TESTING OF GASEOUS FIRE SUPPRESSANTS IN NARROW CHANNEL APPARATUS

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ABSTRACT

In this paper, we develop a testing rig for ranking of halon replacements under conditions corresponding closely to fires of solid fuels. The rig is based on the narrow channel apparatus (3 mm in height, 110 mm in width and 375 mm in length), which allows the determination of the propagation velocity of creeping flames with and without fire suppressants. Strips of thick cardboard are placed at the bottom of a narrow channel, and a mixture of oxygen-enhanced air and an extinguishing agent is introduced into the channel in the direction opposite to propagating flames. The tests are taped and the propagation velocity is obtained simply by plotting the distance travelled by the flames as a function of time. Experiments were performed with dried and undried fuels, and at various gas flow rates to determine the range of operating conditions of the testing device. These experiments indicate great potential of the narrow-channel apparatus both as a testing and an experimental tool for evaluating halon replacements, under conditions, which are easily reproducible in a laboratory. The paper concludes with a presentation of the preliminary suppression results for mitigation of creeping flames with trifluoroiodomethane (CF_3I).

INTRODUCTION

For most practical applications, it is desirable to test the effectiveness of gaseous fire suppression agents, in order to engineer effective fire-mitigation systems [1]. Usually, such tests are performed in the context of idealised gas-phase systems that are realised in laboratory-scale experiments by laminar pre-mixed flames to which a suppressant is added, with one measuring the laminar burning velocity, or flammability limits [1-6]. Laminar diffusion flames, either in counter-current (opposed flow) or co-current (cup burner) geometries provide other experimental configurations to study gas-phase extinguishment. Arguably, the latter (cup-burner) flames mirror more closely real fires, in terms of the fuel used, type of flames and strain rate at extinction. Most fires, however, involve solid fuels, necessitating the development of a testing device capable of ranking the effectiveness of gaseous fire suppressants on fires of solid fuels under controlled conditions.

Flame spread is one of the most important parameters that characterise burning of solid fuels [7]. The flame spread itself varies with the type of solid fuel, its thickness, moisture content, grain orientation, heat flux received by the sample, as well as the composition and velocity of the incoming gases [7-9]. A narrow channel apparatus [10-12] provides a convenient setting to study flame spread over solid fuels and to test the effect of fire suppressants on flame propagation. The apparatus was first introduced in the former Soviet Union [10] to determine the behaviour of flames propagating under microgravity-like conditions. It consists of two-dimensional Helle-Shaw cell, a few millimetres in thickness, with a flat specimen of a solid fuel attached to the bottom plate. The gas diffuser, introducing O_2/N_2 mixture into the channel, and the point of ignition are separated by the length of the channel to induce creeping (counter-current) flames. Flames are easily established and move forward on the fuel surface at a steady rate, in the direction opposite to the gas flow.

The narrow-channel apparatus possesses several attractive features that simplify the fluid mechanics, and to some extent the heat transfer processes, permitting the practitioner to use the device as a testing apparatus and allowing the researcher to concentrate on studying the kinetics of interaction of fire suppressants with well-defined laminar diffusion flames of solid fuels. The flow in the narrow channel is laminar and two-dimensional, except at very high gas velocities when the side boundary conditions may become important. Once the apparatus is oriented horizontally, the effect of gravity, manifesting itself as the buoyancy force, becomes negligible due to the small channel height. With respect to heat transfer, the heat conduction in the solid ahead of the flame front is the dominant heat transfer mechanism in the flame spread [7-9]. Thus, only for thermally-thick materials the conduction become independent of the fuel thickness. The gaseous products transported by the gas stream can be easily collected downstream in the Helle-Shaw geometry for toxicity and combustion by-product testing.

This work aims at exploring the operation and results from the narrow channel apparatus to determine whether or not the apparatus can be used as a testing method to evaluate gaseous fire suppressants on fires of solid fuels. A narrow channel apparatus was constructed based on the information reported in the literature, with tests performed at various flow rates of O_2/N_2 mixture. This allowed to determine a range of conditions suitable for operating the device for testing applications. Preliminary suppression experiments were carried out with various concentration of

CF_3I to identify the sensitivity of the flame spread velocity to the concentration of this agent in the gas mixture.

TEST METHODOLOGY

Figure 1 presents a schematic diagram of the testing device. The device consists primarily of the narrow channel apparatus, an image recording system and a gas delivery system. Gases are introduced into the manifold from one or two compressed-gas cylinders, containing a ready-made O_2/N_2 mixture or O_2 and N_2 gases, respectively. Two mass flow controllers maintain the concentration of oxygen and the flow rate of the gas stream at desired values. An oxygen analyser (ADC 7000) measures the concentration of O_2 in the gas stream. A rotameter serves to dose a fire suppression agent to O_2/N_2 mixture at a preselected flow rate. The gas stream enters the narrow channel via a gas diffuser, which distributes the incoming flow uniformly across the cross-sectional area of the channel.

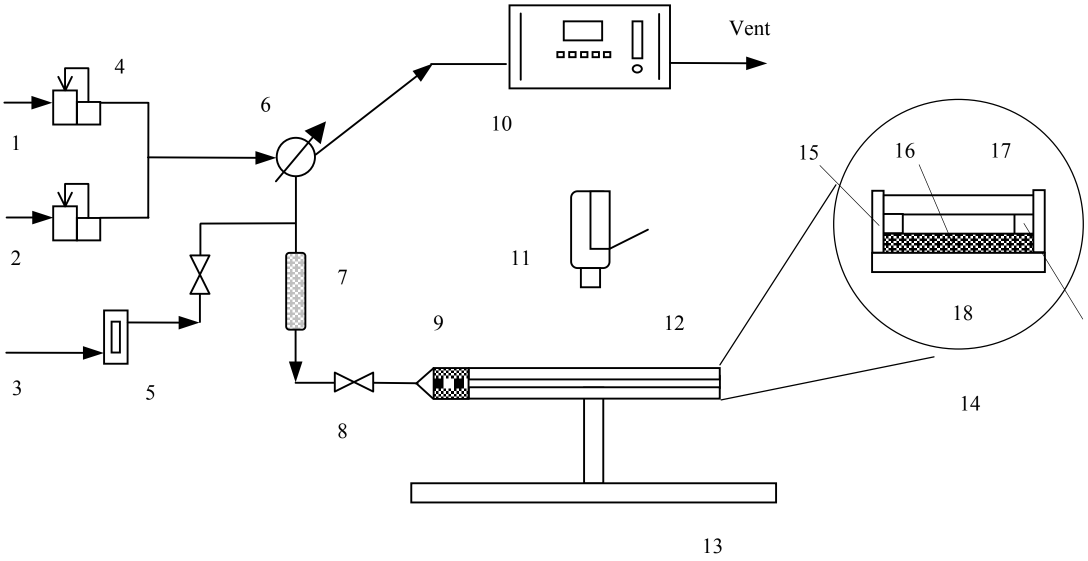


Figure 1 Illustration of the major parts of the testing device.

Two pieces of fire-resistant glass plates separated by two aluminium spacers, which are 3 mm in hight, set the channel's dimensions. Fuel sample, such as a strip of cardboard, is placed on the bottom glass plate, and the spacers are inserted between the cardboard and top glass plate to maintain a 3 mm channel thickness. With the spacers and the gas diffuser in place, the narrow channel is 375 mm in length and 110 mm in width. A nichrome wire, powered by a low voltage transformer, acts as igniter. A digital video camera records the propagating flames during each experiment. A small canopy hood connected to an exhaust duct (not shown in Figure 1) vents, to the outside, the smoke and combustion gases produced in the experiments.

Fuel samples, 120 mm in width and 400 mm in length, were cut from sheets of brown-coloured cardboard, which contained randomly distributed fibres. Solid lines were drawn in pencil in 10 mm increments on the cardboard surface to facilitate the determination of the flame velocity. The present tests were performed with dried and undried samples to explore the effect of the sample's moisture content on the flame spread. The dried samples were prepared in oven at 105°C for more than 48 h, then cooled down in a well-sealed box that contained silica gel. The undried samples contained about 8.2% of moisture. The apparent density of dried and undried samples was 0.58 g/cm^3 and 0.63 g/cm^3, respectively. Suppression tests were conducted with trifluoroiodomethane (CF_3I).

A multi-purpose sealant was applied around the diffuser and between the aluminium spacers and the top glass plate to prevent leaks. The channel assembly was then clamped together and oriented horizontally. At this point, a mixture of 39.9% of oxygen in nitrogen diluent commenced to flow through the channel, with CF_3I added to O_2/N_2 mixture in suppression tests. The cardboard strip was then ignited, uniformly across the channel, with a nichrome wire spanning the width of the cardboard at the open end of the channel. Each test was recorded by a video camera, with the data on flame-spread velocity and flame length extracted from the slow motion play back of the tape. An experiment terminated with shutting off of the flow of the O_2/N_2 mixture to the narrow channel apparatus.

RESULTS AND DISCUSSION

General experimental observations

Figure 2 illustrates the dominant mass and heat transfer processes occurring during flame spread over thermally thick fuel in the test apparatus. A combustion front forms just after the ignition of the sample propagating with a constant velocity on the fuel surface. A substantial portion of the fuel is left uncombusted behind the flame front, with a thin layer of char covering this uncombusted fuel [7-9]. Gaseous pyrolysates that sustain the combustion evolve by thermal decomposition of the solid fuel in the pyrolysis zone underneath the flame and, to the smaller extent, in the preheating zone ahead of the flame. Some of the pyrolysates, together with water vapour, diffuse through the porous fuels condensing at the bottom surface of the cardboard strip. Soot and smoke, produced as a result of the combustion reactions in the flame zone, are transported downstream, though a fraction of soot and smoke particles adhere to the bottom surface of the top glass plate and are not removed with the exhaust gases.

The robustness of the apparatus to produce reliable and reproducible data necessary for testing purposes is investigated in Figure 3. The flame propagation velocity, corresponding to the slopes of the plots in Figure 3, shows remarkable repeatability for tests with and without suppressant, both for dried and undried fuel samples. The flame velocity stays constant and does not vary with position in the channel. This means that buoyancy effects that might have been expected to influence the beginning of each experiment are negligible. Note that the offset along the time axis corresponds to arbitrary starting times of the experiments.

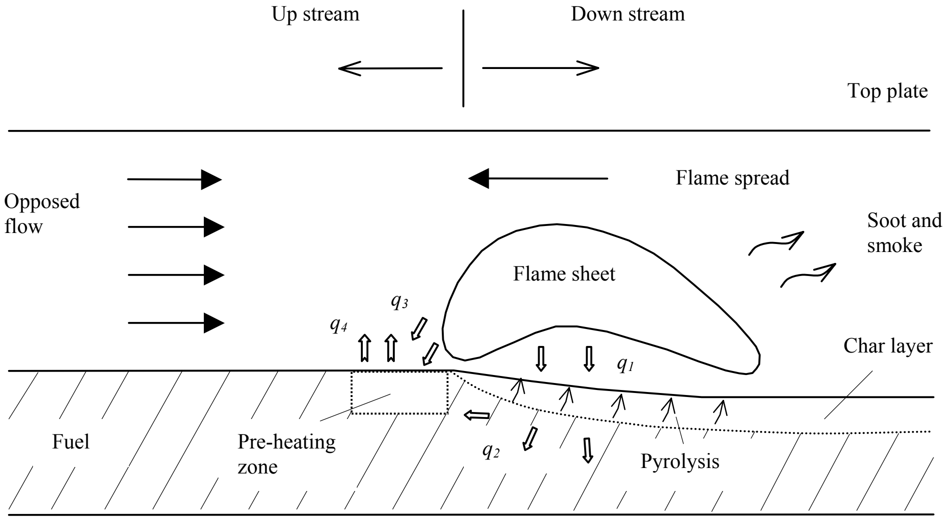
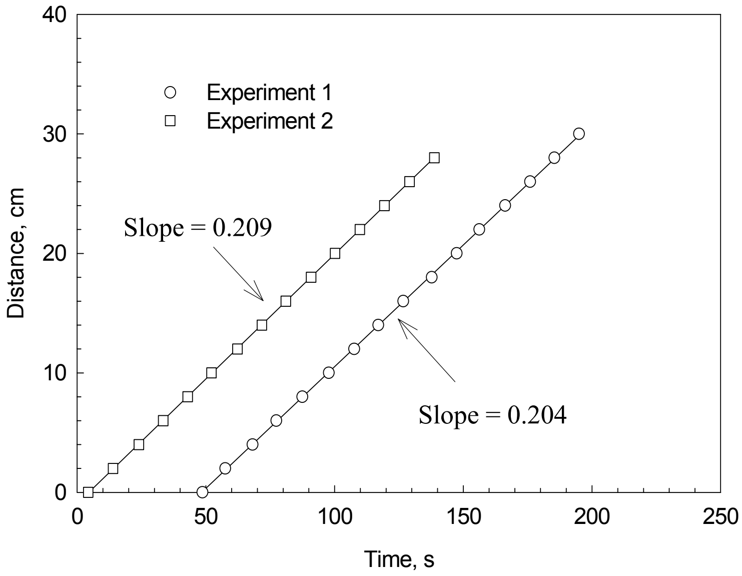
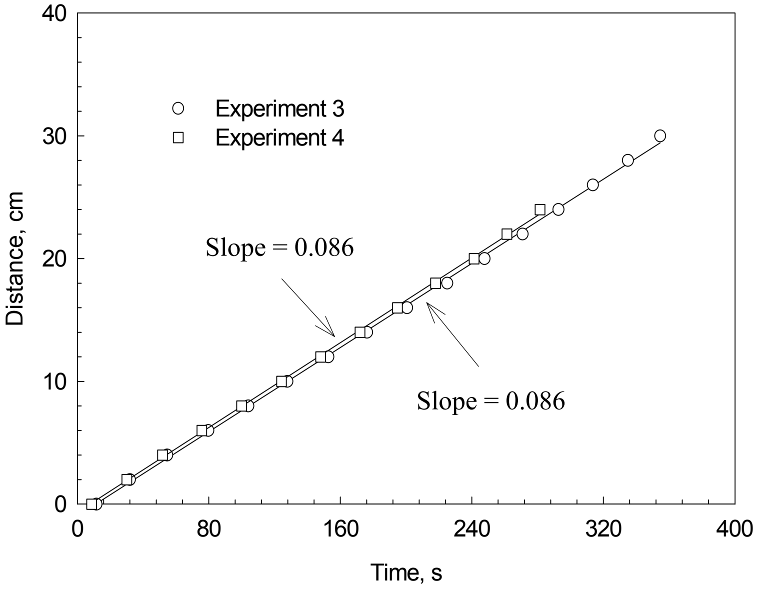


Figure 2 A schematic diagram of flame spread over a cardboard sample in the narrow channel. Figure is not drawn to scale.



(a)



(b)

Figure 3 Readings obtained from the video camera. Experimental points correspond to the flame front crossing 2-cm increment lines drawn on the cardboard surface. (a) Dried fuel, incoming flow rate of gas mixture set at 8.0 L/min, no suppressant. (b) Undried fuel, incoming flow rate of the gas set at 4.2 L/min, 3.2% of CF_3I.

Figure 4 demonstrates the relationship between the rate of flame spread and the flow rate of the incoming gases. The flame cannot be sustained for gas flow rates of less than 1 L/min. In some experiments we were able to ignite the cardboard at less than 1 L/min, but the flame was unable to propagate and self-extinguished soon afterward. The flame spread increases sharply for the gas flows between 1 to 4 L/min, and above 4 L/min it becomes a weak function of the induced gas flow rate. It is this regime that yields itself particularly useful for testing purposes. Although the rate of flame spread depends on the level of moisture of the cardboard samples, the shape of flame-spread curves remains essentially unchanged. That is the curves are relatively flat above 4 L/min.

The length of the propagating flame sheet shows a strong dependence on the gas flow rate (Figure 5). We have also observed that the flame colour, reflecting availability of oxygen and intensity of mixing between pyrolysates and incoming gases, changes from blue to dark red, to bright red and then to bright orange, when the gas flow rate increases from 1.2 to 8 L/min.

The depth of the char layer depends the flow rate of the induced gas stream. Although we have not found a method to accurately measure the depth of the burnt layer (char layer) at the fuel surface, we have observed a thin layer of char and no evidence of pyrolysates diffusion to the bottom of the sample (in other words, the bottom of the sample maintained its initial colour at the completion of the tests) for tests performed at low velocity of the induced gases. At higher gas flow rates, char thickness increased, more soot and tars deposited on the inner surface of the top glass plate and the back surface showed condensation of pyrolysates and water vapour.

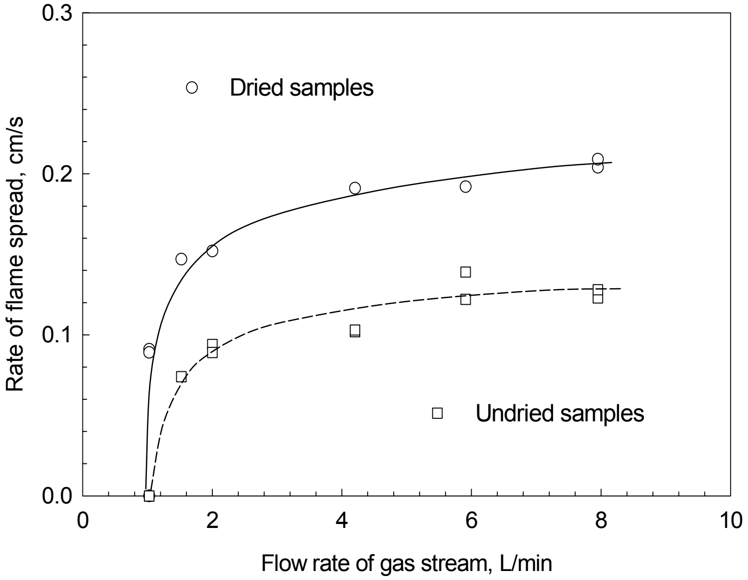


Figure 4 The variation of the rate of flame spread with the flow rate of the incoming (induced) O_2/N_2 mixture.

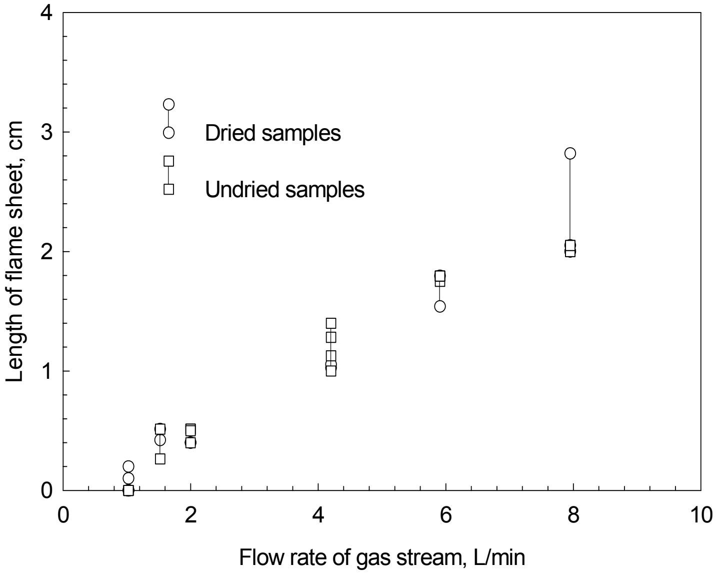


Figure 5 The length of the flame sheet as a function of the flow rate of the oxygen/nitrogen mixture fed to the apparatus.

In the present geometry, two factors limit the rate of flame spread, namely the availability of oxygen and heat losses from the flames. At very low flow rates, the amount of oxygen reaching the flame can only support a narrow flame zone. This restricts the rate of heat transfer to the fuel, limits the rate of pyrolysis and rate of flame propagation. It appears that in this regime, the pyrolysates mix well with the incoming flow and burn completely. With increasing flow rate, the flames elongate, more heat is transferred to the fuel ahead of the flame, which results in acceleration of flame spread. In this regime, the combustion is incomplete with tars deposited on the top glass plate or removed from the narrow channel with the exhaust gases. Finally, at very high flow rates of the induced O_2/N_2 mixture, the rate of flame spread seems to be controlled by heat losses from the flame zone, as a consequence of heat transfer both through top and bottom plates.

High flow rates of the gas fed to the apparatus supply more oxygen to the combustion zone leading to more intense and longer flames, a phenomenon which explains different flame coloration observed in the tests. As the vertical size of flames is limited by the channel thickness, the length of flame sheet increases significantly. This enhances heat transfer between the flames and the solid fuel, leads to higher carbon burnout, faster and more complete pyrolysis, and results in the increased thickness of the char layer. Heat transfer by conduction in the solid fuel ahead of the flame increases as well, substantially rising the velocity of flame spread. This observation is consistent with theoretical predictions and experimental results from studies on opposed-flow flame spread over semi-infinite solid in open space [8,9].

Effect of the fire suppressants on flame spread

The rate of flame spread decreases with increasing concentration of the fire suppression agent (Figure 6). The reduction in the propagation velocity corresponds to 30-40% for CF_3I at concentration up to 4.5%. For comparison, no combustion of premixed hydrocarbon fuels (such as CH_4) can be sustained at the concentration of CF_3I higher than about 6% [13]. The length of flame sheet fluctuates, stretching slightly with enhanced concentration of the added agent (Figure 7).

Chemically active suppressants transported into the flame zone remove the flame propagating radicals such as H and OH; in the present case of CF_3I via the iodine catalytic cycle or by fixing H radicals into hydrogen fluoride [2, 4-6]. This leads to the break down of the exothermic chain reactions in the flame zone, slowing down the combustion process. In the present work, we observed greater amount of soot and smoke produced in suppressed than in unsuppressed tests. In tests with CF_3I suppressant, more tars condensed on the bottom surface of the top glass plates and at the back of the cardboard strip. This observation indicates the role of CF_3I in inhibiting the combustion reactions of the gaseous pyrolysates [1,2]. The observation is consistent with the H and OH removal mechanism that characterises mitigation of premixed hydrocarbon flames with CF_3I. It is possible that oxygen radicals are not as easily removed from the flames, as H and OH, or that O radicals regenerate in subsequent reactions [2], resulting in the length of the flame sheet that does not change with the suppressant concentration.

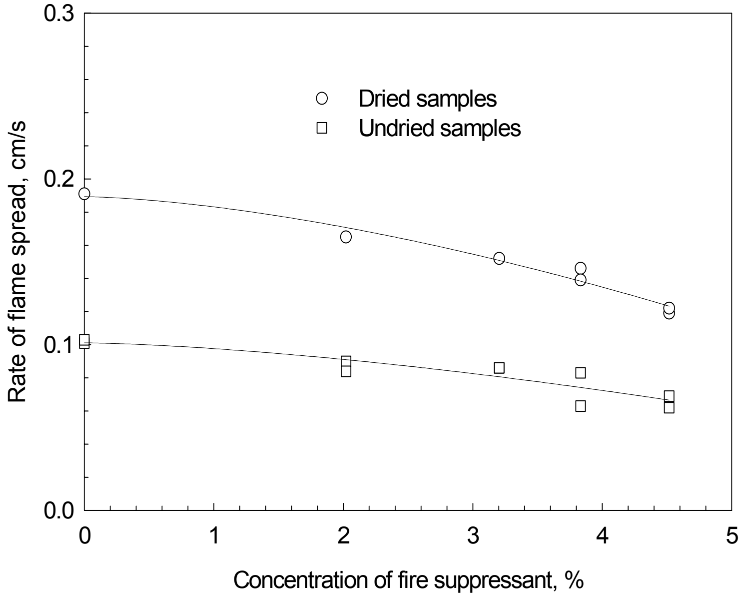


Figure 6 The dependence of the rate of flame spread on the concentration of CF_3I in the gases fed to the apparatus. The flow rate of $O_2/N_2/CF_3I$ mixture was maintained at 4.2 L/min.

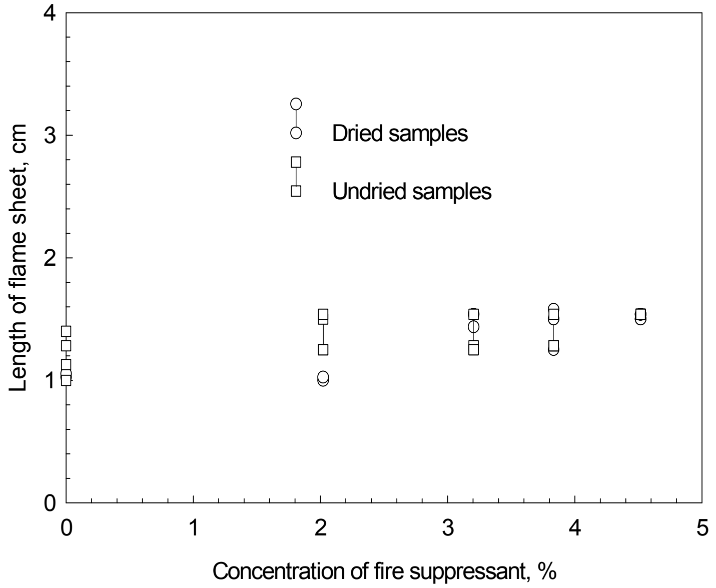


Figure 7 The length of the flame sheet as a function of the concentration of CF_3I in the gas mixtures introduced into the apparatus. The flow rate of $O_2/N_2/CF_3I$ mixture was maintained at 4.2 L/min.

CONCLUSIONS

Preliminary experiments show that the narrow channel apparatus produces uniform rate of flame spread over a solid fuel, in tests with and without fire suppressants. The velocity of the flame spread can be used as a parameter to rank the effectiveness of suppressant on fires of solid fuels. For the present geometry, the apparatus needs to be operated at flow rates higher than 4 L/min, to avoid dependency of the results on flow rate. The rate of flame spread is sensitive to the concentration of the extinguishing agent, with 4.5% CF_3I in the induced gases resulting in 30-40% reduction in the flame spread.

At flow rates in excess of 4 L/min, the fuel used in our investigation can no longer be considered as thermally thick. This means that the current results are affected by heat losses from the fuel to the bottom glass plate. It is recommended that further tests be performed to investigate the effect of fuel thickness on the flame spread. In the limit of thermally thick fuels the test results should be independent of the heat losses from the fuel to the bottom glass plate.

The apparatus can be operated with dried or undried samples. The moisture level of the samples should not change between the tests. Flame spread shows similar dependence on the gas flow rate, regardless of the moisture content of the fuel. It is recommended that dried samples are used in the tests, as they provide a wider range of propagation velocities, which could facilitate differentiation between various suppressants.

The experimental data obtained so far indicate that for the present test geometry and O_2 concentration (39.9%) employed in the trials, combustion conditions exist for flow rates in excess of 1 L/min. In unsuppressed tests, it is the rate of oxygen supply into the flame that determines the rate of flame propagation. At higher flow rates, the velocity of propagating flames plateaus, possibly as a result of heat losses through the top glass plate. This effect deserves further study.

It should be possible to adapt the narrow channel apparatus to collect combustion products leaving the channel. This would allow to determine the formation rates of toxic combustion by-products formed in mitigated and unmitigated flames. Such by-products may involve CO, HF, HI as well as organic species including PAHs, PCBs and PCDD/F. The tars condensed on the glass plates and the uncombusted fuel and char could be also analysed for the presence of pollutants.

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