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Experimental studies on the three-dimensional effects of opposed-flow flame spread over thin solid materials

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ABSTRACT

The three-dimensional effects of flame spread over thin solid materials were experimentally studied using a natural-convection-suppressing horizontal narrow-channel. In a sufficiently wide narrow-channel, the variation of flame spread against the width of the material sample showed different trends for different gas flow speeds and oxygen concentrations. The extent of three-dimensional effects was inversely proportional to the gas flow speed or its square. Near quenching extinction limits, the effects were significant because weak combustion is sensitive to a slight variation of heat loss and oxygen concentration. The effects may be due to different factors such as side heat loss, side oxygen diffusion, or both. Far away from quenching extinction limits, the effects were weak because vigorous combustion is insensitive to a small variation of oxygen concentration and heat loss. In all tests, the effects were limited to the samples of width less than 10 times of the diffusion length. Moreover, a higher oxygen concentration suppressed the effects at a lower gas flow speed. For sufficiently wide samples, in the most range of gas flow speeds, the channel width had almost no effect on flame spread. However, near extinction limits, the flame spread rate decreased with the increasing channel width.

1. Introduction

Material flammability is a critical index used in excluding potential fuels from materials used in manned spacecraft to ensure fire safety [1]. Microgravity tests provide a basis for material flammability assessment. Flame spread tests are important in making the assessment. However, in microgravity tests performed in drop towers or aboard spacecraft or microgravity airplanes, the geometrical sizes of test sections, gas flow rates, and material samples are usually small due to limited conditions. Therefore, it is difficult to realize two-dimensional flame spread tests in microgravity. Meanwhile, in facilities both on the ground and aboard spacecraft, not all materials in actual use are sufficiently wide. Nonetheless, the sizes of flow tunnels and materials will certainly influence flame spread. Consequently, the three-dimensional effects must be considered for both the good interpretation of test results and the exact prediction of material flammability.

Previous studies on the three-dimensional effects of flame spread over solid materials have involved the experimental investigations of opposed-flow flame spread in the buoyantly convective environment of normal and high gravity [2–4] and the numerical simulations of opposed-flow and concurrent-flow flame spread in the low-speed forced flow environment of microgravity [5–8]. These studies were all conducted for thin solid materials. Sibulkin et al. [2] experimentally showed that in the buoyantly convective environment of normal gravity, the downward flame spread rate rises with the increasing sample width, until the width reaches 2 cm at which the flame spread rate arrives at its asymptotic value. This result was supported by Frey and T'ien's experiments [3] for downward flame spread in normal gravity environment of 20.7 kPa and 68.9 kPa. Frey and T'ien's experiments implied that near extinction limits, a small variation of the sample width may strongly influence the flame spread rate. In Altenkirch et al.'s experiments with various pressures and gravity levels (1.0–8.0 g) [4], the downward flame spread rate was observed to be independent of the sample width when it is wider than 1.3 cm. Although it has been believed that the flame spread rate increases with the widening sample is caused by decreased heat loss, more parameters are still necessary to be taken into account.

The three-dimensional effects of flame spread in low-speed gas flows are investigated recently. Mell and Kashiwagi numerically compared two-dimensional and three-dimensional transitions from ignition to flame spread and subsequent flame spread in the forced flows of flow speed less than 12 cm/s [5,6]. It was found that a three-dimensional flame with a narrow width develops more easily than a two-dimensional flame due to additional oxygen diffusion from the lateral sides of the three-dimensional flame. In addition, for opposed-flow flame spread, the effects of

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Nomenclature

B	pre-exponential factor of reaction
Cp	specific heat
D	mass diffusivity
E	activation energy
ΔH	reaction heat
L	length scale
Le	Lewis number
R	universal gas constant, ratio
T	temperature
u	velocity
W	width
x, y, z	coordinates
Y	mass fraction
α	thermal diffusivity
λ	thermal conductivity
ρ	density

Subscripts and superscripts

$'$	dimensionless quantity
c	channel
f	flame or combustible material sample
g	gas
O	oxygen
r	reference value, radiative
x, y, z	coordinates
∞	ambience

the sample width on the flame are more significant in lower speed gas flows. In this case, the flame spread rate over a narrower sample is higher, since side oxygen diffusion relieves the impediment imposed by expansion-induced velocity for oxygen to enter into the reaction region, while the increase of the gas flow speed weakens the effects. These findings indicated another aspect of three-dimensional effects of flame spread. Shih and T'ien [7,8] and T'ien et al. [9] performed three-dimensional numerical simulations for concurrent-flow flame spread and further confirmed two aspects of three-dimensional effects: one is dominated by side heat loss and the other is by side oxygen diffusion. The former occurs when a flame is under conditions far away from its quenching extinction limit, in which case, a wider sample has a quicker flame spread rate and a wider flammability limit. This is in agreement with the above-mentioned experimental results. While the latter happens when a flame is under conditions near the quenching extinction limit where oxygen supply controls the flame, in which case, a narrower sample has a quicker flame spread rate and a wider flammability limit.

To sum up, the influences of many factors on the three-dimensional effects of flame spread remain to be studied experimentally, and numerical simulation results remain to be validated. In addition, no research has been done for the whole range of gas flow speeds including regions near quenching and blow-off extinction limits and the thermal region. The present paper presents our systematic experimental studies on three-dimensional effects of flame spread over thin solid materials, considering parameters such as gas flow speed, oxygen concentration, material width, and flow tunnel size. To avoid the interference of natural convection on flame spread, the experiments used a natural-convection-suppressing horizontal narrow-channel. Such a facility has been used in the research of fingering instability in solid fuel combustion to suppress the natural convection by Zik and Moses [10], and of polymer material combustion to simulate microgravity by Ivanov et al. [11] and Melikhov et al. [12]. Olson et al.'s results on finger-like smoldering in microgravity [13] and Zhang's results on flame spread [14,15] over thin solid materials in normal and microgravity confirmed that the device can suppress natural convection effectively and simulate microgravity. Experimental results in Section 3.3 of this paper also showed the natural-convection-suppressing property of the device.

2. Experiments

As shown in Fig. 1, the experimental system consisted of a test section, a gas supply subsystem, and an image record and analysis

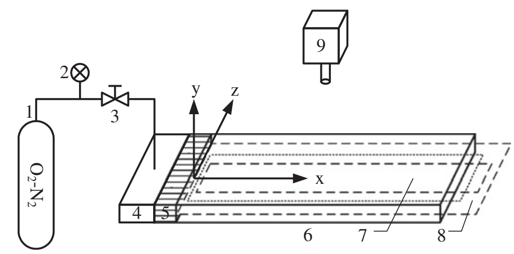

Fig. 1. Experimental system. The test section in this figure was a natural-convection-suppressing horizontal narrow-channel with a length of 70 cm, a height of 10 mm, and an adjustable width in the range of 12–24 cm. (1) O_2–N_2 gas bottle, (2) flowmeter, (3) valve, (4) gas inlet chamber, (5) aluminum honeycomb, (6) combustion chamber, (7) fuel sample, (8) sample frame, (9) camera.

subsystem. The test section was a natural-convection-suppressing horizontal narrow-channel, whose inlet was filled with aluminum honeycomb to ensure a uniform gas flow. The channel had a length of 70 cm, a height of 10 mm, and an adjustable width W_c in the range of 12–24 cm, which was at least 12 times as its height so that a two-dimensional flow was achieved in its central section. For the convenience of observation, channel walls were made of glass with the surface facing the camera being covered with transparent film printed with 1 cm grids as a ruler. The sample frame was symmetric and made of aluminum alloy with a thickness of 1 mm, a length of 70 cm, and an outer width the same as the channel width. During experiments, the sample frames with different inner widths from 1 cm to 12 cm were used to match the combustible sample width or the flame width W_f (which will be called the sample width for brevity in the following). The gas supply subsystem consisted of a gas bottle charged with a mixture of oxygen and nitrogen, a flowmeter, and connecting pipelines. A glass rotor flowmeter with the maximum scale of 6 m^3/h and two mass flow controllers with the maximum scales of 20 l/min and 5 l/min were used to measure the flow rates of the gas at high levels (above 20 l/min), middle levels (20–5 l/min), and low levels (below 5 l/min), respectively, to obtain both good precision and wide measurement range. The mass flow controllers also controlled the flow rates. The image record and analysis subsystem consisted of a Sony DCR-TRV900E Digital Video Camera Recorder with a resolution of 450,000 pixels to record flame images at a speed of 25 frames per second and a PC computer (not shown in Fig. 1) to analyze the recorded images.

The experimental procedure was as follows: a sample was attached onto a sample frame, which was in turn inserted into the middle of the channel with an equal distance to the top and bottom walls of the channel. Then an O_2–N_2 gas mixture flow with a