To describe this case some assumptions have to be taken in account, the effect of the reaction tube with regard to loss of heat or reactive species or viscous drag on the flowing gas may be neglected in an ideal propagation of a premixed flame in a tube. The fuel air mixture is considered to be laminar and uniform across the diameter so that the flame front is planner and perpendicular to the flow.

**Figure 2-15:** the description of a stationary shock wave, subscripts 1 and 2 refer to the pre-and post-shock gases respectively.

The flow rate is equal to in a magnitude but opposite in sign to the burning the burning velocity, so that the flame is stationary.

**Conservation of mass:**

\[ \rho_u S_u = \rho_b S_b = m \ldots (36) \]

Where \( m \) is the (constant) mass flow rate per unit area through the transition, \( S \) is the velocity of the gas stream and \( \rho \) is its density. The subscript U and b refer to unburned
and burned and burned gas, respectively. This terminology follows convention in which $S_U$ is defined as the burning velocity.

**Conservation of momentum (expressed as flux):**

The pressure and density must change in the same direction.

$$p_u + \rho_u S_U^2 = p_b + \rho_b S_b^2 \quad \ldots \ldots \quad (37)$$

$$m = \frac{(p_u - p_b)}{(S_b - S_u)} \quad \ldots \ldots \quad (38)$$

As a result there are two types of process possible, the first is called detonations, in which both pressure and density increase across the transition, the second is called deflagrations (i.e. combustion waves and flames), in which pressure and density decrease across the transition. Deflagrations are low-velocity expansion waves in which chemical reaction is brought about by heat and mass transport [5].

**2.4.4. Adiabatic Flame Temperature:**

In the study of combustion, there are two types of adiabatic flame temperature depending on how the process is completed: constant volume and constant pressure. The constant pressure adiabatic flame temperature (this is the case that reflects the lab conditions) is the temperature that results from a complete combustion process that occurs without any heat transfer or changes in kinetic or potential energy. Its temperature is lower than the constant volume process because some of the energy is utilized to change the volume of the system (i.e., generate work in internal combustion engines). The constant volume adiabatic flame temperature is the temperature that results from a complete combustion process that occurs without any work, heat transfer or changes in kinetic or potential energy. This is the maximum temperature that can be achieved for given reactants because any heat transfer from the reacting substances and/or any incomplete combustion would tend to lower the temperature of the products.[13]
If a fuel-air mixture burns adiabatically at constant pressure, the absolute enthalpy of the products at the final state \((T = T_{ad}, P = 1\text{ atm})\)

\[H_{\text{react}}(T, P) = H_{\text{prod}}(T_{ad}, p) \quad \ldots \quad (39)\]

Or, equivalently, on a per-mass-of mixture basis:

\[h_{\text{react}}(T, P) = h_{\text{prod}}(T_{ad}, p) \quad \ldots \quad (40)\]

The first-law statement the top equation what is called the constant pressure adiabatic flame temperature. Conceptually, the adiabatic flame temperature is simple; however, evaluating this quantity requires knowledge of the composition of the combustion products. At typical flame temperature, the products dissociate and the mixture comprises many species [3].

**2.4.5. Structure of the ideal, adiabatic, one dimensional, laminar, premixed flame:**

In the detailed structure of the flame is composed of four zones as follows cold reactants, preflame, reaction and product zone. The temperature (illustrated in orange) increases smoothly from the initial to the final state. The intermediate (shown in red) and product (shown in pink) concentrations will increase through the first to two zones and later becomes steady, whereas the concentrations of the fuel air mixture (shown in green) must show a corresponding decrease.

The hatched region (reaction zone) on the figure shows the visible part of the flame. The emission is due largely to electronically excited species, such as \(CH, CN, C_2, CHO\), and also \(CO_2\) emitting light, as they return to their ground state.
An element of the flowing gas mixture can receive heat in two ways, either from chemical reactions occurring within it or by conduction from the hotter gas ahead of it. Two distinct regions can be recognised, which are attributed to these processes. Beginning at low temperature $T_0$, for any given cross-section, the heat flow into the cooler region owing to conduction is greater than the corresponding heat loss because the gradient is steeper on the high temperature side $T_b$. Beyond the point of inflexion what happens is the reverse; the heat loss rate exceeds the heat gain rate. However, at this higher temperature the reaction rate has increased sufficiently for a significant amount of heat to be produced by chemical reaction. The temperature therefore continues to increase through the flame although at a progressively slower rate. It eventually reaches a constant value when all the fuel has been consumed and reaction has ceased. Parallel behaviour also occurs in the reactant concentration profile, the major loss initially being diffusion of fuel into the flame but subsequently being consumption by chemical reaction. The concentration of all species in the post-flame zone must approach that defined by thermodynamic equilibrium at the prevailing temperature. The difficulty in the reaction zone is that species may not reside there for a sufficiently long period for thermodynamic equilibrium to be established. Since the predominant termination
reactions are termolecular processes, and therefore they are relatively slow, the spices most affected and, by implication, held at concentrations above those at thermodynamic equilibrium, are the propagating free radicals. Since bimolecular interactions tend to be equilibrated, all other intermediate species tend to be enhanced to super-equilibrium concentrations [5].

2.4.6. The Laminar Flame Speed:
The laminar flame speed (Laminar burning velocity) $S_L$ is defined as the velocity at which unburned gases move through the combustion wave in the direction normal to the wave surface as can be seen on figure 2-16.

![Figure 2-17: shows the burning velocity vector which is normal to the wave surface.](image-url)
By taking a picture of the burning flame, the angle $\alpha$ can be found out and by reading the flow meter ($Q$ is also known) and using the continuity equation we can find the speed $U_u$ and using equation (42) we can find the laminar burning velocity.

$$Q = U_u A \quad \text{...........(41)}$$

$$S_L = U_u \sin \alpha \quad \text{...........(42)}$$

This is some thing similar students are taught in fluid mechanics, laminar and turbulent flows is the flow that can be characterized by using a Reynolds number which we can also use in flame characterization with the assistance with other Dimensionless numbers such as the Damköhler Lewis..... etc with the help of the Borghi chart which is described in detail later.
2.4.7. **Laminar Flame Structure**

![Diagram of laminar Bunsen burner flame](image)

**Figure 2-19**: General description of laminar Bunsen burner flame.

What we can see is that the fuel gas entering the burner induces air into the tube surroundings. As the fuel and air flow up the tube, they mix and before the top of the tube is reached, the mixture is completely homogeneous. The flow velocity in the tube is considered to be laminar and the velocity across the tube is parabolic nature. Thus the flow velocity near the tube wall is very low. This low flow velocity is a major factor, together with heat losses to the burner rim, in stabilizing the flame at the top. The yellow zone designated in the figure 2-18 is the unburned premixed gases before they enter the area of the luminous zone where reaction and heat release take place. The luminous zone is less than 1mm thick. More specifically, the luminous zone (which looks like a purple cap on the top of the flame on the left hand picture on figure 2-18) is that portion of the reacting zone in which the temperature is the highest: indeed, much of the reacting and heat release takes place in this zone. The colour of the luminous zone changes with fuel-air ratio. For hydrocarbon-air mixtures that are fuel-lean, a deep violet radiation due to excited CH radicals appears.
2.4.8. The Theory of Mallard and Le Chatelier:

Both scientists stated that the heat conducted from zone II in the figure shown below is equal to that necessary to raise the unburned gases to the ignition temperature (the boundary zones I and II).

Figure 2-20: A small slice is taken from the flame to be studied.
Figure 2-21: The balance between zone I and zone II. From balancing the Energy on both zones we have:

\[ Q_{\text{zone1}} = Q_{\text{zone2}} \]  

(43)

So from the enthalpy balance then becomes:

\[ \dot{m} c_p (T_i - T_0) = \lambda \frac{(T_i - T_0)}{\delta} A \]  

(44)

Since the problem is considered one-dimensional we use the following continuity equation:

\[ \dot{m} = \rho A u = \rho S_L A \]  

(45)

Because the unburned gases enter normal to the wave by definition

\[ S_L = u \]  

(46)

- \( T_f \): Flame temperature
- \( T_i \): Mixture temperature before the burning layer
- \( T_0 \): The temperature of the gas mixture
- \( \lambda \): The thermal conductivity of \( t \)
- \( \rho \): Flame density mixture
- \( c_p \): Specific heat capacity at constant pressure.
- \( \delta \): Flame thickness
- \( S_L \): Laminar burning velocity
- \( \dot{w} \): Reaction rate in terms of concentration

\[ \rho \dot{u} = \rho S_L = \dot{w} \delta \]  

(47)
\[ S_L = \left[ \frac{\lambda(T_f - T_i)}{\rho c_p(T_i - T_o) \frac{1}{\delta}} \right] \] 
\[ S_L = \left[ \frac{\lambda(T_f - T_i) \cdot w}{\rho c_p(T_i - T_o) \rho} \right]^{\frac{1}{2}} \]

The derivation process is expressed in more detail in reference [1]

2.4.9. Comments on the Mallard and Le Chatelier Theory:

**Comment 1:** If a thorough look is taken at equation (48) on this ratio \( \frac{T_f - T_i}{T_i - T_o} \), what is know is that usually \( T_f = T_i \) so the bigger \( T_i - T_o \) the smaller \( T_f - T_i \) that leads us to the conclusion pre-heating the air-fuel mixture speeds up the laminar burning velocity and this is a practical method and its proof is that its been used in various aspects in combustion engines and In the energy production sector.

**Comment 2:** The flame thickness is something not easy to control were \( \delta = \frac{\rho u}{w} \) because controlling the reaction rate means change the amount of fuel and oxidizer our even change the type of fuel used which is an impractical idea. This thickness should be in an ideal range \( \delta_{\text{min}} < \delta < \delta_{\text{max}} \) where if it is too small the flame will burnout and where it gets to thick it will also cause the chemical reactions to stop.

**Comment 3:** Another parameter is the gas mixture density \( \rho = \rho_{\text{air}} R_{\text{air}} + \rho_{\text{fuel}} R_{\text{fuel}} \) which should be as as small as possible and this can be accomplished by raising the pressure which in return decreases the mixture density as can be seen in this equation \( \rho = \frac{T_{\text{air}}}{P_{\text{air}}} R_{\text{air}} + \frac{T_{\text{fuel}}}{P_{\text{fuel}}} R_{\text{fuel}} \).

**Comment 4:** The thermal conductivity of methane decreases with the rise in temperature until it starts to become an insulator at high temperatures.
Comment 5: The Heat Capacity at Constant Pressure of methane decreases till 200(K) then with the rise in temperature there is a rise in its heat capacity starts.
2.4.10. The Theory of Zeldovich Frank-Kamenetskii, and Semenov:

The three Russian scientists derived an expression for laminar flame speed by an important extension of the very simplified Mallard-Le Chatelier approach.

![Figure 2-22: The balance across a methane flame differential element.](image)

\[ \rho_0 : \text{The initial fuel air density before combustion.} \]
\[ \lambda : \text{The thermal conductivity of the flame} \]
\[ T_f : \text{The flame temperature.} \]
\[ T_0 : \text{The initial temperature of the fuel air mixture before combustion} \]
\[ n_r : \text{The number of moles of reactants} \]
\[ n_p : \text{The number of moles of the products of reaction} \]
\[ R : \text{Gas constant} \]
\[ E : \text{Activation Energy} \]
\( (c_p)_f \): The specific heat value at constant pressure for the flame.

\( \bar{c}_p \): The average specific heat value at constant pressure between \( T_0 \) and \( T_f \).

\( D \): Thermal diffusivity.

A: Constant.

B: Constant.

\[-(D\rho) \frac{d^2(T/\rho)}{dx^2} + m \frac{d(T/\rho)}{dx} \cdot w = 0 \quad (50)\]

From the energy equation:

\[ \frac{d^2T}{dx^2} + \frac{wQ}{\lambda} = 0 \quad (51) \]

From solving this equation and relying on the boundary conditions that would lead us to the two equations:

\[ \frac{dT}{dx} = \left( 2 \frac{Q}{\lambda} \int_{T_i}^{T_f} w dT \right)^{\frac{1}{2}} \quad (52) \]

\[ \frac{dT}{dx} = \frac{m c_p}{\lambda} (T_f - T_0) \quad (53) \]

We know that the temperature before the flame thickness is nearly the same as the flame temperature:

\[ T_i \approx T_f \]

\[ \frac{dT}{dx} = \frac{m c_p}{\lambda} (T_f - T_0) \quad (54) \]

So we will get to this equation:

\[ \frac{m c_p}{\lambda} (T_f - T_0) = \left( 2 \frac{Q}{\lambda} \int_{T_i}^{T_f} w dT \right)^{\frac{1}{2}} \quad (55) \]

With the reliance on the three equation and the substitution of them in the top equation

\[ w = Z e^{-E/RT} \quad (56) \]

\[ m = S \rho \quad (57) \]

\[ Q = c_p (T_f - T_0) \quad (58) \]

\[ S_L = \left[ \frac{2}{a_0} \left( \frac{\lambda}{\rho_0 c_p} \right) (Z e^{-E/RT}) \left( \frac{E T_f^2}{E(T_f - T_0)} \right) \right]^{\frac{1}{2}} \quad (59) \]

\[ \frac{A}{B} = D \rho \left( \frac{\lambda}{c_p} \right) \]
First order equation:

\[
S_L = \left( \frac{2\lambda (c_p) Z' T_0}{\rho_0 c_p^2} \left( \frac{n_r}{n_p} \right) A \left( \frac{RT_f^2}{E} \right) \left( e^{-E/kT_f} \right) \right)^{1/2} \] .............. (60)

Second order equation:

\[
S_L = \left( \frac{2\lambda (c_p)^2 Z' \alpha_0 T_0}{\rho_0 (c_p)^3} \left( \frac{n_r}{n_p} \right)^2 A \left( \frac{RT_f^2}{E} \right)^2 \left( e^{-E/kT_f} \right) \right)^{1/2} \] .............. (61)

The derivation process is expressed in more detail in reference [1]

2.5. Turbulent Reacting Flows and Turbulent Flames:

2.5.1. The Rate of Reaction in a Turbulent Field:

A very good example of how fluctuating parameters can have a big affect on a reacting system, one can examine how the mean rate of a reaction would differ from the rate evaluated at the mean properties when there are no corrections among these properties. in flow reactors, time averaged concentrations and temperatures are usually measured, and then rates are determined from these quantities. Only by optical techniques or very fast response sensors (Thermocouples are the proper instantaneous rate values could be measured, and these would fluctuate with time). The fractional rate of change of a reactant can be written as

\[
\frac{\dot{w}}{w} = -k \rho^{n-1} Y_i^n = -A e^{-E/R} \left( P/R \right)^{n-1} T^{1-n} Y_i^n \] ....... (62)

Where the \( Y_i \)'s is the mass fractions of the reactants. The instantaneous change in rate is given by

\[
d\dot{w} = -A P/R \left( d \frac{P}{R} \right)^{n-1} \left[ \frac{E}{RT^2} e^{-E/RT} T^{1-n} Y_i^n dT + (1-n) T^{-n} e^{-E/RT} Y_i^n dT + ne^{-E/RT} T^{1-n} Y_i^{n-1} dY \right]
\]

\[
d\dot{w} = \left( \frac{E}{RT} \right) \frac{w}{w} \left( dT/T \right) + (1-n) \frac{w}{w} \left( dT/T \right) + w n \frac{dY_i/Y_i} \]

or

\[
\frac{d\dot{w}}{w} = \left[ \frac{E}{RT} + (1-n) \right] \frac{dT}{T} + n \frac{dY_i}{Y_i} \] .............. (63)
For nearly all hydrocarbons flame or reacting systems the overall order of reaction is about 2,E/R is some where 20,000K, and the flame temperature comes to about 2000K, that leads us to equation 64,

\[ \left( \frac{E}{RT} \right) + (1 - n) \equiv 9 \quad \cdots \quad (64) \]

it is noticeable that the temperature variation is the dominant factor in turbulent reacting flows. The temperature effect comes into this situation having a relation with the specific reaction rate that is constant, the problem can be simplified by whether to consider the mean rate constant. This can be represented by the rate constant evaluated at the mean temperature.

In this hypothetical simplified problem one assumes further that the temperature \( T \) fluctuates with time around some mean represented by the form shown on equation 65:

\[ \frac{T(t)}{\bar{T}} = 1 + a_n f(t) \quad \cdots \quad (65) \]

where \( a_n \) is the amplitude of the fluctuation and \( f(t) \) is some time-varying function in which

\[-1 \leq f(t) \leq +1 \quad \cdots \quad (66)\]

And

\[ \bar{T} = \frac{1}{\tau} \int_{0}^{\tau} T(t) \, dt \quad \cdots \quad (67) \]

Over some time interval \( \tau \). in conclusion \( T(t) \) can be considered to be composed of \( \bar{T} + T'(t) \), where \( T' \) is the fluctuating component around the mean temperature as can be seen on figure 2-22.

![Figure 2-23: The temperature at different time intervals.](image-url)
By ignoring the temperature dependence in the pre-exponential, one writes the instantaneous-rate constant as

$$K(T) = A \exp\left(-\frac{E}{RT}\right) \quad \ldots \quad (68)$$

and the rate constant evaluated at the mean temperature as:

$$K(\bar{T}) = A \exp\left(-\frac{E}{RT}\right) \quad \ldots \quad (69)$$

Dividing the two expressions, one obtains:

$$\frac{K(T)}{K(\bar{T})} = \exp\left(\frac{E}{RT}\left[1 - \frac{\bar{T}}{T}\right]\right) \quad \ldots \quad (70)$$

Obviously, then, for small fluctuations:

$$1 - \frac{\bar{T}}{T} = \left[\frac{a_n f(t)}{1 + a_n f(t)}\right] = a_n f(t) \quad \ldots \quad (71)$$

The expression for the mean rate is written as:

$$\int_{\tau_0}^{\tau} dt \frac{K(T)}{K(\bar{T})} = \frac{1}{\tau} \int_{\tau_0}^{\tau} \frac{k(T)}{K(\bar{T})} dt = 1 + \frac{1}{\tau} \int_{\tau_0}^{\tau} \exp\left(\frac{E}{RT} a_n f(t)\right) dt \quad \ldots \quad (72)$$

$$\frac{K(T)}{K(\bar{T})} = \frac{1}{\tau} \int_{\tau_0}^{\tau} \left[1 + \frac{E}{RT} a_n f(t) + \frac{1}{2}\left(\frac{E}{RT} a_n f(t)^2\right) + \ldots\right] dt \quad \ldots \quad (73)$$

But recall

$$\int_{\tau_0}^{\tau} f(t) dt = 0 \text{ And } 0 \leq f^2(t) \leq 1 \quad \ldots \quad (74)$$

Examining the third term in equation 73, it is apparent that

$$\frac{1}{\tau} \int_{\tau_0}^{\tau} a_n^2 f^2(t) dt \leq a_n^2 \quad \ldots \quad (75)$$

Since the integral of the function can never be greater than 1 thus,

$$\frac{K(T)}{K(\bar{T})} \leq 1 + \frac{1}{2}\left(\frac{E}{RT} a_n\right)^2 \quad \text{Or } \Delta = \frac{k(T) - K(\bar{T})}{k(\bar{T})} \leq \frac{1}{2}\left(\frac{E}{RT} a_n\right)^2 \quad \ldots \quad (76)$$

If the amplitude of the temperature fluctuations is of the order of 10% of the mean temperature, one can take $a_n \approx 0.1$; and if the fluctuations are considered sinusoidal, then

$$\frac{1}{\tau} \int_{\tau_0}^{\tau} \sin^{-2} t dt = \frac{1}{2} \quad \ldots \quad (77)$$

Thus for the example being discussed,
\[ \Delta = \frac{1}{4} \left( \frac{E}{RT} a_n \right)^2 = \frac{1}{4} \left( \frac{40000 \times 0.1}{2 \times 2000} \right)^2, \Delta = \frac{1}{4} \] ...... (78)

Or a 25% difference in the two rate constants.

This result could be improved by assuming a more appropriate distribution function of \( T' \) instead of a simple sinusoidal fluctuation as can be seen on figure 2-23; however, this example—even with its assumptions—usefully illustrates the problem. Normally, probability distribution functions are chosen. If the concentrations and temperatures are correlated, the rate expression becomes very complicated and therefore needs very powerful computers to conduct the calculations [1].

![Comparison between a sinusoidal combustion wave and a real combustion wave](image1)

**Figure 2-24:** a comparison between a sinusoidal combustion wave at the top and a real combustion wave at the bottom [17].
Regimes of Turbulent Flame Speed: The previous section 2-5-1 epitomizes and gives a better understanding of how reacting mixtures can be affected by a turbulent field. To understand the detailed effect, one must understand the elements of the field of turbulence. When considering turbulent combustion systems in this regard a suitable starting point is the consideration of the quantities (fuel rich our a fuel lean case) that determines the fluid characteristics of the system.

2.5.2. The Turbulent Flame Speed:

Although a laminar flame speed \( S_L \) is a physicochemical and chemical kinetic property of the unburned gas mixture that can be assigned, a turbulent flame speed \( S_T \) is, in reality, the mass consumption rate per unit area divided by the unburned gas mixture density. This means, \( S_T \) must be a function of the properties of the turbulent field in which it exists and the method by which the flame is stabilized.

![Figure 2-25: The approximation of the turbulent flame to a cone shape.](image)

Area of the cone is:

\[
A_{conearea} = r \pi s \quad \ldots \ldots \quad (79)
\]

Area of the base is:
The base area is neglected in the calculation because we are only interested in the cone area.

\[
A_{basearea} = \pi r^2 \quad \ldots \ldots \quad (80)
\]
There for the formula is:

\[ SA = r \pi s + \pi r^2 \quad \cdots \cdots \quad (81) \]

- \( u' \): Turbulence intensity
- \( t \): Time
- \( l_o \): The flame base diameter
- \( h \): Cone height
- \( A_c \): Cone area
- \( A_B \): Cone base area
- \( S_L \): Laminar burning velocity
- \( S_T \): Turbulent burning velocity

**Figure 2-26:** Model of combustion wave in a turbulent flow.

The turbulence intensity is the change of the height of the flame with time. This is shown in figure 2-26.
\[ u' = \frac{h_2 - h_1}{t_2 - t_1} = \frac{h}{t} \quad \text{............ (82)} \]

**Figure 2-27:** The difference with height at time intervals gives us the turbulence fluctuation.

\[ S_L = \frac{\pi l_0^2}{4t} \quad \text{................... (83)} \]

**Figure 2-28:** shows the laminar burning velocity at one of the cross sections of the flame.

To begin the deriving process:

Surface area=area of the cone
\[ A_c = r \pi S \]
\[ A_c = \pi \frac{l_0}{2} S \]
\[ A_c = \pi \frac{l_0}{2} \sqrt{h^2 + R^2} \]
\[ A_c = \pi \frac{l_0}{2} \sqrt{h^2 + \frac{l_0^2}{4}} \]
\[ A_c = \pi \frac{l_0^2}{4} \sqrt{\frac{4h^2}{l_0^2} + 1} \]
\[ A_c = A_B \left(1 + \left(\frac{4h/l_0}{l_0^2}ight)^2\right)^{1/2} \]

By the division of both sides of the equation with \( t \):
\[ \frac{A_c}{t} = \frac{A_B}{t} \left(1 + \left(\frac{2h}{l_0^2} \frac{1}{t}\right)^2\right)^{1/2} \]

This leads us to the final shape of the equation:
\[ S_r = S_s \left(1 + \left(\frac{2u'/S_c}{2}\right)^2\right)^{1/2} \] \[ \text{................. (84)} \]
Figure 2-29: A 3D look on a combustion wave in a turbulent flow with a slice of a flame profile taken from a larger flame.
Figure 2-30: LES predictions of a free-propagating turbulent premixed methane-air flame using thickened flame with power-law flame wrinkling subfilter scale models[17]
2.6. Length Sales in Turbulent Flows

2.6.1 Characteristic Width of Flow or Microscale L:
This is the largest length scale in the system and is the upper bound for the largest possible eddies. Example 1: in a pipe flow the largest eddy would be equal to the pipe diameter. Example 2: in a jet flow L would be the local width of the jet at any axial location. Example 3: in a reciprocating internal combustion engine might be taken as the time-varying clearance between the piston top and the head, or perhaps the cylinder bore.
Conclusion: In general this length scale is defined by the actual hardware or device being considered. This length scale is frequently used to define a Reynolds number based on the mean flow velocity, but is not used to define turbulence Reynolds number, as are the other three length scales.

2.6.2 Integral Scale or Turbulence Microscale, \( l_o \) The integral scale:
Physically represents the mean size of the larger eddies in a turbulent flow those eddies with low frequency and large wave length.

*Figure 2-31:* shows due in a flow which illustrates large eddies with low frequency and large wave length.

The integral scale is always smaller than L, but is of the same order of magnitude.
Operationally, the integral scale can be measured by integrating the correlation coefficient for the fluctuating velocities obtained as a function of the distance between two points

\[
l_o = \int_0^\infty R(x)dx \quad \ldots \ldots \quad (85)
\]
Where:

\[ R_s (r) = \frac{v_s'(0)v_s'(r)}{v_{x,\text{rms}}'(0)v_{x,\text{rms}}'(r)} \quad \text{......... (86)} \]

In less precise terms, \( l_0 \) represents the distance between two points in a flow where these ceases to be a correlation between the fluctuating velocities at the two locations.

### 2.6.3 Taylor Microscale \( l_\lambda \):

The Taylor Microscale is an intermediate length scale between \( l_0 \) and \( l_k \), but is weighted more towards the smaller scales. This scale is related to the mean rate of strain and can be formally expressed as

\[ l_\lambda = \frac{v_{x,\text{rms}}}{\sqrt{\left( \frac{\partial v_x}{\partial x} \right)^2}} \quad \text{......... (87)} \]

Where the denominator represents the mean strain rate.

### 2.6.4 Kolmogrov Microscale \( l_k \):

The Kolmogrov micro scale is the smallest length scale associated with a turbulent flow and as such, is representative of the dimension at which the dissipation of turbulent kinetic energy to fluid internal energy occurs. Thus, the Kolmogrov scale is the scale at which molecular effects (kinematic viscosity) are significant. Dimensional arguments show that \( l_k \) can be related to the rate of dissipation, \( \varepsilon_0 \) as

\[ l_k = \left( \frac{v^3}{\varepsilon_0} \right)^{\frac{1}{4}} \quad \text{.........(88)} \]

where \( v \) is the molecular kinematic viscosity, and the dissipation rate is approximately expressed as

\[ \varepsilon_0 = \frac{\delta(kl_{\text{turb}})}{\partial t} = \frac{3v^{''} v_{\text{rms}}}{l_0} \quad \text{.........(89)} \]
Note that the integral length scale \( l_o \) appears in the approximation for the dissipation rate, thereby linking the two scales.

### 2.6.5 Turbulence Reynolds Numbers:

Three of the four length scales discussed above are used to define three turbulence Reynolds numbers. In all of the Reynolds numbers, the characteristic velocity is the root-mean-square fluctuating velocity, \( v_{rms}' \). Thus, we define:

\[
Re_{l_o} \equiv \frac{v_{rms}' l_o}{v} \quad \text{................... (90)}
\]

\[
Re_{l_\lambda} \equiv \frac{v_{rms}' l_\lambda}{v} \quad \text{................... (91)}
\]

And

\[
Re_{l_k} \equiv \frac{v_{rms}' l_k}{v} \quad \text{................... (92)}
\]

Equations 90 and 91 defining \( l_k \) and the dissipation rate \( \varepsilon_0 \) can be used to relate the largest (the integral) and the smallest (the Kolmogorov) turbulence length scales:

\[
\frac{l_o}{l_k} = Re_{l_k}^{3/4} \quad \text{................... (93)}
\]

The Taylor micro scale, \( l_\lambda \), also can be related to \( Re_{l_o} \) as follows:

\[
\frac{l_o}{l_\lambda} = Re_{l_o}^{1/2} \quad \text{................... (94)}
\]

Equation 93, expresses, in a semi quantitative way, the wide separation of length scales in high-Re flows discussed earlier in this chapter. For example, with \( Re_{l_o} = 1000 \), the ratio \( l_o / l_k \) is about 178; but when \( Re_{l_o} \) is increased to 10000, by increasing the mean flow velocity, say, the ratio becomes 1000:1.

### 2.7. Flame Regimes and Governing Physical Phenomena:

The interaction between the turbulent flow field and the flame front is described by means of characteristic dimensionless numbers.

The most commonly used are the:

#### 2.7.1. The turbulent Reynolds number (\( Re_T \)):

The Reynolds number describes the ratio of the momentum forces (destabilizing effects) to the viscous forces (stabilizing effect). Reacting flows at high turbulence Reynolds numbers are characterized by highly fluctuating flames.
\[ \text{Re}_r = \frac{u' L_T}{S_L \delta_L} \] ..............(95)

2.7.2. The Damköhler number (\( Da \)):

Is a number that relates the time scale of the turbulent mixing defined as \( L_T/u' \) to the time scale of the chemical reaction defined as \( \delta_L/S_L \).

There are two distinguishable cases for Damköhler number:

A-Large Damköhler numbers (\( Da >> 1 \)):

Refers to a flame where the chemistry is fast and thus the combustion is controlled by mixing processes. As a result these flames form structures of a sheet type.

B-Flame at small Damköhler numbers (\( Da < 1 \)):

Are characterized by intense mixing. The reaction of combustion is controlled by chemical kinetics and flames referred to as well-stirred reactor are formed.

\[ Da = \frac{\tau_m}{\tau_c} = \frac{L_T S_L}{u' \delta_L} \] .................(96)

2.7.3. Karlovitz number (\( Ka \)):

Defined as in Equation (97). The Karlovitz number relates the thickness of the reaction zone represented by the laminar flame thickness \( \delta_L \) to the smallest scales of the turbulent flow represented by the Kolmogorov microscale \( \eta \). Thus the Karlovitz number can be used as a measure of the flame front stretch.

Note: The relations have been derived with the assumption that the thermal diffusivity is equal to the mass diffusivity (Schmidt number \( Sc \equiv 1 \)).

\[ Ka = \left( \frac{L_T}{\delta_L} \right)^{-\frac{1}{2}} \left( \frac{u'}{S_L} \right)^{\frac{3}{2}} \] .................(97)

Using these three characteristic numbers (\( \text{Re}_r, Da \) and \( Ka \)) it is possible to classify the turbulent premixed flames into groups (flame regimes) as already been classified by the scientist Borghi and later extended by Peters.
2.7.4. Lewis Number (Le):

Lewis number is a dimensionless number defined as the ratio of thermal diffusivity to mass diffusivity. It is used to characterize fluid flows where there is simultaneous heat and mass transfer by convection.

\[ Le = \frac{\alpha}{D} \]

where \( \alpha \) is the thermal diffusivity and \( D \) is the mass diffusivity.

2.7.5. Description of the Borghi chart:

1-The \( L_T / \delta_L \) -axis in Figure characterizes the size of the flame structures by means of the ratio of the characteristic length scales (Integral Length Scale of turbulence \( L_T \) to the laminar flame thickness \( \delta_L \)). The characteristic size of the turbulent flow (e.g. vortices) in comparison to the laminar flame thickness grows along the x-axis.
2- The $u'/S_L$ axis refers to the ratio of characteristic velocities represented by an intensity of the flow field fluctuation (turbulence intensity $u'$) to the laminar flame speed $S_L$. The flame regimes of turbulent premixed flames ($Re_T > 1$) and their characteristics are summarized in (figure 2-33).

All of the flame regimes listed in (figure 2-33) except the well stirred reactor are characterized by a Damköhler number on the order or larger than 1 which refers to “fast chemistry” i.e. the reaction zone is relatively thin (fraction of a millimeter for $p > p_{atm}$) and the flame front can be treated as a discontinuity. The characterization of the flame front is in the focus of most of investigations of the turbulent premixed flames. The pictures presented in the last column of figure (2-33) illustrate the main characteristic properties of the flame fronts. The grey color represents the fresh gas mixture (unburned reactants) and the white color the exhaust gases (burned products). The black thick line which separates products and reactants represents the flame front which propagates from right to left in a stagnant fluid [21].

![Figure 2-33: the classification of flame regimes based on three characteristic numbers [21].](image-url)
2.8. Flame Speed Measurements

The Various Experimental Configurations used for flame speed may be classified under the following headings:

A-conical stationary flames on cylindrical tubes and nozzles
B-flames in tubes
C-Soap bubble method
D-constant volume explosion in spherical vessel
E-Flat Flame methods

The methods are listed in order of decreasing complexity of flame surface and corresponds to an increasing complexity of experimental arrangement. Each has certain advantages that attend its usage.

1-burner method
2-cylindrical tube method
3-soap bubble method
3. Experimental setup

3.1. Atmospheric-pressure test facility
All combustion experiments were performed in a generic, cylindrical combustor shown in figure 3-1. High pressure air is passed through the seeder and then mixed with methane the later mixture is then passed through the different types of turbulence plates. Then data is collected and stored on the computer hard drive to be analyzed later.

Figure 3-1: Shows the cylindrical atmospheric test facility.

The liner consists of two coaxial quartz glass tubes (inner quartz glass tube diameter \(D = 75\) mm) which are cooled by natural draft free convection with air.
The combustor inlet diameter $d$ is 25 mm. The flame is stabilized aerodynamically via the recirculation of hot flue gases, induced by the combustor geometry and different installed turbulence plates.

A methane torch igniter (pilot) is used to ignite the homogeneously premixed methane/air mixture. The high level of optical access required for non-intrusive laser diagnostics is provided by the four circular windows.

The turbulence intensity $u'$ and the integral length scale $L_I$ in the inlet are varied by using different turbulence grids (different hole diameters and blockage ratios) or by mounting these grids at different axial positions within the combustor inlet section. The nomenclature of the grids is explained in Figure 3-2.

![Figure 3-2: shows different types of blockage plates.](image)

**Table 3-1 : The Turbulence Plates characteristics :**

<table>
<thead>
<tr>
<th>Diameter of Blank (mm)</th>
<th>Hole Diameter (mm)</th>
<th>Number of Holes</th>
<th>Blockage Ratio %</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>2</td>
<td>61</td>
<td>61</td>
</tr>
<tr>
<td>25</td>
<td>3</td>
<td>37</td>
<td>47</td>
</tr>
<tr>
<td>25</td>
<td>4</td>
<td>19</td>
<td>51</td>
</tr>
</tbody>
</table>

The grid name consists of information about the diameter of the hole in millimeters followed by the blockage ratio (as shown on table 3-1). The position of the grid in the inlet section of the combustor is normalized by the grid-hole diameter. For example
g350xg10 refers to a grid with a hole diameter (dg = 3 mm) and a blockage ratio (bg) of 50% is mounted at 10×dg = 30 mm upstream in the inlet channel (Figure 3-4).

![Figure 3-3: a cross section through the cylindrical atmospheric test bench.](image)

### 3.2. Dantec automated data collection module:

It is connected up with a pc and is given the orders to take samples at certain points and these points are predetermined by the researchers, the hole points form the grid the more points you have the more time is needed to take the samples but you will have more accurate data. For the lab case there was no interest to move the rig on the z axis. So the movement was restricted on the x and y axis.
**Figure 3-4:** is a clear diagram of the Dantec module showing the x, y and z axis of movement.

The pressurized air is supplied from a high-pressure compressor near the lab building and methane is from the city gas supply. The camera with the test-rig operation is controlled from a PC using the data acquisition software. The schematic of the control and supply system is presented in Figure 3-5.
Figure 3-5: The whole test apparatus with all of its secondary circuits.
4. Measuring Techniques

4.1. Introduction:
In the first part of this chapter Principles of Particle Image Velocimetry (PIV) are briefly described. The next part describes Principles Laser Doppler Anemometry (LDA). The third part is devoted to aluminum oxide seeding. Finally in the fourth part is about the high speed imagery camera used.

4.2. Principles of Particle Image Velocimetry (PIV)
Particle Image Velocimetry (PIV) is an optical non-intrusive technique for measurements of instantaneous velocity field.

The main topics in a PIV system are
1-Seeding
2-Camera
3-Laser
4-Correlation
Validation and further analysis

Figure 4-1: Particle Image Velocimetry [16]
4.3. Description of PIV:

Particle Image Velocimetry (PIV) is a measurement technique for obtaining instantaneous whole field velocities. It is based on the well-known equation in PIV, the property actually measured is the distance traveled by particles in the flow within a known interval of time. These particles are added to the flow and are known as seeding. 10µm silver coated glass particles are used as the seeding particles in this set up.

\[
    u = \frac{\Delta x}{\Delta t} \quad \text{(99)}
\]

A light sheet produced by the laser is used to illuminate the particles. A high-speed imaging system (camera) detects the position of the particles. It takes two pictures separated in time and the distance moved by the particles in this time is used to determine their velocities figure 4-2.

**Figure 4-2:** Interrogation areas the seeding particles where the grey particles where taken at time t1 and the red particles taken at t2.
The camera images are divided into rectangular regions called the interrogation areas, and for each of these interrogation areas the image from the first and the second pulse of the light sheet are correlated to produce an average particle displacement vector. Doing this for all the interrogation areas produce a vector map of average particle displacements figure 4-4. The calculation of the particle displacement is based on an analysis of the PIV images. Consequently the calculation yields one vector per every pair of the interrogation windows. From figure 4-2 dividing with the known time between the two images captured the displacement vectors are converted into a map of so-called raw velocity vectors. Applying validation algorithms to the raw vector maps, the erroneous vectors are detected and removed. Further analysis of these validated vectors will produce streamlines, vorticity, and turbulence as can be seen on figure 4-4 [16].

![Figure 4-3](image)

**Figure 4-3:** showing the camera and the particles and the interrogation areas.
Figure 4-4: shows the vectors plotted by the soft wear after the collection of data and its analysis been conducted.
4.4. Principles of LDA:
Back scatter LDA is shown on figure 4-1 back scatter is the light collected after being reflected from the moving particles. The distance \( f \) refers to the distance from the laser lens to the point of laser beam concentration.

![Figure 4-5: Principles of backscatter LDA.](image)

4.4.1. Laser beam:
Gas lasers are very powerful tools to be used to measure mechanical properties, At one point the cross section attains its smallest value, and the laser beam is uniquely described by the size and position of this so called beam waist. With a known wave length \( \lambda \) of the laser light, the laser beam is uniquely described by the size \( d_0 \), and the position of the beam waist as shown on figure 4-1.

With \( z \) describing the distance from the beam waist, the following formulas apply:

![Figure 4-6: Laser beam with Gaussian intensity distribution](image)
With $z$ describing the distance from the beam waist, the following formulas apply:

\[
\text{Beam divergence } \alpha = \frac{4\lambda}{\pi d_0} \quad (100)
\]

\[
\text{Beam diameter } d(z) = d_0 \sqrt{1 + \left(\frac{4\lambda z}{\pi d_0^2}\right)^2} \quad (101)
\]

\[
\text{Wave front radius } R(z) = z\left[1 + \left(\frac{\pi d_0^2}{4\lambda z}\right)\right] \quad (102)
\]

The beam divergence $\alpha$ is much smaller than indicated in figure 4-2, and visually the laser beam appears to be straight and of constant thickness. It is important however to understand that this is not the case, since measurements should take place in the beam waist to get optimal performance of any LDA-equipment. This is due to the wave fronts being straight in the beam waist, and curved elsewhere, and will be explained in the next part.

The wave front radius approach infinity for $z$ approaching zero, meaning that the wave fronts are approximately straight in the immediate vicinity of the beam waist. This means that the theory of plane waves can be used here, greatly simplifying calculations.

### 4.4.2 Doppler Effect:

The Doppler Effect plays an important role in LDA, since the technique is based on Doppler shift of the light reflected (and/or refracted) from a moving seeding particle.

![Light scattering from a moving seeding particle.](image)

**Figure 4-7:** Light scattering from a moving seeding particle.
Based on the Lorenz-Mie scattering theory, light is scattered in all directions instantaneously, but due to our interest we only take into consideration the light reflected towards the receiver.

The illustration in figure 4-3 where the vector $U$ represents the particle velocity, and the unit vectors $e_i$ and $e_s$ describe the direction of incoming and scattered light respectively. The incoming light has the velocity $c$ and the frequency $f_i$, but due to the particle movement, the seeding particle “sees a different frequency $f'_p$, which is scattered towards the receiver. From the receiver's point of view, the seeding particle act as a moving transmitter, and the movement introduce additional Doppler–shift in the frequency of the light reaching the receiver.

Using Doppler-theory, the frequency of the light reaching the receiver can be calculated as:

$$f_s = f_i \frac{1 - e_i (U/c)}{1 - e_s (U/c)} \quad \ldots \quad (103)$$

Even for supersonic flows the seeding particle velocity $U$ is much lower than the speed of light, meaning that $|U/c| \ll 1$.

Taking advantage of this, the above expression can be linearized to:

$$f_s \approx f_i [1 + \frac{U}{c} (e_s - e_i)] = f_i + \frac{f_i}{c} U (e_s - e_i) = f_i + \Delta f \quad \ldots \quad (104)$$

With the particle velocity $U$ being the only unknown parameter, in principle the particle velocity can be determined from measurements of the Doppler shift $\Delta f$.

### 4.4.3. Intersecting beams:

In practice this frequency change can only be measured directly for very high particle velocities (Fabry-Perot interferometer). More commonly the light scattered from two intersecting laser beams is mixed as illustrated in figure 4-3.
In this way both incoming laser beams are scattered towards the receiver, but with slightly different angles of the two laser beams.

\[ f_{s,1} = f_1 \left(1 + \frac{U}{C}(e_s - e_1)\right) \] \hspace{1cm} (105)

\[ f_{s,2} = f_2 \left(1 + \frac{U}{C}(e_s - e_2)\right) \] \hspace{1cm} (106)

4.4.4 Doppler frequency:

When two wave’s trains of slightly different frequency are super-imposed, we get the well-known phenomenon of a beat frequency due to the waves intermittently interfering with each other constructively and distractively. The beat frequencies correspond to difference between two wave-frequencies, and since the two incoming waves originate from the same laser, they also have the same frequency, \( f_1 = f_2 = f \) where subscript 1 refer to incident light:

\[ f_D = f_{s,2} - f_{s,1} \] \hspace{1cm} (107)
4.4.5. The Fringe model:
Although the above description of LDA is accurate, it may be intuitively difficult to quantify. To handle this, the fringe model is commonly used in LDA as a reasonably simple visualization.

![Fringes from where two coherent laser beams cross.](image)

**Figure 4-9**: Fringes from where two coherent laser beams cross.

4.5. The seeding:
4.5.1 Aluminum oxide seeding:

Aluminum is known to produce several molecular band systems. Two in particular, arising from AlO+, should be seen at 435–500 nm and 508–518 nm, the most intense emission centered at 484 nm. The atomic line emission of aluminum should occur at 396.2 nm when flame temperatures are hot enough to allow aluminum to exist in the atomic form. The relative intensities of the atomic line versus molecular bands will vary depending on flame temperature. Higher temperatures will produce more atomic species as the molecules are dissociated. The atomic line emission intensities should rise as the molecular band emissions decrease.

4.5.2 Properties of the seeding material:

The optimal seeding is characterized by:
1. Particles small enough to follow the flow (able to follow the flow).
2. Particles big enough to scatter sufficient amount of light (Good light scatters).
3. Particles homogenously distributed within the flow.
4. Particles chemically inactive (in combustion experiments).
5. Non-volatile, or slow evaporate.
6. Chemically inactive.
7. Clean.
8. Cheap.

**4.5.3 Seeding as flow field tracers:**
In general the motion of particles suspended in a field is affected by
1- Particle shape.
2- Particle size.
3- Relative density of a particle and fluid.
4- Concentration of particles in the fluid.
5- Body forces.
The shape of the seeding particles affect the drag exerted on the particle by the surrounding fluid, and the size of particles along with their relative density influence their response to velocity change of the surrounding fluid.
The concentrations of particles affect particle motion through interaction between different particles. In practice the concentrations used normally so low, that particle interaction can be neglected.
Also body forces, such as gravity, can normally be ignored, except in very slow flows, where buoyancy of the seeding particles may be in an issue. Also in experiments including for example electrostatic fields, body forces may be of importance, but in such cases they can not really be considered a disturbance.

**4.5.4 Particle motion:**
Since the analysis of particle motion is rather complicated even for spherical particles and real particles can’t be modelled properly any way, only spherical particles in an infinite fluid have been analysed. It is assumed, that the results apply qualitatively also for
particles of more irregular shape. This assumption is a good for liquid particles and fair for monodisperse particles, but poor for other solid particles, such as add agglomerates.

\[
\frac{\pi}{6} d_p^3 \rho_p \frac{dU_p}{dt} = -3\pi \mu d_p V + \frac{\pi}{6} d_f^3 \rho_f \frac{dU_f}{dt} - \frac{\pi}{12} d_p^3 \rho_f \frac{dV}{dt} - \frac{3}{2} d_p^2 \sqrt{\pi \mu \rho_f} f_{t_0} \frac{dV}{d\xi} \frac{d\xi}{\sqrt{(t-\xi)}} \quad \ldots \quad (108)
\]

Where subscript \( p \) refer to the seeding particle and subscript \( f \) refer to the field.

The first term in this equation represents the
Note that when the first, third and fourth terms are combined, the accelerating force is equivalent to that of a sphere whose mass is increased by an additional “virtual mass” equal to half the mass of the displaced fluid.

The above equation is valid within the following assumption
1-the turbulence is homogeneous and time-invariant.
2-particles are smaller than the turbulence micro scale.
3-stokes drag law applies (particles are spherical)
4-there is no interaction between particles.

Furthermore external forces, such as gravitational, centrifugal and electrostatic forces have been ignored.

4.6. Photron’s APX-RS high-speed system camera:

The **Ultima APX-RS** provides full mega pixel resolution images at frame rates up to 3,000 frames per second (fps), 512 x 512-pixels resolution at 10,000fps and at reduced frame rates to an unrivaled frame rate of 250,000fps. Utilizing Photron’s advanced CMOS sensor technology, the **APX-RS** provides the higher light sensitivity than any other comparable high-speed imaging system [14].
Figure 4-10: shows the high imagery used in the experiments [14].
5. Results and Discussion

5.1. Turbulence plates fluid dynamics data:

5.1.1. Introduction:

This data is very useful because it illustrates what are the velocity conditions in the chosen section of the flame while at the same time comparing this velocity with the bulk velocity, so it’s like comparing the kinetic energy of the oxide seeding before and after the combustion process. Fluid dynamic data should be presented in terms carefully chosen non dimensional parameters sensitive to major variables of the flow to obtain reliable information. Note that $v/v_{\text{bulk}}$ is the same as $v_{\text{mean}}/v_{\text{bulk}}$ in graphs (1, 3, 5, and 7).

It is assumed that:
- That the graphs (1, 2, 3, 4, 5, 6, 7, 8) are asymmetric around the y axis.
- Steady state process occurs where no change in mass flow and no change in mixture ratios, constant Stochiometric ratio.
- Constant atmospheric parameters surrounding the flame.

5.1.2. Clear factors affecting the velocity parameters in graphs (1, 2, 3, 4, 5, 6, 7, and 8):
- Looking at the tips of the curves, the wall shear stress has an effect on slowing down the gaseous mixture and in return $v_{\text{mean}}$ will be affected while $v_{\text{rms}}$ will be less affected and that is clear in cross sections from $y=1$ to 4. Point of inflexion occurs in cross section $y=5\text{mm}$ where there is an increase in $v_{\text{mean}}$ and $v_{\text{rms}}$ that is due to the chemical reaction and combustion where the aluminium oxide particles gain kinetic energy and move faster in y axis direction, at the burning of the flame at the outer tips, a suction effect is created by the reaction zone.

- Graph (1, 3, 5, and 7) have the same profile layout for all cross sections where the core has parabolic profile which is similar to $V_{\text{mean}} = V_{\text{mean max}} \left(1 - \left(\frac{r}{R}\right)^2\right)$ and the tips have a jump in velocity. The only difference between graph (1, 3, 4) and (7) is that the velocity
Turbulence ratio $v_{\text{mean}} / v_{\text{bulk}}$ in the core for (1, 3, 5) is more well uniformly distributed out compared with graph (7) which shows a clear difference between having a turbulence plate and not having one.

- There is a similarity between graph (1, 2) and graph (7, 8) in velocity ratio profiles except one has a turbulence disc (the first) and one does not (the second). The uniformity of the first is better than the second.
- There is a different velocity ratio profile for each of the three graphs (2, 4, 6) with totally different profiles.
- From graph (1, 3, 5, 7) what is quiet clear the velocity ratio $v_{\text{mean}} / v_{\text{bulk}}$ at $x = 0$ for all $y$ values is in the range of $1.5 < v_{\text{mean}} / v_{\text{bulk}} < 2$.
- looking in depth at (1, 3, 5) graphs the inflection point at $x = \pm 9$ is about $1.4 < v_{\text{mean}} / v_{\text{bulk}} < 1.6$.
- it is noted that in graph 4 is how $v_{\text{rms}} / v_{\text{bulk}}$ is the range $0.05 < v_{\text{rms}} / v_{\text{bulk}} < 0.1$ at all $y$ values and then there is a sudden jump in the velocity ratio at $x = \pm 9$ to a value of in the range of $0.125 < v_{\text{rms}} / v_{\text{bulk}} < 0.2$.
- One of the very clear velocity ratio profiles $v_{\text{rms}} / v_{\text{bulk}}$ on graph 4 which was not clear in any of the other graphs concerned with 2mm and 4mm plate of all the diagrams is that the velocity profile of 7 parabolic profiles (there are 5 small peaks in the core and 2 large peaks at the tips).
- In graph 6 you can count the number of holes by pointing out the peaks which count to 5 where the core peak is the largest while the 2 peaks on the left and on the right are smaller.
- Considering at graph 2 very closely can only show 5 holes profiles out of 9 due to the unification of the profiles at the core.
- The velocity ratio $v_{\text{mean}} / v_{\text{bulk}}$ from graph (1, 3, 5, and 7) at $x = \pm 12.5$ for different $y$ values is in the ranges $0.5 < v_{\text{mean}} / v_{\text{bulk}} < 2.5$. 
5.1.3. The Graphs with a turbulence plate:

Graph 1: The $v/v_{bulk}$ relation with x and y coordinates for 2 mm disc.
Graph 2: The $v_{\text{rms}}/v_{\text{bulk}}$ relation with x and y coordinates for 2 mm disc.
Graph 3: The $v/v_{bulk}$ relation with x and y coordinates for 3 mm disc.
Graph 4: The $\frac{v_{rms}}{v_{bulk}}$ relation with x and y coordinates for 3 mm disc.
Graph 5: The $v/v_{\text{bulk}}$ relation with x and y coordinates for 4 mm disc.
Graph 6: The $v_{rms}/v_{bulk}$ relation with x and y coordinates for 4 mm disc.
Graph 7: The $v/v_{\text{bulk}}$ relation with $x$ and $y$ coordinates for a 25mm diameter tube.
Graph 8: The $v_{rms}/v_{bulk}$ relation with x and y coordinates for a 25mm diameter tube.
5.1.5. The summary chart of the data (Makky chart):

This chart helps out the reader in pointing out directly which turbulence plate has a high or low $v_{rms}/v_{bulk}$ value and the same can be conducted on the value $v_{mean}/v_{bulk}$. The four cases are represented in the graph. The chart is not that accurate because the method conducted in finding it parameters is averaging the $v_{mean}/v_{bulk}$ for each y value and then taking the average for the averaged values the method is illustrated in the two equations:

$$
\frac{v_{mean}}{v_{bulk}}_{\text{average}} = \frac{(v_{mean}/v_{bulk})_{y=1}^{y=2} + (v_{mean}/v_{bulk})_{y=2}^{y=2} + \ldots (v_{mean}/v_{bulk})_{y=20}^{y=20}}{8} \quad (109)
$$

$$
\frac{v_{rms}}{v_{bulk}}_{\text{average}} = \frac{(v_{rms}/v_{bulk})_{y=1}^{y=2} + (v_{rms}/v_{bulk})_{y=2}^{y=2} + \ldots (v_{rms}/v_{bulk})_{y=20}^{y=20}}{8} \quad (110)
$$

So to illustrate a 2mm turbulence plate we need two coordinates which are as follows

$$
(v_{mean}/v_{bulk})_{2mm}^{2mm}, (v_{rms}/v_{bulk})_{2mm}^{2mm}
$$

Note: that the averaged quantities where divided over 8 because the data provided had been taken at the following cross sections y=1 , y=2 , y=3 , y=4 , y=5 , y=10 , y=15 , y=20.

![Makky Chart](image)

**Figure 5-1:** the make chart showing the relationship between $v_{mean}/v_{bulk}$ and $v_{rms}/v_{bulk}$.
5.2. The burning velocity calculation:

5.2.1 Introduction:

More detailed and higher resolution pictures of the flames are illustrated which show clear marks of the scaling. Using Photoshop the change of the colouring of the original flame picture which was provided by a high frame rate camera and its colour had been changed into yellow to show exactly the amount of stretch the flame has because as we know that the flame height has an impact on the burning velocity calculation. With the use of Microsoft picture manger to magnify the picture and see its clear height to be as much accurate as possible in the conducted readings.

5.2.2. The Flow Chart of the calculation procedure for the calculation of the turbulent burning velocity:

This flow chart shows the input data which leads us to burning velocity output, from

**Step one**: by taking a picture of the flame and knowing the scaling we can measure the height of the flame and in conclusion we can evaluate the flame area.

**Step two** by just reading the flow meters for the fuel and air we can calculate the total volumetric flow rate.
5.2.3. The first method is using 3dmax software to calculate the flame area.

The description of the method:

The program 3dmax gives the user an option of tracing the flame profile as shown in the figure 1-18 on the right hand side illustration and then giving the lathe command to the profile, in conclusion the profile will be revolved around the mid axis which runs through the flame so the result is a 3d flame, 3dmax is provided with a command to calculate the area of the 3d model which in our case is the flame. At the end of the calculation and not forgetting to subtract the planner face (which has a circular shape) at the bottom of the 3d model so that it would be excluded from the area calculation.

![Figure 5-2: The flame is traced by taking points on the surface.](image)

After conducting the previously discussed steps above for the turbulence plate that consists of 2mm holes the program output $267789 \text{mm}^2 = 0.267789 \text{m}^2$

5.2.4. The second method used to calculate the flame surface.

To check this calculation mathematically due to the similarity of the flame shape with half an ellipse we can use this equation [26]:

$$\text{area} = \frac{1}{2} \pi r^2$$
\[
\frac{x^2}{a^2} + \frac{y^2}{b^2} + \frac{z^2}{c^2} = 1 \quad \ldots \ldots \ldots \ldots \ldots \ldots (111)
\]

The flame has a cigar shape which is also called a Prolate \( a = b < c \)

\[
(Area)_{\text{Prolate}} = 2\pi(a^2 + c^2 \frac{\alpha}{\tan \alpha}) \quad \ldots \ldots \ldots \ldots \ldots \ldots (112)
\]

Where

\[
\alpha = \arccos \left( \frac{a}{c} \right) \quad \ldots \ldots \ldots \ldots \ldots \ldots (113)
\]

We know that \( a=b=12.5\text{mm} \) and \( c=65\text{mm} \)

After substituting the constants in \( \alpha = \arccos \left( \frac{a}{c} \right) \) we find that \( \alpha = 78.9 \), for our case we have to take half the area of the Prolate:

\[
(Area)_{\text{Prolate}} = 2\pi(a^2 + c^2 \frac{\alpha}{\tan \alpha})
\]

\[
(Area)_{\text{Prolate}} = 205954.67 \text{mm}^2 = 0.205954678 \text{m}^2
\]

Using the cone method [27] the flame area has the following answer:

\[
2597.99 \text{mm}^2 = 0.259799 \text{m}^2
\]

5.2.5. The third method assuming the flame area as a cone area.

The flow bulk velocity is calculated in the following way:

\[
Q = AV_{\text{Bulk}} \Rightarrow V_{\text{Bulk}} = \frac{Q}{A} = \frac{0.000383}{3.14 \times (12.5 \times 0.001)^2} = 0.780694 \frac{\text{m}}{\text{sec}} = 78.0636 \frac{\text{cm}}{\text{sec}}
\]

Finding the laminar burning velocity \( S_L \):

We have the equivalence ratio which is \( \varphi = 1.43 \) and we know that our gas is methane

\[\text{CH}_4\] so from appendix D we can find the burning velocity \( S_L = 31.2 \frac{\text{cm}}{\text{sec}} = 31.2 \times 10^{-2} \frac{\text{m}}{\text{sec}} \)

Finding the turbulent burning velocity \( S_T \):

During the lab test readings were taken to know what the flow rate is \( Q \), and it was as follows

\[
Q = 23 \left( \frac{\text{liter}}{\text{min}} \right) = 3.83 \times 10^{-4} \left( \frac{\text{m}^3}{\text{sec}} \right) , \text{where } H \text{ refers to the height of the cone and } R \text{ the radius of the cone base.}
\]

\[
A = \pi R \sqrt{H^2 + R^2} + \pi R^2 \quad \ldots \ldots \ldots (114)
\]
But because we are only interested with the cone area and not the cone base area the second term is neglected in the equation so this leads us to following form:

$$A = \pi R \sqrt{H^2 + R^2} \quad \cdots \cdots \quad (115)$$

Then just by the substitution of the parameters in the continuity equation this will lead us to the calculation of the turbulent burning velocity.

$$Q = AS_T \Rightarrow S_T = \frac{Q}{A} \quad \cdots \cdots \quad (116)$$

The characteristic width flow in a jet flow $L$ would be the local width of the jet at any axial location as can be seen on figure.

![Figure 5-3: The turbulence plate and a flow existing one of the holes that has a diameter $D$ which is equal to $L$.]

$$\delta_l = \frac{D_m}{S_l} \quad \cdots \cdots \quad (117)$$

The integral length scale of turbulence $L_T = $ The hole diameter

Laminar flame thickness $= \delta_l$

$$\frac{L_T}{\delta_l} = \text{cons tan } t \quad \cdots \cdots \quad (118)$$
Table 1: burning velocity calculation for a 2mm disc

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Height</td>
<td>0.065 m</td>
<td>Cone diameter</td>
<td>0.01 m</td>
</tr>
<tr>
<td>The Equivalence Ratio</td>
<td>1.43</td>
<td>Area</td>
<td>0.002065013 m²</td>
</tr>
<tr>
<td>Flow Rate</td>
<td>0.000383 m³/sec</td>
<td>Integral Length Scale of Turbulence</td>
<td>2 mm</td>
</tr>
<tr>
<td>Burning Velocity</td>
<td>0.185471024 m/sec</td>
<td>Laminar Burning Velocity</td>
<td>0.312 m/sec</td>
</tr>
<tr>
<td></td>
<td>18.5471 cm/sec</td>
<td>Thermal Diffusivity</td>
<td>0.000021 m²/sec</td>
</tr>
<tr>
<td></td>
<td>29.71428571</td>
<td>Flame Thickness</td>
<td>6.73077E-05 (m)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.067308 (mm)</td>
</tr>
</tbody>
</table>
Figure 5-4: shows the flame while a 2mm turbulence plate was tested and the scaling considered.
### Burning Velocity Calculation for 3mm Turbulence Plate:

<table>
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<tr>
<th></th>
<th>Value</th>
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<tbody>
<tr>
<td>Height</td>
<td>0.067 m</td>
</tr>
<tr>
<td>Cone diameter</td>
<td>0.01 m</td>
</tr>
<tr>
<td>The Equivalence Ratio</td>
<td>1.43</td>
</tr>
<tr>
<td>Area</td>
<td>0.002127 m$^2$</td>
</tr>
<tr>
<td>Flow Rate</td>
<td>0.000383 m$^3$/sec</td>
</tr>
<tr>
<td>Burning Velocity</td>
<td>0.180057 m/sec</td>
</tr>
<tr>
<td>$\frac{L_T}{\delta_i}$</td>
<td>44.57143</td>
</tr>
<tr>
<td>Integral Length Scale of Turbulence</td>
<td>3 mm</td>
</tr>
<tr>
<td>Laminar Burning Velocity</td>
<td>0.312 m/sec</td>
</tr>
<tr>
<td>Thermal Diffusivity</td>
<td>0.000021 m$^2$/sec</td>
</tr>
<tr>
<td>Flame Thickness</td>
<td>6.73077E-05 m</td>
</tr>
</tbody>
</table>
Figure 5-5: shows the flame while a 3mm turbulence plate was tested and the scaling considered.
### Table 3: burning velocity calculation for a 4mm disc

<table>
<thead>
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<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Height</td>
<td>0.068 m</td>
</tr>
<tr>
<td>Cone diameter</td>
<td>0.01 m</td>
</tr>
<tr>
<td>The Equivalence Ratio</td>
<td>1.43</td>
</tr>
<tr>
<td>Area</td>
<td>0.002158 m²</td>
</tr>
<tr>
<td>Flow Rate</td>
<td>0.000383 m³/sec</td>
</tr>
<tr>
<td>Burning Velocity</td>
<td>0.177466 m/sec</td>
</tr>
<tr>
<td></td>
<td>17.7466 cm/sec</td>
</tr>
<tr>
<td>( \frac{L_T}{\delta} )</td>
<td>59.42857</td>
</tr>
<tr>
<td>Integral Length Scale of Turbulence</td>
<td>4 mm</td>
</tr>
<tr>
<td></td>
<td>0.004 m</td>
</tr>
<tr>
<td>Laminar Burning Velocity</td>
<td>0.312 m/sec</td>
</tr>
<tr>
<td></td>
<td>31.2 cm/sec</td>
</tr>
<tr>
<td>Thermal Diffusivity</td>
<td>0.000021 m²/sec</td>
</tr>
<tr>
<td>Flame Thickness</td>
<td>6.73077E-05 m</td>
</tr>
<tr>
<td></td>
<td>0.067308 mm</td>
</tr>
</tbody>
</table>
Figure 5-6: shows the flame while a 4mm turbulence plate was tested and the scaling considered.
5.2.6. Flame thickness:

Flame thickness can be found by just having a picture of the flame and changing it colour status on Photoshop flame thickness can be visible where it is for the 2mm turbulence plate its about 1mm at the bottom of the flame and about 1.5mm at the top. This case for a turbulent flame in comparison with a laminar flame for an equivalence ratio of $\phi = 1.43$ the flame thickness is about 1.9mm [3].

Figure 5-7: flame thickness is visible with its several layers.
### 5.3 Turbulence Plate Parameters:

**Table 4: 2mm Turbulence Plate Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number Of Holes</td>
<td>61</td>
</tr>
<tr>
<td>The Diameter of the Holes (mm)</td>
<td>2</td>
</tr>
<tr>
<td>The Velocity Output (each hole)</td>
<td>1.9995532</td>
</tr>
<tr>
<td>The Mach Number Output</td>
<td>0.006402</td>
</tr>
<tr>
<td>The Speed of sound for the Mixture (m/sec)</td>
<td>312.3486</td>
</tr>
<tr>
<td>The Polytrophic Constant</td>
<td>1.03E+00</td>
</tr>
<tr>
<td>The Ideal Gas Constant</td>
<td>321.7743</td>
</tr>
<tr>
<td>The Specific Heat Capacity at Constant Pressure of Air</td>
<td>1.004</td>
</tr>
<tr>
<td>The Specific Heat Capacity at Constant Pressure of Methane</td>
<td>36.20503004</td>
</tr>
<tr>
<td>The Percentage of the Air%</td>
<td>0.756767667</td>
</tr>
<tr>
<td>The Percentage of the Methane%</td>
<td>0.243232113</td>
</tr>
<tr>
<td>The Temperature of Air</td>
<td>20°C</td>
</tr>
<tr>
<td>The Temperature of Methane</td>
<td>20°C</td>
</tr>
<tr>
<td>The Temperature of the Mixture (K)</td>
<td>313K</td>
</tr>
<tr>
<td>The Flow Rate for each Hole (m^3/sec)</td>
<td>6.26E-06</td>
</tr>
<tr>
<td>The Total Flow Rate (m^3/sec)</td>
<td>0.000383</td>
</tr>
<tr>
<td>The Temperature of the Mixture before the plate (K)</td>
<td>293K</td>
</tr>
</tbody>
</table>
Table 5: 2mm turbulence plate Reynolds number and pressure drop work sheet.

<table>
<thead>
<tr>
<th>The Mass Flow Rate (m^3/sec)</th>
<th>6.27869E-06</th>
<th>Hole Diameter (m)</th>
<th>0.002</th>
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</thead>
<tbody>
<tr>
<td>Air Kinematic Viscosity (m^2/s)</td>
<td>1.83E-06</td>
<td>Air Percentage %</td>
<td>0.756768</td>
</tr>
<tr>
<td>Fuel Kinematic Viscosity (m^2/s)</td>
<td>1.09E-04</td>
<td>Methane Percentage %</td>
<td>0.243232</td>
</tr>
<tr>
<td>Mixture Viscosity (m^2/s)</td>
<td>2.79E-05</td>
<td>Number of Holes</td>
<td>61</td>
</tr>
<tr>
<td>Pressure Drop for a Single Hole (N/m^2/m)</td>
<td>-446.262</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plate Thickness (mm)</td>
<td>3</td>
<td>Plate Thickness (m)</td>
<td>0.003</td>
</tr>
<tr>
<td>Single Pressure Drop (N/m^2)</td>
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<td>Total Pressure Drop (N/m^2)</td>
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</tr>
<tr>
<td>Parameter</td>
<td>Value</td>
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<td></td>
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<tr>
<td>------------------------------------------</td>
<td>----------------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number Of Holes</td>
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<td></td>
</tr>
<tr>
<td>The Diameter of the Holes (mm)</td>
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<td></td>
</tr>
<tr>
<td>The Area of each Hole (mm)</td>
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<tr>
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<tr>
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<tr>
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<tr>
<td>(m/sec)</td>
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<tr>
<td>The Temperature of the Mixture before the plate (K)</td>
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<tr>
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</tr>
<tr>
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<tr>
<td>The Specific Heat Capacity at Constant Pressure of Methane</td>
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<tr>
<td>The Percentage of the Air%</td>
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<tr>
<td>The Percentage of the Methane%</td>
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</tr>
<tr>
<td>The Temperature of Air</td>
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<td></td>
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</tr>
<tr>
<td>The Temperature of Methane</td>
<td>20 C</td>
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<td></td>
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</tr>
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<tr>
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<td>Mixture Density (m³/3/kg)</td>
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<td>Parameter</td>
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</tr>
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<td>Number Of Holes</td>
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</tr>
<tr>
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</tr>
<tr>
<td>The Velocity Output (each hole)</td>
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<tr>
<td>The total Flow Rate (m^3/sec)</td>
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<tr>
<td>The Mach Number Output</td>
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</tr>
<tr>
<td>The Flow Rate for each Hole (m^3/sec)</td>
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</tr>
<tr>
<td>The Speed of sound for the Mixture (m/sec)</td>
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<td></td>
</tr>
<tr>
<td>The Temperature of the Mixture before the plate (K)</td>
<td>293</td>
<td></td>
<td></td>
</tr>
<tr>
<td>The Polytrophic Constant</td>
<td>1.03E+00</td>
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<td></td>
</tr>
<tr>
<td>The Temperature of the Mixture(K)</td>
<td>313</td>
<td></td>
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</tr>
<tr>
<td>The Ideal Gas Constant</td>
<td>321.7743</td>
<td></td>
<td></td>
</tr>
<tr>
<td>The Molar Mixture</td>
<td>25.83798</td>
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</tr>
<tr>
<td>The Specific Heat Capacity at Constant Pressure of Air</td>
<td>1.004</td>
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<td></td>
</tr>
<tr>
<td>The Specific Heat Capacity at Constant Pressure of Methane</td>
<td>36.20503</td>
<td></td>
<td></td>
</tr>
<tr>
<td>The Percentage of the Air%</td>
<td>0.756768</td>
<td></td>
<td></td>
</tr>
<tr>
<td>The Percentage of the Methane%</td>
<td>0.243232</td>
<td></td>
<td></td>
</tr>
<tr>
<td>The Temperature of Air</td>
<td>20°C</td>
<td></td>
<td></td>
</tr>
<tr>
<td>The Temperature of Methane</td>
<td>313 K</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 9: 4mm turbulence plate Reynolds number and pressure drop work sheet.

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hole Diameter (m)</td>
<td>0.004</td>
</tr>
<tr>
<td>Air Kinematic Viscosity (m²/s)</td>
<td>1.83E-06</td>
</tr>
<tr>
<td>Fuel Kinematic Viscosity (m²/s)</td>
<td>0.000169</td>
</tr>
<tr>
<td>Methane Percentage (%)</td>
<td>0.243232</td>
</tr>
<tr>
<td>Mixture Viscosity (m²/s)</td>
<td>2.79E-05</td>
</tr>
<tr>
<td>Number of Holes</td>
<td>19</td>
</tr>
<tr>
<td>Pressure Drop for a Single Hole (N/m²2/m)</td>
<td>-89.5453</td>
</tr>
<tr>
<td>Plate Thickness (mm)</td>
<td>3</td>
</tr>
<tr>
<td>Plate Thickness (m)</td>
<td>0.003</td>
</tr>
<tr>
<td>Single Pressure Drop (N/m²2)</td>
<td>-0.26364</td>
</tr>
<tr>
<td>Total Pressure Drop (N/m²2)</td>
<td>-5.10412</td>
</tr>
<tr>
<td>The Reynolds Number for a single hole</td>
<td>239.4867</td>
</tr>
<tr>
<td>Air Density (m³/kg)</td>
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</tr>
<tr>
<td>Methane Density (m³/kg)</td>
<td>0.574712</td>
</tr>
<tr>
<td>Mixture Density (m³/kg)</td>
<td>1.040702</td>
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<tr>
<td>Velocity of Mixture (m/sec)</td>
<td>1.504920</td>
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Table 10: General Data on all turbulence discs:

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<th></th>
<th>0.55</th>
<th>0.57</th>
<th>0.63</th>
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<tr>
<td>Discharge coefficient</td>
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<td>Holes Diameter (mm)</td>
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<td>3</td>
<td>4</td>
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<tr>
<td>Reynolds Number</td>
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<td>164</td>
<td>239</td>
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<tr>
<td>L/D Ratio</td>
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<td>1</td>
<td>0.75</td>
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<tr>
<td>Blockage Ratio%</td>
<td>61</td>
<td>47</td>
<td>51</td>
</tr>
</tbody>
</table>

5.4. The factors affecting the Turbulent Burning velocity:

1. The relation between the burning velocity and integral length scale over laminar flame thickness:

With the reliance on the data provided on (tables 4, 5, 6) the following graph can be plotted

![Graph showing the relation between burning velocity and ratio $L_T/\delta_L$.]

**Figure 5-8**: The relation between the burning velocity and ratio $L_T/\delta_L$.

What is clear is that with the increase in burning velocity there is a decrease in $L_T/\delta_L$; this also means for the case of a 2 mm turbulence disc there is bigger flame thickness than for the 4 mm disc.

2. The relation between the burning velocity and the number of holes:
To plot this graph the data was gathered from tables (4, 5, and 6) for burning velocities and tables (7, 8, and 9) for the number of holes in each disc. It is obvious that with the increase in burning velocity there is an increase in the number of holes on the turbulence disc.

![Graph](image)

**Figure 5-9:** The relation between the burning velocity and the number of holes.

3-The relation between the burning velocity and the diameter of the holes:

The hole size in the turbulence disc has an effect on the burning velocity the smaller the hole size the better burning you have.

![Graph](image)

**Figure 5-10:** The relation between the burning velocity and the diameter of a single hole.
The data for this graph was taken from establishing a relation between the burning velocities in tables (4, 5, and 6) and hole diameters in tables (7, 8, and 9).

4-The relation between the burning velocity and the Reynolds Number:
The graph was plotted after establishing a relation between the burning velocity in tables (4, 5, and 6) and the Reynolds numbers in tables (7, 8, and 9).

![Graph showing the relation between the burning velocity and the Reynolds Number.](image)

Figure 5-11: The relation between the burning velocity and the number of holes.
The smaller the Reynolds number the higher the burning velocity.

5-The relation between the burning velocity and the discharge coefficient:
The graph was plotted after establishing a relation between the burning velocity in tables (4, 5, and 6) and data for discharge coefficients from reference [7]:
Figure 5-12: The relation between the burning velocity and the number of holes.
It’s clear that having low discharge coefficient you means that there is a better burning velocity.

6-The relation between the burning velocity and the ratio $l/D$ (plate thickness over hole diameter):

Figure 5-13: The relation between the burning velocity and the holes diameter.
Gathering and linking the info from tables (4, 5, 6) for the burning velocity with $l/D$ in table 10 the figure is plotted.
7-The relation between the burning velocity and single hole pressure drop:

Figure 5-14: The relation between the burning velocity and the holes diameter.

By linking the info provided in table (4, 5, and 6) for burning velocities with the pressure drop for a single hole in tables (7, 8, and 9) the figure is plotted.

What is obvious the bigger the pressure drop the higher the burning velocity.

8-The relation between the burning velocity and Blockage Ratio%:

Figure 5-15: The relation between the burning velocity and blockage ratio.
Gathering and linking the info from tables (4, 5, and 6) for the burning velocity with the blockage ratio% in table 10 the figure is plotted. The higher the blockage ratio the better results you get for burning velocities notice that for the mid point it’s an inflection point.

5.5. The calculation of the Kolmogrov scales for the three turbulence discs:

A-2mm Turbulence disc:

\[ l_0 = \frac{D_{2mm}}{10} = 0.2\, mm \]

\[ \text{Re}_{2mm} = \frac{\left( \frac{v_{rms}}{y_{rms}} \right)_{\text{average}} D}{v} = \frac{0.138 \times 2 \times 0.001}{2.79 \times 10^{-5}} = 9.89 \]

\[ l_k^{2mm} = l_0 \text{Re}^{-3/4} = 0.035\, mm \]

B-3mm Turbulence disc:

\[ l_0 = \frac{D_{3mm}}{10} = 0.3\, mm \]

\[ \text{Re}_{3mm} = \frac{\left( \frac{v_{rms}}{y_{rms}} \right)_{\text{average}} D}{v} = \frac{0.034 \times 3 \times 0.001}{2.79 \times 10^{-5}} = 3.65 \]

\[ l_k^{3mm} = l_0 \text{Re}^{-3/4} = 0.113\, mm \]

C-4mm Turbulence disc:

\[ l_0 = \frac{D_{4mm}}{10} = 0.4\, mm \]

\[ \text{Re}_{4mm} = \frac{\left( \frac{v_{rms}}{y_{rms}} \right)_{\text{average}} D}{v} = \frac{0.1316 \times 4 \times 0.001}{2.79 \times 10^{-5}} = 18.86 \]

\[ l_k^{4mm} = l_0 \text{Re}^{-3/4} = 0.044\, mm \]

From this data what is visible that the Kolmogrov scales are smallest with the 3mm size of the holes.
5.6. The use of the Borghi to specify where the turbulence discs are situated:

A-For the flame using turbulence plate 2mm:

\[ \frac{L_r}{\delta_L} = 30 \]
\[ \frac{u_{rms}}{S_L} = 0.442 \]

B-For the flame using turbulence plate 3mm:

\[ \frac{L_r}{\delta_L} = 44 \]
\[ \frac{u_{rms}}{S_L} = 0.108 \]

C-For the flame using turbulence plate 4mm:

\[ \frac{L_r}{\delta_L} = 59 \]
\[ \frac{u_{rms}}{S_L} = 0.42 \]

Figure 5-16: The turbulence discs are shown on the Borghi/Peters chart.
7. Conclusion:

1- The discharge coefficient of the turbulence plates has an effect on the burning velocity and that was noticed when low discharge coefficients were used higher burning velocities where achieved.

2- The number of holes and their size had an effect on the burning velocity the smaller the holes the better the burning whereas concerning the number of holes the larger the number of holes the better the burning was.

3- Pre-heat has also an effect on the size of the eddies on the turbulence plate which in turn should increase the $\frac{v_{rms}}{v_{bulk}}$.

4- The increase in loss of pressure has a noticeable effect on the burning velocity which mean that the fuel air mixture is given time to react in the and by looking at graph 2 what we can see is that due to the low velocity ratio in the core and the velocity ratio at the tips gives the fuel air mixture time and the proper place to burn.

5- The blockage ratio has an affect and that is in increasing the burning velocity, the loss in pressure and in increasing the Reynolds number.

6- My conclusion is that to consider that the flame has a cone shape and to be considered that it has that shape an external air flow must flow around the flame in a way the velocity vector should be perpendicular on the surface of tube outlet area.

7- More tests should be conducted to get more accurate results.

8- The pressure profile before the plate had a big impact on the profile of $\frac{v_{rms}}{v_{bulk}}$ but the $\frac{v_{mean}}{v_{bulk}}$ stayed the same having the same profile through out the four graphs the only difference was that the velocity ratios were better uniform with the use of turbulence plates than without.
This Equation is for Stochiometric case and constant flow rates:

\[
\frac{S_T}{S_T'} = f\left(\frac{n_i}{n}, \frac{\zeta}{\zeta_i}, \text{Re}, \phi, \alpha, \beta, \sigma, \phi_i, \alpha_i, \beta_i, \sigma_i\right)
\]

\[
\frac{S_T}{S_T'} = \left(\frac{D_i}{D}\right)^2 \left(\frac{\mu}{\mu_i}\right) \left(\frac{Q_{\text{real}}}{Q_{\text{real}}}\right)^2 \left(\frac{\partial P}{\partial P_i}\right)^2 \left(\frac{n}{n_i}\right) \left(\frac{1 - n_i D_i}{D_{\text{tube}}/D}\right) \left(\frac{v_i}{v}\right)
\]
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### Appendix D:

The source of this table is [1].

**TABLE 1** Burning Velocities of Various Fuels at 25°C Air–Fuel Temperature (0.31 mol% H₂O in Air). Burning Velocity S as a Function of Equivalence Ratio \( \phi \) in cm s⁻¹

<table>
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<tr>
<th>Fuel</th>
<th>( \phi = 0.7 )</th>
<th>0.8</th>
<th>0.9</th>
<th>1.0</th>
<th>1.1</th>
<th>1.2</th>
<th>1.3</th>
<th>1.4</th>
<th>( S_{\text{max}} )</th>
<th>( \phi ) at ( S_{\text{max}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saturated hydrocarbons</td>
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<td>Ethane</td>
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<td>( n )-Butane</td>
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