FLAME SPREAD OVER PMMA IN NARROW CHANNEL

H. Wang[a], J. Hicks[a], E. M. Kennedy[a], B. Moghtaderi[a], M. A. Delichatsios[b] and B. Z. Dlugogorski[a*]

[a] Process Safety and Environment Protection Research Group
Faculty of Engineering and Built Environment
The University of Newcastle
Callaghan, NSW 2308
Australia

[b] FireSERT
University of Ulster at Jordanstown
Newtownabbey, Co. Antrim, BT37 0QB
Northern Ireland, UK

ABSTRACT

In this paper, we study the performance of a testing apparatus developed for evaluating the behaviour of gaseous suppressants under conditions corresponding closely to fires of solid fuels. A narrow channel, 3 mm in height, 110 mm in width and 375 mm in length, constitutes the most important component of this apparatus. Thick PMMA plates were placed at the bottom of the channel. A mixture of oxygen-enhanced air was introduced into the channel, and the fuel was ignited downstream to allow the flame to propagate in the direction opposite to the gas stream. The tests were recorded with a digital video camera and the rate of flame spread and the visible flame length were determined by analysing the recorded images. The mass loss during an experiment was quantified by weighing a sample before and after each experiment. Extensive experimentation demonstrated that, the flame spread over the fuel in the channel is dominated by the velocity and oxygen content of the introduced gas stream, and a steady flame can be readily and reproducibly established. The paper reports the thickness of the pyrolysis layer in the solid, noting that for all experiments the ratio of the pyrolysis rate to air flowrate is approximately 0.5.

INTRODUCTION

Understanding the behaviour and measuring the extinguishment concentration of gaseous fire suppressants are necessary for engineering design of fire-mitigation systems. From a fundamental perspective, the first step to attain this objective comprises an analysis of the behaviour of suppressants under idealised gas-phase conditions. Usually, these conditions are realised in laboratory-scale experiments of laminar pre-mixed flames, which involve measuring of laminar burning velocity followed by mechanistic calculations (e.g., Simmons, 1995; Babushok et al., 1996; Fallon et al., 1996; Bozzelli et al., 1997; Yuan et al., 1997). In such calculations, it is convenient to evaluate the contribution of chemistry (reaction rates) and physics (thermal capacity and dilution) to the agent's effectiveness. Laminar diffusion flames, either in counter-current (opposed flow) or co-current (cup burner) geometries provide other experimental configurations to study the gas-phase extinguishment.

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[*] Corresponding author, email: Bogdan.Dlugogorski@newcastle.edu.au, fax: + 61 2 4921-6920.

Until present, no methodologies have been developed to evaluate the performance of chemically active or inert gaseous suppressants for the extinguishment of fires of solid fuels. For example, currently, the design concentrations of gaseous suppressants against fires of solid fuels are obtained from the cup-burner experiments, which involve heptane as a liquid hydrocarbon fuel. This may be due to the fact that flames generated by solid fuels are often affected by a number of factors, including the physical and chemical properties of the solid, spatial geometry of the fuel, flow field around the fuel and the presence of external energy sources. Furthermore, it is difficult to make detailed observations of the interaction between fire suppression agents and flames, as flames in an open space are considerably modified by natural convection. In addition, the burning of a solid is in general an unsteady process, with the combustion intensity often changing with time.

For the purpose of developing a test method for examining the behaviour of gaseous suppressants applied to fires of solid fuels, an attempt was made by the current authors to establish a stable flame over a solid fuel in a well-defined system (Dlugogorski et al., 2002). The geometry of the system was based on the so-called Helle-Shaw cell, composed of two parallel thermally-resistant glass plates, placed close to each other to form a narrow channel. A specimen of solid fuel was located on the bottom plate and the distance between the top plate and the fuel was in the order of a few millimetres. Gas flow with a pre-defined concentration of oxygen was introduced into the channel from one end at the rate of a few litres per minute. The fuel was ignited downstream of the incoming flow to produce the so-called creeping (counter-current or opposed-flow) flame spread.

Preliminary experiments with a thin cardboard material indicated that, the flame was easily established and moved forward along the fuel surface at a steady rate, when the flowrate of the incoming flow was set within a reasonable range. The flame propagation velocity in the channel was controlled by the rate of the induced gas flow and its composition. Fire suppression agents added to the gas stream affected the chemical reactions occurring in the flame zone. However, the previous work has also demonstrated three drawbacks of using thin samples of cardboard material: (i) Such fuels are not thermally thick, making it difficult to simplify the energy equation that describes the flame spread. (ii) The pyrolysis behaviour of the cardboard material leads to complex kinetics of the pyrolysis and gas phase reactions, adding to the difficulty in untangling the effect of gaseous suppressants. (iii) Large internal surface area and hygroscopic nature of dried cardboard specimens lead to uncontrollable absorption of moisture, even during short time periods necessary for mounting specimens in the experimental rig, after specimen removal from a desiccator and prior to commencement of the flow of nitrogen in a narrow channel. Preliminary experiments revealed that, the flame propagation velocity depends strongly on the moisture content at the cardboard surface, which in turn is a function of temperature and air humidity, with both of these parameters varying from day to day.

In the current work, efforts were made to improve the existing system. We introduced a new fuel type into the system, in the form of PMMA plates, 10 mm in thickness, to replace the thin cardboard material. The PMMA material, which has known physical and chemical properties, has been widely used in studies of flame spread over solid fuels. The plate introduced in the current system is thick enough to be considered thermally thick. The characteristics of flame spread over PMMA plates in the channel are then studied by extensive experimentation, by varying the flowrate and oxygen concentration of the incoming gas stream.

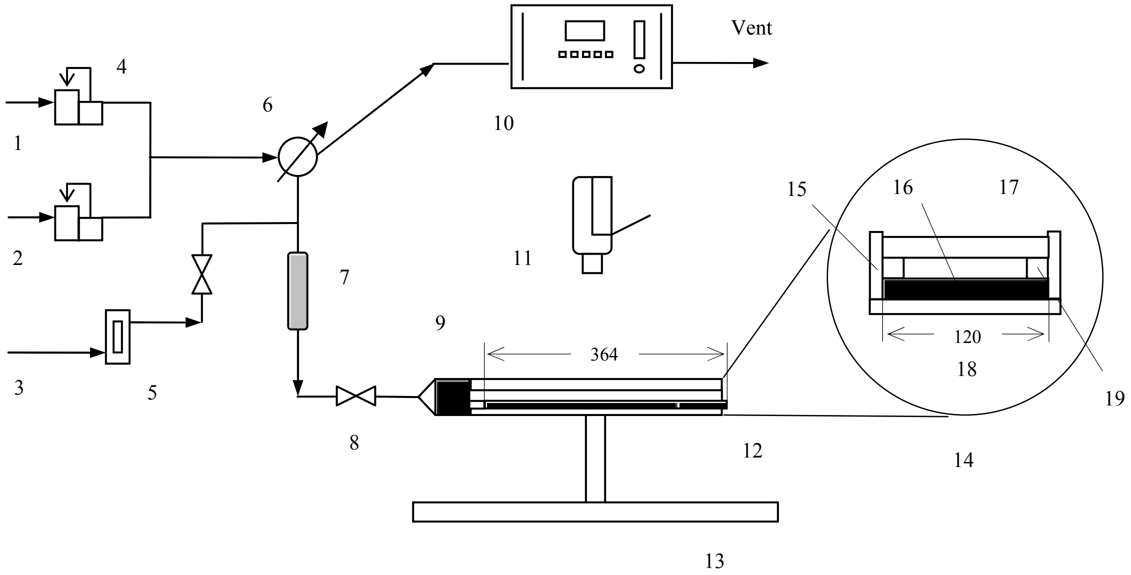
EXPERIMENTAL SETUP

A schematic diagram of the experimental setup is shown in Fig. 1. The apparatus consists primarily of gas lines, narrow channel, and image recording system. Gases are introduced into the manifold from two compressed gas cylinders, which contain an O_2/N_2 mixture or O_2 and N_2 gases, separately. Using a pair of mass flow controllers, the concentration of oxygen and the flowrate of the gas stream can be set to any level. Oxygen concentration in the gas stream can be measured using an oxygen analyser (ADC 7000). Fire suppression agents can be added into the main stream at a pre-set flowrate. The gas stream is introduced into the narrow channel by a gas diffuser placed at the inlet of the narrow channel. The diffuser was designed to distribute the gas stream uniformly across the cross-sectional area of the channel.

Fuel samples, 10 mm thickness, are placed on an aluminium support. Placing a transparent fire-resistant glass plate on two aluminium spacers, separating the glass from the fuel, constitutes the channel. The distance between the fuel surface and the glass is always kept at 3 mm. The scale marks were etched on the bottom side of the top glass plate in increments of 10 mm. As the fuel and glass are very close to each other, this provides a reference for recording the flame spread over the sample. The narrow channel is 110 mm in width and 375 mm in length. A straight nichrome wire, powered through a low voltage transformer, is used to generate a linear flame on the sample surface just upstream of the channel exhaust. A digital video camera (DCR-TRV30E, Sony) serves to record the propagating flames in each experiment. A small canopy duct (not shown in Fig. 1) was used to vent the soot and smoke emerging from the channel exhaust.

Polymethyl-methacrylate, i.e., PMMA, was selected as the fuel in the current study. A local plastic supplier provided the material. The dark grey coloured pieces of PMMA (density 1.18 g/cm^3), supplied in 10 mm thickness, were cut into the rectangular shape, 364 mm in length and of 120 mm in width. The samples were stored in a well-sealed container, in the presence of silica gel, for more than ten days. The thermal properties of the PMMA material have been reported in the literature (e.g., Chen and Delichatsios, 1994; West et al., 1996), with the melting temperature of between 220 and 240 °C, the pyrolysis temperature of about 367 °C, the specific heat of 2.2 kJ/(kg K) and the thermal conductivity of 0.282 W/(m K).

Prior to an experiment, a dried PMMA sample was weighed using an analytical balance (Mettler PM600) and then placed on the pre-shaped aluminium trough and held by two aluminium spacers at the sides. The glass plate and the aluminium spacers were held in place with a sealant. The entire channel assembly was clamped together to prevent leaks. The channel was then adjusted to the horizontal position using a spirit level. Gas mixtures of oxygen concentration of 49.8%, 79.8% and 100.0% were introduced into the channel through the diffuser at predetermined flowrates between 1.96 and 7.32 L/min. Each experiment started by igniting the PMMA plate at the exhaust end of the channel using an ignition device. As soon as the flame was well established and commenced to propagate uniformly along the surface of the PMMA plate, the digital video camera was started to record the spreading flames. Once the flame approached the diffuser by a distance of less than 10 mm, turning off the gas stream terminated the experiment. The sample was removed from the channel and weighed again, to determine the mass loss caused by the flame-spread process.



1 Gas line for nitrogen
2 Gas line for oxygen
3 Gas line for fire agents
4 Mass flow controller
5 Rotameter
6 Three-way valve
7 Drying tube
8 Gate valve
9 Gas diffuser
10 Oxygen analyser
11 Digital video camera
12 Narrow channel
13 Stand for narrow channel
14 Enlarged cross-section of narrow channel
15 Clip for the top plate
16 Solid fuel
17 Top plate
18 Bottom supporter
19 Aluminium spacer

Figure 1. Schematic diagram of the experimental apparatus.

By playing back the time–indexed images of flame spread recorded during each run, we extracted the location of the flame as a function of time. The average rate of flame spread was then determined from plots of distance versus time. The flame length was also measured from the recorded images of the flame.

RESULTS AND DISCUSSION

A schematic diagram of flame spreading over the PMMA fuel in the narrow channel is illustrated in Fig. 2. The oxidative reactions in the flame zone generate a large amount of heat, with a portion transferred to the fuel by conduction and radiation. With a continuous heat penetration into the fuel, ahead of the flame, the PMMA polymer unzips (pyrolyses) into methyl methacrylate (MMA) monomer. Mixing of MMA fragments with the incoming oxidation medium, in conjunction with the energy transfer from the existing flame zone, allows the flame to move forward over the fuel surface (e.g., Fernandez-Pello, 1995). Smoke, formed as a result of the combustion reactions in the flame zone, is transported downstream by forced convection, with some smoke particles adhering on the bottom side of the top plate. The fuel surface after burning is fairly clean with only a small amount of char particles left on its surface.

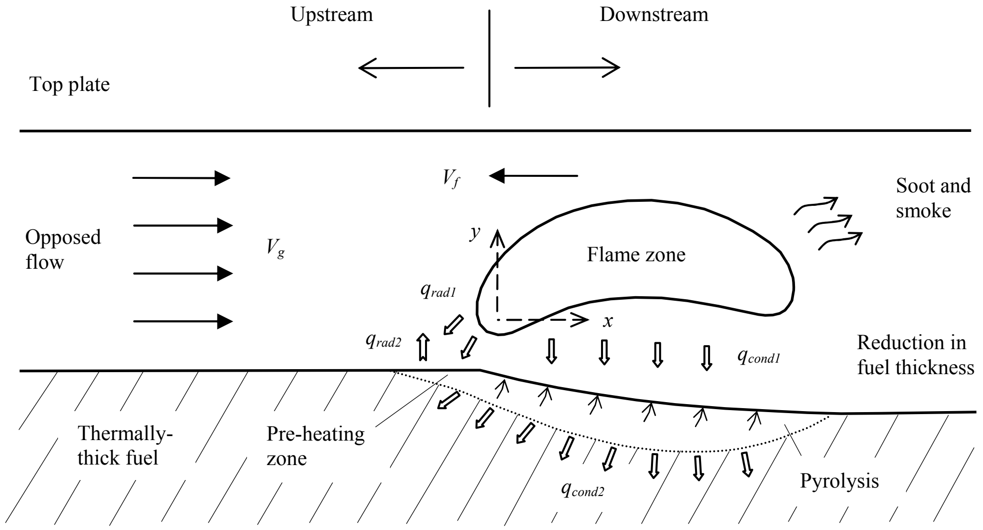


Figure 2. Illustration of flame spread over a PMMA sample in the narrow channel.

Rates of flame spread for a number of upstream velocities and different oxygen concentration in the gas stream are shown in Fig. 3(a). At a fixed oxygen concentration in the gas stream, the rate of flame spread increases monotonically with the gas velocity. The rate of flame spread is also sensitive to the oxygen concentration in the gas stream. For the same gas velocity, the rate of flame spread increases with increasing in the oxygen concentration in the gas stream. With an increase in the gas velocity, the flame length increases considerably, although the length of flame zone does not indicate a statistically-significant dependence on the oxygen concentration; see Fig. 3(b).

The rate of the oxidation reactions increases linearly with oxygen concentration in the gas stream, allowing a larger amount of heat to be produced in the flame zone. This results in a significant increase in the average flame temperature, as supported by the direct observation of the change in flame colours under conditions of different oxygen concentrations. Owing to higher combustion intensity in the flame zone, heat transfer into the solid phase is more efficient for higher oxygen concentration, leading to the increased rate of flame spread, as showed in Fig. 3(a).

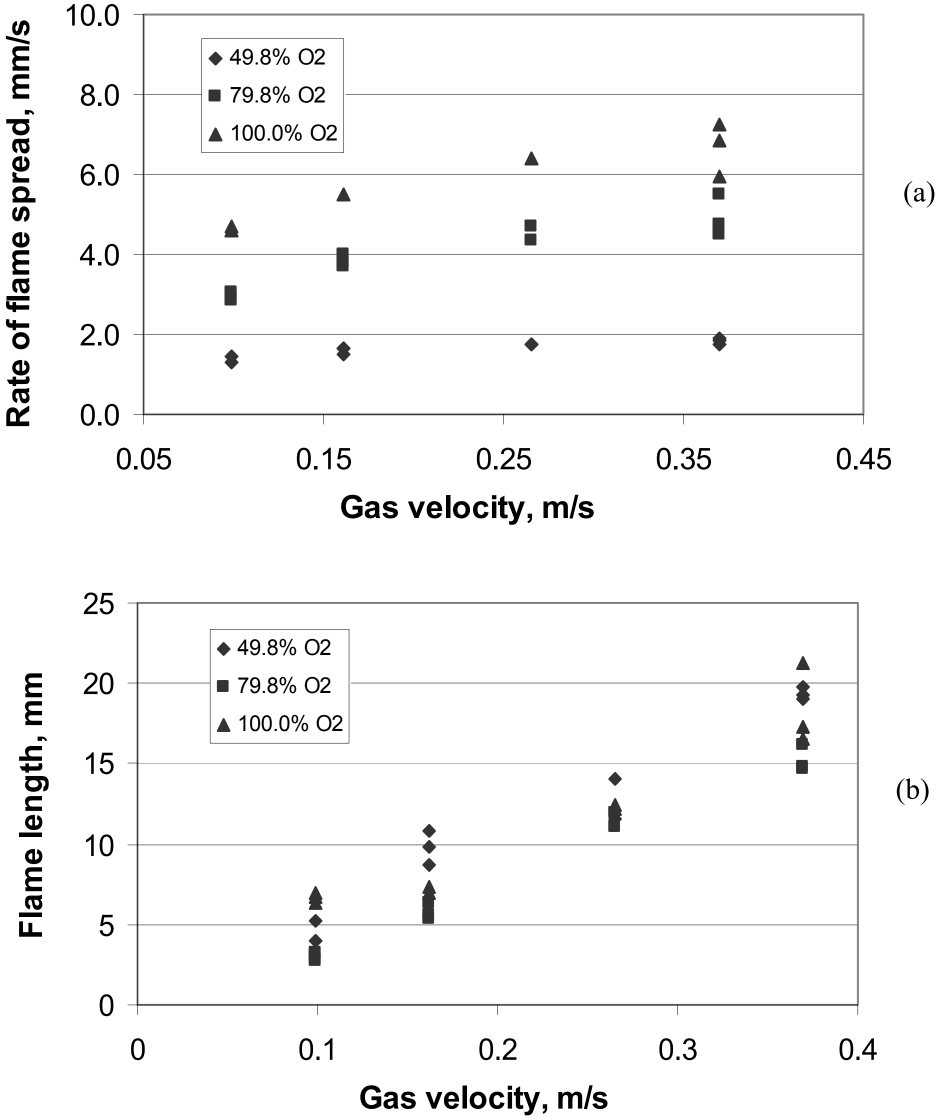


Figure 3. Effect of the flowrate of the induced gas stream on the rate of flame spread (a) and the length of flame zone (b). Experiments were performed with mixtures containing 49.8, 79.8 and 100.0% of O_2.

Mass loss during the flame spread over the solid fuel was found to be dependent on the induced gas flowrate and the oxygen concentration in the gas stream (Fig. 4). For the gas mixture containing 79.8% of O_2, and for the gas flowrate varying from 0.099 to 0.37 m/s, the mass loss increased from ~ 1.5 to ~ 6.0 g. Likewise, at the mean gas velocity of 0.37 m/s, the mass loss increased from ~ 3.8 g to ~ 10.4 g with the oxygen concentration decreasing from 100 to 49.8%. Mass loss during an experiment occurs as a consequence of heat transfer from the adjacent flame to the fuel surface. The depth of the pyrolysis zone in the solid was estimated by dividing the mass loss by the fuel density and the burnt surface area.

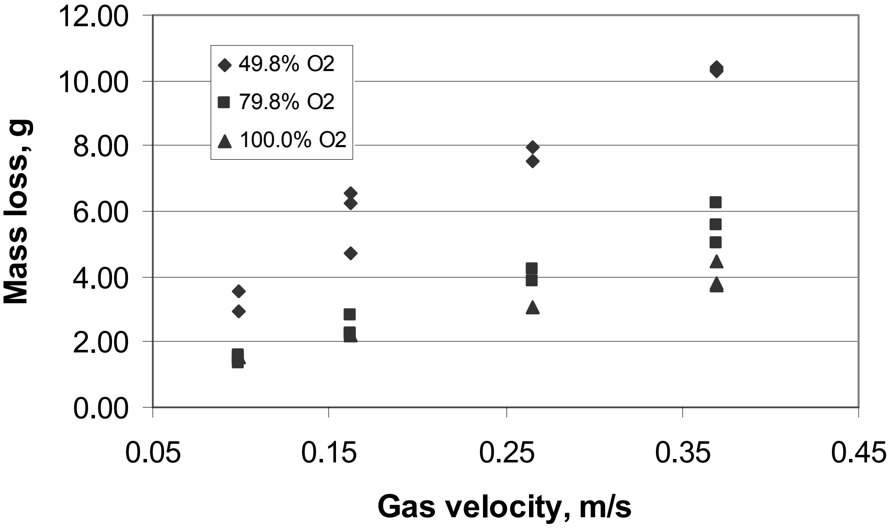


Figure 4. Relationship between mass loss during flame spread and upstream gas velocity.

The mean residence time of the flame at a specific location on the fuel surface is calculated by dividing the visible flame length by the rate of flame spread. The flame residence times for various runs are shown in Fig. 5. It is seen that the trend in the flame residence time is similar to that of mass loss. That is, the time of a flame to pass over a certain location on the fuel surface is proportional to the thickness of the pyrolysis zone in the solid. This linear dependence is also illustrated in Fig. 6.

We made several attempts to correlate phenomenologically the depth of the pyrolysis layer in the solid fuel with the gas velocity and the rate of flame spread. The depth of the pyrolysis layer versus the ratio of V_a and V_f, as shown in Fig. 7, provided the best fit to the experimental results:

$$\delta_v \propto \frac{V_a}{V_f}. \tag{1}$$

With some simple substitutions, Equation 1 can be recast in terms of the ratio of the pyrolysis rate to the incoming air flowrate

$$\frac{\dot{m}_p}{\dot{m}_a} \approx 0.5\text{, independent of oxygen concentration.} \tag{2}$$

This result reminds one of the similar relationship for enclosure ventilation-controlled fires, which is

$$\frac{\dot{m}_p}{\dot{m}_a} \approx 0.2. \tag{3}$$

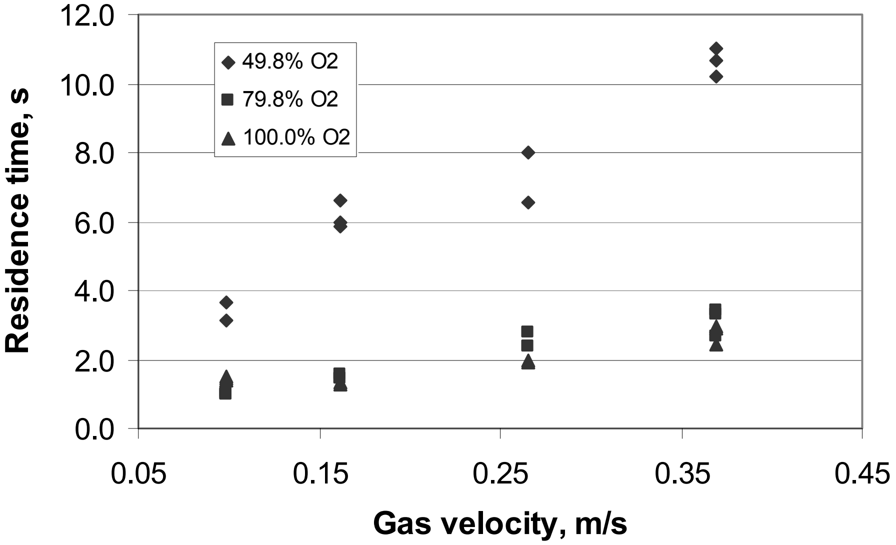


Figure 5. **Relationship between the flame residence time and the upstream velocity.**

Mass transfer of the reactants to the flame zone and chemical kinetics of the combustion reactions dominate the flame spread in the narrow channel. Thus, fire suppressants added in the gas stream would definitely play a role in the flame zone. The narrow channel apparatus has the potential to become a standard rig for testing the efficiency of gaseous fire suppressants, by determining the rate of flame spread, visible flame length and the mass loss during the measurements. Furthermore, a micro gas chromatograph or a residual gas analyser could be incorporated in the experimental apparatus, allowing quantitative measurements of the gas products formed during flame spread over solids in the narrow channel. Using either of these analytical techniques, one can perform a more detailed examination of the role of fire suppression agents on chemical reactions occurring in the flame zone, including determination of the emission factors of toxic byproducts produced in mitigated flames.

CONCLUDING REMARKS

It was observed that flame propagates uniformly across thermally-thick plates of PMMA. The flame properties, i.e., the rate of flame spread and the length of the flame zone, are dependent on the velocity of the induced gas mixture and the oxygen concentration in the gas stream. Thickness of the pyrolysis layer, determined from the mass loss, is also a function of the gas velocity and oxygen concentration in the gas stream. The rate of flame spread increases monotonically with the velocity of the induced gas flow.

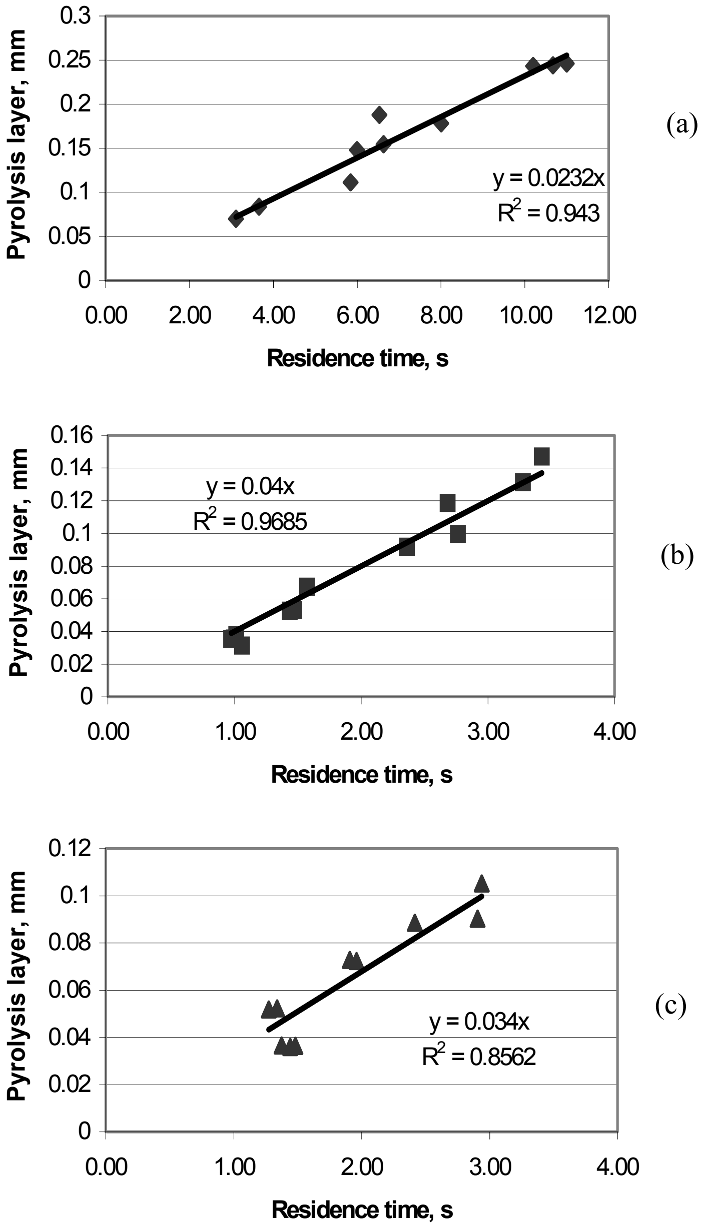


Figure 6. **Relationship between the thickness of the pyrolysis layer and the flame residence time for oxygen concentration of 49.8% (a), 79.8% (b) and 100.0% (c).**

The narrow-channel apparatus is able to generate stable, slowly-moving flames propagating over surfaces of solid fuels. The apparatus provides a convenient setting to test the effectiveness of gaseous fire suppressants. Both inert and chemically active agents can be easily added into the gas stream, to be transported into the flame zone. The rate of flame spread and the flame length measured during testing can be used as indices to rank the performance of gaseous agents. Furthermore, a gas chromatograph or a residual gas analyser can be set up to sample the composition of the exhaust gases, to determine the rates of formation of toxic combustion by-products in mitigated flames.

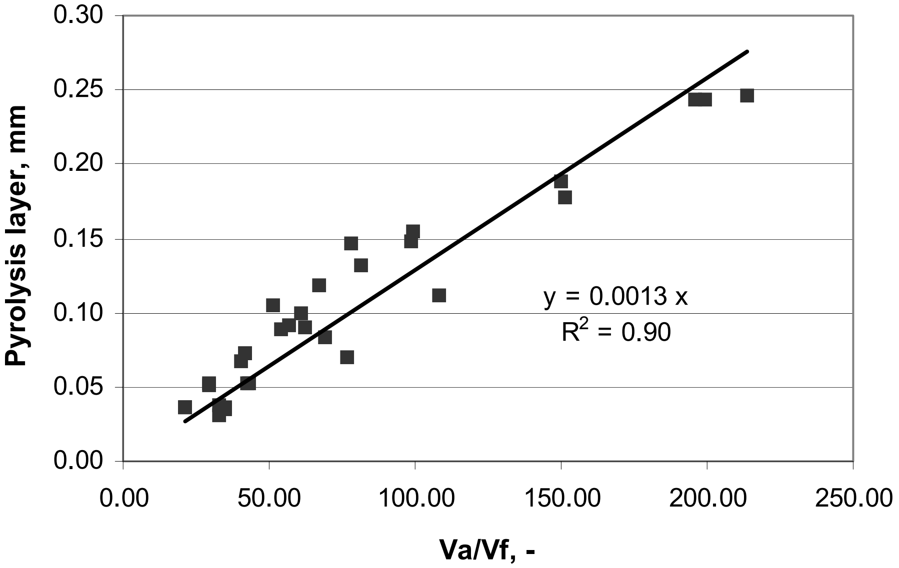


Figure 7. Correlation between the thickness of the pyrolysis layer and the ratio of the upstream gas velocity and the rate of flame spread.

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