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# Experimental study of the channel effect on the flame spread over thin solid fuels

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ABSTRACT

We experimentally burn thin solid fuels and obtain the speed of the flame front when it propagates (1) within a narrow channel (closed cross section), (2) within a channel with lateral walls only and (3) through a free cross section (plain case). The latter configuration is the classical one and it has been extensively studied with analytical, numerical and experimental methods by other authors. Our experiments have been carried out at different geometrical configurations and angles of inclination of the sample and also at several values of oxygen molar fraction. All experiments are restricted to purely buoyant flow. Our main results are as follows: (1) sidewalls reduce the flame spread rate in a non-monotonous trend when varying its height; (2) in horizontal flame spread, two simultaneous flame fronts that propagate at different velocities may arise in the channel case at high oxygen levels. The fastest flame front speed may be higher than that obtained in the plain case; (3) in upward flame spread, the channel effect configuration produces the highest flame front speed. We finally analyze the correlation of the downward flame front speed data in terms of the Damkohler number.



## 1. Introduction

Surface flame spread may become a very important component of fire propagation [1]. It arises after igniting a solid fuel that pyrolizes and releases fuel volatiles. These gases react with the ambient oxygen in an exothermic way, producing a flame. The energy released in the combustion process preheats the surface ahead of the flame front. Such a temperature increase may eventually lead to a pyrolysis reaction in the virgin solid close to the flame leading edge and, hence, the whole mechanism acts again. This sequence explains the self-sustained propagation of the flame front [2].

In fire dynamics studies, flame spread over both thick and thin materials has been extensively analyzed, being thoroughly reviewed in Refs. [3–5]. Very few studies, however, have been focused on the behavior of the flame front speed of thin solid fuels when traveling in channels with either open or closed cross sectional areas. In very narrow channels with a closed cross section (on the order of 1 cm height) buoyancy effects are suppressed and smoldering fronts may occur [6–9]. In small channels with an open cross section, sidewalls act as barriers of lateral flow entrainment and, as a consequence, the speed of downward flame fronts is substantially reduced [10].

The potential hazard of fires in small channels has been pointed out, for example, in Refs. [7,9]. In channels with small gaps (height on the order of 1 cm) under forced flow, almost undetectable flamelets may propagate and, once reached proper conditions, raise as vigorous flames that may have dramatic consequences. This was the apparent cause of the 1998 Swissair Flight 111 crash [11]. Other flames that propagate in small enclosures include, for example, fires inside electronic devices, behind walls, in close proximity regions as in folds of cloth, etc. On the other hand, channels with slightly greater heights (on the order of few cm) are often employed as service lines in several industrial applications. For example, combustible lines between the fuel tank and the engine are located in service tunnels below the passengers compartment in motorcoaches. Under some circumstances, these tunnels may enhance the fire propagation as it apparently happened in a motorcoach fire during the evacuation of the hurricane Rita in 2005 [12]. The previous examples are evidences of the practical interest of flame spread studies in small channels.

The aim of the present paper is to study the effect of the channel type on the burning spread rate of a thin cellulosic-type fuel. As far as we know, it is the first time that the effect of small channels of few cm (height of 4 cm or 10 cm) is analyzed in a purely buoyant configuration (i.e., with no forced flow) at several oxygen concentration levels. The common reasoning suggests that the flame front propagates at a slower speed than in the plain (no channel) case when burning downwards due to an increase of the background flow in upward direction. Although such an expected

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**Table 1**
Summary of studies that obtain the flame front speed of thin solid fuels as a function of the angle of the sample inclination.

| Ref. | Angles[a] | $X_{O2}$ (%) | Channel type | Type of sample | Sample properties | Sample dimensions (cm × cm) |
|---|---|---|---|---|---|---|
| Hirano | [0°, 90°] | atm[b] | Plain[c] | Computer card | $2\tau$ = 0.16 mm | 18.7 × 8.2 |
| Hirano | [−90°, 90°] | atm | Plain | Computer card | $2\tau$ = 0.16 mm | 20 × 6.4 |
| Sibulkin | [0°, 90°] | atm | Plain | Cellulose | $2\tau$= 0.21 mm, $\rho_s$ = 433 kg m$^{-3}$ | × [0.6, 7.6] |
| Kashiw | [0°, 90°] | atm | Plain | Cellulose | $2\tau$ = 1 mm, $\rho_s$ = 470 kg m$^{-3}$ | 28 × 14 |
| Drysdale | [−30°, 0°] | atm | Burning at 8 mm above an aluminum plate | Computer card | $2\tau$ = 0.18 mm | 19 × [2, 6] |
| Quintiere | [−90°, 90°] | atm | Burning on an insulating plate | Paper napkin | $2t$ = 0.168 mm, $\rho_s$ = 220 kg m$^{-3}$ | 30.5 × 5.4 |
| Present | [−90°, 90°] | 22, 25, 30, 50, 70 | See Fig. 1 | Cellulose | $2\tau$ = 0.186 mm, $\rho_s$ = 462 kg m$^{-3}$ | 26 × 4, 26 × 8, 36 × 4 |

[a] Vertically upwards = −90°. Vertically downwards = 90°.
[b] atm = experiments at atmospheric oxygen molar fraction.
[c] Plain case.

behavior is confirmed as a whole, our experimental study reveals that there exist other features that may have serious implications in fire safety issues. For example, the possibility of having two simultaneous fronts that propagate at different velocities in the horizontal configuration.

In our geometrical configurations, we also investigate the effects of changing the sample inclination angle. The study of fires in inclined trenches for thick solid fuels has been extensively analyzed (see, e.g., [13–15]). In thin solid fuels, few studies have analyzed the effect of the inclination angle, being summarized in Table 1. Note, however, that works cited in Refs. [16–21] assume atmospheric conditions for the oxygen concentration and samples suspended with thin metal frames (except in [20] and in [21] where burning occurs with one face almost in contact with an aluminum and an insulating plate, respectively).

## 2. Experimental set up

We burn cellulose samples 4 cm wide and 26 cm long, 8 cm wide and 26 cm long, and 4 cm wide and 36 cm long depending on the case being analyzed. The physical properties of our fuel material were already obtained in Ref. [10] being here listed for completeness: conductivity $\lambda_s$ = 0.101 W m$^{-1}$ K$^{-1}$ at 293 K, specific heat at constant pressure $c_p$ = 1180 J K$^{-1}$ kg$^{-1}$ at 300 K, solid density $\rho_s$ = 461.9 kg m$^{-3}$ and half-thickness $\tau$=0.0933 mm. A thermogravimetric analysis using air at ambient pressure with four different heating rates (2 K min$^{-1}$, 5 K min$^{-1}$, 10 K min$^{-1}$ and 20 K min$^{-1}$) provides a vaporization temperature of $T_v$ = 620 K approximately.

The samples are dried in an oven at 105 °C during 2 h and left in a dessicator for a minimum of 24 h. Then, they are placed within different types of enclosures whose cross sectional areas are shown in Fig. 1. The plain case corresponds to the classical experiment with the fuel sample held laterally by two thin aluminum plates on each side (2 mm high and 4 cm wide). Our previous studies reveal that side effects are not important in a sample of 4 cm wide burning downwards in the plain case, so the flame is essentially two dimensional in this particular configuration [10].

The sidewalls case shown in Fig. 1 uses lateral walls made of Neoceram, a fire resistant ceramic glass with a total height (aluminum holder plus glass wall) of either $h$=2 cm or $h$= 5 cm above the sample surface. The Neoceram plates are 4 mm wide and have a thermal conductivity $\lambda$=1.7 W m$^{-1}$ K$^{-1}$ and heat capacity $c_p$ = 800 J kg$^{-1}$ K$^{-1}$ at 298 K.

Finally, we analyze the behavior of the flame front within the closed cross sectional channel shown in Fig. 1. It uses the same sidewalls as in the preceding case but with a ceiling $w$=4 cm or

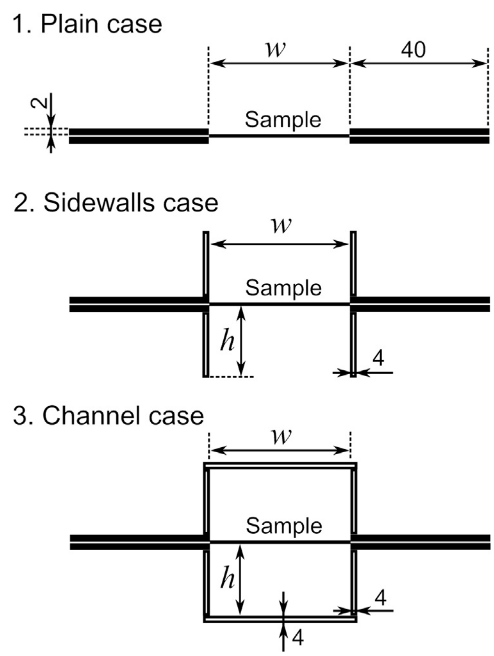


**Fig. 1.** Different geometrical configurations employed in our experiments: (1) plain case, (2) sidewalls case, (3) channel case. Sizes in mm. The sample length is 26 cm in all cases except in those with a longer channel, then being 36 cm.

$w$= 8 cm wide also made of a Neoceram glass 4 mm wide. These configurations correspond to channels with square cross sectional areas (high × wide; 2 h × w in Fig. 1) of 4 cm × 4 cm, 10 cm × 4 cm and 4 cm × 8 cm. With such a total height of minimum 4 cm, a flame is observed since the smoldering limit is not attained (it would occur within a closed channel with a total height of 1 cm approximately accordingly with Ref. [7]).

Samples are placed within a closed combustion chamber with a cylindrical shape and a capacity of 45 l. A TELSTAR 2G-6 vacuum pump allows us to reach an absolute pressure below 0.25 × 10$^{-3}$ times the absolute external value. We refill the chamber with oxygen and nitrogen by controlling their partial pressures (see Fig. 2) whose values depend on the concentration of the desired mixture. All experiments are carried out at 10$^5$ Pa of absolute pressure. From the accuracy of our instruments (digital manometer WIKA CPG1000), the uncertainty in the atmospheric oxygen concentration is less than 0.5% the absolute value [22]. Room temperature varies between 18 °C and 23 °C. There is enough free room on both open sides of the channel case in order to not to have obstacles that interfere with the flow direction at the entry and at the exit. Channel lengths are 22 cm in most of the cases,