

Flame propagation and structure

1. OBJECTIVE

The objectives of this experiment are:

- To measure the speed at which a flame propagates in methane-air mixtures.
- To demonstrate the differences between premixed and non-premixed flames.
- To demonstrate the dual structure of the reaction zone in rich premixed flames surrounded by air.

2. INTRODUCTION

About 90% of the world's energy use comes from the use of fossil fuels, released mostly through combustion of the fuel with air in *flames*. Flames are thin reaction zones, typically blue, which, in the case of premixed fuel and air, separate the burnt from the unburnt reactants and have an associated propagation velocity. The velocity at which a plane flame front moves normal to its surface relative to the adjacent unburnt mixture is called the *burning velocity* and is one of the most important quantities in combustion. It depends on the nature of the fuel and the oxidant, their amounts, the temperature, and the pressure. In the first part of this experiment, the velocity of flames propagating in a tube is measured as a function of *equivalence ratio* (the ratio of fuel to air volume fractions divided by the same ratio at stoichiometric conditions) and the measurements are compared with values from the literature.

Premixed flames can also be stabilised on a burner, e.g. a Bunsen burner. The flame front will always adjust itself so that at any point in the front the component of the flow velocity normal to the flame front is equal and opposite to the burning velocity at that point. Near the burner rim, the burning velocity decreases due to heat loss to the metal and this opens up the possibility that the flame stabilises somewhere at the boundary layer formed next to the burner wall. If the flow velocity is too slow, the flame may *flashback* into the burner, a dangerous situation. If it is too high, the flame cannot be stabilised and will *blow-off*. In the case of *non-premixed flames*, as when a jet of fuel discharges into still air, the flame is formed between the two reactants and does not propagate. The reactants move towards the reaction zone, and the products of combustion move away from it, by the action of diffusion. No flashback can occur, but blow-off occurs at high velocities. Non-premixed flames are also more prone to be of a yellowish colour due to the *soot* that is often formed in very fuel-rich regions. The particular case of a rich premixed flame can be used to demonstrate a dual structure of the reaction zone. This refers to the fact that, in the absence of sufficient oxygen in the premixed mixture, the fuel forms partial products of oxidation (mainly CO and H₂), which combust in a diffusion flame once they meet the surrounding air into the final products into CO₂ and H₂O. These phenomena are explored in the second part of the experiment.

3. METHOD

3.1 Apparatus

The apparatus is shown in Fig. 1. The air flow is provided by a small blower inside the control unit and its rate is adjusted by a valve and measured by a variable area flow meter (rotameter). The gas is supplied from a cylinder and is adjusted and measured in a similar manner. As an additional safety measure, gas flow is permitted only if a foot switch is kept depressed. Both air and gas are separately introduced into a mixing block designed to accommodate (i) various mixing tubes for the experiments on flame appearance and stability limits and (ii) an elbow fitted with a flame trap. A supporting ring that fits on one of the straight tubes and a length of heat resistant glass tube is provided to enable primary and secondary flames to be separated, while a diffuser fitted with a bluff body is provided to create bluff-body stabilised flames. The elbow is used to pass the mixture to a long plastic pipe, connected to a glass tube of 2 m length and 25 mm diameter, in which the flame propagation speed will be measured.

3.2 Experimental Procedure

SAFETY WARNINGS

- **Safety glasses to be worn by all in the area**
- **Never change the apparatus without consulting the demonstrator.**
- **During the flame structure experiment, use the heat-resistant gloves.**
- **During the measurements with the bluff body, the burner will get very hot. Ask the demonstrator to alter the arrangement for you, if needed.**
- **Never leave an open flame unattended. Be careful with paper sheets, sleeves and long hair!**

Part 1. Flame propagation

With the elbow in position, the plastic tube is connected to the mixing block. A known mixture is allowed to pass through the tube and both control valves are shut simultaneously. The arrested mixture is then ignited by means of a spark plug. The time for the flame to pass over a known distance is recorded.

Initially, set the air flow meter at a reading of 18 and the gas meter at 4 (these settings correspond to an approximately stoichiometric mixture). Then, light the mixture at the downstream end of the tube over the wire gauze so that unburnt fuel is not released to the lab. Adjust the flow rates to give the required fuel-air ratio and wait for some time for the tube to be filled with the new mixture. One of the operators must then close both valves, while the other must press the spark and time the flame with the stopwatch. Take a few measurements at each setting to decrease experimental uncertainty and repeat for a series of equivalence ratios. Eventually, you will not be able to ignite very lean or very rich flames; mark down these conditions. The air-gas flow should be allowed to dry out the condensation in the pipe between runs.

Part 2. Flame appearance and structure

Fit one of the straight tubes in the mixing block. Allow only fuel to go through at a setting of about 5 cm. Ignite the flame and observe its appearance (make a hand sketch). Gradually, open the air valve (e.g. readings in steps of 1 cm) and observe the differences in flame appearance. Mark down the conditions relating to the disappearance of the yellow colour, the first appearance of an inner cone, and the disappearance of the outer flame. These changes mark the progression from non-premixed to rich premixed to lean premixed flame. Note that lift-off may occur before the full range of flames is seen. For very low flow rates, flashback may also be observed.

The dual structure of aerated flames can be demonstrated as follows. Fit the adaptor ring over one of the mixing tubes and then the glass tube over the ring. Lower both so that the metal burner tip is exposed. Ignite a rich flame with a clearly defined blue inner cone and then lift the glass tube until the ring is just below the top of the mixing tube. The blue cone should remain in position, but the outer faint flame should be at the top of the glass tube. Write down the conditions of the mixture and your observations. **WARNING: DO NOT ATTEMPT THIS EXPERIMENT WITHOUT THE HEAT RESISTANT GLOVES. DO NOT HOLD THE GLASS TUBE RAISED FOR MORE THAN A FEW SECONDS.**

3.3 Data reduction

Flow rates

The rotameter readings can be converted into volume flow rates \dot{V} in litres per minute (l/min) through the following equations (based on curve fits to a calibration chart provided by the manufacturer), with x the reading in cm:

$$\text{gas: } \dot{V}_{fuel} = 0.9071 + 0.3166x + 0.0024x^2$$

$$\text{air: } \dot{V}_{air} = 2.9605 + 0.9059x + 0.0048x^2$$

Equivalence ratio

The equivalence ratio is defined as: $\phi = \frac{\dot{V}_{fuel}}{\left(\frac{\dot{V}_{fuel}}{\dot{V}_{air}}\right)_{stoich}}$. For methane in air, the stoichiometric fuel:air volume ratio is 1:9.524.

Error analysis

The uncertainty in the flow rates is about $\pm 5\%$, due to the error in reading the float height, the rotameter calibration and the error in the curve fit. Estimate the combined uncertainty in the calculation of the equivalence ratio. You must also estimate the uncertainty in the measurement of the flame speed and the lean extinction limit, which depend on the operator's procedure and reflexes.

4. Results

- (a) Plot the measured flame speed as a function of equivalence ratio. Compare these results with the accepted values in the literature. You will also have a chance to compare these results with the PIV results in another station. Is the agreement good or bad? Is your experiment a true manifestation of the theoretical concept of a free, planar, steadily-propagating premixed flame?
- (b) Sketch and discuss briefly the flame appearance during the progression from the non-premixed to the premixed flame. At what equivalence ratio does the inner cone appear?

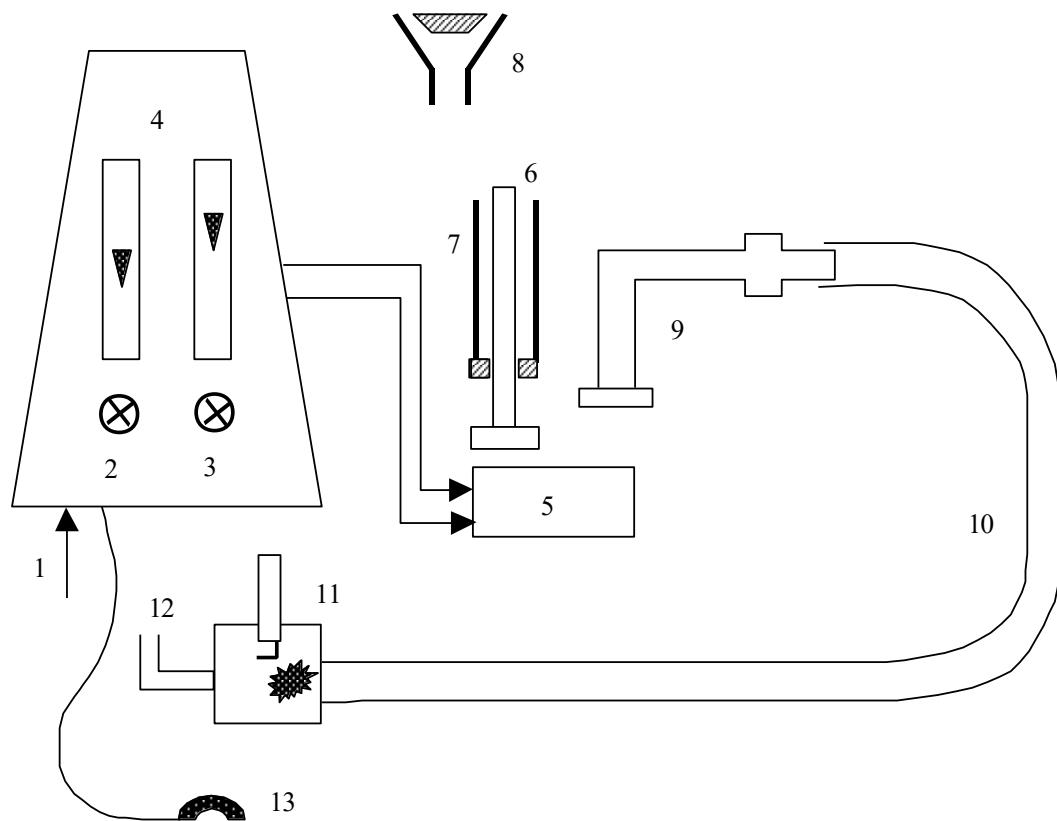


Figure 1. Schematic of the apparatus.

- 1: gas from cylinder
- 2: gas control valve
- 3: air control valve (fan inside unit)
- 4: flow meters
- 5: mixing block
- 6: straight tube burner
- 7: glass tube and ring
- 8: bluff-body
- 9: elbow with flame trap
- 10: plastic tube and straight glass section
- 11: spark plug
- 12: vent with wire gauze
- 13: foot switch to allow gas flow

APPENDIX: THEORY

Combustion occurs in a series of chemical reactions. In these reactions, the fuel is under attack from radicals such as O, OH and H to produce more H and/or to break down in smaller fragments. For example, CH₄ is transformed consecutively to CH₃, CH₂ and CH. Various oxygenated intermediates are formed initially with the carbon in the fuel first becoming CO and the hydrogen in the fuel becoming H₂. All intermediates are later further oxidised, again through the action of radicals, into CO₂ and H₂O. A large part of the total heat release occurs in this second stage. This sequence is responsible for the self-sustaining nature of combustion and can occur only at high temperatures (e.g. above 1500 K) because only at such high temperatures can the radicals, necessary to bring about a complete fuel transformation and intermediate species oxidation, be generated at a rate faster than they are consumed.

When a spark is given to a premixed fuel-air mixture, the temperature rises locally to high values, which increases the reaction rate, which in turn causes combustion of the fuel and hence heat release. Through heat conduction to the adjacent regions that are still unburnt, the temperature, and hence the reaction rate, increases and therefore combustion occurs there too. We see that the diffusion of heat is responsible for flame propagation. The speed at which this combustion wave propagates depends on the temperature reached after combustion and the thermal diffusivity of the unburnt mixture. Mass diffusion is also important in order to bring the radicals from the high temperature zone in contact with the reactants in the low temperature unburnt gas; usually mass and heat diffusion occur at the same rate.

In the present experiment, the unburnt mixture temperature and pressure are ambient. The flame propagation speed will depend only on the amounts of fuel and oxygen in the mixture, which in turns control the flame temperature. Lean ($\varphi < 1$) and rich ($\varphi > 1$) flames will have smaller flame temperatures than stoichiometric ones ($\varphi = 1$), because away from stoichiometry there is additional matter present to pick up the heat generated by the combustion of the fuel that can be burned. In reality, the temperature peaks at an equivalence ratio a little above unity because the specific heat capacity of the products is slightly lower than at stoichiometry. Table A1 lists values of the laminar burning velocity S_L of methane-air mixtures measured in experiments where extra care has been taken to produce a planar steady flame and to eliminate heat losses.

If the mixture is too lean, the burnt gas temperature is too low to allow significant radical production and hence flame propagation becomes impossible. If the mixture is too rich, the large amounts of fuel absorb the radicals and hence do not allow the second stage of combustion to proceed. Hence, flame propagation is possible only in a certain range of equivalence ratio and these are called flammability limits. For methane-air mixtures, the lean limit is $\varphi = 0.53$ and the rich $\varphi = 1.6$.

Table 1: Laminar burning velocity of methane-air mixtures (Glassman, 1996).

| φ | 0.8 | 0.9 | 1.0 | 1.08 | 1.1 | 1.2 | 1.3 | 1.4 |
|-------------|------|------|------|------|------|------|------|------|
| S_L (m/s) | 0.30 | 0.38 | 0.43 | 0.45 | 0.44 | 0.40 | 0.31 | 0.18 |

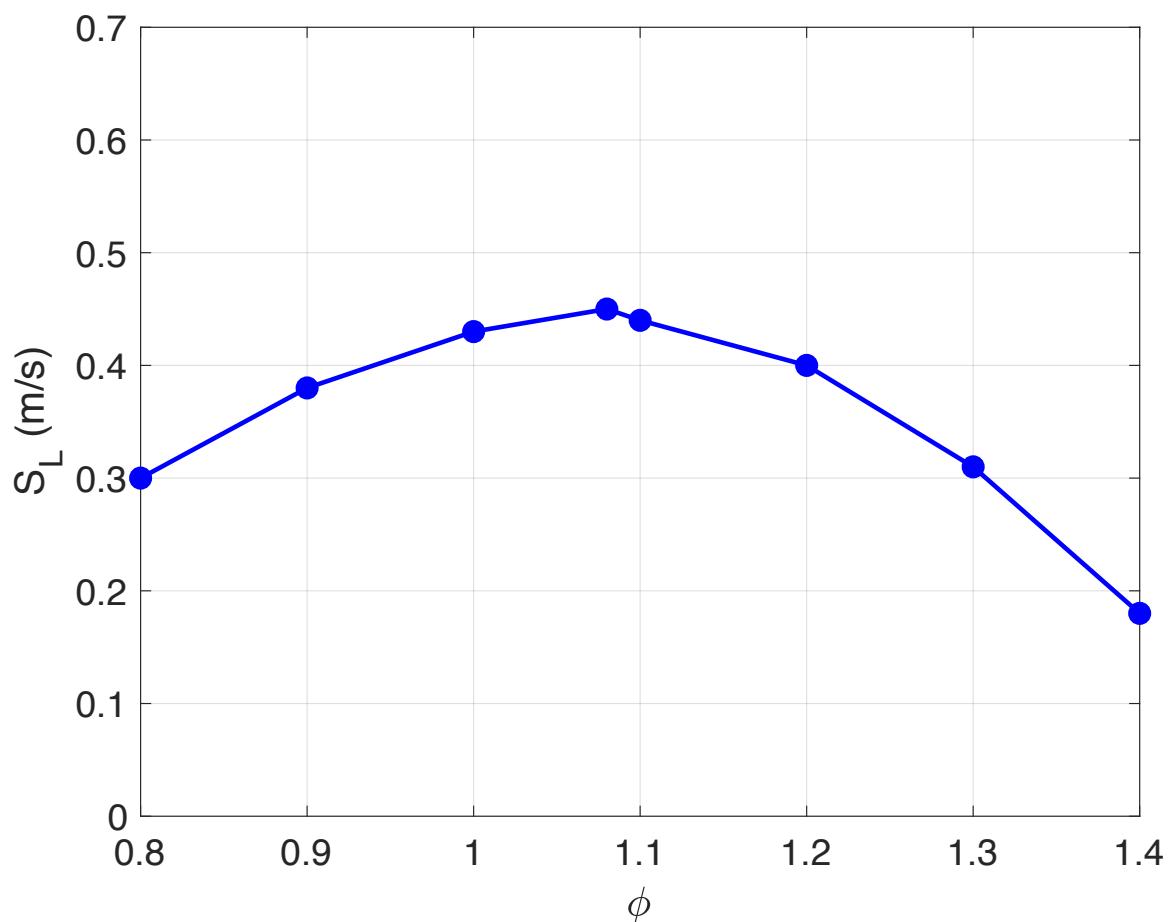


Figure 1. Accepted values for the burning velocity of methane (Glassman, 1996).