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# FLAME SPREAD IN A VITIATED CONCURRENT FLOW

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## ABSTRACT

Experiments have been conducted to study the effects of forced gas flow velocity and oxygen concentration on the flow assisted flame spread over a flat solid combustible surface. All the tests are performed with thick PMMA Sheets as fuel and mixtures of oxygen and nitrogen as oxidizer. The spread rate is measured for flow velocity ranging from 0.5 to 2.0 m/sec and oxygen mass fraction from 0.19 to 0.23. It is found that the flame spread rate increases linearly with the main flow velocity and the oxygen concentration within the experimental conditions. In order to determine the effect of buoyancy on the flame spread rate, data in the ceiling and floor configurations are compared. The exhaust gas composition are also measured to detect possible buoyancy effects on the chemical reactions in the flame. Despite the overall similarity between the characteristics of ceiling and floor surface flame spread, some substantial differences have been observed. The experimental results indicate that buoyancy has two main effects in the ceiling case, one is the enhancement of heat transfer from the flame to the solid surface, and the other is the flame quenching through cold wall effect. For large flow velocities, the enhanced heat transfer is found to be dominant and results in a faster flame propagation in the ceiling than in the floor. For low flow velocities, the flame quenching effect becomes more important and the opposite result is observed. The transition velocity decreases as the oxygen mass fraction decreases.

## INTRODUCTION

The spread of fire is a problem of great interest in fire research and much work has been carried out to study the chemical and physical parameters that determine the flame spread process. Among the different modes of flame spread, the concurrent mode of flame spread is the fastest and most hazardous because the gas pushes the flame ahead of the burning region which enhances the heat transfer from the flame to the unburnt material and consequently the spread of the flame.

In concurrent flame spread, upstream from the pyrolysis front the solid fuel is pyrolyzed by the heat transfer from the flame. The vaporized fuel is diffused and convected outward and forward reacting with the ambient oxidizer and a diffusion flame is established in the boundary layer next to the solid surface. The fuel vapor that is not consumed in the upstream flame is convected downstream from the pyrolysis front where it keeps reacting with the oxidizer, extending the diffusion flame downstream. The onset of fuel pyrolysis determines the progress of the pyrolysis front and consequently the flame spread rate. Previous work on this subject is summarized in the review of Fernandez-Pello et al. (1983).

The most important and frequently studied controlling factors are chemical parameters such as fuel type, gas oxygen concentration, and flow conditions such as flow type, flow rate, turbulence intensity and buoyancy and other factors such as external radiation. Among these factors, the buoyancy and the flow oxygen concentration are often investigated both experimentally and numerically for their ubiquitous existence (Orloff et al. 1972, Orloff et al. 1975, Fernandez-Pello 1977, Loh et al. 1985, Sibulkin 1988). Previous work on buoyancy effect mostly dealt with vertical configuration and not much work has been done on horizontal configuration. The buoyancy effect can be studied by comparing the flame spread rate at the floor burning configuration and at the ceiling burning configuration. The controlling mechanism of ceiling flame spread have many similarities to those of the more frequently studied floor configuration except for the effect of gravity on the heat and mass transfer processes. For a diffusion flame spreading over a horizontal surface in the case of ceiling burning, the buoyancy effect drives the reaction zone upward, which enhances heat transfer to the solid, and also introduces the conditions that may inhibit the chemical reaction due to quenching effect. The buoyancy effects are especially evident under low flow velocity and low oxygen concentration conditions.

Recent work by Mekki et al. (1990) carried out a detailed experimental investigation of the laminar flow flame spread over wood and PMMA in the ceiling configuration. It is found that the flame spread rates for both materials vary nearly linearly with the free steam velocity. The flame spread rate for PMMA varies with the oxygen concentration at a power of 1.4. The ,expression contradicts results from previous experiments (Loh et al. 1985) which shows a quadratic dependence of flame spread rate on oxygen concentration. No buoyancy effect was considered in that work. This points out the need for further experimental investigation to determine which of the experiments or assumptions made are responsible for the observed discrepancies, and how buoyancy can affect the flame spread. It has been noticed that most of the works done on concurrent flame spread were on the side of high oxygen concentration and scarce fundamental information has been obtained on the low oxygen concentration conditions. Furthermore, fires in buildings often occur under vitiated conditions, and there is a need of further information about the spread of fire at low oxygen concentration.

The object of the present study is to carry out a systematic experimental study of both floor flame spread and ceiling flame spread under a low oxygen concentration flow at laminar condition.

## EXPERIMENTAL ARRANGEMENT

The experimental apparatus is shown schematically in Fig. 1. It consists of a laboratory scale wind tunnel designed to conduct condensed fuel flame spread experiments under various flow conditions and the supporting instrumentation. The wind tunnel has a 0.89 m long settling chamber with a rectangular cross section 0.31 m by 0.18 m, which supplies air flow to the tunnel test section through a converging nozzle with an area reduction ratio of 5.6 to 1. The side walls of the test section are made of 6 mm Pyrex glass for visual observation and optical diagnostic access, and the floor and ceiling are made of 55 mm thick Marinite slabs. The exhaust section is 1.22 m long and connected to the test section. Four mixing plates of different shapes are placed inside the exhaust section to generate sufficient disturbance in the flow and produce uniform concentration profile. The combustion tunnel is mounted horizontally on a three axis positioning table, while the optical instrumentation is kept stationary.

The air flow in the test section is supplied from a centralized air compressor and nitrogen gas is supplied from gas cylinders. The amount of flow is controlled by critical nozzles. The oxygen concentration in the air is varied by mixing nitrogen into the main stream flow. The air flow velocity and turbulence intensity are measured with a one-component Laser Doppler Velocimeter operating in the dual-beam, forward scattering mode. The experimental installation also includes a Schlieren system with a 0.45 m diameter collimated light beam and an array of eight thermocouples placed evenly on the fuel surface along the centerline, which are used to measure and monitor the solid combustible surface temperatures. Gas analyzers are used to measure the concentrations of major species $O_2$, CO, $CO_2$, NO and unburned hydrocarbons in the exhaust gas flow.

The fuel specimens used in this work are made from 12.7 mm thick PMMA (polymethylmethacrylate) sheets manufactured by Rolm and Haas (Plexiglas G), with a dimension of 300 mm by 70 mm. PMMA is chosen because of its well-known and uniform properties and non-Charring burning. A fuel sample is placed flush in the Marinite ceiling or the floor of the tunnel test section with eight thermocouples embedded on its surface. The specimen is ignited at its upstream edge with an electrically heated Nichrom wire which initiates the flame spread over the

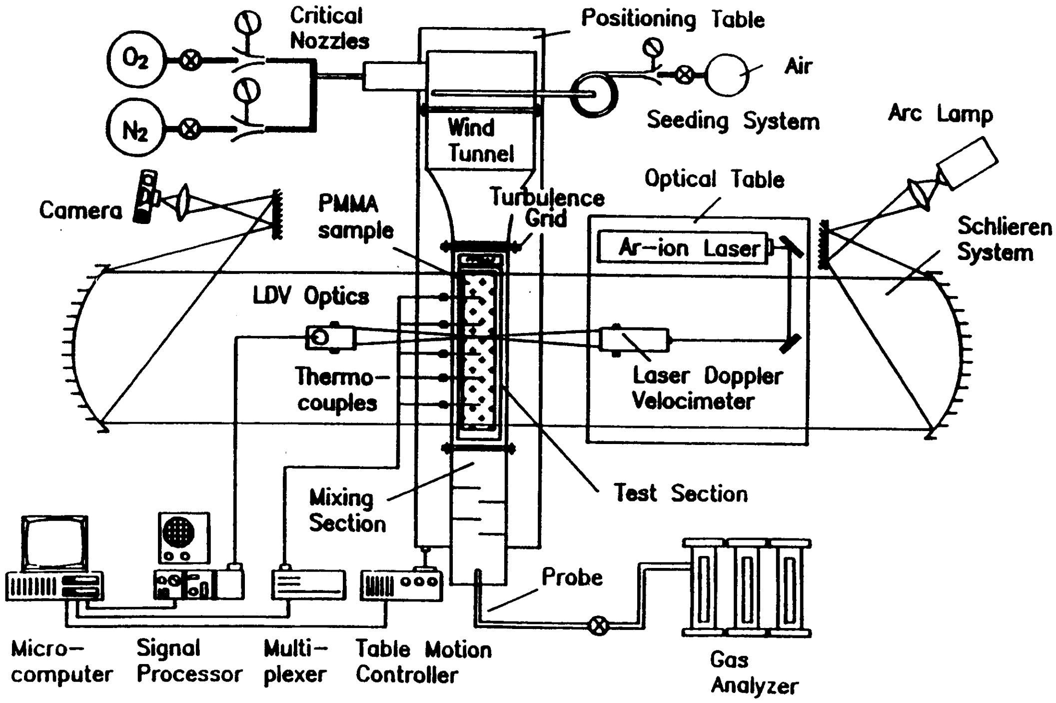



Fig. 1. Schematic drawing of the experimental apparatus.

length of the PMMA sheet. The flame spread rate is calculated from the time interval needed for the pyrolysis front to travel the fixed distance between two consecutive thermocouples, which can be deduced from the surface temperature histories measured. After the pyrolysis front has reached the last thermocouples, the combustion is extinguished with nitrogen in less than 20 seconds.

## RESULTS AND DISCUSSION

The measured flame spread rate of PMMA sheet in ceiling and floor burning are shown in Fig. 2 to 5, as a function of free flow velocity ranging from 0.5 to 2.0 m/sec and oxygen mass fraction ranging from 0.19 to 0.23. The spread rate is an average of the values deduced from consecutive thermocouples throughout the specimen length and from two different tests. The flame spread rate is quite steady along the length of the specimen and the standard deviation is, in most cases, of the order of 7%. No data for oxygen mass fraction lower than 0.19 has been obtained because the spread of the flame could not be initiated or flame extinction occured after the flame had propagated for a short distance.

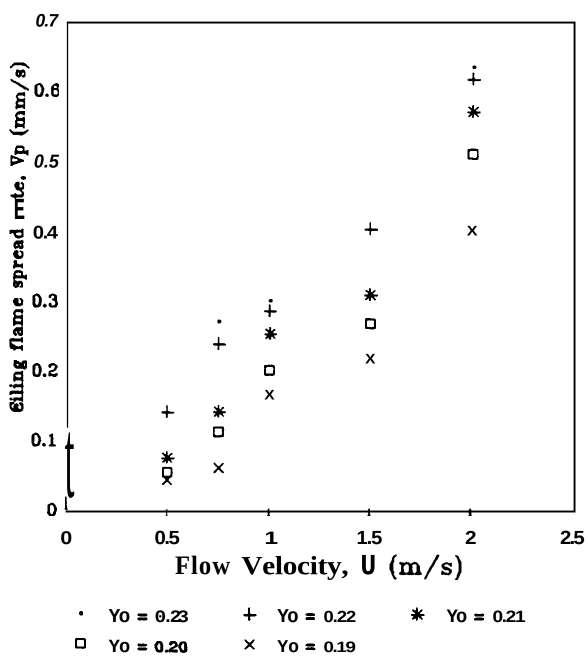



Fig. 2. Variation of ceiling flame spread rate with flow velocity at different oxygen mass fractions.

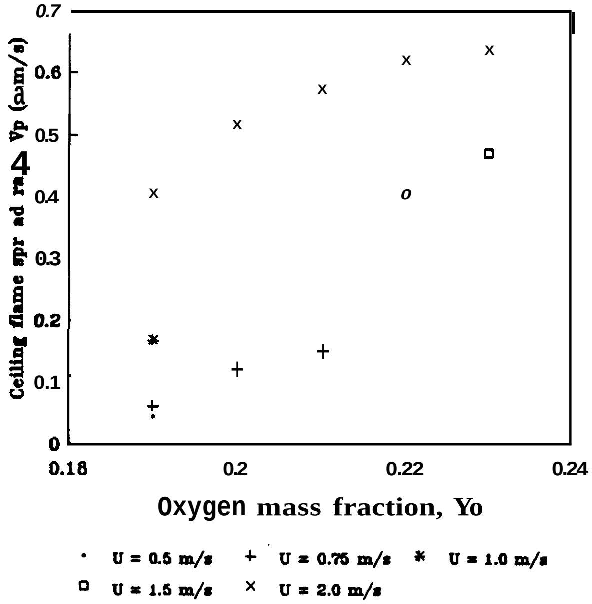



Fig. 3. Variation of ceiling flame spread rate with oxygen mass fraction at different flow velocities.

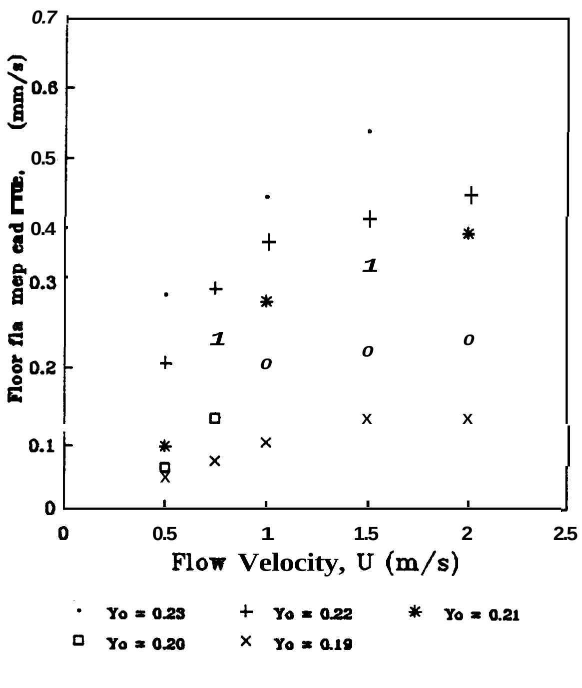



Fig. 4. Variation of floor flame spread rate with flow velocity at different oxygen mass fractions.

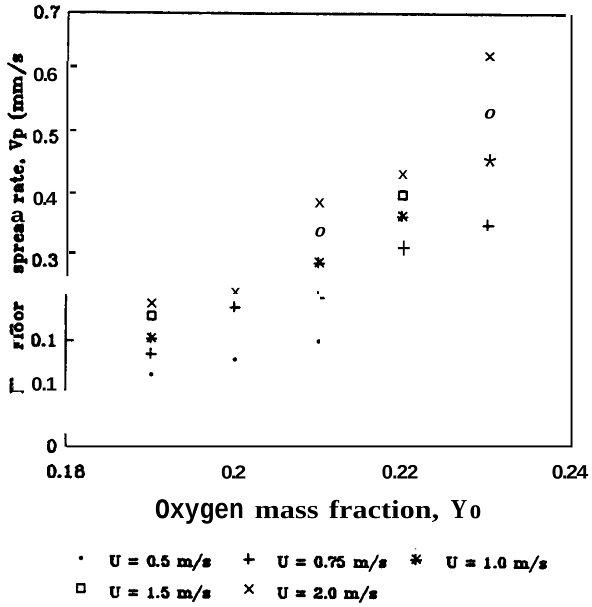



Fig. 5. Variation of floor flame spread rate with oxygen mass fraction at different flow velocities.

From the figures, It is seen that the flame spread rate varies approximately linearly with the flow velocity. As per the oxygen mass fraction for both ceiling and floor configurations, no clear trends are observed, although it appears that the spread rate varies approximately linearly with the oxygen mass fraction.

In order to understand the characteristics of the experimental results better, it is convenient to briefly examine the mechanisms of the flame spread. Previous experimental and theoretical work on the concurrent mode of flame spread indicate that heat transfer from the flame to the solid fuel is the dominant controlling mechanism (Fernandez-Pello et al. 1983, Loh et al. 1985, Zhou et al. 1990). An expression for the flame spread rate can be obtained by a simple energy analysis applied to a control volume in the unburnt solid downstream from the pyrolysis front (Quintiere 1981, Saito et al. 1986).

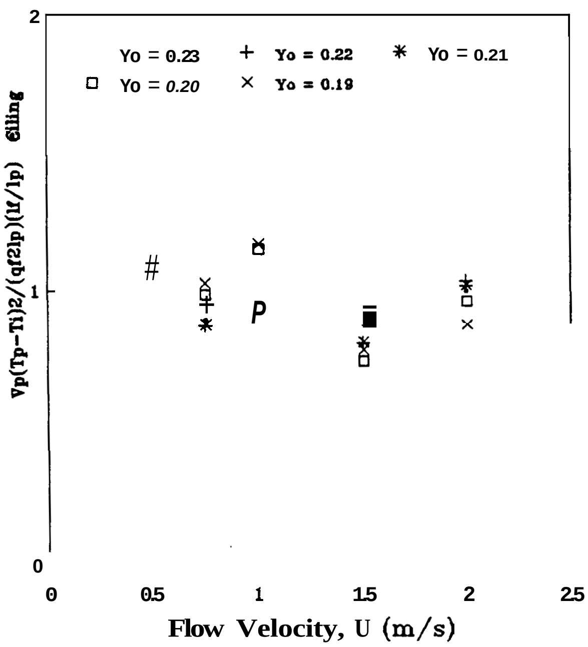
$$V_p \sim \frac{q^2_f l_f}{(T_p - T_i)^2} \qquad (1)$$

$$\sim \frac{(Tf-Tp)^2 U(l_f/l_p)}{(Tp-Ti)^2} \qquad (2)$$

$$\sim \frac{Yo^2 U(l_f/l_p)}{(Tp-Ti)^2} \qquad (3)$$

where Vp is the flame spread rate, Tf is the flame temperature, Tp is the pyrolysis temperature, Ti is the initial solid temperature, U is the flow velocity, $q_f$ is the heat flux from the flame to the solid fuel and $l_f$ is the flame length, which is defined as the distance between the pyrolysis front and the point where the heat transfer from the flame to the specimen starts.

Effort has been made to normalize the data by plotting $Vp(T_p-T_i)^2/(q_f^2 l_p)(l_f/l_p)$ against U and the results are shown in Fig.6 and 7. $q_f^2 l_p$ and $l_f/l_p$ are calculated from the temperature history of the specimen. It is found that $Vp(T_p-T_i)^2/(q_f^2 l_p)(l_f/l_p)$ is nearly a constant for different values of U and Yo, It provides a further validation for the simple energy analysis used here to determine the flame spread rate.




Fig, 6. Correlation of the ceiling flame spread data in terms of a non-dimensional flame spread rate deduced from Eq. (1).

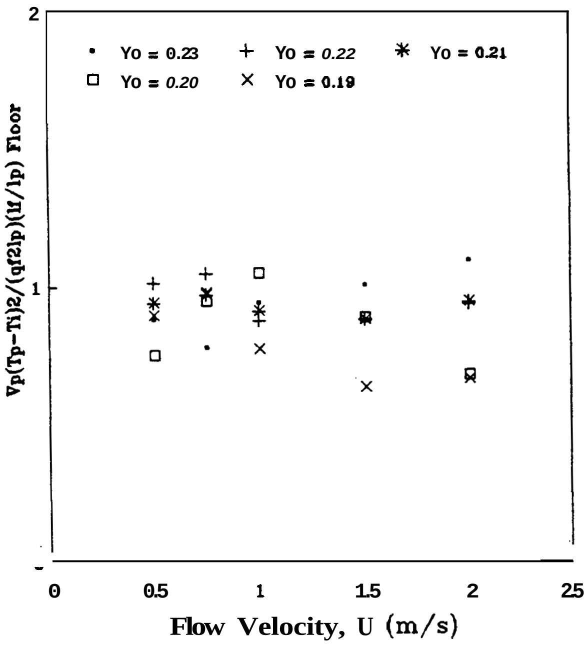



Fig. 7. Correlation of the floor flame spread data in terms of a non-dimensional flame spread rate deduced from Eq. (1).

The theoretical model predicts that Vp varies linearly with U and quadratically with Yo. The latter seems contradictory to the experimental result that Vp varies linearly with Yo. One point that needs special attention is that in deriving equation (3), the flame chemical reaction is assumed to be complete. However, the experiments in the present study were conducted at low enough oxygen concentration conditions that incomplete combustion occurs, and so it is not suitable to simply assume that $q_f$ is linearly proportional to Yo. Another factor which may affect the dependence of Vp on Yo is the ratio, $l_f/l_p$. For combustion process at high oxygen concentration, it is usually assumed that $l_f/l_p$ is independent of the oxygen mass fraction according to previous experimental results (Loh et al. 1985, Mekki et al. 1990). However, whether the same assumption can be made under low oxygen concentration condition is debatable. Therefore, more work has to be done to determine the relationship between $q_f$ and Yo and that between $l_f/l_p$ and Yo at low oxygen concentration condition in order to explain the discrepancy between the previous theoretical model and the present experimental results.

In order to further investigate the importance of chemical kinetics in determining the flame spread rate and comparing the difference between ceiling burning and floor burning under low oxygen concentration conditions, concentrations of major species $O_2$, CO, $CO_2$, NO and unburnt hydrocarbons in the exhaust gas flow were measured. A good indication of the completeness of the combustion is the CO and unburnt hydrocarbons concentrations, thus they have been plotted against different flow conditions and oxygen mass fractions in Fig. 8 to 11. The gas concentrations were measured when the pyrolysis front has reached 270 mm downstream from the ignition point. The less complete reaction will go with higher concentrations of CO and unburnt hydrocarbons. From these measurements, it can be concluded that the chemical reactions are less complete at lower oxygen mass fraction and lower main flow velocity conditions. It can also be noticed that the reaction is less complete in the ceiling configuration than in the floor configuration, which agrees with previous experimental works (Zhou et al. 1991).

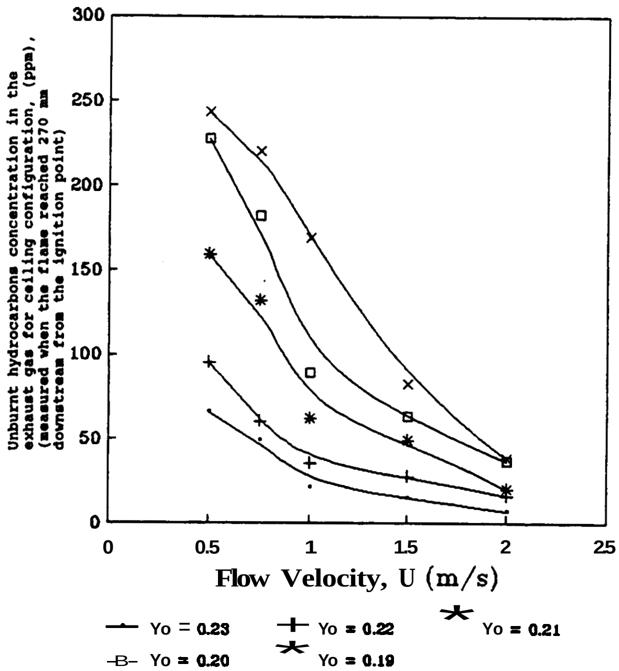



Fig. 9. Variation of Unburnt hydrocarbons concentration in the exhaust gas with flow velocity at ceiling configuration under different oxygen mass fractions.

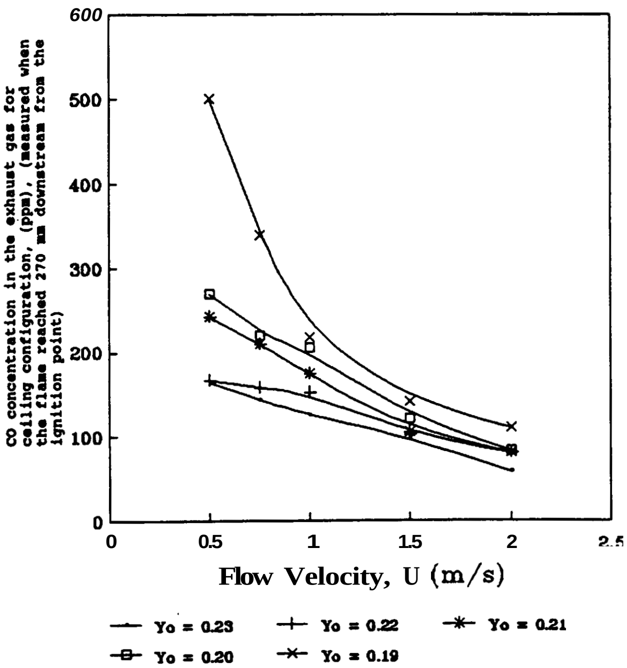



Fig. 8. Variation of CO concentration in the exhaust gas with flow velocity at ceiling configuration under different oxygen mass fractions.

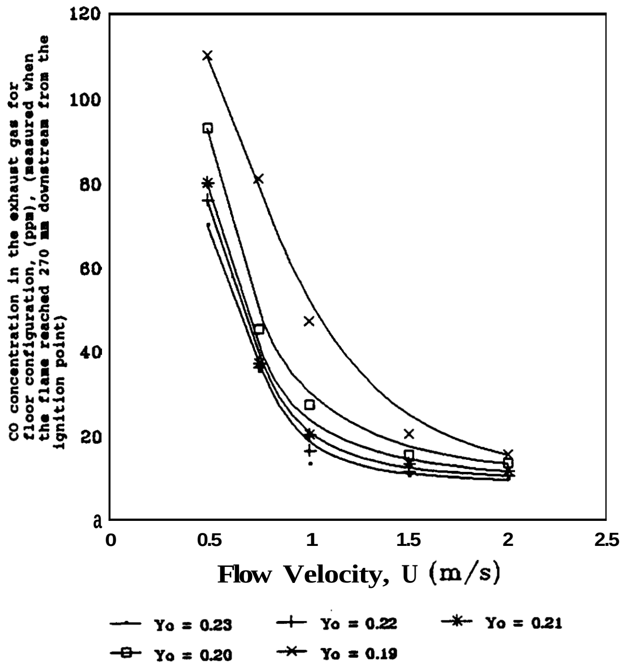



Fig. 10. Variation of CO concentration in the exhaust gas with flow velocity at floor configuration under different oxygen mass fractions.

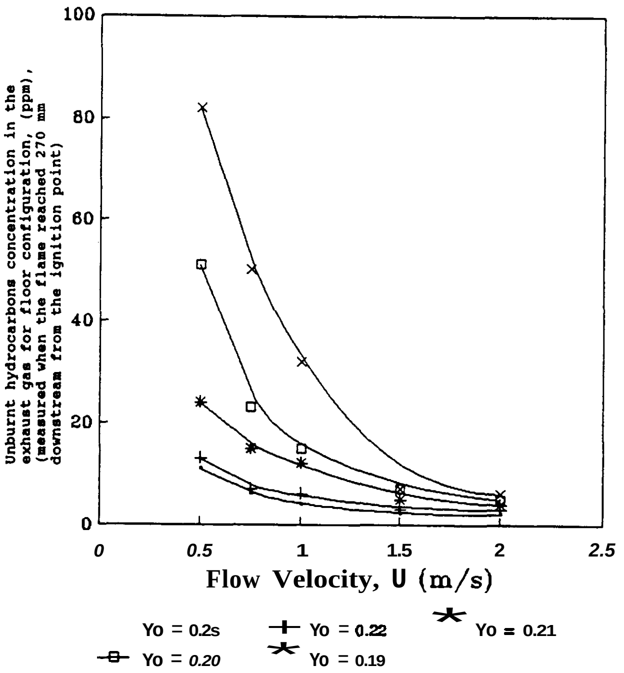



Fig. 11. Variation of unburnt hydrocarbons concentration in the exhaust gas with flow velocity at floor configuration under different oxygen mass fraction.

The main difference between ceiling and floor flame spread is caused by buoyancy effects. In the ceiling flame spread, the hot fuel vapor stays at the top and cold air stays under the flame to form a relatively stable layer that hinders the mixing processes and it is possible that there is insufficient oxygen in the reaction to proceed completely. In the floor flame spread, the buoyancy force lifts the hot gas upward favoring the mixing of the fuel vapor and the oxidizer, and it can be expected that a more complete reaction can be attained. This phenomenon is particularly evident at low flow velocity and low oxygen concentration cases.

Furthermore, in the ceiling case, buoyancy force pushes the flame closer to the fuel surface, which produces two opposite effects. It enhances the heat transfer fromthe flame to the fuel and can lower the flame spread rate due to quenching effect (Zhou et al. 1991). From the experimental results shown in Fig. 2 to 5, it is found that when the free flow velocity is larger than 1.5 m/s, the enhanced heat transfer effect dominates and thus the flame spread rate at ceiling case is higher than that at floor case. When the free flow velocity is less than 1.5 m/s, quenching effect dominates and the flame spread rate at the ceiling is less than that at the floor due to larger heat losses. The transition velocity seems to decrease when the oxygen mass fraction is decreased. For example, when Yo is larger than 0.21, the transition velocity is around 1.5 m/s. When Yo is 0.20, the transition velocity is in between 1.0 m/s and 1.5 m/s. When Yo is 0.19, the transition velocity is in between 0.75 m/s and 1.0 m/s. Thus it appears that the transition velocity is a function of the oxygen mass fraction.

## CONCLUDING REMARKS

The results of this study show that oxidizer flow velocity and oxygen concentration have a strong influence on the flame spread rate under both ceiling and floor configurations. The experimental results indicate that the flame spread rate has a linear relationship with the oxygen level and flow velocity when the fuel is burnt at low oxygen concentration and low flow velocity conditions. This may have a significant impact in fire modeling because flame spread rate under vitiated conditions is important in the development of room fire models.

The experiments further indicate that apart from the heat transfer model which has frequently been used in describing concurrent flame spread over a solid fuel, chemical kinetics may be a key factor in determining flame spread rate under low oxygen concentration conditions. In order to resolve the discrepancy between theoretical model and the experimental results, relationship between heat flux and oxygen mass fraction and relationship between flame length and oxygen mass fraction at low oxygen level must be obtained.

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