CONCURRENT TURBULENT FLAME SPREAD

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ABSTRACT

The rate of flame spread over the surface of thick PMMA sheets has been measured as a function of the velocity and turbulence intensity of a forced air flow concurrent with the direction of flame propagation. It is shown that the flow turbulence has a strong influence on the flame spread process. For all turbulence intensities, the flame spread rate increases approximately linearly with the flow velocity, although the slope is smaller for larger turbulence intensities. For a given flow velocity, the spread rate decreases as the turbulence intensity is increased, the effect being more pronounced for larger flow velocities. These effects appear to be due to a strong influence of the turbulence intensity on the flame length, which decreases as the turbulence intensity is increased, thus reducing the net heat flux from the flame to the unburnt combustible. The results are significant since the prediction of the flame length and spread rate as a function of the problem parameters are important factors in the development of room fire models.

1. INTRODUCTION

In most practical situations, the spread of fire occurs under turbulent flow conditions. Since the flow turbulence effects both the heat transfer and the chemical kinetic mechanisms that control fire spread, it is necessary to determine how these controlling mechanisms are affected by turbulence in order to predict the spread of fire under realistic conditions. Among the different modes of fire spread the concurrent, or flow assisted, mode of flame spread is the fastest and most hazardous because the flames are pushed ahead of the burning region by the gas flow, which facilitates the transfer of heat from the flame to the unburnt material. This mode of flame spread is particularly affected by flow turbulence because the heat transfer to the unburnt material occurs over the large region bathed by the downstream flame, and the flame characteristics are strongly influenced by turbulence. Thus, the study of concurrent turbulent flame spread is of great interest in the fire development modeling, and in the establishment of flammability test methods.

The only works published to date on turbulent flame spread are those of Orloff et al. [1] for upward turbulent flame spread over large PMMA sheets, and of Saito and co-workers [2,3] for upward turbulent spread of flames over PMMA and wood sheets. In these works, the gas flow is buoyancy induced, and the turbulence is naturally generated depending on the sample scale. The studies concentrate in measuring the rate of flame spread dependence on scale [1] or the magnitude of an imposed radiant flux [2]. With the exception of the study of Zhou et al. [4] for opposed flow flame spread, no systematic studies have been performed to date to observe the effect of flow turbulence intensity on the rate at which flames spread over the surface of a solid fuel. In the present work, a parametric study is carried out of the spread of flames in a concurrent turbulent forced flow with the objective of determining what is the effect of turbulence intensity on the rate of flame spread, and to infer through these measurements how turbulence affects the different mechanisms controlling the spread of the flame.

2. EXPERIMENT

The experimental apparatus consists of a laboratory scale combustion tunnel, designed to conduct combustion experiments under varied flow conditions, and the supporting instrumentation, based primarily on optical and thermocouple measuring methods. The tunnel has a 0.89 m long settling chamber with a rectangular cross section 0.3 m by 0.18 m, which supplies gas flow to the tunnel test section through a converging nozzle with a reduction area of 5.5 to 1. The test section is 0.6 m long and has a rectangular cross section 0.13 m wide and 76 mm high. The side walls are made of 6 mm Pyrex glass to enable visual observation and optical diagnostic access, and the floor and ceiling sides are made of 25.4 mm thick Marinite sheet. The tunnel is mounted horizontally on a three axis positioning table.

The gas flow in the tunnel is supplied from centralized compressed air and the flow rates controlled and measured with critical nozzles. Turbulence is generated by means of grids, or perforated plates, placed at the exit of the tunnel converging nozzle. A prescribed turbulence intensity is obtained through a combination of flow velocity and plate blockage ratio. This means of turbulence generation, however, cannot provide high turbulence intensity at very low flow velocities. The distribution of turbulence intensity through the test section is characterized by an initial region, approximately 50 mm where the turbulence decays sharply, followed by a 0.2 m region of relatively constant turbulence, and a final region where the turbulence decays again due to entrainment effects at the test section exit. The gas velocity and turbulence intensity are measured with a one component Laser Doppler Velocimeter (LDV) operating in the forward scattered mode. The laser source is a Spectra Physics Ar-Ion laser with a 2 W total output power. The signal is processed with a TSI frequency counter and transferred to an IBM/AT micro-computer. The experimental installation also includes a Schlieren system with a 45 cm diameter collimated light beam that is used to provide qualitative information about the effect of the flow turbulence on the flame and thermal layer structure. In addition the installation contains a network of thermocouples for gas and solid phase temperature measurements.

The fuel specimens are 12.7 cm thick PMMA (Rohm and Hass, Plexiglas G) sheets, 76 mm wide by 0.3 m long. They are mounted flush in the tunnel Marinite floor with their upstream edge placed 15 mm from the tunnel convergent nozzle exit. The flame spread process is initiated by igniting the top upstream edge of the sheet with an electrically heated nichrome wire placed in close contact with the PMMA. The flame spread rate is measured from the surface temperature histories as given by thermocouple placed at fixed intervals along the fuel surface. Eight Ch.-Al. thermocouples 0.127 mm diameter are embedded on the PMMA with their beads flush with the PMMA surface at distance 32 mm apart. The thermocouples output is processed in the micro-computer. With the surface temperature histories, the rate of spread of the pyrolysis front is calculated from the time lapse of pyrolysis arrival to two consecutive thermocouples and the known distance between the thermocouples.

3. RESULTS

The measurements of the flame spread rate over PMMA sheets as a function of the concurrent air flow velocity are shown in Fig. 1 for several values of the turbulence intensity. It is seen that the spread rate increases approximately linearly with the flow velocity, and that the slope decreases as the turbulence intensity decreases. The dependence of the concurrent flame spread rate on the turbulence intensity is presented in Fig. 2. It is seen that the spread rate decreases as the turbulence intensity increases, and that the effect is more pronounced for larger flow velocities. These results are very interesting and somewhat surprising since this mode of flame spread is controlled by heat transfer from the flame to the fuel, and it is well known that turbulent boundary layer heat transfer is larger than the laminar flow one. The results, which appear to be due to a strong effect of the turbulence intensity on the flame length, are very important not only because they introduce new aspects about the flame spread process not previously predicted, but because it may have significant influence in the application of flame spread formulas in models of room fire development.

The mechanisms by which turbulence affects the flame spread rate can be inferred from the theoretical analysis of the spread process. A simplified heat transfer model of the flame spread provides the following expression for the rate of spread [2]

$$V_f = q^2\, l_f/(k\rho c\,(T_p - T_i))^2 \qquad (1)$$

where q is the surface heat flux, l_f the flame length, $k\rho c$ are the thermal properties of the solid and T_p and T_i the solid pyrolysis and initial temperatures respectively. The flow velocity and turbulence intensity can affect both q and l_f and through them the flame spread rate. Thus, it is important to determine how turbulence affects these parameters. In the work performed to date, we have not measured these effects directly. However, it is possible to deduce them approximately from the surface temperature histories. The flame length is determined with the spread rate and the time required for the surface temperature at a thermocouple position to rise from ambient to the pyrolysis value. The surface heat flux is calculated from the time variation of the surface temperature by assuming that the fuel behaves as a semi-infinite solid. The calculated variation of the flame length with the flow velocity and turbulence intensity are presented in Figs. 3 and 4 respectively. Figure 3 shows that the dependence of the flame length on the flow velocity is different depending on the turbulence intensity. For low turbulence intensities, the flame length increases with the flow velocity and for large turbulence intensities, it decreases. From the results of Fig. 4 it is seen that for all flow velocities the ratio of flame length to pyrolysis length decreases as the turbulence intensity is increased. The effect is more marked for large flow velocities. These effects seem to be due primarily to the convective cooling of the reaction zone by the cold air induced toward the flame by the turbulent eddies.

In order to obtain more information about the mechanisms causing the shortening of the flame length with the turbulence intensity, a Schlieren system was constructed and applied to produce Schlieren images of the flame. The Schlieren system has a collimated light beam 0.5 m in diameter. It consists of a Tungston lamp light source, beam expanding and converging lenses and two 0.5 m parabolic mirrors. A characteristic example of the flame images obtained with this system is shown in Fig. 5. It is seen that as the flow turbulence intensity increases, more cold air is introduced into the flame zone and the mixing of the flow becomes more intense. These are the effects that appear to cause the shortening of the flame length with the turbulence intensity.

The calculated variation of the surface heat flux downstream of the pyrolysis front with the turbulence intensity is shown in Fig. 6. It is seen that the heat flux is only weakly affected by the flow turbulence, decreasing slightly with the turbulence intensity for large flow velocities and increasing slightly for low flow velocities. All of the above results have been combined in Fig. 7 where the ratio V_f/Ul_f (deduced from Eq. (1)) is plotted versus the flow turbulence intensity. It is seen that this ratio is independent of the flow velocity and turbulence intensity, which indicates that the effect of the flow turbulence on the flame spread rate takes place primarily through the flame length.

4. CONCLUSIONS

The results of this study show that flow turbulence has a strong influence on the flame length and on the concurrent flame spread rate. Both the observed shortening of the flame length and decrease of the flame spread rate as the turbulent intensity is increased are significant observations since the prediction of flame lengths and rates of flame spread as a function of the environmental conditions are important factors in the development of room fire models and the establishment of material flammability tests.

Given the potential impact of the present results on the theoretical prediction of the spread of flames, it is important to extend the work to the study of the other aspects of the process. For example, it is important to know how turbulence affects the flame spread process in a vitiated environment, or how the characteristics of the flow turbulence (free flow or boundary layer turbulence) may quantitatively affect the rate of spread for a given turbulence intensity. Also important is to know if and how turbulence affects the rate of mass burning in the pyrolyzing region, the rate of soot production and the radiative properties of the flames.

ACKNOWLEDGEMENTS

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REFERENCES

1. Orloff, L., De Ris, J. and Markenstein, G.H., "Upward Turbulent Fire Spread and Burning of Fuel Surface," 15th Symposium (International) on Combustion, The Combustion Institute, Pittsburgh, PA, p. 183, (1975).

2. Saito, K., Quintiere, J.G. and Williams, F.A., "Upward Turbulent Flame Spread," 1st International Symposium on Fire Safety Science, Hemisphere Publishing Company, P. 75, (1986).

3. Saito, K., Williams, F.A., Wichman, I.S. and Quintiere, J.G., "Upward Turbulent Flame Spread on Wood Under External Radiation," 24th National Heat Transfer Conference, Pittsburgh, PA, August 1987.

4. Zhou, L., Fernandez-Pello, A.C. and Cheng, R., "Flame Spread in an Opposed Turbulent Flow," submitted to Combustion and Flame, (1988).

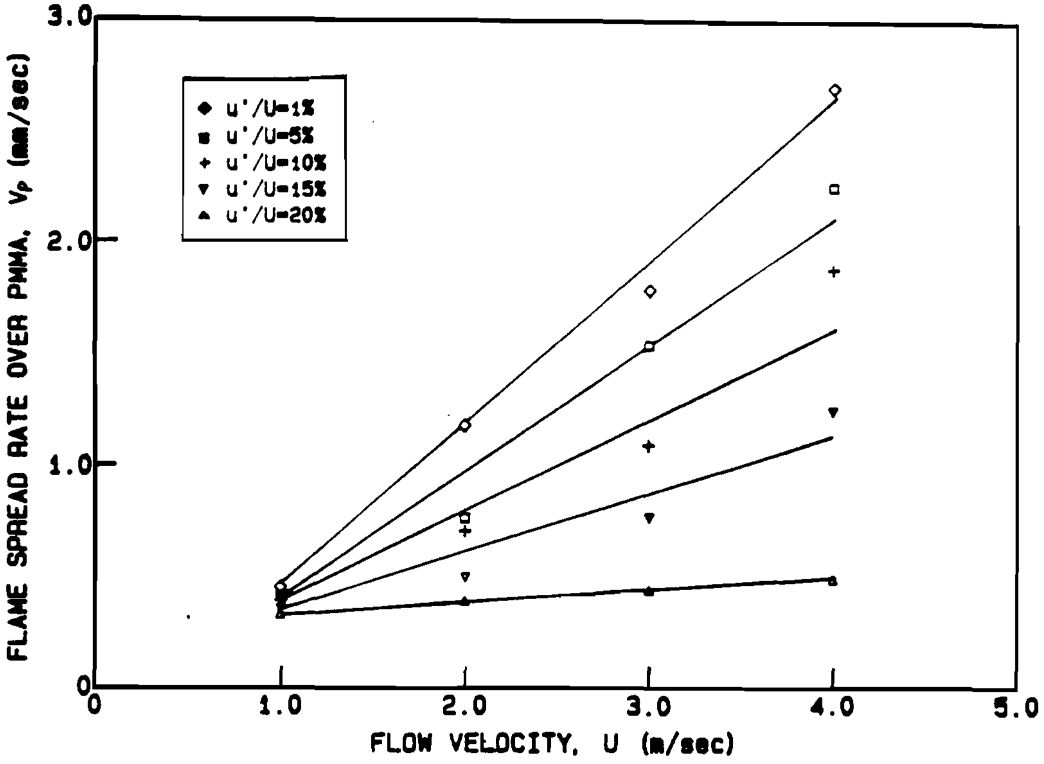


FIGURE 1.

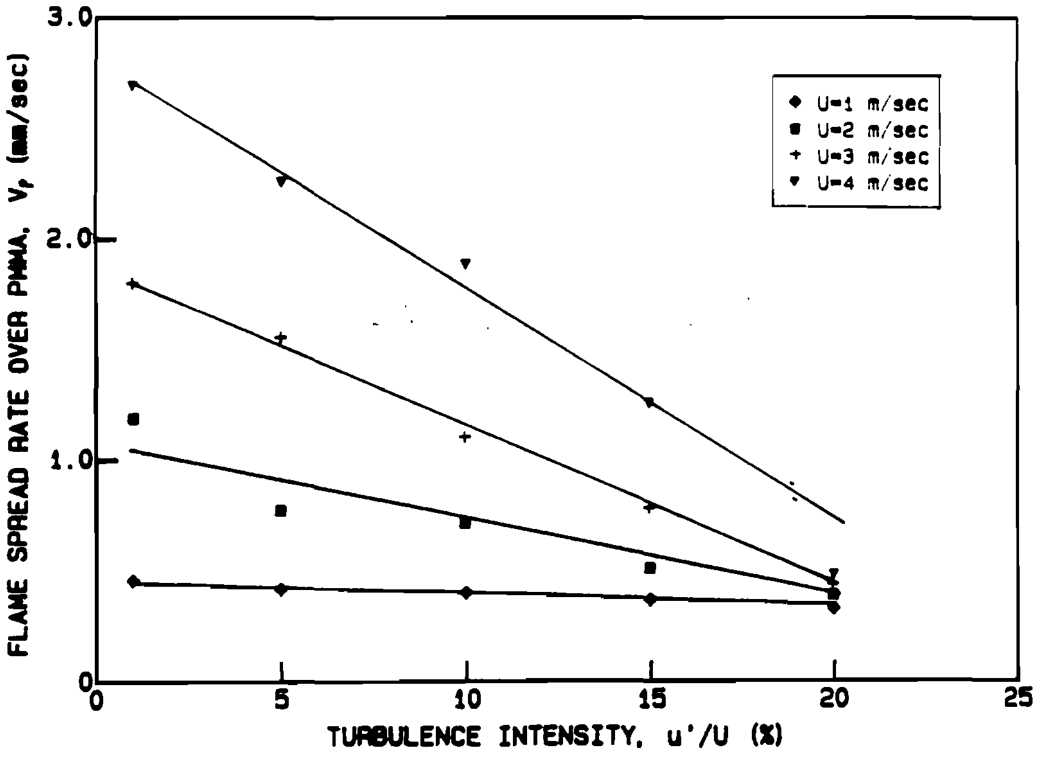


FIGURE 2.

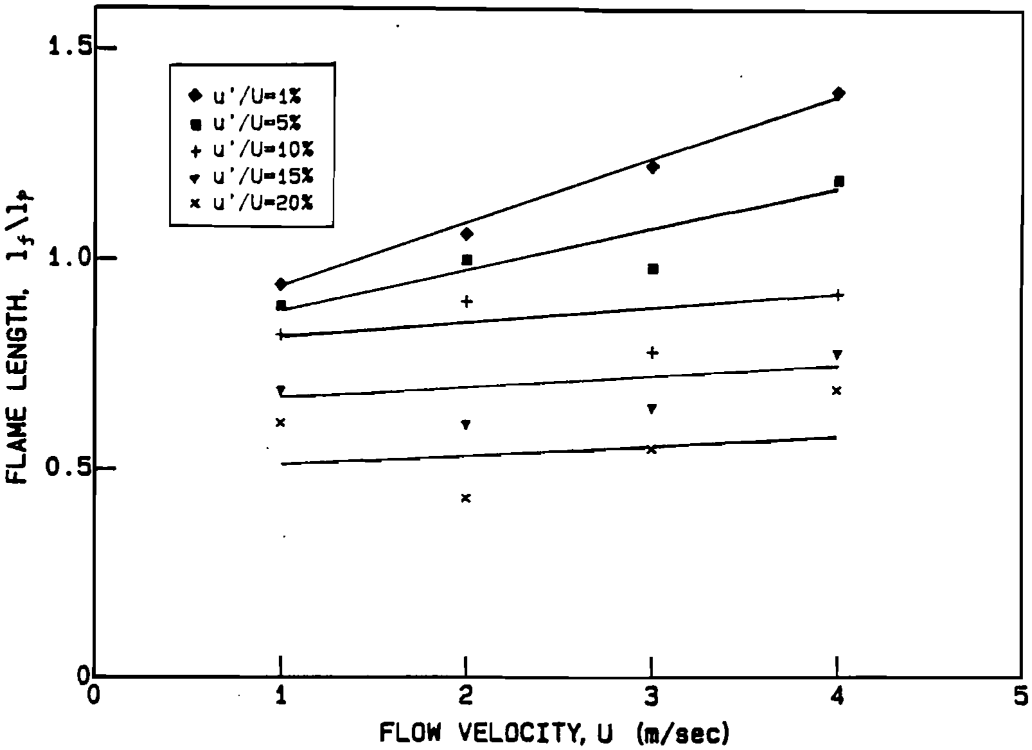
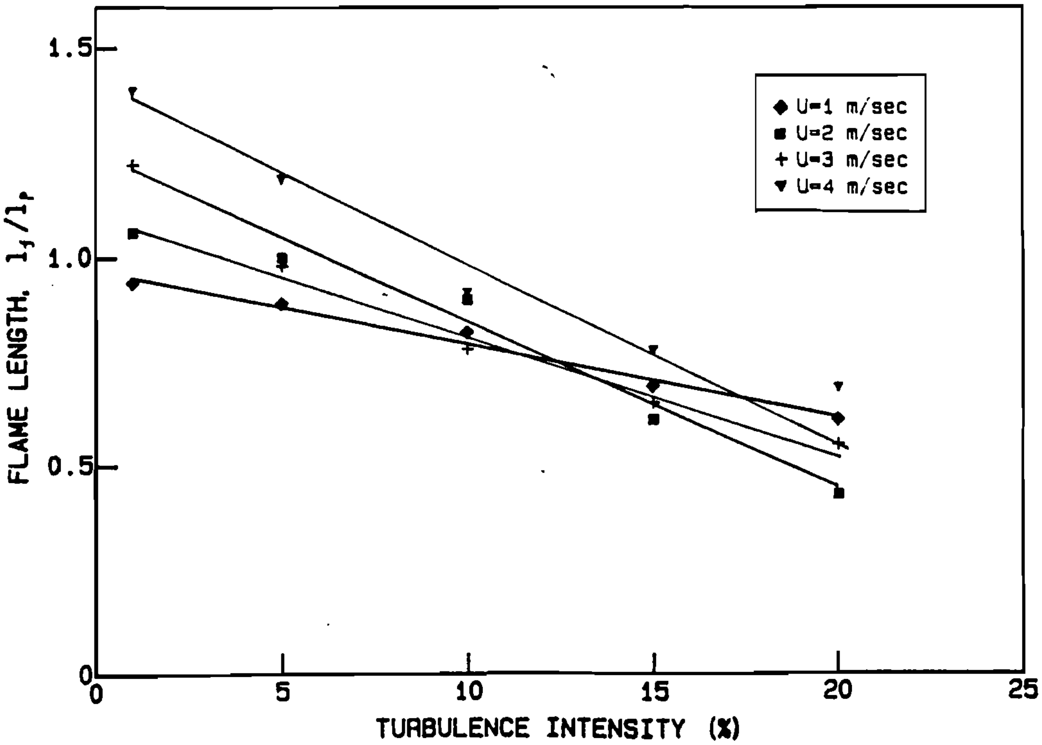


FIGURE 3.



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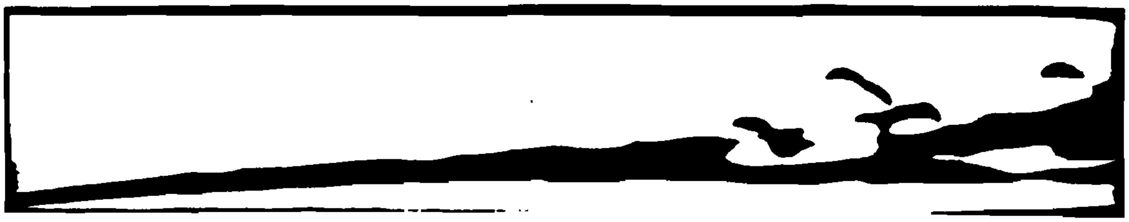

U = 3 m/sec   u'/U = 1%

U = 3 m/sec   u'/U = 5%

U = 3 m/sec   u'/U = 15%

FIGURE 5.

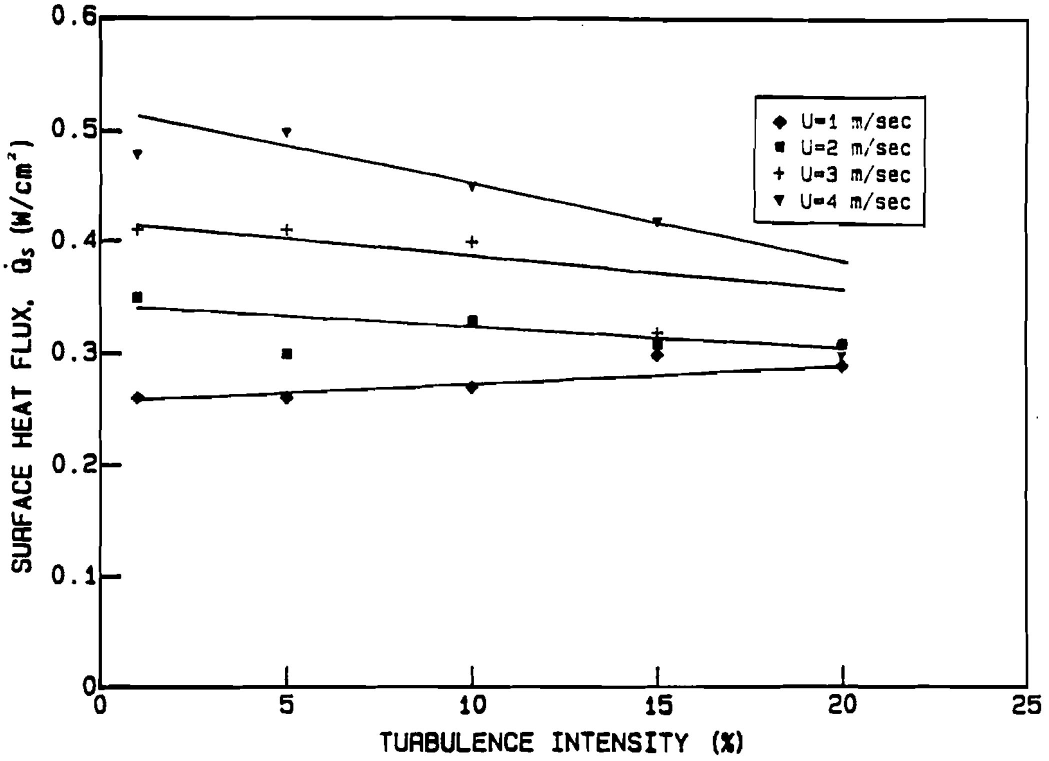

FIGURE 6.

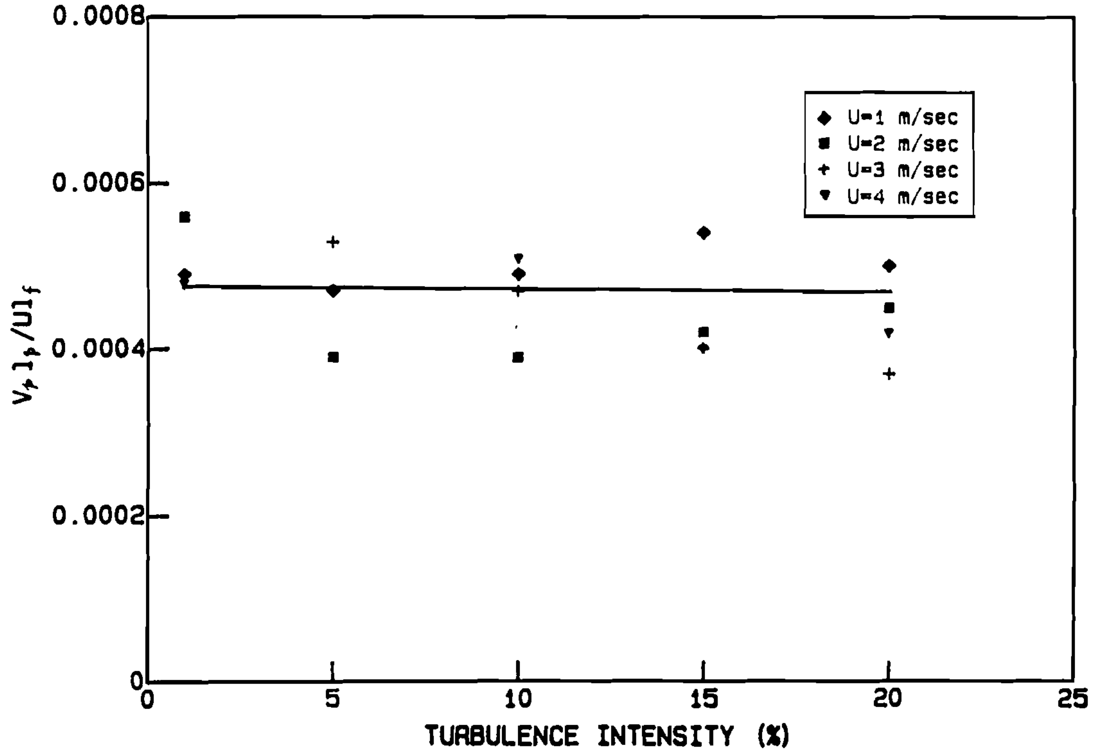

FIGURE 7.