EFFECTS OF AIR VELOCITY AND EXTERNAL RADIATION ON PILOTED IGNITION OF (PMMA)

M. Abu-Zaid
Mech. Eng. Dept., Mu'tah University,
Al-Karak, Jordan.

A. Atreya
Mech. Eng. Dept., The University of Michigan,
Ann Arbor, Michigan, U.S.A.

ABSTRACT

Radiative ignition experiments were conducted on PolyMethyl MethAcrylate (PMMA) in a small scale combustion wind tunnel, by exposing horizontal samples to irradiance levels in the range 0.9-3.2 W/cm^2 under piloted ignition at air velocities 0.1, 0.9, and 1.5 m/sec. Simultaneous measurements of ignition time, sample surface temperature, and external radiation were made. The experimental results indicate that the ignition delay time increase as the air velocity increases at the same heat flux. Also, it was found that the ignition temperature increases with the increase in both external radiation and air velocity. Two empirical relationships were derived and presented, to predict the ignition delay time and ignition temperature as a function of heat flux and air velocity within the studied range.

INTRODUCTION

With the extensive use of thermoplastics in aircraft domes, building construction, and surgical appliances, the fire hazards have increased. Efficient utilization of these materials and prevention of hazardous fire require an understanding of the combustion process. For prevention purposes, it is desirable to predict the occurrence of fire after its commencement under a given set of external conditions. These conditions include external radiation from a ceiling layer of hot gases and air velocity.

Recently, much efforts have been expended on the study of ignition of thermoplastics and cellulosics. Drysdale and Thomson [1] studied the piloted ignition of nine horizontal samples of nine thermoplastics. They determined the minimum evolution rate of decomposition products necessary to support sustained flaming. Kashiwagi [2] investigated the effects of sample orientation on ignition delay time minimum external radiant flux for auto ignition using Polymethyl methacrylate (PMMA) and red oak samples. He found that the ignition delay time was shorter with the horizontal sample than with vertical one at the same external radiant flux, while the surface temperature at ignition was higher with vertical samples at the same external radiant flux. Also, he found that the minimum external radiant flux for ignition was smaller for the horizontal sample. Kishore and Nagarajan [3] investigated the effect of transition metal salicylates of Co, Ni, Mn, and Fe on the ignition and combustion of polystyrene. They indicated that the presence of salicylates increase the rate of polystyrene gasification prior to ignition. They explained the sensitization in the combustion considering the increase in the surface temperature in the presence of salicylates; this increase is due to the exothermic decomposition of salicylates on the surface.

Kashiwagi [4,5] conducted radiative ignition experiments on PMMA and red oak samples under auto ignition and piloted ignition in air. He concluded that attenuation of the incident radiation by the decomposition products is important during the ignition period; the incident flux was attenuated as much as 75-80% for both samples. Also he found that the maximum surface temperature of PMMA during the ignition delay period tends to be independent of the initial radiant flux, while this temperature for red oak tends to increase with the decrease in the initial radiant flux. Also, he derived a quantitative empirical relationship between the attenuation of the initial radiation by the decomposition products and the initial radiant flux. Thomson and Drysdale [6] investigated the validity of the sample surface temperature criterion for piloted ignition for several thermoplastics, by direct measurement of the surface temperature during material heating and piloted ignition. They concluded that the critical surface temperature criterion is suitable for use in engineering predictions of piloted ignition of solids.

Kashiwagi and Omori [7] investigated the effects of material characteristics on piloted ignition using two different polystyrene samples and two PMMA samples. They measured ignition delay time, surface temperature profiles, and sample weight changes in an external radiant flux in the range 0.9-3.0 W/cm^2. They indicated that the transport process of in-depth degradation products through the molten polymer layer to the sample surface has a negligible effect on piloted ignition. Also, they found that the thermal stability of the material has significant effect on the ignition delay time and surface temperature at ignition.

The purpose of this study is to investigate experimentally the effects of air velocity and external radiation on piloted ignition of polymethyl methacrylate, and to provide data which may be used to obtain a better understanding of the factors controlling piloted ignition. This will assist in predicting fire of the as-yet-unburned materials under certain conditions.

APPARATUS AND PROCEDURE

The experiments were performed in a small scale combustion wind tunnel. The main features of this tunnel are:

1) It provides variable external radiation,
2) It provides a well controlled atmospheric pressure over the sample,
3) It is capable of providing a flat plate boundary layer flow on the sample at the desired free stream velocity.

A schematic of the experimental arrangement is shown in Figure (1). The external radiation w provided by nine radiant heaters; three hi temperature quartz heaters and six U-shaped chroma coil heaters. The heaters were controlled by a 3-ph 440 volt variable transformer. These heaters have maximum black body radiation temperature of 1200 and therefore, well suited to simulate external radiati in fires [8]. A small natural gas flame was located the mixing layer, pointing upward as shown in Fig (1). The air was provided to the tunnel from compressed air line through a large pressure tank. T mechanical oscillations of the air flow initiated at compressor were damped in this tank. After passi through a control valve, air enters a sonic nozzle. T nozzle maintains the desired air flow rate by adjusti the pressure upstream the nozzle. The air flow rate w calculated by knowing the upstream pressure, noz diameter, nozzle discharge coefficient, and temperature.

The test sample (15 cm length, 7.0 cm width and cm thick) were instrumented with surface thermocou (chrome-aluminum, 0.075 mm diameter). T thermocouple was heated electrically a simultaneously pressed into the surface prior to test.

The procedure consists of placing the instrument sample flush with the kaowool insulating board, a then exposing the sample to a known exter radiation. This external radiation was continuou monitored by a heat flux sensor located upstream t sample. A computer data acquisition system was us to collect and store the signals from the thermocou and the heat flux gauge in real time. The incid radiation on the sample was determined using calibration process performed prior to the experimen In addition to the heat flux gauge located upstream t sample, shown in Figure (1), identical gauge w placed at the sample location. The heat flux at bo locations was measured at the three air velocities a the whole range of heat flux studied. Therefore t initial heat flux at the sample surface in ea experiment was determined, using the reading of t sensor upstream the sample and the correspondi calibration curve for the same conditions.

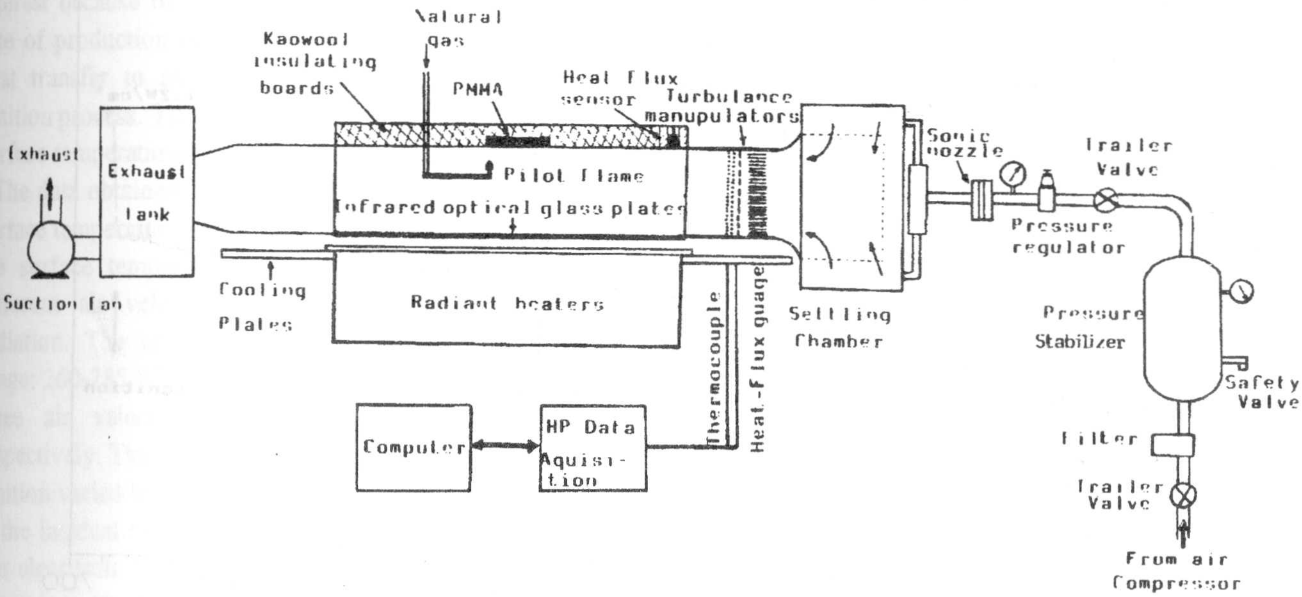

Figure 1. Schematic diagram of the experimental setup.

EXPERIMENTAL ERRORS

The error in the measurement of ignition temperature may be estimated by considering the error in the thermocouple used. Such an error is 2.2 °C or 0.75% whichever is greater [15]. Thus the error in the measurement of the ignition temperature is estimated to be in the range 0.751-0.853%. The error in the measurement of the heat flux at the sample location due to calibration, is estimated to be less than 1.4%. For the measurement of time, the data acquisition equipment records 5 readings per second. This will cause an uncertainty in the measured time of (± 0.2) second. Thus the error in the ignition delay time is estimated to be in the range 0.03-0.54%. The error in the air flow rate is estimated using the method presented by kline and McClintock [16]. Using the error in the pressure measurement (± 0.5 psia), and the error in the determination of air temperature (± 4°R). The error in the air flow rate is estimated to be in the range 1.00-1.07% for the three flow rates used. It is clear that the estimated errors in the measurements of the basic and derived quantities, do not significantly influence the overall uncertainty in the final results.

RESULTS AND DISCUSSION

An experimental investigation was conducted to study the effect of air velocity on piloted ignition of PMMA. A series o 30 experiments were performed under well controlled external radiation in the range 0.9-3.2 W/cm^2, and at three air velocities; 0.1, 0.9, 1.5 m/sec. It was not possible to increase the air velocity more than 1.5 m/sec., because at higher velocities the pilot is distinguished.

In Figure (2) and (3) the measured surface temperatures were plotted as a function of time at different heat fluxes, and various air velocities. Figure (2) shows that the rise in surface temperature is faster for higher heat fluxes, note the sharp rise in these temperatures due to flaming combustion. Figure (3) shows the effect of air velocity on surface temperature. It is clear from this figure that as air velocity increases the rate of increase of surface temperature during the heating time decreases at nearly the same external heat flux.

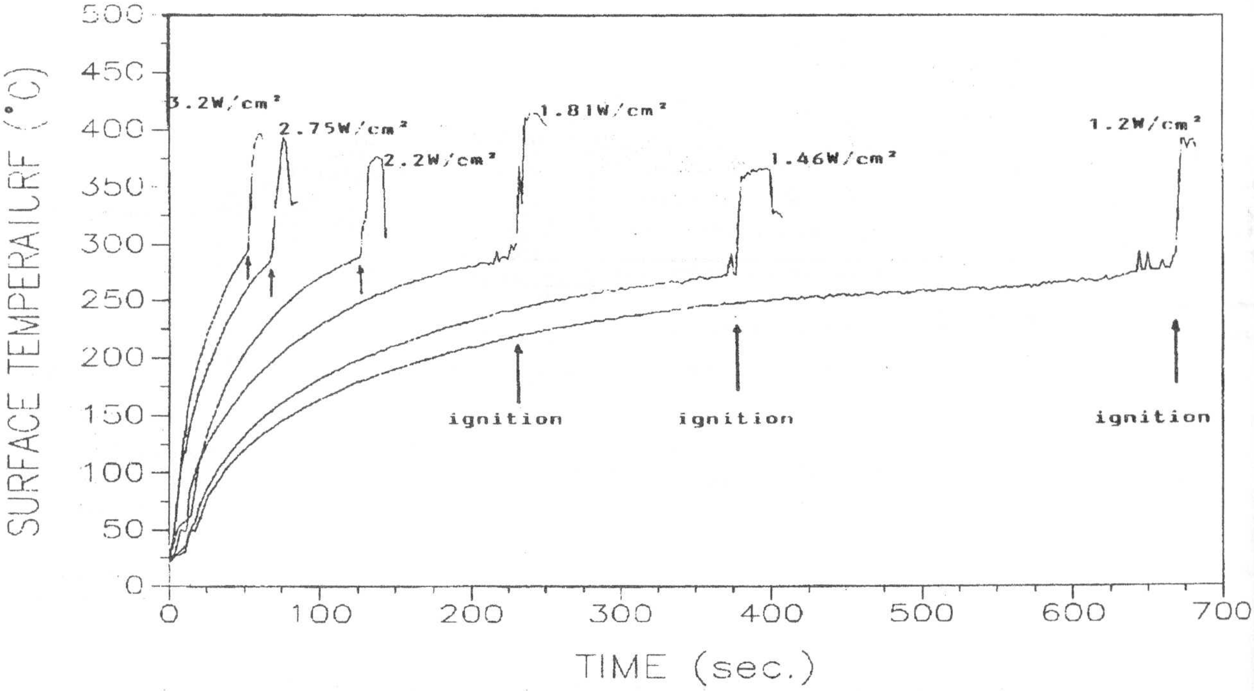

Figure 2. Surface temperature versus time for various heat fluxes at air velocity of 1.5 m/sec.

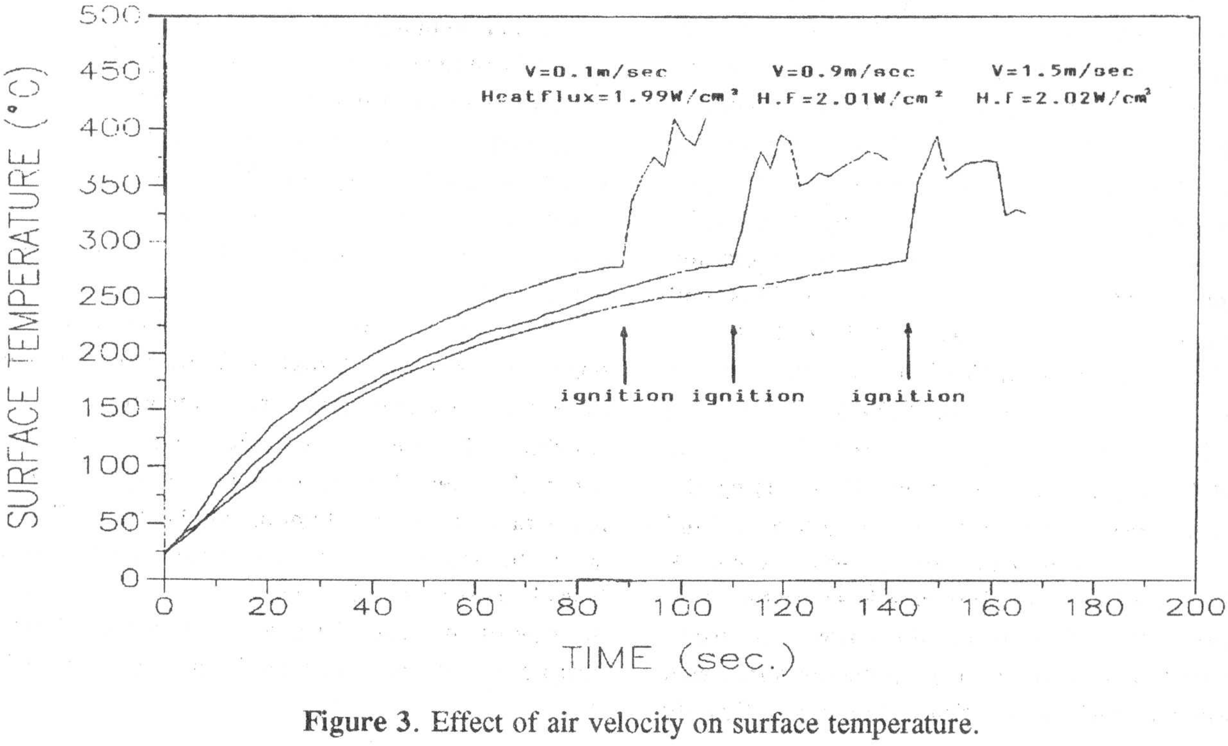

Figure 3. Effect of air velocity on surface temperature.

The surface temperature histories have been of interest because of its importance in determining the rate of production of the evolved gases. The rate of heat transfer to and from the solid is essential in ignition process. This phenomenon is controlled by the surface temperature of the solid.

The data obtained was used to determine the critical surface temperature at ignition. Figure (4) summarises the surface temperature at the time of ignition at different air velocities as a function of external radiation. The ignition temperature data lies in the range: 260-285 °C, 258-285°C, and 277-293°C for the three air velocities: 0.1, 0.9, and 1.5 m/sec., respectively. Thus the measured surface temperature at ignition varied by less than $\pm$ 14 K with the variation in the incident radiant flux for each in velocity tested. It is clear from Figure (4) that the ignition temperature increases with the increase in both external radiation and air velocity over the range studied. Thomson and Drysdale [6] showed that there is a slight tendency for the ignition temperature to increase with increasing heat flux. This observation is consistent with the fact that the depth of heated zone at ignition decreases with increasing heat flux, thus requiring higher surface temperature to provide a flow of volatiles necessary to sustain flaming. This trend is opposite to that found by Atreya et al. [9,10]] for wood, in which clear layer particularly develops at low incident heat flux, which tends to increase the surface temperature at ignition.

The time required to initiate and sustain flaming was recorded under various external radiant fluxes and air velocities. As mentioned before, the appearance of the flame in the gas phase above the sample, would produce a sharp rise in the surface temperature. Therefore, the ignition delay time was determined, at the moment of the sudden large jump in the surface temperature of the sample. These times are marked by arrows in Figures (2) and (3). Figure (5) shows the measured ignition delay time. There is some scatter in the data, but the trend is nearly a straight line. Kashiwagi and Omori [7] showed that the relationship between ignition time and incident external radiation is a straight line in the logarithmic plot with different slopes for the four samples used. Also, it is clear from Figure (5) that as the air velocity increases the time of ignition increases at the same incident heat flux.

Pilot ignition will occur, when a mixture of evolved products decomposited from the sample and the surrounding air should be within flammability limits. This indicates that, at surface temperature at ignition, the rate of volatiles is sufficient to produce a flammable mixture. Flaming is sensitive to boundary layer conditions existing at the sample surface. As air velocity increases, the boundary layer thickness above the sample decreases. This will result in an increase in both convective heat transfer coefficient and mass transfer coefficient. This will causes an increase in heat loss from the sample, and an increase in mass flux of volatiles gases. The effect of increase in the air flow rate, and the increase in the heat loss will be predominant to the increase in the rate of volatiles gases. This will result in a higher surface temperature at ignition, and longer time to produce the necessary mixture to support sustained flaming, and consequently a longer ignition delay time.

The experimental results for ignition delay times and ignition temperatures, have been correlated with the heat flux and air velocity. A multiple linear regression of the ignition temperature data in Figure (4) was used, to derive the following relationship.

$$T = 248.95 + 11.32\,H + 6.95\,V \qquad (1)$$

where, T is the surface temperature at ignition (°C), H heat flux (W/cm^2), and V air velocity (m/sec.). Also, a multiple linear regression of the log-transformed ignition delay times data in Figure (5) was used, to derive the following relationship:

$$t = 499.83\,H^{-1.93}\,V^{0.21} \qquad (2)$$

where, t is ignition delay time (sec), H heat flux (W/cm^2), and V air velocity (m/sec.). These correlations can be used, to predict ignition delay times and ignition temperatures, for piloted ignition of PMMA under conditions of various heat fluxes and air velocities. The correlations are valid within the range of heat fluxes and air velocities studied.

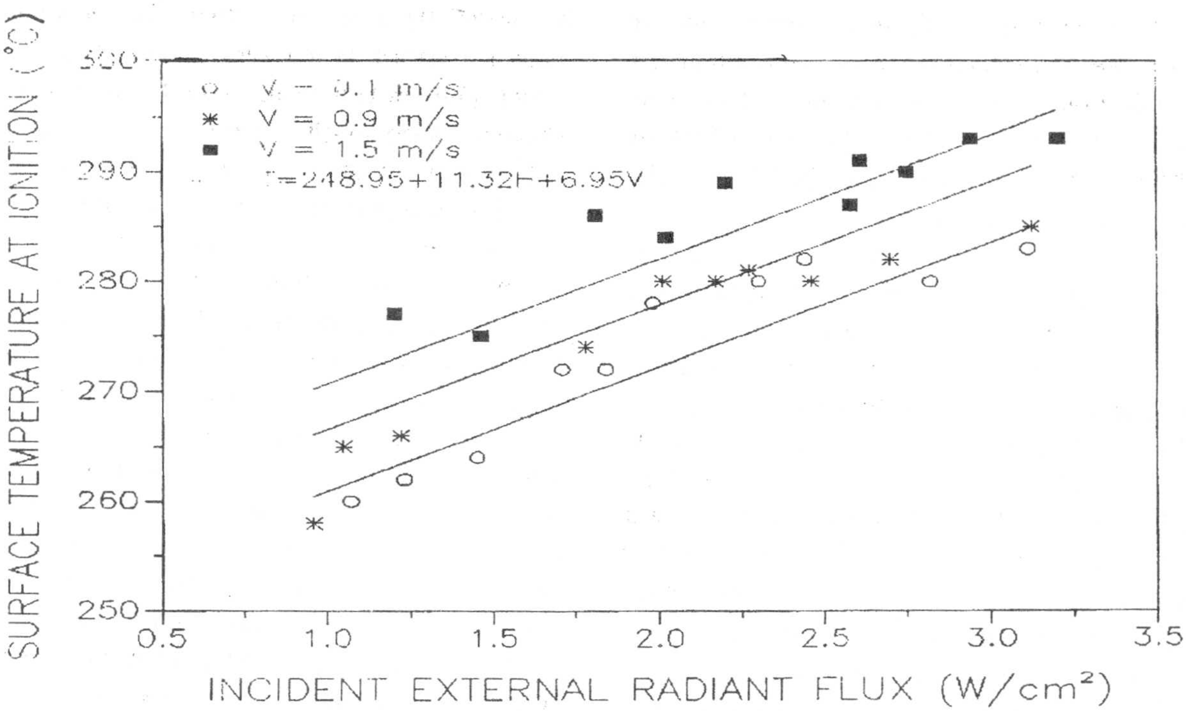

Figure 4. Surface temperature at ignition versus incident external radiant flux at various air velocities.

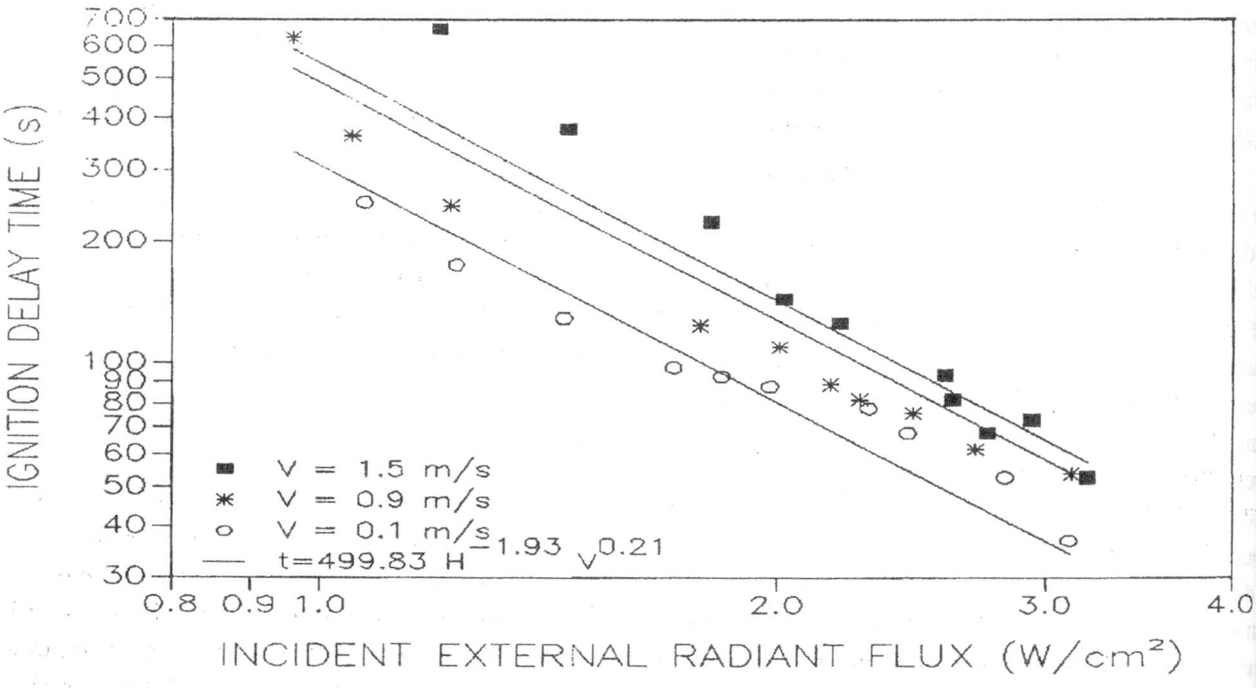

Figure 5. Ignition delay time versus incident external radiant flux at various air velocities.

CONCLUSIONS

The following conclusions are apparent from this study:

1- The ignition delay time increases as the air velocity increases at the same incident heat flux. This is because, as the air velocity increases, the convective heat loss and the mass flux of volatile gases from the sample increase. Meanwhile, the increase in the air flow rate and the heat loss are predominant to the increase in the mass flux of the volatile gases. This will result in a longer time to provide a flammable mixture.

2- The ignition temperature increases with the increase in both external radiation and air velocity over the increase in both external radiation and air velocity over the range studied. This is because, the depth of the heated zone at ignition decreases with increasing heat flux. On the other hand, the convective heat loss from the sample surface increases with increasing air velocity. Thus requiring higher surface temperature to provide a flow of volatiles necessary to sustain flaming.

3- The temperature gradient during heating time increases as the external heat flux increases and air velocity decreases.

4- Two empirical relationships were derived and presented, to predict the ignition delay time and ignition temperature as a function of heat flux and air velocity within the range studied.

ACKNOWLEDGMENTS

The first author is most grateful to the Council for International Exchange of Scholars for their support of this project. The experiments were carried out during the first author fulbright post-doctoral research visit in the combustion laboratory at Michigan State University, U.S.A. This research program was sponsored by the United State Information Agency under grant no. 14099. Also, the authors would like to thank Mr. K. Mekki for this assistance in conducting the experiments.

REFERENCES

[1] D.D. Drysdale and H.E. Thomson, "Flammability of Plastics II: Critical Mass Flux at the Firepoint", *Fire Safety Journal*, vol. 14, pp. 179-188, 1989.

[2] T. Kashiwagi, "Effects of Sample Orientation on Radiative Ignition", *Combustion and Flame*, vol. 44, pp. 223-245, 1982.

[3] K. Kishore and R. Nagarajan, "Effect of Metal Salicylates on the Ignition and Combustion of Polystyrene", *Fire Safety Journal*, vol, 15, pp. 391-401, 1989.

[4] T. Kashiwagi, "Experimental Observation of Radiative Ignition Mechanisms", *Combustion and Flame*, vol. 34, pp. 231-244, 1979.

[5] T. Kashiwagi, "Effects of Attenuation of Radiation on Surface Temperature for Radiative Ignition", *Combustion Science and Technology*, vol, 20, pp. 225-234, 1979.

[6] H.E. Thomson and D.D. Drysdale, "An Experimental Evaluation of Critical Surface Temperature as a Criterion for Piloted Ignition of Solid Fuels", *Fire Safety Journal*, vol. 13, pp. 185-196, 1988.

[7] T. Kashiwagi and A. Omori, "Effects of Thermal Stability and Melt Viscosity of Thermoplastics on Piloted Ignition", personal contact.

[8] H.R. Wesson, J.R. Welker, and C.M. Sliepcevich, "The Piloted Ignition of Wood by Thermal Radiation", *Combustion and Flame*, vol. 16, pp. 303-310, 1979.

[9] A. Atreya "Pyrolysis, Ignition and Flame Spread on Horizontal Surfaces of Wood", *Ph.D. Thesis*, Harvard University, 1983.

[10] A. Atreya, C. Carpentier, and M. Harkleroad, "Effect of Sample Orientation on Piloted Ignition and Flame Spread", *Proc. First International Symposium on Fire Safety Science*, vol. 1, pp. 97-118, 1985.

[11] C.D. Woodward, "The Industrial Fire Problem", *Fire Safety Journal*, vol. 15, pp. 348-366, 1989.

[12] T. Kashiwagi, T.J. Ohlemiller, and K. Werner,

"Effects of External Radiant Flux and Ambient Oxygen Concentration on Nonflaming Gasification Rates and Evolved products of White pine", *Combustion and Flame*, vol. 96, pp. 331-345, 1987.

[13] J. Quintiere, "A Simplified Theory for Generalizing Results from a Radiant Panel Rate of Flame Spread Apparatus", *Fire and Materials*, vol. 5, No. 2, pp. 52-60, 1981.

[14] F.A. Williams, *Combustion Theory*, Second Edition, The Benjamin/Cummings Publishing Company, Inc., p. 510, 1985.

[15] Omega Engineering, "Temperatur Measurements Handbook and Encyclopedia *Omega Engineering, Inc.*, Stanford, vol. 27, Z-39, Z-40, 1991.

[16] J.P. Holman, *Experimental Methods fo Engineers*, McGraw-Hill, Inc., 5th edition, 41, 1989.

[17] S.C. Chapra and R.P. Canale, *Numerica Methods for Engineers with Personal Compute Applications*, McGraw-Hill, Inc., 1985.