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WIND-AIDED FLAME SPREAD OVER CHARRING AND VAPORIZING SOLIDS

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KAMEL EL MEKKI

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DOCTOR OF PHILOSOPHY degree in MECHANICAL ENGINEERING

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WIND-AIDED FLAME SPREAD OVER CHARRING AND VAPORIZING SOLIDS

By

Kamel El Mekki

A DISSERTATION

Submitted to Michigan State University in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Department of Mechanical Engineering

1991

ABSTRACT

WIND-AIDED FLAME SPREAD OVER CHARRING AND VAPORIZING SOLIDS

By

Kamel El Mekki

This work presents the results of a detailed experimental investigation and analysis of laminar forced flow wind-aided flame spread over wood and PMMA in the ceiling configuration. This investigation includes measurements of flame spread rate and heat and mass transfer.

In the flame spread work, the speed of propagation of the pyrolysis front and the flame front and the production rates of the major chemical species were measured as a function of time. The effect of the free stream velocity and the oxygen mass fraction on the flame spread rate and the production and depletion rates of major chemical species were investigated for both wood and PMIMA. The effect of external radiation was investigated only for wood, because use of external radiation for PMMA results in excessive melting and dripping. It was found that all these environmental parameters, and especially the oxygen mass fraction, control the flame spread rate and the chemical species production rates.

In the heat transfer part of this work, the effect of wind speed and ambient oxygen mass fraction on heat transfer to the surface underneath and ahead of the flame tip during wind-aided flame spread were investigated experimentally. The data were correlated according to a simple theoretical model. The experiments were also performed in the ceiling configuration. High-temperature ceramic solids containing surface and in-depth thermocouples were used downstream of the burning PMMA sample to measure the net heat transfer to the surface. Simultaneous measurements of the PMMA surface temperature (to determine the pyrolysis front), ceramic solidphase temperatures (to determine the conduction heat transfer), gas-phase temperatures (to determine the convective heat transfer), and the flame tip location were made. Since the excess pyrolyzate (which produced a flame front that was only slightly ahead of the pyrolysis front) was low for all experiments, the heat transfer measurements underneath the flame were conducted with a natural gas diffusion flame in the boundary layer over the ceramic solids mounted in the ceiling configuration. For these laminar flames, it was found that convection by the hot gases is the dominant mode of heat transfer to the surface ahead of and underneath the flame. The radiation component becomes more significant as the free stream oxygen mass fraction increases. Surface temperatures and flame spread rate equations were derived from these heat transfer correlations. It was found that the flame spread rate is linearly with free stream velocity, as expected, and varies to the 1.5-power of the free stream oxygen mass fraction. To my father; Mohammed, my mother; Zohra, my wife; Dalila, and my children; Wafa and Karim for their confidence, devotion, and understanding in helping me attain this important milestone of my life.

Acknowledgement

The author is greatly thankful to his advisor Professor Arvind Atreya. His constant guidance, encouragement and direct involvement in every step of the work was of invaluable help in the completion of this work. I deeply appreciate his patience and his friendship. I would also like to thank the members of my Committee, Dr. I. S. Wichman, Dr. J. Beck, Dr. K. Mukherjee and Dr. P. Hunt for their input and guidance.

I would like to thank my colleagues and friends; especially Sanjay Agrawal for his help in conducting the flame spread experiment on PMMA.

This work was supported by USDA under contract number 86-FSTY-9-90192.

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Appendix D

Figure D.xx Heat flux measurements during flame spread on PMMA.

NOMENCLATURE

- C = Specific Heat
- f = Mass-based stoichiometric coefficient
- h = Convective heat transfer coefficient
- ΔH = Heat of combustion per unit mass of PMMA
- k = Thermal conductivity
- m'' = Mass flux
- Nu = Nusselt number
- Pr = Prandtl number
- q" = Heat flux
- Re = Reynolds number
- t = Time
- T = Temperature
- U,V = Velocity
- x = Streamwise coordinate
- y = Transverse coordinate
- Y = Mass fraction

Greek

- α = Thermal diffusivity
- ρ = Density
- $\theta = T T_{-}$

Subscripts

- f = Flame
- g = Gas
- o = Oxygen
- p = Pyrolysis
- s = Surface
- T = Total
- x = at x
- ∞ = free stream

CHAPTER ONE

Introduction and Literature Review

Wood is, and has been, for centuries a common construction material. But unfortunately, wood is combustible and is involved in hazardous building fires. In residential rooms or buildings, once wood is ignited, fire spreads in different directions depending on the location of the wood with respect to gravity (floor, ceiling, wall). The spread of fire in a building goes through complex interactions between physical, heat and mass transfer, and chemical reaction processes. Thermal radiation from a ceiling layer of hot gases and hot walls is the primary mode of energy transfer in a fire to the as-yet-unburned materials. The flame-spread rate strongly depends upon the magnitude of this incident heat flux, which causes the surface temperature to reach the ignition (or pyrolysis) temperature. At this temperature, the solid starts to pyrolyze and feed combustible gases into the fire plumes. As the fire burns in a closed room, the oxygen concentration decreases to a point where the flame can no longer exist. Hence, the oxygen concentration is also expected to significantly affect the rate of flame spread. Finally, as windows and doors are broken or burned, air currents develop, which along with buoyant currents cause the flame to spread in different directions. This results in wind-opposed (fire spread and incoming air in opposite directions) and wind-aided (fire spread and incoming air in the same direction) modes of flame spread. The three environmental conditions identified above, namely; incident heat flux, ambient oxygen concentration, and wind speed; are the primary external parameters that control the flame-spread rate over combustible materials like wood [Emmons 1974].

The room-fire problem has been approached in two different ways: some investigators have focused on understanding the effect of building geometry on fire growth [Emmons 1980, Quintiere 1980], while others have conducted experiments searching for the flammability characteristics and behavior of fire growth on different building materials, such as polymethylmethacrylate (PMIMA), paper, wood, etc. However, the results of some of these experiments are different because the investigators failed to control some of the environmental parameters [Emmons 1980]. Such independent control of wind speed and oxygen mass fraction have proved to be very helpful in identifying the controlling mechanisms of wind-opposed flame spread [Fernandez-Pello et al. 1981]. Only one similar experimental investigation of wind-aided flame-spread, on PMMA, has been reported in the literature [Loh and Fernandez-Pello 1984]. This investigation did not consider external radiation as one of the variables. Experimental studies of wind-aided flame spread on (thick) charring materials like wood have not been reported.

In this work, wind-aided flame-spread over wood is extensively studied for all the above mentioned environmental parameters. Similar experiments are also conducted on PMMA for comparison with the available results of Loh and Fernandez-Pello (1984).

1.1 Background

1.1.1 Pyrolysis

To study flame spread over combustible solids, one has to understand the solidphase decomposition (pyrolysis) of the material, because the incident heat flux from the existing flame leads to gasification of the material producing the fuel, which in turn sustains the flame. Thus, the rate of the solid gasification is central to the rate of flame spread. The pyrolysis of non-charring and charring solids represents two extreme cases of solid-phases degradation. For PMMA, the solid is totally consumed and essentially "vaporizes". However, for wood, a char layer is formed at the surface while the pyrolysis front propagates into the solid.

1.1.1.1 Pyrolysis of vaporizing solids (PMMA)

As the surface temperature reaches the pyrolysis temperature, the solid starts to pyrolyze and surface regression is observed as gasification continues. For a constant incident heat flux, the mass flux was found to reach a steady state as illustrated in Figure 1.1 [Vovelle et al. 1987]. Tewarson and Pion (1976) observed that the mass loss rate correlates as

$$\dot{\mathbf{m}} = \frac{(\dot{\mathbf{Q}} - \dot{\mathbf{Q}}_{ls})}{\mathbf{L}_{G}} \tag{1.1}$$

where

 \dot{Q} = incident flux (W/cm²) \dot{Q}_{LS} = heat loss from the surface (W/cm²) L_{G} = heat of gasification (J/g) + heat conducted into the solid

This linear dependency on the incident heat flux was also confirmed by Vovelle et al. (1984). However in a real fire, the incident heat flux at the surface increases as the flame approaches, therefore a transient mass loss rate would result. Such a study has been carried out by Vovelle et al. (1984) when they examined the effect of known variable incident heat flux on the mass loss rate of both PMMA and particle board in an inert atmosphere. As expected, the mass loss rate of the PMMA sample rises with the heat flux as shown in Figure 1.2.



Figure 1.1 PMMA surface temperature and mass flux histories during pyrolysis experiment (Y_{on}=0.233, q^{*}=3W/cm²) [Vovelle 1987].



Figure 1.2 Mass flux behavior of PMIMA sample under different rates of external radiation [Vovelle 1984].

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1.1.1.2 Pyrolysis of charring solids (WOOD)

As soon as the sample is exposed to an external heat, the so-called inert heating stage starts. During this stage, the temperature rises without decomposition. However, some moisture evaporation occurs. This phenomenon holds true until the pyrolysis temperature is reached at the surface. At this moment the pyrolysis stage and the release of volatiles are initiated. As the surface temperature continues to increase, the volatile mass flux rapidly increases until it reaches a maximum when a thin char layer starts to form at the surface. Then as the char layer thickness increases, the volatile mass flux gradually decreases. This phenomenon, shown in Figure 1.3, has been observed by a number of investigators [Vovelle et al. 1984, Atreya 1983, Nurbakhsh 1989].



Figure 1.3 Typical mass flux history of a wood sample during pyrolysis [Nurbakhsh 1989].

Due to its lower thermal conductivity than the original wood, char becomes a barrier to the incoming heat flux and prevents it from passing into the inward propagating pyrolysis zone. In addition, the re-emitted radiant flux by the char surface increases owing to its high emissivity. This causes the conduction heat transfer to the in-depth virgin wood to drop in time.

Thus, for these two different combustible materials, wood and PMMA, one expects that during wind-aided flame spread: For PMMA, the flame will stay attached to the leading edge as the flame tip propagates downstream. For wood, however, an extinction-front would propagate behind the pyrolysis-front due to the lack of fuel caused by the thick char-layer.

1.1.2 Flame Spread

Pyrolysis-front spread rate and heat transfer to the solid ahead and underneath the flame have been investigated, both experimentally and theoretically, for different materials and at different angles relative to gravity [Loh and Fernandez-Pello 1984, Atreya 1983, Saito et al. 1987, Fernandez-Pello and Williams 1975, Fernandez-Pello and Hirano 1983, Saito et al. 1986]. Figure 1.4 shows qualitatively the effects of gravity and air flow on propagating flames. Clearly, the most hazardeous cases are wind-aided flame spread in the ceiling configuration and upward (buoyancy driven) flame spread. The flame in these configurations is pushed closer toward the unburned surfaces, thus increasing the heat transfer by the hot gases to the as-yet-unburned surfaces.

Several theoretical papers have been published on the upward buoyancy driven flame spread [Saito et al. 1986, Fernandez-Pello 1978, Annamalai and Sibulkin 1979, Markstein and deRis 1973, Orloff and deRis 1976, Sibulkin and Kim 1977, Fernandez-Pello and Quintiere 1982, Kulkarni and Fisher 1988]. All of these models are in qualitative agreement with the experimental results. Fernandez-Pello (1978) developed a model that predicted flame heights larger than the experimental data.



Figure 1.4 Schematics of different modes of flame spread relative to gravity.

This larger predicted flame height increases the heat flux to the surface, causing higher flame-spread rate predictions. Saito et al. (1986) conducted experiments on both PMMA and Douglas-fir and developed a model for upward flame spread. They predicted that the pyrolysis front spread rate goes as

$$V_{p} = \frac{x_{f} - x_{p}}{\tau} , \qquad (1.2)$$

where the characteristic ignition time τ depends on the fuel properties, and the heat flux (assumed constant) from the flame to the surface underneath, and x_f and x_p are the flame-front and the pyrolysis-front locations, respectively, as shown in Figure 1.5. The experimental results agree very well with the predictions and previous theories for PMMA. However for wood, the authors did not use external radiant heaters; and, therefore, no well defined continued flame spread occured. Thus, their prediction of an initial acceleratory spread, before reaching steady state, for charring material could not be confirmed.



Figure 1.5 Schematic of upward flame spread on wood sample.

A number of models for wind-aided flame spread have also been rier et al. 1980, Carrier et al. 1983, DiBlasi 1987, Wichman and A these models have focused on vaporizing solids. Recently Wichman and (1991) and Carrier et. al. (1990) have also developed such models. These models predict steady flame spread rates, and assume a steady state in the pyrolyzing zone. Wichman and Agrawal (1991) predicted the flame spread rate as

$$\frac{V_{p}}{U_{\infty} - V_{p}} = \frac{\rho_{\infty}C_{p\omega}\lambda_{\infty}}{\rho_{s}C_{s}\lambda_{s}} \left[\frac{T_{f}-T_{p}}{T_{p}-T_{\infty}}\right]^{2} \left[\frac{\exp(-M^{2}Pr)}{\operatorname{erfc}(-M\sqrt{Pr})}\right]^{2} .$$
(1.3)

This formulation shows the dependency on solid and gas properties, flame temperature and wind speed. The experimental study and the model of Loh and Fernandez-Pello (1984) for PMMA were in agreement, and the pyrolysis front spread rate was found to be:

$$V_{p} = U_{\infty} \frac{\rho_{\infty} C_{p\infty} \lambda_{\infty}}{\rho_{s} C_{s} \lambda_{s}} \left(\frac{T_{f} - T_{p}}{T_{p} - T_{\infty}} \right)^{2} .$$
(1.4)

The above equations look similar, but discrepancies exists between the results of Loh and Fernandez-Pello (1984) and those of Wichman and Agrawal (1991) and the complicated mathematical analysis and numerical solution of integral equations by Carrier et al. (1980). These two latter models predict that $V_p \sim Y_{ooo}$; however, Loh and Fernandez-Pello concluded from their analysis and experiments, that $V_p \sim Y_{ooo}^2$. This certainly points out the complexity of the wind-aided flame spread process and the need to experimentally control the external conditions carefully. Also it seems essential to evaluate the validity of the several simplifying assumptions made in the theoretical models.

Transient solutions, with finite rate gas phase kinetics, were obtained by DiBlasi et al. (1987, 1988a) using a finite-difference scheme. They concluded that as the oxygen mass fraction decreases, the flame temperature and the heat fluxes to the unburned fuel surface drop. This causes a slower fuel production rate, and consequently, a slower spread rate. At a very low oxygen mass fraction, the effects of finite kinetics appear mainly at the leading edge, where extinction begins.

Previous investigators have primarily focused on non-charring materiala because of the difficulty in simultanously analyzing the solid-phase processes for charring solids. Carrier et al. (1983) made the first and only attempt toward the development of models for wind-aided flame spread over charring solids. They treated the char and the virgin wood as solids with different thermal properties. The surface temperature was considered to rise to th pyrolysis temperature at the arrival of the pyrolysis front, then to keep rising until some temperature T_e at which time char starts to chemically erode to form gas. The transient problem was formulated, but only the steady state part of the solution was obtained. The numerical solution for both Blasius-type and Oseen-type flow were also obtained. While the flame temperature was found to be invariant under both flow-field approximations, the char-layer thickness and the flame position under the Blasius-type flow were about twice as large as those under the Oseen-type flow. The char layer thickness was also found to be sensitive to both the temperature T_e and the latent heat.

DiBlasi et al. (1988b) solved numerically the problem of wind-aided flame spread over thin charring solids. Their results show that the pyrolysis front spread rate initially accelerates while the flame foot is still at the leading edge. As the burn-out front starts to propagate, the pyrolysis front spread rate decelerates. Steady state is then reached when both the pyrolysis front and the burn-out front spread rates are equal. If the burn-out front spread rate keeps accelerating, extinction occurs. These results were in agreement with previous experimental data. However, the dependency of the pyrolysis front spread rate on the flow velocity was not fully resolved. Although the experiments indicate that the spread rate becomes constant for relatively high flow speeds, the model predicts that the spread rate keeps increasing.

All the above models for wind-aided flame spread are for the laminar case and can be classified as thermal models where one step infinitely fast gas-phase chemical reaction ($v_fF+v_oO-\rightarrow$ products) is assumed. Finite rate chemical reactions were found

to have an effect only at the leading edge and the flame tip, since flame temperature drops at these locations [DiBlasi et al. 1987, 1988a, 1988b].

The flame spread rate is determined by the rate at which the surface temperature is raised to the solid pyrolysis temperature (i.e. $V_p=dx_p/dt$ where $T_s=T_p$ (or T_{ig}) at x_p). The flame spread rate depends on how fast the solid surface temperature is raised to its pyrolysis temperature, which depends on the convective and radiative heat flux from the flame. The convective heat flux is proportional to the gas-phase temperature gradient at the surface, which depends on both the flame temperature and the boundary layer thickness. Therefore, the most important variables that affect this mode of flame spread are the wind speed, which controls the boundary layer thickness, and the oxygen mass fraction, which controls the flame temperature. The above equations show the flame spread rate dependency on these two parameters.

Flame spread experiments over PMMA samples are conducted to compare the results with those of Loh and Fernandez-Pello (1984) and to seek the reason(s), if any, for the above-mentioned discrepancies.

Previous experiments on PMMA have proved that the heat flux by flame radiation and convection by the hot gases is sufficient to bring the solid surface temperature to its ignition temperature and allow the flame to spread. Therefore, only the wind speed and the ambient oxygen mass fraction have been studied for PMMA. For the experiments on wood, however, a minimum external radiant flux level is necessary for the spread to occur [Saito et al. 1987]. The magnitude of this incident heat flux and the preheat time have a significant effect on the flame spread rate. The incompleteness of combustion as well as flame radiation, which both affect the flame temperature, were not previously studied and are investigated in detail in the present study. The objective is to provide a complete physical understanding of this mode of fire spread over charring and non-charring solids. The combustion products were only measured and analyzed by Atreya (1983) in his pyrolysis, ignition, and fire spread on horizontal surfaces of wood, and by Abu-Zaid (1988) and Nurbakhsh (1989) in their pyrolysis experiments on wood. The flame spread results of Atreya (1983) show that the measured average mass flux is initially proportional to the 4/3 power of the fire radius, then stays constant due to the balance between the attenuation due to charring and increase in fire size, and finally becomes inversely proportional to the fire radius due to char build-up. In this work, the mass production rate of all the major chemical species are measured and analyzed.

1.1.3 Heat transfer to the solid

Figure 1.6 shows a typical surface temperature history during flame spread on PMIMA. The rise of the solid surface temperature from the ambient temperature T_{∞} to the pyrolysis temperature T_p at the pyrolysis front is due both to both the preheating upstream of the flame tip $x>x_f$ and the preheating underneath the flame $x_p<x<x_f$ (the overfire region). Therefore, the heating of the surface to its pyrolysis temperature in the overfire region depends on the surface temperature at the flame tip arrival $x=x_f$. The higher this temperature, the less is the heating needed from the flame in the overfire region, and hence the shorter the distance (x_f-x_p) .

Clearly, the preheating downstream of the flame tip cannot be neglected and has to be well understood for proper and realistic theoretical models, since in analytical solutions, the heat flux in the preheat zone is required to develop the flame spread model [Fernandez-Pello 1978].

Sibulkin and Kim (1977) obtained the following expression for wind-aided flame spread

$$V_{p} = \frac{(q_{f})^{2} \delta_{f}}{k\rho C (T_{ig} - T_{s})^{2}}$$
(1.5)

where kpC is the square of the solid-phase thermal responsivity, T_{ig} is the ignition or pyrolysis temperature, T_s is the upstream surface temperature, δ_f is an effective flame

heat transfer distance measured from the pyrolysis front, and q_f is the heat flux at the pyrolysis front. Therefore, the flame spread rate can be found through the knowledge of q_f and δ_f . Quintiere et al. (1986) completed this cycle by performing upward flame spread experiments where they measured the heat flux (at the wall underneath and ahead of the flame), and the flame height for different combustible materials. They found that the heat flux at the wall ahead of the flame correlates as $q_w \sim x^{-p}$, where p=2.4, and x measured from the base of the sample. This is very close to the results of Ahmad and Faeth (1979) who found that p=2.33. Ahmad and Faeth (1978) found, both experimentally and theoretically, that the heat flux underneath the flame is approximately constant and that the distance $(x_f - x_p)$ is dependent on fuel and ambient oxygen mass fractions.



Figure 1.6 PMMA surface temperature history during flame spread experiment.

The purpose of this work is to quantify this heat transfer for wind-aided flame spread in the ceiling configuration. The available tools, used by Quintiere et al. (1986), for measuring these heat fluxes are water-cooled radiometers. However, these radiometers are inappropriate because they provide total heat flux measurements to a watercooled surface rather than to an already-heated surface whose surface temperature is changing with time. To overcome this problem, ceramic detectors with surface and indepth thermocouples were developed.

1.2 Prospects of this work

The flame spread and the heat transfer experiments are conducted in a small scale combustion wind tunnel. Two materials representing the extremes of a broad spectrum of available building materials are studied. These are (i) wood, which chars during burning, and (ii) PMMA, which vaporizes during burning. Species concentrations, and surface temperature histories, are measured as a function of time. In addition, video records of the flame tip are taken. The surface temperature measurements are used to determine the pyrolysis-front arrival; and the video records show the transient flame tip position, while the species concentration measurements provide a measure of the evolved mass flux during the flame spread process. This mass flux and the pyrolysisfront spread rate reveal the burning zone condition and the incompleteness of combustion.

Since wood chars and PMMA melts and drips during flame spread, surface and indepth temperature measurements are difficult and inadequate for incident heat flux computations. Therefore, high temperature ceramic samples were cast with surface and indepth thermocouples. The optimum design for the number and location of the thermocouples in the solid was determined experimentally. It was found that a total of three thermocouples, one at the front surface, one at the back surface, and one indepth near the surface exposed to the external heat flux, provide a sufficient number of temperature measurements for accurate incident heat flux computations, given the thermal properties of the ceramic (assumed linear with temperature). These ceramic detectors were also painted black to make their emissivity near unity.

The heat transfer in the preheat zone ahead of the flame tip was studied by conducting flame spread experiments on PMMA samples upstream of the ceramic detectors. The heat transfer underneath the flame, however, was studied with the help of a natural gas diffusion flame existing in the boundary layer over the solid surface in the ceiling configuration.

Inverse heat conduction calculations were used to obtain the net (total) heat flux as a function of time. The convective heat transfer component was derived from the temperature gradient at the solid-gas interface. The re-radiation heat flux component was computed from the knowledge of the surface and surrounding temperatures and the surface emissivity. Finally, the flame radiation component of the net heat flux was computed by applying an energy balance at the solid-gas interface. The effect of the free stream velocity and the ambient oxygen concentration on the convective and radiative components of the net heat transfer to the solid was studied.

The purpose of this work is to conduct a thorough experimental study of windaided flame spread over charring and vaporizing materials in the ceiling configuration. The objectives are summarized bellow:

- 1- To provide a physical understanding that will serve as a basis for the development or refinement of theoretical models.
- 2- To provide new measurements for charring materials like wood, under stringently-controlled test conditions.
- 3- To develop a model for correlating the results.
- 4- To provide additional measurements for vaporizing materials like PMMA, and discover the reasons for the discrepencies, if any, between this work and available results in the literature.
- 5- To provide precise measurements of the convective and radiative components of the net heat flux to the surface ahead and underneath the diffusion flame.

CHAPTER TWO

Experimental Apparatus and Procedure

The flame spread and the heat transfer experiments were conducted in a small scale combustion wind tunnel. This apparatus was designed by the principal investigator of the project. This wind tunnel is a unique facility where all the environmental variables mentioned $[U_{ee}, Y_{oee}, \dot{q}^{"}]$ can be easily controlled. The schematic of the apparatus is shown in Figure 2.1. It consists of three main parts: (i) a small-scale combustion wind tunnel, which is capable of providing a desired external radiation on the sample surface along a flat-plate boundary-layer flow at a given free stream velocity and composition; (ii) a set of continuous gas analyzers for measuring the total unburned hydrocarbons THC, the depletion of oxygen, and the production of CO₂, CO, and H₂O; and (iii) data acquisition equipment to collect, store and process the data. Each of these parts is described in detail in the following sections.

2.1 Small-scale combustion wind tunnel

The wind tunnel consists of three sections: (i) an inlet section where the wind speed and composition are controlled; (ii) a test section where the flame spread over the sample takes place; and (iii) an exhaust section where the produced species



mix with the core flow. Each of these sections is designed such that it can be detached and modified separately. 2.1

2.1.1 Inlet section

The desired air flow and composition results from the mixture of air and oxygen (or nitrogen) after flowing through sonic orifices, as illustrated in Figure 2.1. The air supplied by the building compressor first enters a large tank in order to dampen all the mechanical oscillations. The air then flows through a sonic orifice, of a known diameter, at a certain upstream pressure. This pressure should be higher than the critical sonic pressure, whereas the downstream pressure is close to atmospheric. However, oxygen and nitrogen are supplied by pressurized gas cylinders to a large tank before flowing through another sonic orifice. Knowing the nozzle diameter, upstream pressure and flow density and temperature, the mass flow rate can be computed as [Holman 1984]

$$\dot{\mathbf{m}} = \mathbf{A}_{\mathrm{N}} \mathbf{P}_{\mathrm{i}} \sqrt{\frac{2 \mathbf{g}_{\mathrm{c}}}{\mathbf{R} \mathbf{T}_{\mathrm{i}}}} \left[\frac{\gamma}{\gamma + 1} \left[\frac{2}{\gamma + 1} \right]^{\frac{2}{\gamma - 1}} \right]^{1/2}$$
(2.1)

where

 \dot{m} = mass flow rate (lbm/sec)

 A_N = area of the nozzle (in²)

 P_i = inlet static pressure (Psia)

 $g_c = \text{gravitational conversion factor (32.2 lbm.ft/lb.sec}^2)$

R = gas constant (ft.lbf/lbm.R)

 $T_i = inlet temperature (R)$

 γ = ratio of specific heats of the gas (C_p/C_v)
The sonic nozzles were calibrated using a tracer gas technique where a known flow rate of methane is introduced downstream of the orifice, and the mole fraction of the methane-air mixture was measured. The discharge coefficient C_D of each nozzle was carefully determined from the flow measurements and found to be 0.97 [Abu-Zaid 1988]. The mixture flows through a 20 foot long, 3 inch inside diameter tube before entering the settling chamber through 8 pipes, which branch out of the manifold at equal angles.

2.1.2. Turbulence manipulation section

The flow exits the settling chamber with large and small scale eddies. Hence, before running through the test section, the flow is first conditioned in the turbulence manipulation section. Combinations of honeycombs, glass beads and fine screens were tested for Blasius type of flow in the test section. The honeycombs are used to damp the large scale eddies and the fine screens are used to dissipate the small scale eddies. However, a two-inch space full of glass beads provides an inlet uniform flow. Unfortunately, due to the high velocity near the walls of the settling chamber, the velocity has a peak near all the four sides of the test section as shown in Figure 2.2. Different combinations of honeycombs, glass beads and screens did lower these peaks, but didn't make them disappear.

Finally, after several trials, the peak in the velocity profile disappeared when a screen frame, shown in Figure 2.3, was installed. The velocity profile measured for different free-stream velocities is shown in Figure 2.4. These results are very close to the Blasius-type of boundary-layer over a flat plate. The optimum combination of the honeycomb, glass beads, and screens is shown in Figure 2.5.



Figure 2.2 Velocity profile at the leading edge of the sample (x=0) before and after installing the frame metal screen.



Figure 2.3 Frame metal screen used in the turbulence manipulation section.









2.1.3. Test section

The useable portion of the tunnel test section is 0.81 m long and 0.153 m wide. The test sample (0.76 m long, 0.076 m wide and 0.019 m thick) is placed horizontally along the tunnel top while the bottom of the tunnel is hinged at the inlet allowing the tunnel depth to be adjusted. The tunnel depth at the inlet is 0.1 m but can be increased to 0.13 m at the exhaust end. This provides a maximum 30% increase in the cross-sectional area at the exhaust end to compensate for the acceleration of the gas core because of boundary layer growth and gas expansion due to heat release. The damper on the exhaust fan and the exit tunnel depth were adjusted to provide atmospheric pressure in the tunnel test section to within 1×10^{-4} torr. This was necessary to prevent gas leakage in or out of the tunnel for chemical measurements and also to maintain a nearly constant free stream velocity. A maximum 10% increase in the free-stream velocity at the exit was observed. To further reduce the effect of variation in the free-stream gas velocity, data for only the first 0.5 m were used. The RMS level of turbulent fluctuations inside the tunnel was found to be less than 1% of the freestream velocity. Furthermore, the measurements of the velocity profile inside the tunnel (see Figure 2.4), show that the flow is laminar.

2.1.4. External radiation source

External radiation on the sample surface was provided from below by two types of electrically-operated radiant heaters. The first type consists of three high-temperature (with maximum filament temperature of 1230 K) quartz electrical heaters (10 in x 10 in) placed at the bottom of the heater assembly shown in Figure 2.6. The second type consists of six U-shaped Chromlox coil heaters (3/8 in diameter, Incoloy sheath, type UTU, each 1.8 KW) installed above the quartz heaters. The heaters are separately controlled by two 3-phase 440-Volt variable transformers. These heaters are housed in an insulated box with the inside frame sides being highly reflective aluminum sheets. This housing is covered by water-cooled shutters which slide out at the beginning of the experiment.





This heaters assembly is suited to simulate external radiation in building fires.

The incident radiation from the heaters passes through an optical glass window (0.153 m wide and 0.76 m long) contained in the hinged bottom portion of the tunnel. About 70% of the infrared radiation is transmitted to the sample surface. However, due to the view factor, the radiation is a maximum at the center of the sample and drops by about 30% at the two ends of the sample. To overcome this difficulty, three screens have been installed between the heaters and the infrared optical glass window to scatter the radiation. After a number of trials with the width and number of screens, an optimum combination (see Figure 2.7) was configured such that the radiation measured at the sample surface was uniform to within $\pm 3\%$ over the entire length of the sample, as shown in Figure 2.8. The entire tunnel test section was maintained between 315 K and 335 K by cooling water.

2.1.5. Exhaust section

The main part of the exhaust section is the mixing chamber. In order to obtain a representative gas sample for transient chemical analysis, the stratified products of combustion have to be well mixed with the core flow. This mixing process is acheived through the use of a combination of baffles, a series of electric tapes for large-scale mixing, and a net of electric resistance wires for small-scale mixing. A metal louver is added at the outlet of the mixing chamber to assure the mixing of gases as shown in Figure 2.9. The electric tapes and the net of electric resistance are heated to avoid condensation of heavy hydrocarbons or water.

A well mixed representative sample of gases is then extracted through the sampling probe for chemical analysis. The rest of the flow then goes through a large chamber before getting sucked by the exhaust fan. This large chamber is used to suppress the mechanical oscillations created by the exhaust fan.







Figure 2.8 Measured heat flux profiles along the sample (x=0 corresponds to the leading edge of the sample).





2.2. Gas analysis equipment

For the species concentration measurement, a constant flow rate of a representative sample from the tunnel was supplied to the gas analyzers by a metal bellow vacuum pump. To reduce errors due to condensation, the lines running to the total hydrocarbon [THC] and H₂O analyzers were heated by either electrical tape or hot water as shown in Figure 2.10. The gas was then passed through a cold-trap at -5° C and dried before passing through the O₂ and the CO-CO₂ analyzers.

Prior to every experiment, the gas analyzers were first zeroed with nitrogen gas flowing through, then they were adjusted to the proper reading for the known concentration of every specie of the calibration gas running through.

2.2.1. Total Hydrocarbons analyzer [THC]

The total hydrocarbons were measured by a Flame Ionization Detector (FID) gas chromatograph GC-3BF, which used a 40%H₂-60%He mixture for fuel. The FID had a very good response time and a time constant of 1.0 second.

2.2.2. Water analyzer

The water vapor concentration history was measured by a condensation Dew-Point hygrometer (General Eastern 1200APS). The dew-point temperature was measured by optically detecting the condensation on a temperature-controlled mirror surface. The instrument had an accuracy of ± 0.2 °C and a time constant of 1.0 second.

2.2.3. CO-CO2 analyzer

An infrared IR702 nondispersive dual gas analyzer was used for CO and CO₂ concentration measurements. The flow was dried before entering the analyzer. The meter had a good accuracy of $\pm 1\%$ of full scale (CO : 0-3\%, 0-12\%; CO₂ : 0-6\%, 0-20\%) and a time constant of 2.6 seconds.



Figure 2.10 Gas analysis equipment.

2.2.4. O2 analyzer

The oxygen concentration was measured by a Beckman OM-11 polarographic analyzer. This meter also required dry flow. The meter had an accuracy of $\pm 0.1\%$ and a time constant of 1.5 seconds.

2.3. Data acquisition

The analog signals from thermocouples, gas analyzers and the radiometer were fed to a data acquisition/control unit (HP3497A). The data was then acquired by an HP 486 personal computer using LabWindows software (National Instruments). The handshaking commands and data transfer between the computer and the HP data acquisition unit were assured by the use a GPIB card with a standard IEEE 488 interface cable. The data was taken at 12 readings per second with a 10^{-6} Volts accuracy.

2.4. WOOD and PMMA sample preparation

The samples used for the flame spread experiments were obtained from clear boards of poplar and white sheets of PMMA. These were first conditioned at room humidity and temperature (50% RH and 294 K) and then instrumented with nine thermocouples on the surface 0.05 m apart. These thermocouples were made from fine chromel and alumel wires 76 μ m in diameter. The method employed to install the thermocouples on wood surface was developed by Atreya (1983). Two very fine layers of wood were skinned off from the surface using a sharp razor blade, then a portion of the thermocouple wire of each side on the junction was secured underneath each layer using wood glue. A very fine drop of this glue was also put on the thermocouple junction. The assembly was then allowed to dry under a heavy weight for about 2 hours. For the PMMA samples, however, an electric heat gun was used to heat the surface so that the thermocouple wires stick.

2.5. Ceramic samples preparation

The available tools for measuring the heat flux at the surface are water-cooled wide-angle radiometers. However, these radiometers are inappropriate because they provide total heat flux measurements to a water-cooled surface rather than to an already heated wall whose surface temperature is changing with time. Since wood chars and PMMA melts and drips during flame spread, indepth temperature measurements are difficult and inadequate for incident heat flux computations. To overcome this problem, ceramic detectors with surface and indepth thermocouples were developed.

These high temperature ceramic samples were cast with surface and indepth thermocouples (6 in length by 3 in width and 1 in thickness). The optimum design for the number and location of the thermocouples was experimentally determined. It was found that a total of 3 thermocouples, one at every boundary and one indepth near the surface exposed to external heat flux, provide a sufficient number of temperature histories for accurate incident heat flux computations. For accurate results, all the ceramic samples have one thermocouple at each boundary and three indepth. The exact location of the indepth thermocouples and thermal properties, at different temperatures, of each ceramic sample, were carefully determined [Beck and Arnold 1977]. See Appendix A for details. These ceramic detectors were also painted black to make their emissivities near unity.

2.6 Flame spread experimental procedure

The test samples (30 in long, 3 in wide and 3/4 in thick) were placed horizontally along the tunnel top. The wood samples were obtained from clear boards of poplar, and the PMMA samples were obtained from white sheets of PMMA. They were first conditioned at room temperature and humidity and then instrumented with nine thermocouples two inches apart on the surface. Once all the desired conditions were set, the sample was ignited with a small methane porous metal burner placed at the inlet with its face parallel to the sample surface as shown in Figure 2.11. The fuel flow rate to the igniter was controlled such that the flame overhang on the sample surface was about 0.02m. After ignition, the physical process that occurs inside the tunnel is schematically shown in Figure 2.11. Surface temperature and species concentration histories were collected and stored in the computer. In addition, video records of the flame tip were taken. The surface temperature measurements provided the pyrolysis front arrival, and the video records showed the transient flame tip position, while the species concentration measurements provided the mass flux during the flame spread process. This mass flux and the pyrolysis front spread rate would reveal the burning zone condition and the incompleteness of combustion.



Figure 2.11 Schematic of wind-aided flame spread on wood.

2.7 Heat transfer experimental procedure

To study the heat transfer in the preheat zone ahead of the flame tip, a spreading flame on 10 inch and 16 inch PMMA samples upstream of the ceramic detectors was used. Time varying solid and gas-phase temperatures were measured. Video records of the flame tip were also collected. Figure 2.12 shows a schematic of a spreading flame on PMMA sample upstream of the ceramic detectors. The heat transfer underneath the flame, however, will be studied for the case of a natural gas diffusion flame existing in the boundary layer over the solid surface in the ceiling configuration, as illustrated in Figure 2.13. The porous-metal burner used in the latter case was increased in size to 4 inches and specially constructed (see Figure 2.14) to reduce the exit velocity at the porous metal surface for long flame experiments. A lower exit velocity allows the flame to be more buoyantly dominated. This will certainly cause the porous metal burner diffusion flame to have a stand-off distance close to that of the excess pyrolyzate in the overfire region during an actual flame spread experiment under similar environmental conditions.

Inverse heat conduction calculations were used to obtain the net (incident) heat flux as a function of time. The convective heat transfer component was derived from the temperature gradient at the solid-gas interface. The re-radiation heat flux component was computed from the knowledge of the surface and surrounding temperatures and the surface emissivity. Finally, the flame radiation component of the total heat flux was computed by applying an energy balance at the solid-gas interface. The effect of the free stream velocity and the ambient oxygen concentration on the flame convective and radiative components of the total heat transfer to the solid was studied.



Water cooled plate

Figure 2.12 Schematic of wind-aided flame spread on PMMA with ceramic solids mounted downstream for transient heat transfer measurements.



Water cooled plate

Figure 2.13 Schematic of natural gas diffusion flame over ceramic solids for steady-state heat transfer measurements.



Figure 2.14Diagram of the porous-metal burner used in heat transfer experiments.The natural gas comes only from the sides of the tubes.

2.8. Error analysis

The experimental determination of any parameter is based upon measurements, which usually contain errors. Two kinds of errors exist: uncertainty or random errors and systematic errors. The uncertainty errors in the measurements can be neglected since the data were collected by the computer through a data acquisition unit with a 10^{-6} Volts accuracy. Systematic errors, however, fall into one of two categories:

- 1. Calibration errors in the measurement devices.
- 2. Neglecting significant outside influences.

Since these systematic errors can exist in the measurements, a great deal of attention has been focused on calibrating the gas analyzers (errors of the 1st kind) and keeping atmospheric pressure in the test section to prevent leakage (errors of the 2nd kind). All the experiments were repeated to confirm the results. Accuracy of the species mass balance, the pyrolysis-front spread rate and the heat flux measurements are described in the following sections.

2.8.1. Mass balance

The chemical measurements along with the measured mass flow rate inside the tunnel yield the production and destruction rates of chemical species. These data were then reduced in terms of the mass production rate of the species at the instant at which they were produced. Investigation of the existence of systematic errors was performed by checking the mass balance of all the species.

A known mass flow rate of methane was introduced into the burner prior to ignition. To reduce errors due to incompleteness of combustion, the methane flow rate was originally set such that a blue flame was established after ignition. The results of such experimentation are shown in Figure 2.15, where the methane mass flow rate was set at 0.016 g/s.



Figure 2.15 Mass balance test experiment on CH₄ diffusion flame.

The following overall chemical reaction then describes the process (neglecting CO formation; as shown in Figure 2.15, CO concentration is small)

$$CH_4 + 2 O_2 \longrightarrow CO_2 + 2 H_2O$$

The predicted and measured mass flow rate of all the species are summarized in Table 2.1. The largest error in the species measurements is about 3%, which is acceptable.

Specie	Prediction (g/s)	Experiment (g/s)	%Error
CH4	0.016	0.0155	3.0
02-depl.	0.064	0.063	1.5
C02	0.044	0.043	2.3
Н2О	0.036	0.035	2.5

Table 2.1Mass balance for CH4 diffusion flame.

The accuracy of the species mass production rate measurements during an actual flame spread experiment can also be checked for the case of room air condition. Figure 2.16 shows the species mass production rates for the case of flame spread on PMMA where $U_{\infty}=0.9$ m/s and $Y_{0}=0.233$. For PMMA, the overall chemical reaction is described by:

$$C_5H_8O_2 + 6O_2 \longrightarrow 5CO_2 + 4H_2O$$

The predicted and measured mass flow rates at t=1500 sec. (see Figure 2.16) are summarized in Table 2.2. Since the total mass consumption rate of the sample is not known, all the predictions are based on the oxygen depletion rate. The very low percent errors shown in Table 2.2 show the reliability of all the gas analyzers and provide confidence in the species measurements.

Specie	Prediction (g/s)	Experiment (g/s)	%Error
02-depl.	0.05	0.05	
C02	0.06	0.058	3.3
H20	0.0188	0.019	1.3

Table 2.2Mass balance for PMMA diffusion flame.



Figure 2.16 Mass production rates histories during wind-aided flame spread on PMMA $(U_{\infty}=0.9 \text{ m/s and } Y_{\infty}=0.233).$

2.8.2. Pyrolysis-front spread rate

The accuracy of the pyrolysis-front spread rate was determined by the repeatability of the experiments. Hence, all of the flame spread experiments were repeated to confirm the results. Figure 2.17 shows three pyrolysis-front histories for three separate experiments conducted for the case where $U_{\infty}=0.9$ m/s and $Y_{\infty}=0.233$. The deviation in the pyrolysis-front spread rate is about 2% from its average value.

2.8.3. Heat flux

The accuracy of the incident heat flux measurements can be analyzed in two ways: (i) the low level of the errors (RMS) of the output results of the inverse heat conduction calculations, (ii) and the repeatability of the experiments.

The low RMS values show the good agreement between the measured and predicted temperature histories, which in turn shows that there is low error in the calculated heat flux.

The repeatability, however, can be investigated by looking at the heat flux results of experiments repeated for the same condition. Figure 2.18 shows the incident heat flux with the corresponding convected heat flux for two separate tests where $U_{\infty}=0.9$ m/s, $Y_{0\infty}=0.233$ and x=32in. The results of the two experiments are in very good agreement, with an average difference of 4% for the net heat flux and 5% for the convected heat flux.

The good repeatability of the results for species measurements, pyrolysis-front spread rate, and heat flux measurements provide confidence that all the measured quantities are within acceptable experimental error bounds.



Figure 2.17 Pyrolysis-front history on PMMA sample ($U_{\infty}=0.9$ m/s and $Y_{\infty}=0.233$).



Figure 2.18 Measured incident and convected heat fluxes repeatability $(U_{\infty}=0.9m/s, Y_{\infty}=0.233, x=32in.).$

CHAPTER THREE

Flame Spread over Vaporizing Solids

This chapter presents a detailed experimental investigation on laboratory-scale laminar wind-aided flame spread along a ceiling-mounted slab. The gas flow along the slab is forced, and its speed and composition are controlled.

Recent models for non-charring materials [Wichman and Agrawal 1991, Carrier et al. 1990] have sparked a considerable controversy since they seemingly disagree with the detailed experimental study of Loh and Fernandez-Pello (1984). The models suggest that the speed of the pyrolysis front varies linearly with the free stream oxygen mass fraction, while the experiments suggest a quadratic dependence. This clearly points out the need for further experimental investigation to determine whether any of the assumptions made during the development of the models or possible experimental errors are responsible for the discrepancy. Thus, the objectives of this work are to (i) provide a physical understanding that will serve as the basis for the development or refinement of theoretical models; and (ii) provide additional measurements for noncharring materials like PMMA.

3.1. Results

As shown in Figure 2.11, the fuel vapors generated in the pyrolysis region which extends from x = 0 to $x = x_p$, are burned in the diffusion flame, which extends from x = 0 to $x = x_f$ with $x_f > x_p$. The hot combustion products that flow downstream of x_f and the flame extension $(x_f - x_p)$ help to convectively and radiatively heat the pristine solid to a temperature (T_p) at which it begins to vigorously pyrolyze and contribute fuel to the flame. Thus, the flame spread process consists of the spread of the pyrolysis front. Clearly, the rate of flame spread will depend on how fast the surface temperature of the solid is raised to its pyrolysis temperature.

3.1.1. Temperature Measurements

Figure 3.1 shows the measured surface temperatures for PMMA as the flame propagates along the ceiling-mounted sample. These temperatures are typical of all the measurements. These measurements show a temperature plateau at about 643 K, which is taken as the melting or vaporization temperature.

From visual observations it was found that the peak rate of change in the surface temperature after ignition occurs is at the instant the flame tip arrives at the thermocouple location for both wood and PMMA. By writing a surface energy balance it can also be demonstrated that this peak corresponds to a sharp increase in the incident heat flux, which is caused by the flame tip arrival. Thus, the flame tip location, x_f , may be determined as a function of time from the measured temperature profiles by calculating the maximum value of dT_g/dt . Results of such calculations show excellent agreement with x_f determined from video records for both wood and PMMA. Figure 3.2 shows such agreement for PMMA where the solid lines correspond to the temperature measurements and the dashed lines correspond to the video records.



Figure 3.2 Flame-front history comparison between video records (dashed lines) and surface temperature measurements (solid lines).

The pyrolysis front location, x_p , is now found by defining a constant surface temperature, T_p , at which the solid begins to vigorously pyrolyze and contribute fuel to the flame. For PMMA this is the vaporization temperature (643 K). Unfortunately, at these temperatures the thermocouples often detach from the surface due to melting. Thus, operator judgement is required in determining x_p . To eliminate this difficulty, Δt between x_f and x_p was consistently determined by $(T_p - T_{x_p})/(dT_s/dt)_{max}$. An example of this method of determining x_f and x_p is illustrated in Figure 4.1. Figure 3.3 shows both the pyrolysis-front location x_p and the flame-front location x_f histories for most of the experiments (solid lines: x_p , dashed lines: x_f). Notice how close x_p and x_f are.

It is also important to note that the surface temperatures at x_f are much higher than ambient. They range from 533 K to 573 K for PMMA. This implies that most of the temperature rise has occurred in the preheat zone ahead of the flame. This observation is in sharp contrast with the previous assumption [Loh and Fernandez-Pello 1984, Annamalai and Sibulkin 1979] where the surface temperature is taken as ambient until the arrival of the flame tip.

3.1.2. Flame Spread Rates

Once x_f and x_p are determined as a function of time (Figure 3.3), the pyrolysisfront speed V_p (defined as dx_p / dt) and the flame-front speed V_f (defined as dx_f / dt) are obtained from the slope of the least square fit lines. Data for only the first 0.5m were used to minimize errors from an increase of the free stream velocity (U_{∞}) downstream of the tunnel. In the first 0.5 m of the sample, both x_p and x_f increase nearly linearly with time whereas in the last 0.15 m they exhibit slight acceleration. Figure 3.4 shows V_p and V_f plotted against the free stream velocity; it is seen that V_p and V_f increase linearly with U_{∞} .









Figure 3.5 shows V_p and V_f plotted against the oxygen mass fraction (Y_{osc}). Note that several different measurements of V_p and V_f for PMMA (from reflective to blackened water-cooled bottom aluminum plate) are presented. It is once again noteworthy that V_p and V_f are nearly equal (see Figures 3.4 and 3.5).

Figure 3.5 also shows that V_p depends upon the surface finish of the aluminum plate directly under the burning sample. The aluminum plate was used only for PMMA since external radiation was not required. For the experiments on wood samples described in the next chapter, this plate was replaced with an infrared optical glass window to allow external radiation. As is evident from Figure 3.5, the surface condition of this plate (and to a lesser degree, the two vertical sides of the tunnel that contain the observation windows) considerably alters the flame spread rate because it reflects the flame radiation back to the sample surface. This effect magnifies as Y_{ore} increases because the flame radiation increases. Measurements show that the flame radiation at the plate surface increases linearly from nearly zero at $Y_{ooo} = 0.2$ to 3.5 W/cm² at $Y_{or} = 1$ (Figure 3.6). Thus, for a reflectivity as small as 0.1, the reflected radiation becomes comparable with the external radiation used for the wood samples discussed in chapter 4. The spread rate measured with a reflective aluminum foil for $Y_{\infty} = 0.6$ is 2.7 times the spread rate for blackened and water-cooled aluminum plate and 1.6 times the spread rate for a dull aluminum plate. Thus, the flame spread rate depends upon the reflections inside the tunnel, and the result closest to the truth is that of the blackened and water-cooled plate. For PMMA, these measurements show that $V_p \sim Y_{000}^{1.4}$. This differs from the previous measurements for PMMA [Loh and Fernandez-Pello 1984] (dotted line in Figure 3.5), which show that $V_p \sim Y_{\infty}^2$. However, the present results involving a dull aluminum plate agree well with those of Loh and Fernandez-Pello 1984; indicating that reflection of radiation inside the tunnel may be the reason for disagreement (this corresponds to the systematic errors of the 2nd kind described in chapter 2). Results for a water-cooled plate agree well with the recent theoretical predictions for PMMA [Wichman and Agrawal 1991, Carrier et al. 1990], which are shown plotted by the dashed line in Figure 3.5.







The effect of the oxygen mass fraction on the flame spread rate can be further examined by looking at the chemistry and the flame temperature. The following one step chemical reaction can be used to describe the combustion process during flame spread:

$$C_{x}H_{y}O + (x + \frac{y}{4} - \frac{1}{2})O_{2} \longrightarrow x CO_{2} + \frac{y}{2}H_{2}O$$

(\dot{m}) ($\dot{m}_{\Delta O_{2}}$) ($\dot{m}_{CO_{2}}$) ($\dot{m}_{H_{2}O}$)

+ [CO , THC , SOOT] (m_{ub}) (Incomplete Combustion)

+ $\chi_A f \Delta H (1-\chi_R)$, (3.1)

(Heat Liberated)

where χ_A is the correction factor due to incompleteness of combustion ($\chi_A=1$ for complete combustion), and χ_R is the correction factor due to flame radiation losses ($\chi_R=0$ for no flame radiation). If f is the stoichiometric fuel to oxygen ratio by mass, then fY_{∞} gm of fuel requires Y_{∞} gm of O_2 and liberates $[fY_{\infty}\chi_A\Delta H(1-\chi_R)]$ J of heat. This energy is utilized to

- (i) raise the temperature of a unit mass of (O_2, N_2) mixture from T_{∞} to T_f : $[C_p(T_f - T_{\infty})];$
- (ii) raise the temperature of fY_{ooo} gms of fuel vapor from T_p to T_f : $[C_p(T_f T_p)fY_{ooo}]$;
- (iii) provide for the heat required by the solid to produce fuel at the surface $[QfY_{or}]$.

Thus, an energy balance would then lead to

$$fY_{oss}\chi_A(1-\chi_R)\Delta H = C_p(T_f-T_{so}) + C_p(T_f-T_p)fY_{oss} + QfY_{oss}$$
(3.2)

After rearranging the terms the flame temperature can be expressed as

$$(T_{f} - T_{p}) = \frac{fY_{\infty}[\chi_{A} \Delta H(1 - \chi_{R}) - Q] - C_{p}(T_{p} - T_{\infty})}{C_{p}(1 + fY_{\infty})}$$
(3.3)

where $Q = L + C_{p_a}(T_p - T_{\infty})$, where L is the latent heat of the solid.

For complete combustion and no flame radiation $[\chi_A(1-\chi_R)=1]$

$$T_f - T_p \sim Y_{\infty}$$

which leads to

$$V_p \sim Y_{o}^2$$

since $V_p \sim (T_f - T_p)^2$.

However, as will be explained in section 3.1.3.2, the data show that χ_A decreases and χ_R increases with Y_{occ} . This makes the flame temperature less dependent on the oxygen mass fraction, and so also the pyrolysis-front spread rate. The results show that $V_p \sim Y_{occ}^{1.4}$. Figure 3.7 shows 2 pictures taken of the flame during the flame spread experiments (a) $U_{\infty}=0.9$ m/s, $Y_{occ}=0.233$, and (b) $U_{\infty}=0.9$ m/s, $Y_{occ}=0.61$. Notice the difference in the flame brightness which indicates the change in flame radiation intensity.

3.1.3. Species Production Rates

The species mass production and depletion rate histories are presented in Appendix B for all the experiments performed. Figures 3.8 and 3.9, respectively, show the species production rates for different free stream velocities and different oxygen mass fractions plotted against the pyrolysis length, x_p . Production rates of CO and total unburned hydrocarbons are not presented because they are two orders of magnitude smaller than the others; however, they are extremely important in fire research since they were the primary reasons for many lost lives in building and other fires.



(a)



(b)

Figure 3.7 Picture of flame spreading on PMMA (a) U_=0.9m/s, Y_{_{00}}=0.233 (b) U_=0.9m/s, Y_{_{00}}=0.61.



Figure 3.8 Dependence of the species mass production rates on the pyrolysis-front location for different wind speed (Y_{ou}=0.23; 1-U_u=0.6m/s; 2-U_u=0.9m/s; 3-U_u=1.5m/s).



Figure 3.9 Dependence of the species mass production rates on the pyrolysis-front location for different oxygen mass fraction (U_{se}=0.9m/s; 1-Y_{ose}=0.233; 2-Y_{ose}=0.43; 3-Y_{ose}=1.0).
The data for small x_p is omitted since the measurements are affected by the igniter flame and, hence, they are subjected to a large percentage error. Also, the soot production rate was not measured even though a substantial amount of soot was formed, especially during experiments at high Y_{∞} .

3.1.3.1. Burning zone behavior during flame spread

Species data were collected even after the flame had spread over the entire sample, i.e., in the boundary-layer burning zone. These data are presented only for Y_{oss} =0.43 for purposes of clarity (the rest of the data are in Appendix B). Vertical straight lines are obtained (see Figure 3.9) because x_p does not change during this period since the pyrolysis front has already reached the end of the sample. The mass production rate more than doubles during this period before achieving a steady-state value for the case Y_{oss} =0.43. The fact that the species production rate continues to change substantially even after the pyrolysis front has reached the end of the sample shows that the steady-state condition is not achieved in the boundary layer burning zone. Vovelle et al (1987) showed that the mass loss rate kept increasing even after the surface temperature reaches steady state at about 300 sec, however the mass flux reaches steady state at about 700 sec. Thus, the fact that the surface temperature in the burning zone has become steady does not imply that the mass loss rate has become steady.

The measured species mass rate can be expressed as

$$\dot{m}(t) = W \int_{0}^{x_{p}(t)} \dot{m}''(x,t) dx$$
, (3.4)

where W is the width of the sample.

Taking the time derivative of the above equation gives

$$\frac{\mathrm{d}\dot{\mathbf{m}}(t)}{\mathrm{d}t} = \mathbf{W} \int_{0}^{\mathbf{x}_{p}(t)} \frac{\partial}{\partial t} [\dot{\mathbf{m}}''(\mathbf{x},t)] \mathrm{d}\mathbf{x} + \mathbf{W} \dot{\mathbf{m}}''(\mathbf{x}_{p},t) \frac{\mathrm{d}\mathbf{x}_{p}}{\mathrm{d}t} , \qquad (3.5)$$

where $\frac{dx_p}{dt} = V_p = \text{constant.}$

If a steady-state condition exists in the burning zone, $(\dot{m}''(x,t)=\dot{m}''(x))$, then

$$\dot{m}''(x_p) = \frac{[d\dot{m}/dx_p]}{W}$$
 (3.6)

For complete combustion, the production rates of CO₂ and H₂O and the depletion rates of O₂ are directly related to the total fuel production rate between x = 0 and $x = x_p$. For the local mass flux to vary as $x^{-0.5}$, the total fuel production rate at any instant must vary as $x_p^{1/2}$. Incompleteness of combustion will only serve to further reduce this power. However, the data in Figure 3.9 shows that this power is greater than 0.5 and closer to 1; for PMMA at $Y_{osc} = 1.0$ it is even greater than one. In addition, if x_p =constant (end of the sample) then $dx_p/dt=0$. Then, any changes in the mass loss rate m(t) are due only to transient effects, with

$$\frac{d\dot{m}}{dt} = W \int_{0}^{x_{p}(t)} \frac{\partial}{\partial t} [\dot{m}''(x,t)] dx \quad . \tag{3.7}$$

Consider now the experimental results of Figure 3.9. These results show that the mass production rate keeps increasing even after the pyrolysis-front has reached the end of the sample (or x_p has become constant). This proves that the burning zone is in a transient state during flame spread. This argument was further confirmed by conducting flame spread experiments on 10 inch long PMMA samples. Video records of these experiments showed that the flame length kept increasing even after the pyrolysis-front had reached the end of the sample.

3.1.3.2. Incompleteness of combustion

Referring to Figure 3.9, we note that the production rate of H_2O (\dot{m}_{H_2O}) seems to follow that of CO_2 (\dot{m}_{CO_2}) for all the experiments. The mass production rate of CO_2 is always larger than that of H_2O . However, this is not true for the comparison between the mass production rate of CO_2 and the mass depletion rate of O_2 ($\dot{m}_{\Delta O_2}$). For $Y_{\infty} = 0.23$, $\dot{m}_{CO_2} > \dot{m}_{\Delta O_2}$, whereas for $Y_{\infty} = 1.0$, $\dot{m}_{CO_2} < \dot{m}_{\Delta O_2}$. The crossover between \dot{m}_{CO_2} and $\dot{m}_{\Delta O_2}$ can be seen at $x_p = 0.5$ m for $Y_{\infty} = 0.43$. This indicates that the combustion chemistry is changing as x_p and Y_{∞} are increased. Carbon in the fuel is converted to unburned soot leading to lower \dot{m}_{CO_2} . Reaction equation 3.1 implies that:

$$\left(\frac{\dot{m}}{\dot{m}_{CO_2}}\right)_{comp. comb.} < \left(\frac{\dot{m}}{\dot{m}_{CO_2}}\right)_{incomp. comb}$$

This agrees with the physical observation that both larger flames and flames at higher $Y_{o\infty}$ are brighter. Figures 3.10 and 3.11 show $\dot{m}_{CO_2}/\dot{m}_{\Delta O_2}$ and $\dot{m}_{CO_2}/\dot{m}_{H_2O}$, respectively, normalized with the corresponding mass based stoichiometric fraction (i.e. a value of 1 corresponds to complete combustion), where PMMA is $C_{2.5}H_4O$. The data show that $\dot{m}_{CO_2}/\dot{m}_{\Delta O_2}$ is slightly decreasing with x_p and that it drops significantly with $Y_{o\infty}$. However, $\dot{m}_{CO_2}/\dot{m}_{H_2O}$ seems to be constant for all $Y_{o\infty}$. The data in Figure 3.8 shows that the major chemical species mass rates increase with the wind speed, as expected, since the heat transfer to the solid increases with U_{∞} as will be explained in detail in Chapter 5.



combustion).



Figure 3.11 Normalized $\dot{m}_{CO_2}/\dot{m}_{H_2O}$ with the corresponding mass based stoichiometric fraction (i.e. the value of 1 corresponds to complete combustion).

3.2. Discussion

It is interesting to note that there are several areas of agreement and disagreement between these experimental results and the recent theoretical models developed for non-charring materials [Wichman and Agrawal 1991, Carrier et al. 1990].

As predicted by previous theories[Wichman and Agrawal 1991, Carrier et al. 1990], both V_p and V_f are found to be linear with U_{∞} (Figure 3.4). However, these theories also predict that usually V_f is significantly larger than V_p , which is in contrast with the experimental results (Figures 3.4 and 3.5), which show that $V_f \approx V_p$. Likewise, x_f is found to be only slightly larger than x_p (between 5 and 10%), regardless of the free stream velocity or the oxygen mass fraction. This discrepancy arises because the theoretical models utilize the steady-state Emmons' (1956) solution in the boundary layer burning zone. As discussed earlier (Figure 3.9), the burning zone is unsteady in the solid phase during the flame spread process. This leads to lower instantaneous fuel mass production rates that result in smaller-than-predicted value of x_f and V_f . The existence of this unsteady burning zone is further confirmed by the fact that the species production rates vary roughly as x_p rather than as $x_p^{0.5}$.

As is evident from Figure 3.5, the theoretically predicted [Wichman and Agrawal 1991, Carrier et al. 1990] dependence of V_p on $Y_{o\infty}$ agrees well with that determined experimentally. Increase in $Y_{o\infty}$ increases V_p primarily by increasing the heat flux from the flame to the as-yet-unburned solid surface. This heat flux increases because the flame temperature increases proportionally with $Y_{o\infty}$ in the absence of flame radiation and incompleteness of combustion. This heat flux also decreases because of increased shielding of the fuel surface from the flame by the evolved fuel mass flux. As discussed earlier, the theoretical models overestimate the evolved fuel mass flux in the burning zone by assuming steady state Emmons' solution. This results in an overestimation of the heat blockage factor. Fortunately, it is compensated by overestimating the flame temperature by neglecting flame radiation and incompleteness of combustion.

CHAPTER FOUR

Flame Spread over Charring Solids

Previous experimental work on charring materials has been done on particle boards in the upward (buoyancy-driven) flame spread mode [Saito et al. 1986, Kulkarni and Fisher 1988, Quintiere et al. 1986]. However, studies in the forced convective mode have been primarily limited to non-charring solids, such as PMMA [Fernandez-Pello et al. 1981]. As discussed in Chapter 3, even for PMMA, uncertainity exists regarding the prediction of flame spread rates under different environmental conditions. The problem is further complicated for charring solids due to the formation of an insulating char layer. In addition, since wood requires preheating [Mekki et al. 1990, Saito et al. 1986]. This problem is further complicated because it introduces two new parameters namely the external radiation and the preheat time. Atreya (1983) studied the effect of the preheat time for certain incident heat fluxes on the horizontal flame spread rate on wood. The results of his experimental work indicated that the flame spread rate on wood increases with increasing either or both the external radiation and the preheat time. His work also showed the dependency of the flame spread rate on both the internal solid properties and the external environmental conditions. This Chapter presents an experimental study of wind-aided flame spread over wood slabs in the ceiling configuration. This study covers the three external conditions that control the flame spread rate: wind speed ($U_{\infty}=0.2$ to 1.5 m/s), oxygen concentration ($Y_{\infty}=0.233$ to 1.0), and external radiation ($\dot{q}''=0.5$ to 1.3 W/cm²). The objectives of this work are to (i) provide a physical understanding that will serve as the basis for the development or refinement of theoretical models; and (ii) provide measurements for charring materials like wood.

4.1. Results

4.1.1. Temperature measurements

Figure 2.11 shows the schematic of the wind-aided flame spread in the tunnel over a ceiling mounted sample of wood. The flame spread rate depends on how high is the surface temperature at the end of the preheat (i.e. prior to ignition). For a certain prescribed external radiation, both the surface temperature and the char layer thickness increase in time. A high external radiation with a long preheat time will bring the sample surface temperature close to its ignition temperature. This makes the flame spread rate approach, at a critical point ($\dot{q}''(U_{\infty}, Y_{0\infty}, t_{\text{preheat}})$), that of the premixed-gas flame propagation (flash through). In addition, the preheat time has to be chosen such that the surface would undergo only a minor change due to external radiation. Therefore, after a number of experimental trials, a 600 sec preheat time was chosen for low external radiation (0.5 and 0.9 W/cm²) and 300 secs for high external radiation (1.3 W/cm²). Under these conditions, as shown in Figures 4.1 and 4.2, the surface temperature nearly equilibrates with the surface heat loss; and its rate of change with time becomes almost zero -i.e. prior to ignition. Thus, any changes in the surface temperature due to external radiation, during the flame spread process, can be ignored as shown in Figures 4.1 and 4.2. These temperature histories also show that the external radiation is uniform along the wood sample surface as discussed in section 2.1.4.



Figure 4.1 Measured surface temperatures and their rate of change with time for wood during flame spread (U_=0.6m/s, $Y_{o=}=0.233$, $\dot{q}^{*}=0.5$ W/cm²).



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The effect of wind speed on the flame spread rate was investigated for all these sets of external radiation and preheat time. In studing the effect of the oxygen mass fraction on the flame spread rate, however, a low level of external radiation (0.5 W/cm²) and a large preheat time (600 secs) were used. This low external radiation was selected so that a clear flame spread process is observed at high $Y_{o\infty}$, and to facilitate comparison with PMMA (which burns without external radiation).

4.1.2. Pyrolysis and flame fronts

As previously mentioned in Chapter 3, visual observations led to the conclusion that the peak rate of change in the surface temperature after ignition occurs at the instant the flame tip arrives at the thermocouple location (Figure 4.1). Thus, the flame tip location, x_{f} , and the pyrolysis-front location, x_p , may be determined as a function of time from the measured temperature profiles as explained in section 3.1.1. The methodology is illustrated on Figure 4.1. Results of such calculations agree exactly with x_f determined from video records. The pyrolysis temperature is taken as the piloted ignition temperature (375 °C), at which the solid begins to vigorously pyrolize and contribute fuel to the flame. Results of such calculations agree exactly with x_f determined form video records.

The three steps of preheating can now be distinguished during the flame spread process. First the preheat by external radiation, then, after ignition, by the post-combustion gases, and then by the diffusion flame extending downwind of the burning zone. This extended flame is caused by the excess pyrolyzate. It is worth noting that the surface temperature at the flame tip arrival ranges from 300 to 340 °C, which is higher by almost 120°C than at the conclusion of the preheating by the external radia-tion. This indicates that there is major preheating by the hot gases ahead of the flame.

Figures 4.3 to 4.6 show both the pyrolysis-front and the flame-front histories, after ignition, for different conditions. Both x_p and x_f have an almost exactly linear dependency on time and are very close to each other in all cases.



Figure 4.3 Pyrolysis and flame front histories $(Y_{oss}=0.233, \dot{q}^{*}=0.5W/cm^{2})$.



Figure 4.4 Pyrolysis and flame front histories ($Y_{oss}=0.233$, $\dot{q}^{"}=0.9$ W/cm²).



Figure 4.5 Pyrolysis and flame front histories (Yom=0.233, q''=1.3W/cm²).



Figure 4.6 Pyrolysis and flame front histories (U_=0.9m/s, q'=0.5W/cm²).

The excess pyrolyzate (fuel that is not burned in the burning zone $0 < x < x_p$) causes the flame front to be always ahead of the pyrolysis front. As the ambient oxygen mass fraction increases, oxygen rich case, most of the fuel is consumed in the burning zone causing the excess pyrolyzate to drop. Therefore the distance $(x_f - x_p)$ should decrease with increasing the ambient oxygen mass fraction Y_{∞} . The data shown in Figure 4.6 (as well as in Figure 3.4 for the case of PMMA) certainly agree with this hypothesis.

4.1.3. Spread rate

Once x_f and x_p are determined as a function of time, the pyrolysis-front speed V_p (defined as dx_p/dt) and the flame-front speed V_f (defined as dx_f/dt) are obtained from the slope of the least square fit line. Data for only the first 0.5 m was considered to minimize errors due to changes in the free stream velocity. Figure 4.7 shows V_p and V_f plotted against the ambient oxygen mass fraction Y_{∞} where both the free stream velocity and the external radiation were kept constant at 0.9 m/s and 0.5 W/cm², respectively. For these environment condition, both V_p and V_f show a nearly linear dependency on Y_{∞} .

As discussed in Chapter 3 for the flame spread study on vaporizing solids, both the decrease in combustion efficiency χ_A and the increase in the flame radiation cause the flame temperature to be much less than that of the adiabatic case as the ambient oxygen mass fraction increases. This is also true for charring solids. Brighter flames (higher radiation) and soot deposition on the walls were observed as Y_{ooo} was increased. In fact, these two parameters are related since the brightness of the flame is due to the hot soot particles. The data shows that $V_p \sim Y_{ooo}^{1.1}$.



Figure 4.8 shows that both V_p and V_f sharply increase with the external radiation for all the free stream velocities. Therefore, if the wind speed and the preheat time are kept constant, increasing further the external radiation would result in a "flash-through" at some critical point ($\dot{q}_{cr}^{"}(U_{\infty}, Y_{0^{\infty}}, t_{preheat})$). This very rapid flame spread would occur when the surface temperature, at the end of the preheating -i.e. prior to ignition, is at or above the ignition temperature of the solid (375°C). Figure 4.9 shows the linear dependency of both V_p and V_f on U_{∞} for all $\dot{q}^{"}$. Figures 4.7, 4.8, and 4.9 show how close the flame spread rate V_f is to the pyrolysis-front spread rate V_p for all experiments.

It is interesting to see the effect of the wind speed on the flame spread rate as shown in Figure 4.9 where the flame spread rate for $U_{\infty}=0.2$ m/s and $\dot{q}''=1.3$ W/cm² is almost equal to that of $U_{\infty}=1.5$ m/s and $\dot{q}''=0.5$ W/cm². However, the effect of Y_{∞} can be seen when noting that V_p for $Y_{\infty}=1.0$ with $\dot{q}''=0.5$ W/cm² (Figure 4.7) is very close to that of $Y_{\infty}=0.233$ and $\dot{q}''=0.9$ W/cm² (Figure 4.8). This shows that the flame radiation for high Y_{∞} may be thought of as external radiation. Stable flame spread below 1.3 W/cm² for 0.2 m/s was not possible.

4.1.4. Species production rates

The species production and depletion mass rate histories are presented in Appendix C. A typical species production rate history during the three processes namely: preheat, flame spread, and extinction, is shown in Figure 4.10 ($U_{\infty}=0.6 \text{ m/s}$, $Y_{\infty}=$ 0.233, $\dot{q}''=1.3 \text{ W/cm}^2$). Since in all the experiments performed, the total unburned hydrocarbons (THC) and CO were negligible, only the major chemical species (production of CO₂ and H₂O, and depletion of O₂) mass rates are plotted versus the pyrolysis-front x_p and are presented in Figures 4.11 to 4.14 for all the conditions studied. The data for $x_p < 12 \text{ cm}$ is not included because it is expected to have large errors due to the ignition process. These figures are plotted in log-log scale to show the relationship between the mass production rate and the pyrolysis-front.



Figure 4.8 Dependence of the pyrolysis and flame front speeds on the external radiation $(Y_{om}=0.233)$.



Figure 4.9 Dependence of the pyrolysis and flame front speeds on the free stream velocity $(Y_{on}=0.233)$.







Figure 4.11 Dependence of the species mass production rates on the pyrolysis-front location for different wind speeds $(Y_{om}=0.233, \dot{q}^{"}=0.5W/cm^{2})$.



Figure 4.12 Dependence of the species mass production rates on the pyrolysis-front location for different speeds $(Y_{ore}=0.233, \dot{q}^{*}=0.9W/cm^{2})$.



Figure 4.13 Dependence of the species mass production rates on the pyrolysis-front location for different wind speeds ($Y_{om}=0.233$, $\dot{q}^{*}=1.3$ W/cm²).



Figure 4.14 Dependence of the species mass production rates on the pyrolysis-front for different oxygen mass fraction ($U_{ss}=0.9$ m/s, $\dot{q}^{"}=0.5$ W/cm²).

The chemical species mass rate are related to the total quantities over the entire burning zone by

$$\dot{m}(t) = \int_{x=0}^{x_p(t)} \dot{m}'(x,t) dx$$

with the local mass flux being higher near the pyrolysis front due to low char depth.

As the fire spreads, the mass rate increases roughly proportional to the pyrolysisfront. When the pyrolysis-front reaches the end of the sample, the mass rate slightly increases before reaching a plateau, then sharply drops (see Appendix C). The duration of this plateau depends on the environment condition, it increases with increasing the external radiation or the oxygen mass fraction. Therefore a thick char layer is expected in these cases. The drop in the mass rate, however, is due to (i) the local mass flux drop as shown in Figure 1.3, and (ii) the propagation of the extinction-front (flame foot) behind the pyrolysis-front as observed during the experiments. However, the flame does often flash back, as observed in the experiments, when some fuel has occumulated enough to support a premixed flame upstream of the extinction-front.

The flame stand-off distance from the combustible surface in the ceiling configuration mainly depends on the buoyancy, the wind speed, and the ambient oxygen mass fraction. The buoyancy causes the flame (high temperature zone) to rise. The wind speed controls the oxygen mass transfer rate to the flame. And the ambient oxygen mass fraction controls the stoichiometric plane (or the flame) stand-off distance from the surface and the flame temperature. The lower $Y_{o\infty}$ is, the higher the flame stand-off distance and flame lenght are. Therefore, a combination of high wind speed and high oxygen mass fraction would result into a short flame stand-off distance from the surface, which in turn increases the net heat flux at the surface causing higher mass flux.

The data shows that the mass production rates of the major chemical species increase with U_{∞} , $Y_{0\infty}$, and \dot{q}'' . This is expected since the flame approaches the surface with increase in U_{∞} , the flame temperature increases with $Y_{0\infty}$, and the pyrolysis-

front propagates deeper into the solid with increase in \dot{q} ".

For complete combustion, the production rates of CO_2 and H_2O and the depletion rate of O_2 should be related to the total fuel production rate between x=0 and x=x_p (the burning zone). For high Y₀₀₀, due to soot formation and deposition of heavy hydrocarbons on the tunnel walls, the depletion rate of O_2 is not expected to follow the production rates of CO_2 .

As discussed in the previous chapter for PMMA, for the local mass flux to vary as $x^{-0.5}$, the total fuel production rate at any instant must vary as $x^{0.5}$. However, the data shows that this power is about 0.4 at $Y_{osc}=0.233$, and increases with Y_{osc} up to 1 at $Y_{osc}=1$. The steady-state solid-phase can not be addressed in the charring solids like wood due to the char build-up which continuously attenuates the production of the pyrolysis products as shown in Figure 1.3.

Using the one step chemical reaction described in chapter three, the ratio of the production rate of CO_2 to the depletion rate of O_2 is (equation 3.1)

$$\frac{\dot{m}_{CO_2}}{\dot{m}_{\Delta O_2}} = \frac{44 \text{ x}}{8 (4 \text{ x} + \text{y} - 2)}$$

Where the chemical composition of the volatiles for poplar wood is shown in Table 4.1 taken from Atreya (1984). The above ratio should approach the value 1.25 for the complete combustion case ($Y_{osc}=0.233$). Figure 4.15 shows $\dot{m}_{CO_2}/\dot{m}_{\Delta O_2}$, normalized with its mass based stoichiometric fraction, plotted versus x_p . Most of the room air oxygen concentration experiments are close to 1 (complete combustion). However, as Y_{osc} increases, the normalized ratio $\dot{m}_{CO_2}/\dot{m}_{\Delta O_2}$ drops to an almost 0.4 at 100% oxygen environment. This indicates that the chemistry has changed as Y_{osc} is increased. Carbon in the fuel is converted to unburned soot leading to lower \dot{m}_{CO_2} as discussed in section 3.1.3.2. This agrees with the physical observation that both larger and flames at higher Y_{osc} are brighter. Figure 4.16 shows a picture of the flame taken during the flame spread experiment ($U_{cs}=0.9 \text{ m/s}$, $Y_{osc}=0.233$, $\dot{q}''=0.5 \text{ W/cm}^2$).



Figure 4.15 Normalized m_{CO}/m_{AO2} with the corresponding mass based stoichiometric fraction (i.e., the value of 1 corresponds to complete combustion).



Figure 4.16 Picture of a spreading flame on wood sample (U_=0.9 m/s, Y_{ou}=0.233, $\dot{q}^{*}=0.5W/cm^{2}$).

	Char Yield	Empirical Formula	Lower Heat of Combustion (KJ/gm)
Poplar	0.33 (avg)	C H O 1.66 2.43	19.33
Char	-	C H O 5.44 3.12	26.86
Volatile	-	С Н О 0.99 2.31	15.62

Table 4.1Empirical formula of Poplar wood [Atreya 1984].

Figure 4.17 shows, in chronological order, pictures of the flame as it spreads ($U_{\infty}=0.9$ m/s, $Y_{0\infty}=0.61$, $\dot{q}''=0.5$ W/cm²). The flame color in these pictures certainly indicates the increase in the flame radiation with $Y_{0\infty}$. Figure 4.18 shows $\dot{m}_{CO_2}/\dot{m}_{H_2O}$, normalized with its mass based stoichiometric fration 2 (according to Table 4.1), for all the cases studied. The data shows that all the experiments fall close the value of 1.



(1)



(2)



(3)





Figure 4.17 Instantaneous pictures taken of a spreading flame on a wood sample $(U_{=}0.9m/s, Y_{=}=0.61, \dot{q}^{*}=0.5W/cm^{2}).$



stoichiometric fraction (i.e. the value of 1 correspond to complete Normalized mco_/mn_10 with the corresponding mass based combustion). Figure 4.18

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CHAPTER FIVE

Convective and Radiative Heat Transfer to the Solid

During wind-aided flame spread over combustible solids, radiative and convective energy transfer occur from the flame and the hot gases to the as-yet-unburned solid surface. The rise of the solid surface temperature from ambient temperature far downstream of the flame to the ignition temperature at the pyrolysis front is due to (i) the preheating downstream of the flame tip $x>x_f$ and (ii) the preheating underneath the flame $x_p < x < x_f$ (the overfire region). Therefore, the heating of the surface to its pyrolysis temperature in the overfire region depends on the surface temperature at the flame tip arrival ($x=x_f$). The higher is this temperature, lesser is the heating job needed from the flame in the overfire region, and hence the shorter the distance ($x_f - x_p$). During the flame spread experiments, the surface temperature at x_f ranged from 573 K to 613 K for wood and 533 K to 573 K for PMMA. It was noted from the experiments that this temperature increases and the distance ($x_f - x_p$) decreases with Y_{os} , which supports the above hypothesis. This latter point has also been reported by Ahmad and Faeth (1978) in their upward flame spread model. Clearly preheating downstream of the flame tip cannot be neglected, it has to be well understood for proper and realistic theoretical models, since in an analytical solution, the heat flux in the preheat zone is required to develop the flame spread model [Fernandez-Pello 1978]. Heat transfer underneath the flame is also equally important.

5.1. Formulation

A very interesting experimental observation leads to the development of a simple model. It was observed in all the flame spread experiments in the ceiling configuration, (that is for all free stream velocities and ambient oxygen mass fraction used), that the flame lies just underneath the sample at an almost constant stand-off distance all along the flame, from the attachment point to the flame tip. Gas-phase temperature measurements (discussed in section 5.2.2) show that the flame stand-off distance changes by almost 2 mm from near the leading edge to near the flame tip when $x_f=254$ mm. Hence, the problem can be justifiably treated as that of a constant free-stream velocity flow along a semi-infinite plate with an arbitrarily specified surface temperature (Figure 5.1).



Figure 5.1 Schematic diagram of the model.

The surface temperature can then be considered as

$$T_{s} = T_{\infty} \qquad x < 0$$

$$T_{s} = T_{f} \qquad 0 < x \le x_{f}$$

$$T_{s} = F(x) \qquad x_{f} < x$$

Thus, the heat flux from the wall surface in the preheat zone is [Kays and Crawford 1980]

$$\dot{q}'' = \int_{0}^{x} h(z,x) \frac{dT_s}{dz} + \sum_{i=1}^{i=k} h(z_i,x) \Delta T_{s,i}$$
 (5.1)

where h(z,x) is the local unit conductance from the single-step function solution, defined as:

$$h(z,x) = \frac{0.332 k_g Pr^{1/3} Re_x^{1/2}}{x} \left[1 - \left(\frac{z}{x}\right)^{3/4} \right]^{-1/3}$$
(5.2)

There exists two discontinuous surface temperature: one at the leading edge and another one at the flame tip location x_f . This will result in two terms in the above summation. In the integral term, however, the surface temperature gradient with downstream distance is zero for $x < x_f$. For $x > x_f$, the integral can only be solved if the surface temperature is known. Since the resultant integral term in the preheat zone is only a correction to the computed heat flux at the surface, and especially that dT/dz is only significant near the flame tip, the temperature is assumed uniform $(F(x)=T_{\infty})$ in the rest of the analysis.

Hence, the heat flux to the surface in the preheat zone $(x > x_f)$ takes the form

$$\dot{q}'' = \frac{0.332 k_g Pr^{1/3} Re_x^{1/2}}{x} (T_f - T_{\infty}) \left[-1 + \left[1 - \left[\frac{z}{x} \right]^{3/4} \right]^{-1/3} \right]$$
(5.3)

or

$$\frac{\mathrm{Nu}_{\mathrm{x}}}{\mathrm{Pr}^{1/3} \mathrm{Re}_{\mathrm{x}}^{1/2}} = 0.332 \left[-1 + \left[1 - (\mathrm{x}^{*})^{-3/4} \right]^{-1/3} \right]$$
(5.4)

where $Nu_x = \dot{q}'' x/(T_f - T_{\infty}) k_g$ and $x^* = x/x_f$ is the related distance from the flame tip.

5.2. Results and discussion

5.2.1. Transient heat flux measurements

Figure 2.12 shows a schematic of a spreading flame on PMMA sample upstream of the ceramic detectors used in this study. The procedure to compute the heat transfer modes from the transient measurements of the solid and gas phase temperature is as follows. Inverse heat conduction calculations were used to obtain the incident heat flux as a function of time [Beck et al. 1985]. The heat flux algorithm used in the inverse heat conduction analysis is sequential, where few future temperatures, associated with future times, are used to compute the heat flux at every instant. The main aspect of this algorithm is the use of the least squares criterion to estimate the heat flux at the surface q^m from the measured temperatures $Y_1, ...Y_j$, at times t^m, t^{m+1} , ..., t^{m+r-1} . The parameter r is the number of future time step and J is the number of thermocouples. The criterion is to minimize S with respect to q^m

$$S = \sum_{i=1}^{K} \sum_{j=1}^{J} \left(Y_{j}^{m+i-1} - T_{j}^{m+i-1} \right)^{2}$$
(5.5)

where Y_j^{m+i-1} is the measured temperature at the jth sensor and at time t^{m+i-1}, and T_j^{m+i-1} is the corresponding calculated temperature. The convective heat transfer rate from the surface was computed from the temperature gradient at the solid-gas interface as

$$\dot{q}_{cv}'' = -k_g \frac{dT}{dy}$$
(5.6)

where k_g is the gas thermal conductivity evaluated at the surface temperature. In the transient flame spread experiments on PMMA, four thermocouples were maintained in the gas-phase at some known distances from the surface. This small number of points makes it difficult to rely with confidence on the curve fit results from which the

gradient is computed. Thus, the temperature gradient for these experiments is approximated as $dT/dy = (T_g-T_s)/\Delta y$, where T_g is the gas temperature at distance Δy from the surface. This is a good approximation since the thermocouple used is very close to the surface ($\Delta y << \delta_t$, where δ_t is the thermal boundary layer). First, the thermocouples were constructed in such a way that measurements error due to heat conduction in the thermocouple wires are reduced. Then, one thermocouple was placed about 1 mm from the surface. An error of 0.1 mm on this distance causes a 10% error in evaluating the heat convection. Therefore, the distance y has to be accurately found for every experiment. At far distances from the flame, $x/x_f >>1$, the radiation from the flame to the surface located at distance x is negligible, then an energy balance at the surface leads to \dot{q}_T " = \dot{q}_{cv} ". Hence the distance Δy can be well estimated using least square fit of the total and convection heat fluxes using all the data points N for $x/x_f >2$

$$\Delta y = \frac{k_{g} \sum_{i=1}^{N} \Delta T_{i}^{2}}{\sum_{j=1}^{N} \Delta T_{j} \dot{q}_{Tj}^{"}}$$
(5.7)

This distance is then used to determine the convected heat flux during the whole experiment.

The radiative heat flux from the surface was computed from the knowledge of the surface and surrounding temperatures and the surface emissivity. Finally, the flame radiation was computed by applying an energy balance at the solid-gas interface.

In order to compare and correlate the results of different conditions, the data has to be plotted vs. $x^*=x/x_f$, which is the related distance from the flame tip. However, to get the heat flux a function of x^* for every experiment, the time dependent temperatures and flame tip have to be curve fitted by a very low filter and outputed with the same time increment. Figure 5.2 shows such curve fitting for the gas-phas temperature. The different modes of heat transfer were then computed and are shown in Figures 5.3 (U_∞=0.9m/s, Y_{o∞}=0.233) and 5.4 (U_∞=0.9m/s, Y_{o∞}=1.0) and Appendix D.







Figure 5.4 Heat flux measurements during flame spread on PMMA $(U_{ee}=0.9 \text{ m/s}, Y_{oue}=1.0).$

In all the 21% oxygen experiments, the flame color was blue (see Figures 3.7 and 4.16), which indicates low flame radiation to the surface ahead of the flame. This is confirmed by the results in Figure 5.3. The total heat conducted in the solid equals the heat convected by the hot gases. Both radiation from the flame to the surface ahead of the flame tip and the surface radiation to the surrounding are negligible. However, as the oxygen mass fraction increases, the flame becomes brighter (see Figures 3.7 and 4.17), which indicates a significant radiation to the surrounding. This observation is confirmed by the results shown in Figure 5.4 for the case of 100% oxygen. As the flame tip approaches, the radiation from the flame to the surface becomes more significant. It was also observed that the deposition of soot on the walls increases with increasing oxygen mass fraction. This introduces an error of the gas-phase temperature measurements very close to the flame tip for high oxygen mass fraction, which in turn under-estimates the computed heat convection. Again, this is only true for high oxygen mass fraction and very close to the flame tip.

Since the energy lost by the flame to evaporate the fuel from the pyrolyzing surface $[C_p(T_f - T_p)fY_{or}]$ is not considered in the model (the flame is on the surface), then the following adiabatic flame temperature is used in correlating the results

$$(T_{f} - T_{\infty}) = \frac{f Y_{o\infty}}{C_{p}} (\Delta H - Q)$$
(5.8)

where C_p, the gas specific heat, is computed at the average temperature by the integral

$$\int_{T_{n}}^{T_{t}} C_{p}(T) dT = f Y_{osc} (\Delta H - Q)$$
(5.9)

This makes the flame temperature go nearly (because C_p increases with Y_{oso}) linear with Y_{oso} . The flame temperature is then over-estimated because the real T_f is reduced due to incompleteness of combustion and flame radiation. As discussed in both Chapter 3 and Chapter 4, it was found that complete combustion holds only for ambient air condition. As the oxygen mass fraction increases, the combustion process becomes less efficient (χ_A decreases with Y_{oso}). In addition, the flame gets brighter as Y_{osc} increases, (χ_R increases with Y_{osc}). Clearly, these two factors reduce the flame temperature more significantly as Y_{osc} increases.

To approximate this incompleteness of combustion and radiation losses dependence on Y_{oee} , the convective heat flux measurements for different oxygen mass fraction were normalized with $(Y_{oee}/0.233)^n$. This normalization makes the flame temperature adiabatic at ambient air condition, and less efficient as Y_{oee} increases. The power n was then approximated by using least square analysis on all the results. Expressing the normalized convective heat flux measurements as in equation 5.4, the following equation results

$$\frac{Nu_{x}}{Pr^{1/3} \operatorname{Re}_{x}^{1/2} \left(\frac{Y_{o\infty}}{0.233}\right)^{n}} = C x^{*m}$$
(5.10)

where C = 0.5, m = -2.3, and n = -0.25. The gas properties used in the above equations are evaluated at the film temperature $T_{film} = (T_f + 3T_{\infty})/4$. The experimental results normalized according to the left hand side of the above equation for all the conditions tested are presented in Figure 5.5. In the same figure, the theoretical results of equation 5.4 are also presented.

The flame radiation, however, is treated as in the case of an expanding plane in the flame spread direction with known temperature and emissivity and at a constant stand-off distance from the surface (Figure 5.6). The view factor is then determined utilizing contour integration (Stoke's theorem) and is

$$F_{d1-2} = \frac{1}{\pi} \left[\frac{x_{f} - x}{\sqrt{(x_{f} - x)^{2} + d^{2}}} \tan^{-1} \left[\frac{a}{\sqrt{(x_{f} - x)^{2} + d^{2}}} \right] + \frac{a}{\sqrt{a^{2} + d^{2}}} \left[\tan^{-1} \left[\frac{x}{\sqrt{a^{2} + d^{2}}} \right] - \tan^{-1} \left[\frac{x - x_{f}}{\sqrt{a^{2} + d^{2}}} \right] \right] + \frac{x}{\sqrt{x^{2} + d^{2}}} \tan^{-1} \left[\frac{a}{\sqrt{x^{2} + d^{2}}} \right]$$
(5.11)



Figure 5.5 Nondimensional measured and predicted convective heat transfer during flame spread on PMMA.



Figure 5.6 Schematic diagram of an expanding plane underneath the sample surface.

where a = W/2 (W is the width of the sample) and d is the flame stand-off distance.

Using the adiabatic flame temperature, as in the convection analysis, and the radiometer measurements taken at the bottom of the test section, the flame emissivity is approximated. The flame radiation is then computed and is shown in Figure 5.7 with the experimental results. The predicted radiation is much higher than the experimental data near the flame tip due to the adiabatic flame temperature asumption. Both experimental and predicted results, however, show that (i) radiation can be neglected near room air conditions (ii) and as the oxygen mass fraction increases, the radiation becomes significant only underneath and very near the flame tip. For the case of 100% oxygen experiment, the radiation and convection are 24 and 76 percent of the total energy transfer at the flame tip, respectively.



Figure 5.7 Measured and predicted flame radiation for different Y_{out}.

5.2.2. Steady-state heat flux measurements

To simulate the heat transfer from a diffusion flame in the overfire region (due to excess pyrolyzate) during an actual flame spread, a long, steady and non-sooty flame with low fuel flow rate and 19% free stream oxygen concentration was maintained in the boundary layer over ceramic detectors for all experiments. Figure 2.13 shows a schematic of the porous-metal burner diffusion flame used in this study.

Both the net heat flux into the solid and the surface radiation to the surrounding are calculated as explained in the previous section and are presented in Figure 5.8 with the total heat flux $(\dot{q}''_{cond} + \dot{q}''_{rerad})$ (U_w = 1.2m/s, x_f=10 in, x= 7in). It is clear from this figure that the gas-phase achieves steady-state relatively quickly. Hence, the gas-phase thermocouple can be traversed at any instant after 300 seconds. The measured gasphase temperature profiles (after thermocouple radiation correction) are shown in Figure 5.9 for the case where $U_{\infty}=1.5$ m/s and $x_f=10$ in. The convective heat flux is then computed by calculating the temperature gradient at the solid-gas interface, and using air thermal conductivity evaluated at the surface temperature. The combustion plumes in Figure 5.9 show that the flame stand-off distance from the surface slightly decreases in x: 2 mm in 152 mm distance. This certainly proves the validity of the above simple model. Figure 5.9 also shows the flame temperature decreasing in x. This shows that the presence of a cool wall inhibits complete combustion of the excess pyrolyzate by quenching the reaction near the flame tip [Groff and Faeth 1978] in addition to the fact that the rate of reaction in the flame decreases as the fuel concentration at the wall decreases [Ahmad and Faeth 1978].
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gure 5.9 Measured gas-phase temperature profiles of a methane diffusion flame $(U_m=0.9m/s, Y_{om}=0.233, x_f=25.4cm)$

The flame radiation is then computed by performing an energy balance at the surface. Figure 5.10 shows the convective and flame radiative heat fluxes for all experiments performed for different free stream velocities and flame lenghts. As expected, for this non-sooty flame, convective heat transfer is dominant both ahead and underneath the flame. Radiation from these flames is very small and can be ignored for this case. This is consistent with the conclusions drawn in the previous section for room air oxygen concentration conditions.

Figure 5.10 shows that the convective heat transfer is decreasing in x both underneath and ahead of the flame. However, to get a better insight on the dependence of this energy transfer on the variables studied in this work (U_e, x, x_f), the experimental results have to be correlated. Using the same correlation developed in the above section, equation 5.10, the data ahead of the flame tip, where the formulation is valid, did fall together for all cases studied (Figure 5.11) and drops as x^{-p} where p=2.2 (obtained from best fit), or $\dot{q}'' \sim x^{-2.7}$. This proves that the combination of the heat transfer parameters (Nu_x, Pr, Re_x) are only a function of the related distance (x/x_f) as shown in equation 5.10. This clearly justifies the formulation. These results of methane diffusion flame are in good agreement with those of flame spread on PMMA in the previous section. Ahmad and Faeth (1979) found p=2.33 in their upward turbulent natural convection fires. This is consistent with the distribution measured by Quintiere et al. (1986) who found p=2.4 in their upward natural convection flame spread over different combustible materials.

Eventhough the formulation is not valid underneath the flame, the data does correlate when subjected to equation 5.10 and is approximately constant with x/x_f (or $\dot{q}'' \sim x^{-0.5}$). This result is in good agreement with Emmons' boundary-layer steady-state solution. Therefore, the combination of these parameters (shown in equation 5.10) can be justifiably used both ahead and underneath the flame.



Figure 5.10 Measured convective and radiative heat fluxes underneath and downstream of steady porous-metal burner diffusion flames (Y_{our}=0.211).



Figure 5.11 Nondimensional measured convective heat flux underneath and downstream of porous-metal burner diffusion flames (Y_{our}=0.211).

5.2.3. Surface temperature

To obtain the sample's surface temperature during the flame spread, the one dimensional heat conduction in a semi-infinite solid is examined. The solid is initially at ambient temperature, then experiences a transient heat flux at the surface

$$\theta_{s} = T_{s} - T_{\infty} = 0 \qquad y \ge 0 \qquad t = 0$$
$$\dot{q}_{s}'' = \dot{q}''(\theta_{s}, T_{\infty}, t) \qquad y = 0 \qquad t > 0$$

Since the heat flux applied at the surface in equation 5.10 can be expressed as $(x_f = V_f t)$

$$\dot{\mathbf{q}}'' = \mathbf{f}(\mathbf{t}_{\mathbf{f}}) \left[\frac{\mathbf{t}}{\mathbf{t}_{\mathbf{f}}} \right]^{\mathbf{b}} \qquad 0 < \frac{\mathbf{t}}{\mathbf{t}_{\mathbf{f}}} < 1$$
 (5.12a)

$$\dot{q}'' = f(t_f)$$
 $1 < \frac{t}{t_f} < \frac{t_p}{t_f}$ (5.12b)

(where t_f and t_p are the times x_f and x_p reach x, respectively, and b=2.3), the problem can be solved using the Green's function or Duhamel's integral [Atreya 1983]. The surface temperature is then expressed as

$$\theta_{s} = \frac{f(t_{f})}{t_{f}^{b} \sqrt{\pi \rho C k}} I(t,b)$$
(5.13)

where

$$I(t,b) = \int_{\tau=0}^{t} \frac{\tau^{b}}{\sqrt{t-\tau}} d\tau \quad . \tag{5.14}$$

Ahead of the flame $(0 < t/t_f < 1)$, I(t,b) is reduced to a Beta function, and the surface temperature solution becomes

$$\theta_{s} = \frac{f(t_{f}) t^{b+1/2}}{A t_{f}^{b} \sqrt{\rho C k}}$$
(5.15)

where

$$A = \frac{\Gamma(b+3/2)}{\Gamma(b+1)}$$

 $A \approx \sqrt{\pi}$ at b=2.3. The surface temperature ahead of the flame finally becomes (is terms of all the parameters)

$$\left[\frac{T_s - T_{\infty}}{T_f - T_{\infty}}\right] \left[\frac{Y_{o\infty}}{0.233}\right]^{0.25} \left[\frac{V_f}{U_{\infty}}\right]^{1/2} \left[\frac{\sqrt{\rho \ C \ k}}{\sqrt{\rho_g C_p k_g}} \ Pr^{1/6}\right] = \frac{0.5}{\sqrt{\pi}} \ (x^{*)-2.8}$$
(5.16)

The PMMA surface temperature measurements of all cases are normalized as in the left hand side of the above equation and presented in Figure 5.12 (a knowlege of the flame spread rate is needed to find the surface temperature distribution). The right hand side of the equation is also shown in solid line in the same figure. During the sample ignition process, heat is transferred from the burner diffusion flame to the sample surface downstream as indicated by the gas-phase temperature rise presented in Figure 5.2 at x=33cm and 1mm from the surface. This heat transfer causes the surface temperature to rise above ambient and becomes dependent on the downstream distance x as shown in Figure 3.1 near 100 sec (end of ignition). Therefore, the normalized measured surface temperature would be higher near the leading edge than far downstream for small x_f (or large x/x_f), as indicated in Figure 5.12. At the flame tip arrival, however, the measured surface at different locations varies within 5 degrees for the same experiment and is between 533 and 573 K for all the experiments conducted as mentioned in section 3.1.1. Therefore, the normalized measured surface temperature is expected to vary at the flame tip arrival as indicated in Figure 5.12. Hence, the predicted surface temperature is expected to be lower than the measured for large x/x_f for the first reason mentioned above. Near the flame tip, however, the predicted surface temperature is expected to fall close to the measured data that corresponds to low oxygen concentration experiments where flame radiation is negligible (since the model only considers convection).



Nondimensional measured and predicted PMMA surface temperatures. Figure 5.12

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Underneath the flame, however, I(t,b) is reduced to an incomplete Beta function which may be approximated by the series

$$I(t,b) = \frac{\sqrt{t}}{t_f^b} \left[2 - \frac{b}{b+1} \left(\frac{t_f}{t} \right) - \frac{b}{4(b+2)} \left(\frac{t_f}{t} \right)^2 - \frac{b}{8(b+3)} \left(\frac{t_f}{t} \right)^3 - \frac{5b}{64(b+4)} \left(\frac{t_f}{t} \right)^4 \right]$$
(5.17)

This series converges very quickly where the 5th term is less than 1%. At the pyrolysis-front arrival $(t=t_p)$, the $t_p^{1/2}$ dependency on the pyrolysis temperature is in good agreement with Quintiere et al. (1986) results.

5.2.4. Flame spread rate

The pyrolysis-front spread rate V_p can be deduced from equations 5.15 and 5.17

$$V_{p} = \frac{0.25D^{2}}{\pi} \frac{1}{P_{T}^{1/3}} \left(\frac{\rho_{g} C_{p} k_{g}}{\rho C k} \right) U_{\infty} \left[\frac{T_{f} - T_{\infty}}{T_{p} - T_{\infty}} \right]^{2} \left(\frac{Y_{o\infty}}{0.233} \right)^{-0.5}$$
(5.18)

where D is the series inside the brackets of equation 5.17 evaluated at $t=t_p$. The limits of D are 1<D<2, where 1 corresponds to (since $t_f/t_p=V_p/V_f$) $V_p=V_f$ (all the heating is accomplished in the preheat zone) and D—2 when $V_f \gg V_p$ (all the heating is accomplished under the flame). Since V_f is unknown, D is approximated by fitting equation 5.18 to the experimental results and found to be 1.3. Once again, the air properties are evaluated at the film temperature $(T_f+3T_{\infty})/4$.

Equation 5.18 reveals the pyrolysis-front spread rate dependency on solid and gas thermal properties and environment conditions. Figures 5.13 and 5.14 show experimental and predicted V_p dependency on U_{∞} , and $Y_{0\infty}$, respectively. The flame spread rate is, therefore, linear with the free stream velocity and is proportional to $Y_{0\infty}^{1.5}$ for PMMA as given by equation 5.18. This dependency is in agreement with the experimental results where V_p was found to be linear with U_{∞} and is proportional to $Y_{0\infty}^{1.4}$. Loh and Fernandez-Pello (1984) found $Y_{0\infty}^{1.8}$ dependency on their floor configuration assisted flow flame spread experiments. However, it was concluded that reflection



Figure 5.13 Measured and predicted pyrolysis-front spread rate dependence on U_{∞} (Y_{ox}=0.233).



Figure 5.14 Measured and predicted pyrolysis-front spread rate dependence on Y_{om} (U_m=0.9m/s).

from the surroundings, in addition to the buoyant flame radiation, to the surface ahead of the flame tip is the reason behind this higher dependency on Y_{∞} .

Equation 5.18 is a typical wind-aided flame spread formula as for those derived in previous theories [Wichman and Agrawal 1991, Carrier et al. 1990] except for the difference in the constant coefficient. Wichman and Agrawal (1991) who employed the Oseen flow assumption, have a constant coefficient of 1 (see equation 1.3). Carrier et al. (1990), however, who employed the boundary-layer assumption from the onset and later invoked the Oseen flow approximation, have a coefficient of 0.25. The high coefficient in Wichman and Agrawal (1991) derivation explains their high predicted ratio V_f/V_p . This coefficient is therefore dependent on the pyrolysis zone part of the problem which determines the flame length and consequently the relation between V_p and V_f .

CHAPTER SIX

Conclusions

The focus of this study was to understand the wind-aided flame spread on wood and PMMA. This included understanding and determening (i) the pyrolysis-front and flame-front spread rates and (ii) the major chemical species mass production rates. In the process, it was necessary to determine the the convective and radiative heat transfer to the solid both ahead of and underneath the flame.

The conclusions of this work are summarized in the following two sections. Section 6.1 summarizes the conclusions derived from the flame spread experiments on charring and non-charring solids. Section 6.2 summarizes the conclusions derived from the results of the heat transfer study.

6.1 Flame Spread Experiments

The wind-aided flame spread experiments were conducted on both charring (poplar wood) and non-charring (PMMA) solids mounted in the ceiling configuration. The pyrolysis front and the flame front spread rates were determined from the pyrolysis-front and the flame tip histories, respectively. The mass production rates of the major chemical species were derived from the transient species concentration measurements during the experiments.

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Several significant conclusions can be derived from the experimental results:

- 1- The pyrolysis-front and the flame-front are much closer to each other than that predicted by theoretical models. This is also true for the pyrolysis-front and flame-front speeds regardless of the free stream velocity, external radiation (applied only for wood), and/or the oxygen mass fraction for both wood and PMMA. This is because unsteady conditions exist in the burning zone.
- 2- The pyrolysis-front and the flame-front spread rates vary linearly with the free stream velocity for both wood and PMMA. The theoretical models for non-charring materials predict the pyrolysis-front speed quite accurately despite the solid phase assumption in the burning zone. This underscores the fact that the flame spread rate depends primarely on local heating of the solid by the flame tip in the adjacent preheat zone.
- 3- The pyrolysis-front and the flame-front spread rates sharply increase with the external radiation for wood.
- 4- The pyrolysis-front and the flame-front spread rates vary with the free stream oxygen mass fraction as $Y_{\infty}^{1.1}$ for wood and $Y_{\infty}^{1.4}$ for PMMA.
- 5- The species measurements show that the pyrolysis mass flux is roughly constant both for wood and PMMA rather than vary as $x^{-0.5}$ as predicted by Emmons theory. The species measurements also show that the chemistry is changing as x_p and Y_{osc} are increased because of incompleteness of combustion.

6.2 Heat Transfer Experiments

The heat transfer to the preheat zone ahead of the pyrolysis front in wind-aided flame spread has been addressed experimentally and theoretically. Even though the model is simple, it provided the necessary heat transfer nondimentional parameters to correlate the results both ahead of and underneath the flame. Several key results emerge from this study:

- 1- The convection is the dominant mode of heat transfer for near room air oxygen concentration condition both ahead and underneath the flame.
- 2- The flame radiation becomes more significant underneath and near the flame tip as the ambient oxygen mass fraction increases.
- 3- The steady-state convective heat flux measurements agree with those of the transient case ahead of the flame tip. This shows that the gas-phase reaches steadystate rather fast (compared to the solid-phase)
- 4- Correlations have been developed for the convective heat transfer, the surface temperature and the flame spread rate.
- 5- Ahead of the flame, the convection is transient $(\dot{q}'' \alpha t^{2.3})$ and goes as $x^{-2.8}$. Underneath the flame, however, the convection is steady and goes as $x^{-1/2}$ (boundary-layer dependency).
- 6- The predicted pyrolysis-front spread rate varies linearly with U_{∞} and varies to the 1.5-power of Y_{∞} . These predictions are in agreement with the experimental results.

Appendix A

Appendix A

Study of number and location of thermocouples in a ceramic solid for heat flux computations

The minimum error can be reached by using many thermocouples indepth and at the surface in order to collect as much information as possible. However, extra information is sometimes irrelevant and not worth the trouble of placing thermocouples in the cast ceramic solid. Thus, the sufficient number of thermocouples needed for accurate heat flux computation was investigated.

In addition, for a given number of thermocouples, the location of each thermocouple plays a role in the computed heat flux accuracy. The closer the thermocouple is to the surface where heat flux is applied, the more sensitive it is to changes in heat flux. Thus, the thermocouple locations were also investigated.

After casting a ceramic sample with indepth thermocouples, one needs to know the exact thermocouple locations after the ceramic solid has dried out. The effect of such error on heat flux results was also investigated. Error in solid properties is also reported.

A.1. Experiment

Two thin resistance circular heaters were placed between two identical solid cylinders of ceramic. Thermocouples were placed in the top solid as shown in Figure A.1. The heaters were set at 6.45 volts and 1.531 amps for more than 3 hours in order to reach steady state temperatures in the solid. The power was then increased to 12.8 volts and 3.156 amps for 92 seconds and then turned off. This power step input is shown in Figure A.2.

During this time, temperature data was collected from all the thermocouples, and is presented in Figure A.3. As the data acquisition unit scanned over those 8 thermocouples, the timestep varied in time from 0.7 to 0.9 seconds for each thermocouple. Therefore, for simplicity, a low filter was used to approximate the temperature data at equal timestep of 1 second. A comparison of the temperature at x=0 before and after smoothing is presented in Figure A.4.

Then the program CONTPC was run to compute the transient heat flux at the surface. The number of future times used in all the computations was kept constant at a value of 4.

A.2. Results and discussion

A.2.1. Using only one thermocouple indepth

The case of each thermocouple that was studied is presented in Figure A.5. As the indepth distance of the thermocouple increases, the thermocouple becomes less sensitive to heat flux changes at the surface, and so, the error in the heat flux, as seen in Figure A.5, increases. The case of the deepest thermocouple, at x=2.7cm, has oscillations with high magnitude. Therefore it is not reported.

Figure A.6 shows the residual of those cases presented in Figure A.5. Unlike the heat flux; as the thermocouple location from the surface increases; the error between the calculated and the actual temperature decreases.



Figure A.1 Experimental setup.



Figure A.2 Power step input history.



Figure A.3 Temperature histories at the surface and in-depth



Figure A.4 Comparison of measured and smoothed temperature data.



Figure A.5 Computed heat flux history using one in-depth thermocouple measurements.



Figure A.6 Temperature residuals when using one in-depth thermocouple measurements for heat flux calculations.

A.2.2. Using two thermocouples indepth

Several cases were studied and are presented in Figure A.7. As the distance to the first thermocouple from the surface increases, the error in the heat flux increases. The residual (Y-T) of the cases in Figure A.7 are shown in Figures A.8.1 and A.8.2 for the first and second thermocouple, respectively. Figure A.8.1 shows that a maximum error of 0.6° C exists for the first thermocouple. However Figure A.8.2 shows a maximum error of 2° C for the second one because the minimization of the root mean square is heavily weighted on the first thermocouple.

A.2.3. Using one thermocouple at the surface and others indepth

The thermocouple at the surface is more sensitive to changes in the heat flux than the indepth ones. Thus, its effect dominates over the rest of thermocouples. Several Cases were studied on using one or two thermocouples indepth.

The cases of using one thermocouple indepth are shown in Figure A.9. All the results are very close, and a maximum error of 2% in the heat flux is seen for the case of x=1.14cm. The domination of the thermocouple at the surface, mentioned earlier, can be observed in the case of having a thermocouple at x=1.14cm. The addition of the thermocouple at the surface brought the results from 10% oscillations to stable results with low percent error.

The results of having two thermocouples indepth, in addition to the one at the Surface, are very close, as shown in Figure A.10.

The cases of using 1, 2, and 3 thermocouples indepth with the one at the surface are shown in Figure A.11. A maximum error of about $0.02W/cm^2$ (2%) is observed. For comparison, the case of using all 7 thermocouples to compute the heat flux is **Presented** in Figures A.9, A.10, and A.11.



Figure A.7 Computed heat flux history using 2 in-depth thermocouple measurements.



Figure A.8.1Temperature residuals of the 1st thermocouple when using
2 in-depth thermocouple measurements for heat flux calculations.



Figure A.8.2Temperature residuals of the 2nd thermocouple when using
2 in-depth thermocouple measurements for heat flux calculations.



Figure A.9 Computed heat flux history when using the thermocouple at x=0 and another in-depth.



Figure A.10 Computed heat flux history when using the thermocouple at x=0 and another 2 in-depth.



Figure A.11 Effect of the number of thermocouples used on the computed heat flux.

A.3. Thermocouple locations

As mentioned in the previous section, the closer the thermocouples to the surface are, the better the results are. This is shown in Figures A.7 and A.8 for heat flux and error, respectively.

A.4. Errors in the thermocouple location

For a given temperature history, an error in the thermocouple location would lead to an error in the heat flux results. This is shown in Figures A.12 and A.13 for the cases of two and one thermocouple indepth, respectively, with a location error of 2mm. Comparing these results with those of Figure A.7, it is seen that as the thermocouples are closer to the surface, the results show more sensitivity to location errors.

A.5 Errors in thermal properties

All the above results were computed by using published ceramic thermal properties. Just recently, the real properties of each ceramic block were computed by using the parameter estimation code developed by Dr. J. Beck. For comparison, the heat flux results of both cases are presented in Figure A.14 where all the thermocouples were used to compute the heat flux at the surface. The error is more significant at the beginning and the end of the step input.

A.6. Conclusions

- Besides the thermocouple at the other boundary, it has been shown that the addition of another thermocouple gives approximate results if it is very close to the surface where the heat flux is applied.
- Two thermocouples give even better results. For higher accuracy, one of the two thermocouples must be at the surface.
- The location of the 2nd thermocouple can be anywhere indepth as long as the 1st is very close to the surface.



Figure A.12 Effect of 2mm location error of the in-depth thermocouple on the heat flux results (using 2 thermocouples).



Figure A.13 Effect of 2mm location error of the in-depth thermocouple on the heat transfer results (using one thermocouple).



Figure A.14 Effect of properties error on the computed heat flux (using all the thermocouple measurements).

- An error in the thermocouple location has more effect on those that are close to the surface, since they are have higher sensitivity coefficients.
- A maximum error of 2°C in the temperature was observed for the deepest thermocouple, in case of using 2 thermocouples indepth.
- Errors in the solid properties have high effects on the results when sharp changes happen in the heat flux applied at the surface. In addition, the computed thermal properties of each ceramic solid give better results than the published ones.

Appendix B

Results of flame-spread experiments on PMMA



Figure B.T1 Species mass production rates history during flame spread on PMMA ($U_{\infty}=0.6$ m/s, $Y_{\infty}=0.233$).



Figure B.Xp1 Species mass production rates plotted against the pyrolysis-front location for PMMA ($U_m=0.6m/s$, $Y_{om}=0.233$).



Figure B.T2 Species mass production rate history during flame spread on PMMA (U_==0.9m/s, Y_o==0.233).



on PMMA (U_m=0.9m/s, Y_{om}=0.233).



Figure B.T3 Species mass production rates plotted against the pyrolysis-front location for PMMA ($U_m=1.5m/s$, $Y_{om}=0.233$).



Figure B.Xp3 Species mass production rates history during flame spread on PMMA ($U_{m}=1.5$ m/s, $Y_{om}=0.233$).



Figure B.T4 Species mass production rates history during flame spread on PMMA (U_=0.9m/s, Y=0.43).



Figure B.Xp4 Species mass production rates plotted against the pyrolysis-front location for PMMA ($U_m=0.9m/s$, $Y_{om}=0.43$).



Figure B.T5 Species mass production rates history during flame spread on PMMA ($U_{\infty}=0.9$ m/s, $Y_{\infty}=1.0$).



Figure B.Xp5 Species mass production rates plotted against the pyrolysis-front location for PMIMA ($U_m=0.9$ m/s, $Y_{om}=1.0$).

Appendix C

Results of flame-spread experiments on wood



Figure C.T1 Species mass production rates history during flame spread on wood ($U_{\infty}=0.2m/s$, $Y_{\infty}=0.233$, $\dot{q}^{*}=1.3W/cm^{2}$).





Figure C.T2 Species mass production rates history during flame spread on wood ($U_{m}=0.6m/s$, $Y_{m}=0.233$, $\dot{q}^{*}=0.5W/cm^{2}$).





on wood (U_m=0.6m/s, Y_{om}=0.233, \dot{q} "=0.9W/cm²).



Figure C.Xp3 Species mass production rates plotted against the pyrolysis-front location for wood ($U_m=0.6m/s$, $Y_{m}=0.233$, $\dot{q}^{"}=0.9W/cm^2$).


Figure C.Xp4 Species mass production rates plotted against the pyrolysis-front location for wood (U_=0.6m/s, $Y_{ow}=0.233$, $\dot{q}^{*}=1.3$ W/cm²).





location for wood (U_=0.9m/s, Y_=0.233, \dot{q} "=0.5W/cm²).



Figure C.T6 Species mass production rates history during flame spread on wood (U_w=0.9m/s, Y_w=0.233, \dot{q} "=0.9W/cm²).





Figure C.T7 Species mass production rates history during flame spread on wood ($U_{m}=0.9m/s$, $Y_{m}=0.233$, $\dot{q}^{*}=1.3W/cm^{2}$).



Figure C.Xp7 Species mass production rates plotted against the pyrolysis-front location for wood ($U_{\infty}=0.9$ m/s, $Y_{\infty}=0.233$, $\dot{q}^{*}=1.3$ W/cm²).







Figure C.T9 Species mass production rates history during flame spread on wood ($U_{\infty}=1.5$ m/s, $Y_{\infty}=0.233$, $\dot{q}^{*}=0.9$ W/cm²).



location for wood ($U_{\omega}=1.5$ m/s, $Y_{\omega}=0.233$, $\dot{q}^{*}=0.9$ W/cm²).



Figure C.T10 Species mass production rates history during flame spread on wood ($U_{\omega}=1.5$ m/s, $Y_{\infty}=0.233$, $\dot{q}''=1.3$ W/cm²).



location for wood (U_w=1.5m/s, Y_{ow}=0.233, \dot{q} "=1.3W/cm²).



Figure C.T11 Species mass production rates history during flame spread on wood ($U_{\infty}=0.9$ m/s, $Y_{\infty}=0.33$, $\dot{q}^{"}=0.5$ W/cm²).



Figure C.Xp11 Species mass production rates plotted against the pyrolysis-front location for wood ($U_{\infty}=0.9$ m/s, $Y_{\infty}=0.33$, $\dot{q}^{*}=0.5$ W/cm²).

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Figure C.T12 Species mass production rates history during flame spread on wood ($U_{a}=0.9m/s$, $Y_{ca}=0.43$, $\dot{q}^{*}=0.5W/cm^{2}$).



Figure C.Xp12 Species mass production rates plotted against the pyrolysis-front location for wood ($U_{\infty}=0.9m/s$, $Y_{\infty}=0.43$, $\dot{q}^{"}=0.5W/cm^{2}$).







Appendix D

Results of heat transfer experiments

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 $(U_{\infty}=0.9m/s, Y_{\infty}=0.233, x=33cm).$









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