

ABSTARCT

Title of Thesis: RADIANT AUTO-IGNITION OF WOOD

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Although piloted-ignition is well studied, auto-ignition is not, and under some conditions the latter may initiate the former. For that reason, the dynamics and mechanisms in the auto-ignition of redwood by radiant heating were experimentally studied. An open-cone radiant source heated an insulated cubical vertical sample 4 cm on a side. Infrared (IR) and normal video cameras were used to view the surface of the wood. Surface temperature (by thermocouple and IR) and mass loss were continuously recorded. The wood grain orientation was aligned either perpendicular or parallel to the incident heat flux. The time for flaming ignition is measured up to 70 kW/m^2 and compared to piloted ignition results of Spearpoint and Quintiere [28,29] with little difference above 40 kW/m^2 . With no visible flame, the surface temperature of the wood can achieve 700 C , while the corresponding inert fibrous insulation achieves only 500 C . This is indicative of surface oxidation, which likely plays a role in the flaming ignition of redwood. For

example, at 40 kW/m^2 , heating perpendicular to the grain, flaming ignition occurs in 1000 s. The initiation of flaming ignition is seen in the gas phase above the sample consistent with the observations of Simms [25].

The purpose of this study is to examine experimentally and theoretically the auto-ignition of wood. The important parameters for ignition: ignition time, ignition temperature, mass loss rate, critical heat flux, and thermal inertia are examined and compared with the piloted ignition. The ignition contributed by glowing ignition, and flaming ignition is also discussed.

RADIANT AUTO-IGNITION OF WOOD

by

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LIST OF ABBRIVIATIONS

α	Absortivity (-)
β	Dimensionless heat flux parameter (-)
c	Specific heat (J/kg.K)
δ	Thermal penetration (m)
ε	Emissivity (-)
$\bar{h}$	Average convective heat transfer coefficient (W/m ² K)
k	Thermal conductivity (W/m.K)
m	Mass (g, kg)
$\dot{m}''$	Mass flux (g/sm ²)
$\dot{q}''$	Heat flux (kW/m ²)
ρ	Density (kg/m ³)
T	Temperature (C, K)
t	Time (s)
σ	Stefan-Boltmann constant (W/m ² .K)
V	Volume (m ³)
W	Work (J)

Subscripts

0	Initial condition, ambient
<i>cr</i>	Critical
<i>i</i>	Incident
<i>ig</i>	Flaming ignition
<i>glowing</i>	Glowing ignition
<i>TC</i>	Thermocouple measuring value
<i>IR</i>	Infrared camera measuring value

Chapter 1. Introduction

1.1 Overview

Wood is a common material used for building construction, furniture, and various decorative purposes. As wood fueled fires occur, wood will ignite and burn creating hazard to life and property. Therefore, it is necessary to understand the ignition and burning characteristic of wood to help in determining its potential fire hazard and fire growth rate.

The ignition phenomenon of wood is complex. It involves chemical reactions, heat transfer, and mass transfer. First, the wood starts to produce the pyrolysis products once it is heated from a heat flux (i.e. from a fire in the building) until its temperature reaches the pyrolysis temperature. The pyrolysis products then come out and mix with air from the surrounding creating a combustible mixture. When the combustible mixture concentration reaches its lower flammable limit, and its temperature is suitable the ignition occurs. The decomposition process of wood can be described as the flow chart adapted from Kanury [15] as shown in Figure 1.1.

The ignition of wood can occur in two ways. Piloted ignition occurs when gases given off from heated wood are ignited by an external flame source. Auto-ignition occurs when the temperature of the pyrolysis gases reach their “auto-ignition” temperature without an external flame source. This paper focuses on the auto-ignition of wood by a radiant heat source.

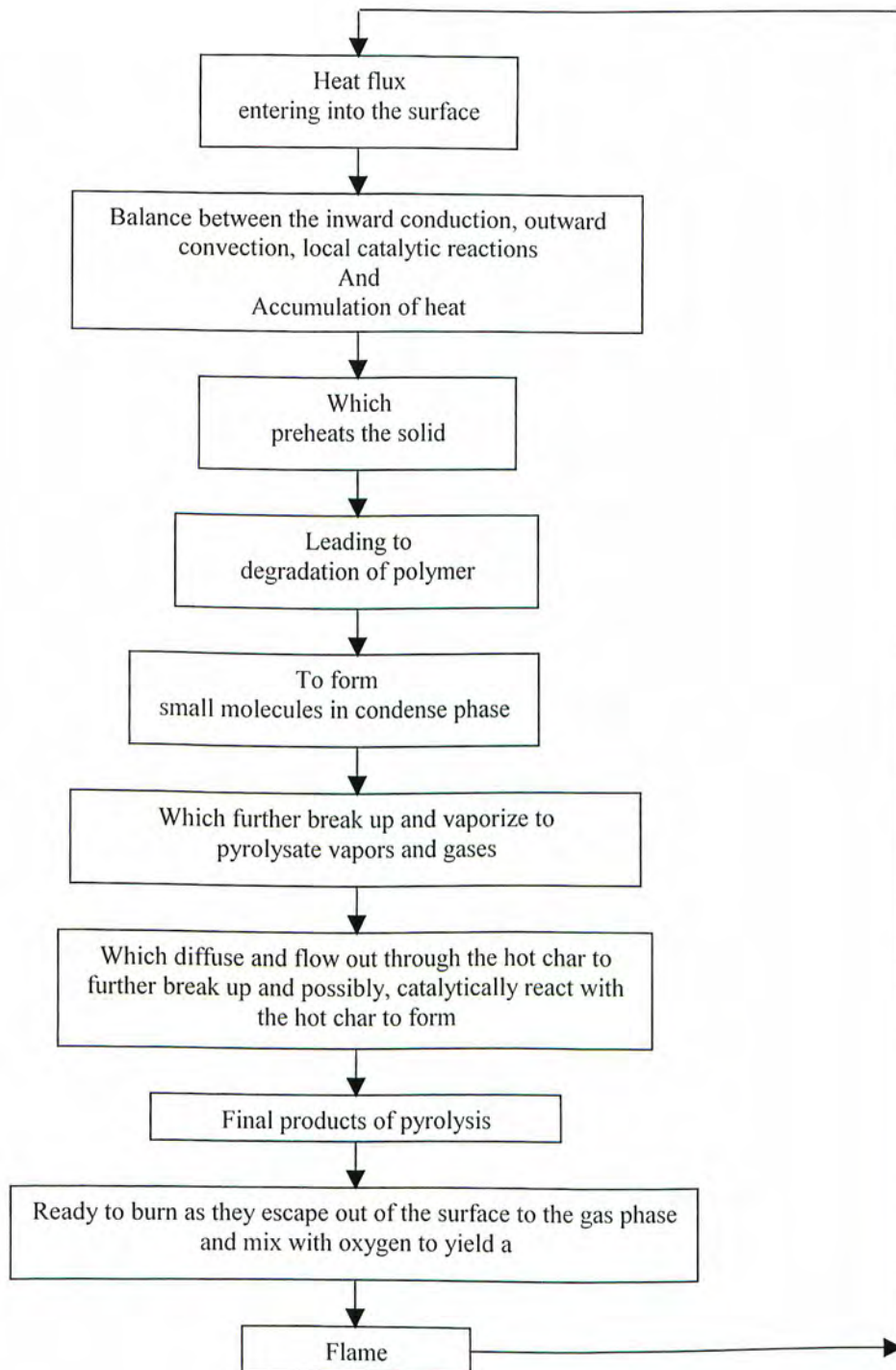


Figure 1.1: Flow diagram of development of an event in a fire [15].

1.2 Structure of Wood

The purpose of this section is to give an overview of the wood structure. As trees grow, they insert a new layer of wood between existing wood and bark over the entire stem, branches, and roots. Each layer for each growing year, called an annual ring, is composed of a number of fiber-tubes aligned along the tree stem. We call the direction of those fiber-tubes grain orientation. Water, minerals and nutrients are transported through these fiber-tubes to other parts of the tree.

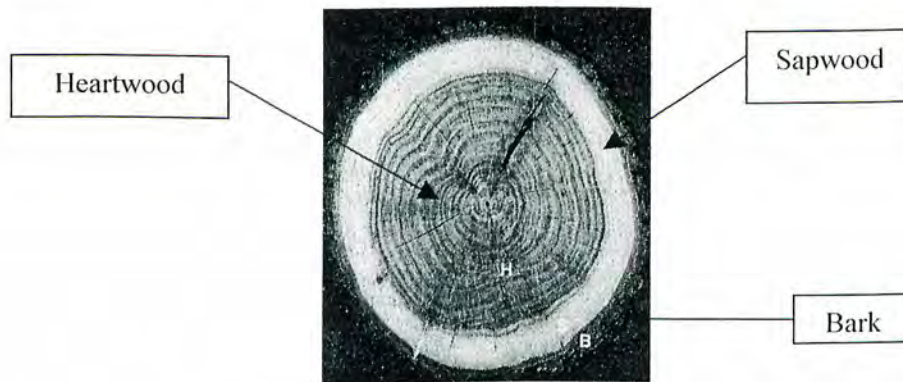


Figure 1.2: A cross section of a tree stem [20].

Considering the cross section of a tree stem as shown in Figure 1.2, we can divide the tree stem into three portions. The center portion of the cross section is called heartwood. This part consists of inactive cells (dead cells). The middle part, called sapwood, consists of active cells (living cells). This part is the most recently formed wood. The outer portion of the cross section is bark. This part covers the entire tree stem. For construction purposes, both sapwood and heartwood are used. Both portions have almost the same mechanical properties. Nevertheless, the heartwood portion is often denser than the sapwood portion.

The grain structure of wood will affect the ignition mechanism. Considering two heating scenarios as shown in Figure 1.3, the pyrolysis products will easily travel out from the wood when an incident heat flux flows parallel to the grain since the grain orientation contributes the flow. When an incident heat flux flows perpendicular to the grain, the pyrolysis products travel out much more slowly since the cell walls of the fiber-tubes have to decompose first before the pyrolysis product can escape. Because the ignition occurs when the concentration of the flue (pyrolysis products) achieve a suitable concentration (i.e. lower flammable limit), we might expect that the ignition of wood when we heat it parallel to the grain is easier than when we heat perpendicular to the grain.

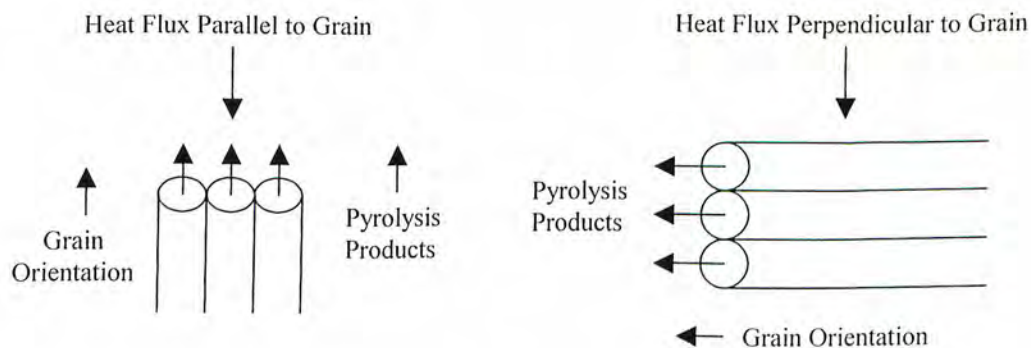


Figure 1.3: Heating direction and grain orientation.

1.3 Literature Review

A number of studies have been carried out on the ignition of wood and cellulosic materials for both piloted ignition and auto-ignition. The purpose of this study is not to review the previous work; however, some relevant studies have been reviewed here as references.

Alvares and Martin [2] conducted significant work on auto-ignition of cellulosic material. In their work, they constructed a model including both condensed phase and gas phase effects. They suggested a criterion that claims the auto-ignition of wood occurs when the wood temperature reaches a critical temperature of 600 C. This critical temperature is independent of incident heat flux. Martin [21] suggested that the ignition of cellulosic material could be divided into three regions: (a) ablation controlled, (b) diffusion controlled, and (c) convection controlled.

Simms [25] also contributed an excellent work on the auto-ignition of cellulosic material. He commented that the critical temperature for auto-ignition was 525 C. He also suggested that this critical temperature did not depend on incident heat flux and it was constant for wide range of moisture contents in the wood up to 60% moisture content [26]. Gandhi and Kanury [8,16] argued that besides a critical ignition temperature, a critical mass flux could be used for the ignition criteria. They suggested that the ignition would occur when the pyrolysis rate was approximately 2.5×10^{-4} g/cm²s.

Atreya and Wichman [3] carried out excellent work on piloted ignition of cellulosic solids. They constructed a model considering both condensed phase and gas phase. Atreya, Carpentier, and Harkleroad [4] also did excellent work on piloted ignition and flame spread on wood. In their work, they examined the effect of sample orientation for both the vertical and horizontal cases.

Kashiwagi [18,19] conducted the experiment on both auto-ignition and piloted ignition of wood and PMMA in the horizontal orientation. He considered the effect of attenuation of the radiation, via the decomposition products in the gas phase, to the sample surface. He suggested that the attenuation via the decomposition products highly affected the surface temperature when the sample was exposed horizontally to a low incident heat flux since the decomposition gases would dilute the intensity of the incident heat flux.

A numerical solution considering both gas phase and condense phase has been widely used to solve the ignition problem. Many researchers have done these work such as Kashiwagi [17], Ndubizu and Durbetaki [23], and Gandhi and Kanury [9]. However, these solutions are complicated due to the reaction in the gas phase. To simplify the ignition problem, an integral method considering only the condensed phase has been introduced. Spearpoint and Quintiere [28,29] used a one-dimensional integral model considering only the condensed phase to predict the ignition time for piloted ignition. Their model on was in a good agreement with the experimental data. Delichatsios, Panagiotou, and Kiley [5] used an integral method and compared the results with the exact solution for a one-dimensional semi-infinite solid heat transfer problem. Moghtaderi, Novozhilov, and Fletcher [22] also investigated the ignition time by using an integral analysis.

In this study, we will mainly use an integral model solution developed by Spearpoint and Quintiere [28,29] in approaching the ignition problem. Other quantitatively

examinations are also presented for the mass loss rate (mass flux) and surface temperature at ignition.

Chapter 2. Experiment Setup

2.1 General

The ignition characteristic of redwood was studied. The samples were cut into a cubical shape 4 cm on a side. The wood grain orientation was aligned either parallel (heated parallel to grain) or perpendicular (heated perpendicular to grain) to the incident heat flux. Figure 2.1 shows how a sample was aligned to the incident heat flux as desired in this study.

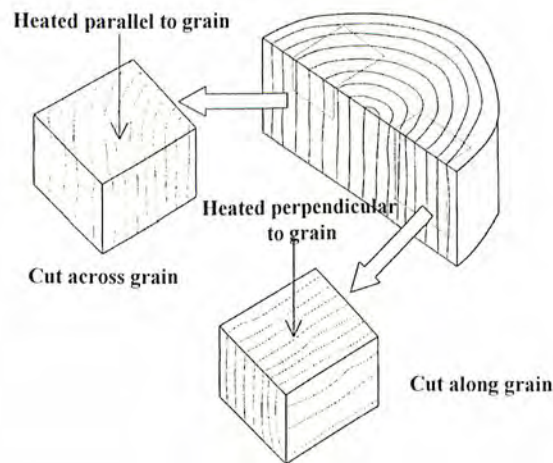


Figure 2.1: Sample grain orientation.

The samples were dried in an oven at 100 C for 24 hours and then kept in desiccators at 11% relative humidity and 20 C to control moisture content. Prior to each test, the moisture content was measured by a digital moisture meter. The average value of moisture content was 6%. All samples were insulated on the back and side with fiber

insulation in order to promote one dimensional heat transfer and then mounted vertically in a sample holder as shown in Figure 2.2.

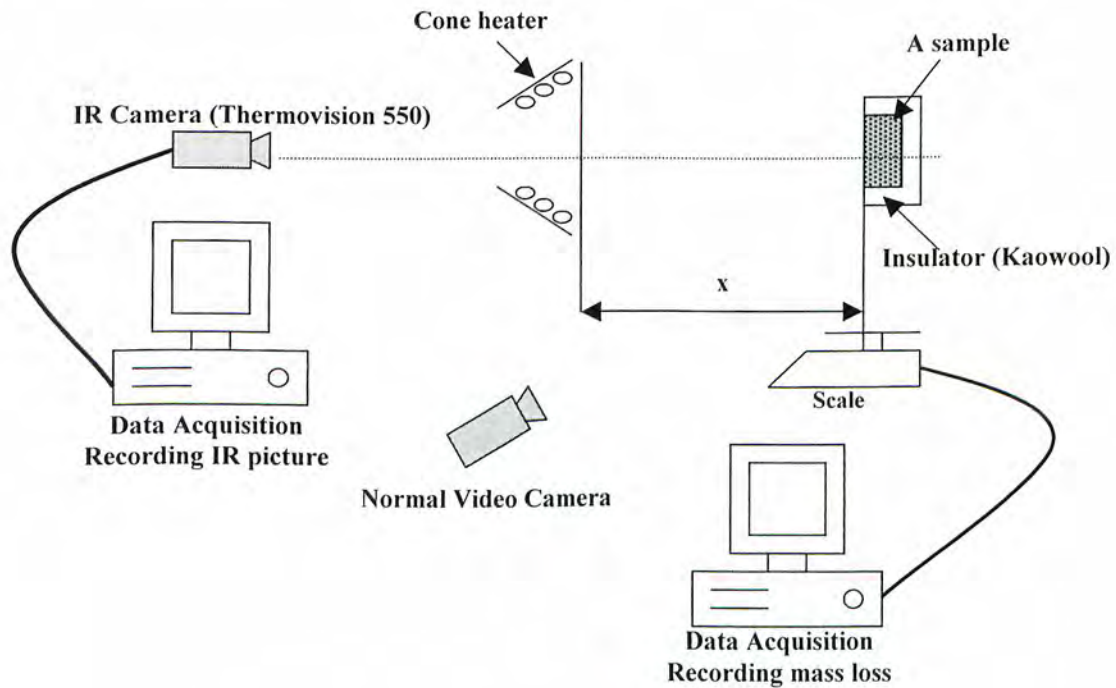


Figure 2.2: Experiment apparatus setup.

The samples were exposed to an incident heat flux range from 32 kW/m^2 up to 70 kW/m^2 . The incident heat flux was measure by a heat flux meter with calibration factor of $5.4 \text{ kW/m}^2/\text{mV}$. Prior to each test, the desired heat flux was varied by varying the distance between the sample and the cone heater panel. The calibration curve for the heat flux varying distance from the cone heater panel is shown in Figure 2.3. By placing the sample on a specific distance form the cone heater panel, the incident heat flux can be calculated.

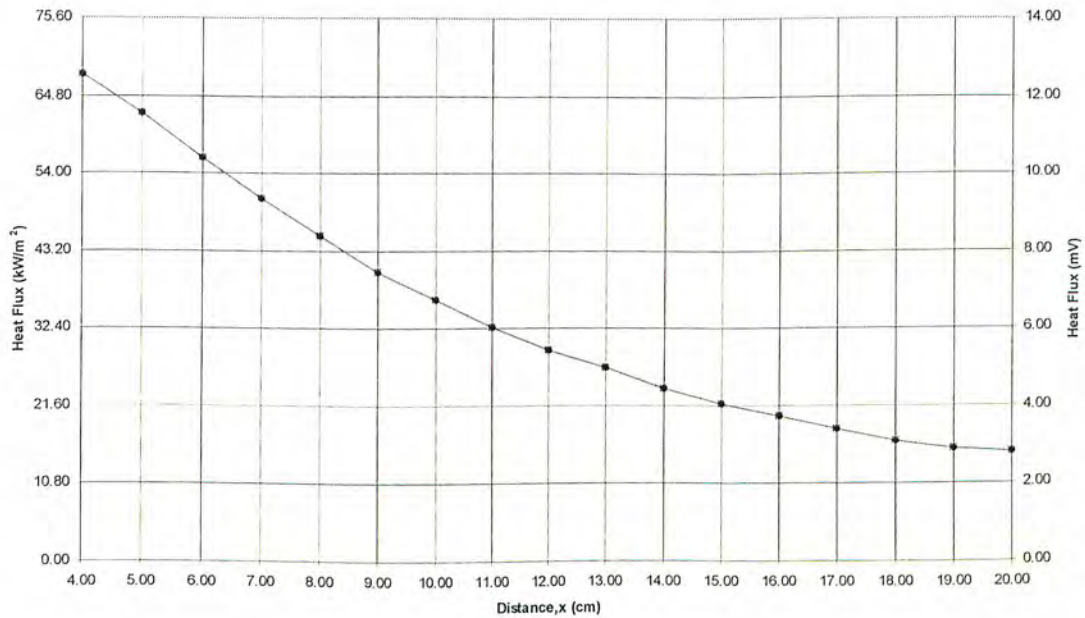


Figure 2.3: Calibration curve for the cone heater.

Many tests were conducted at low incident heat flux to find a critical heat flux. Time to ignition was measured and defined as the duration time from once a sample is exposed to an incident heat flux until it ignites (flaming ignition). The ignition time used in the analysis purpose is an average value of ignition times measured from 3 sources: one value from the ignition time measured by eye and two values from the ignition time measured by re-running the video record. A normal video camera was used to view the ignition process and then the series of pictures were converted to a digital format with the resolution of 30 frames per second. By examining frame by frame of the ignition process pictures, the location where ignition occurred could be found.

At high incident heat flux the test was terminated when a sustained visible flame occurred; however, at low incident heat flux, the sample might not show a visible flame. In these cases, the experiments were kept running up to 40 minutes until the sample was gone even though no flaming ignition was seen.

2.2 Mass Loss Measurement

The mass loss of the sample was continuously recorded by a digital scale (Navigator Balance model NV-210). The scale has an accuracy of ± 0.01 g with maximum capacity of 210 g. The sampling rate of the scale is 1 data point per second. The scale was connected to the data acquisition board (CIO-DAS08 and EXP32 expansion board). The acquisition boards were controlled from the computer via LabTech NoteBookpro version 10. The mass of the samples ranged from 18.57 g to 22.60 g with an average value of 19.51 g. Raw mass loss data was smoothed by a 3-point moving average and the mass loss rate was calculated from a 5-point numerical differentiation. More detail of a 5-point numerical differentiation can be found in reference [10].

2.3 Surface Temperature Measurement

The surface temperature is one of the important parameters to indicate the ignition of a sample. However, it is very difficult to measure the surface temperature accurately. Normally, there are two typical techniques employed to measure the surface temperature: (1) by thermocouple mounted to the sample surface and (2) by infrared camera. Nevertheless, both techniques have disadvantages.

The significant error of measuring the surface temperature with a thermocouple occurs when the thermocouple is not properly contacting the sample surface. A huge drop in temperature is obtained since the thermocouple picks up the hot gas temperature surrounding the sample surface rather than the actual sample surface temperature [32]. For the measurement of surface temperature by infrared camera, the foremost problem is determining a suitable emissivity of the sample surface. The emissivity of the sample surface changes when the sample is heated as the sample surface darkens. The emissivity of oven dry wood ranges from 0.6 up to 0.72 [28]. However, the emissivity would approach unity once the sample ignites.

In this study, we mainly used an infrared camera (Thermovision 550) to measure the surface temperature. The infrared camera was controlled by the software AGEMA Research 2.1. The infrared camera was well calibrated with thermocouples in order to correct for the emissivity issue. In the calibration procedure, the samples were exposed to an incident heat flux of 40.2 kW/m² and 56.2 kW/m². The surface temperatures were then measured by both the infrared camera with a emissivity setting of unity, and a type K, Chromel-Alumel thermocouple, with an approximately wire diameter of 0.5 mm. The thermocouple bead was flattened to obtain a thin film before installed underneath, approximately 1 mm, the sample surface. We produced a calibration curve by using the temperature measured by thermocouple as a reference temperature. We assumed that the ratio of the thermocouple measured temperature to the infrared camera measured temperature is a function of the infrared camera measuring temperature ($\frac{T_{TC}}{T_{IR}} = f(T_{IR})$).

Using a best curve fit to the data, the calibration curve was obtained. The plot of the calibration results as shown in Figure 2.4 and the calibration correlation can be expressed as in equation 2.1:

$$\frac{T_{TC}}{T_{IR}} = f(T_{IR}) = -107.5 + 30.89[\ln(T_{IR})] - 2.20[\ln(T_{IR})]^2 \quad (2.1)$$

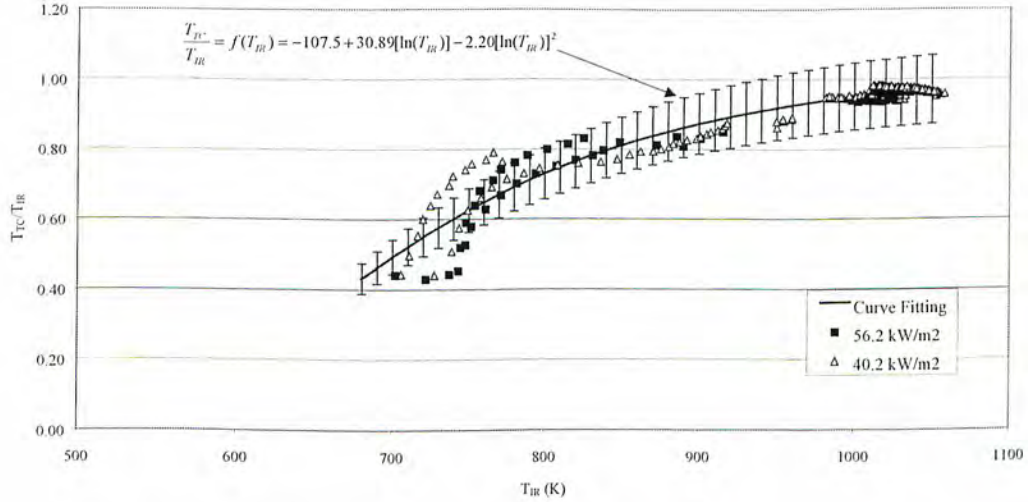


Figure 2.4: Calibration curve for infrared camera with 10% error bar.

The curve represents the best fitting function to the calibration data with 10% error bars. The ratio of T_{TC} to T_{IR} can refer to the emissivity of the sample. It can imply that the emissivity of the sample increases when surface temperature increases. This ratio is almost constant (~ 0.95), when the surface temperature is approximately greater than 950K.

Chapter 3. Thermo-Physical Properties of Wood

To investigate the ignition of wood, we need to evaluate a number of properties of wood. These properties can be obtained from the experiment while others are obtained from some of literature.

3.1 Density

The density of wood is dependent on the species, the age of the tree and sapwood or heartwood. In this study redwood was examined. The density of the oven dry sample was calculated from the formula such that

$$\rho_w = \frac{m_w}{V} \quad (3.1)$$

Prior to each test, the mass and volume of a sample was measured, so that density could be calculated from equation 3.1.

3.2 Moisture Content

Wood exchanges moisture with the surroundings depending on the relative humidity and the surrounding temperature [27]. The amount of moisture accumulated in the wood will significantly affect the ignition time. First, it will effectively increase the thermal capacity of the sample due to the high heat capacity of water. Second, the water contained will evaporate to vapor and dilute the pyrolysis products; therefore, the time taken to achieve a flammable limit may be longer than an oven dried sample. However, the moisture in the sample should not affect the value of a critical heat flux since the critical heat flux is measured after a long time, which means the sample will have

enough time to dry. The idea that the moisture content does not affect the critical heat flux was experimentally confirmed in [22].

3.3 Thermal Conductivity

The thermal conductivity is a measure of the rate of heat flow through one unit thickness of a material subjected to a temperature gradient. For wood, the thermal conductivity is affected by a number of factors: density, moisture content, and grain orientation. However, in this study the main effect of thermal conductivity is caused by grain orientation. The literature [27,33] suggested that the thermal conductivity of wood is 1.5 to 2.8 times greater when heat flow is parallel to the grain than when heat flow is perpendicular to the grain. Therefore, we might expect that more heat will accumulate at the surface of a sample when heating perpendicular than when heating parallel to the grain resulting that the sample surface temperature when heated perpendicular to the grain will be greater than when heated parallel to the grain.

3.4 Specific Heat Capacity

The specific heat capacity is defined as the amount of energy needed to increase one unit of mass one unit in temperature. The specific heat capacity of wood depends on the temperature and the moisture content of the wood. The specific heat capacity of wood with high moisture content is greater than dry wood according to the large specific heat of water.

3.5 Thermal Inertia

The thermal inertia ($k\rho c$) is a product of three material properties: thermal conductivity (k), density (ρ), and specific heat capacity (c). It is a quantity that indicates how quickly a material takes to heat up when it is exposed to an incident heat flux. A material with higher thermal inertia takes longer to heat up. Thermal inertia is temperature dependent; therefore, the value of thermal inertia obtained at ambient temperature is not the same as at the ignition temperature. In this study, we derived the apparent thermal inertia from experiment data for analysis purposes. The use of apparent thermal inertia is reasonable since the apparent value will account for the effect of temperature change.

3.6 Emissivity

The emissivity of a material is the ratio of the radiative energy that can emit from a real surface to the radiative energy that emits if consider that material surface as a black body. The emissivity of oven dry wood ranges from 0.6 up to 0.72 [28]. However, the emissivity would change during heating as the wood surface darkens.

Chapter 4. Experimental Results and Interpretation

Three important ignition parameters: ignition time, surface temperature, and mass loss were measured in the experiment. The complete of experimental results are presented in appendix A and appendix B. A discussion here will present the results from measurement of ignition time, surface temperature, and mass loss rate and from observations.

4.1 Ignition Time

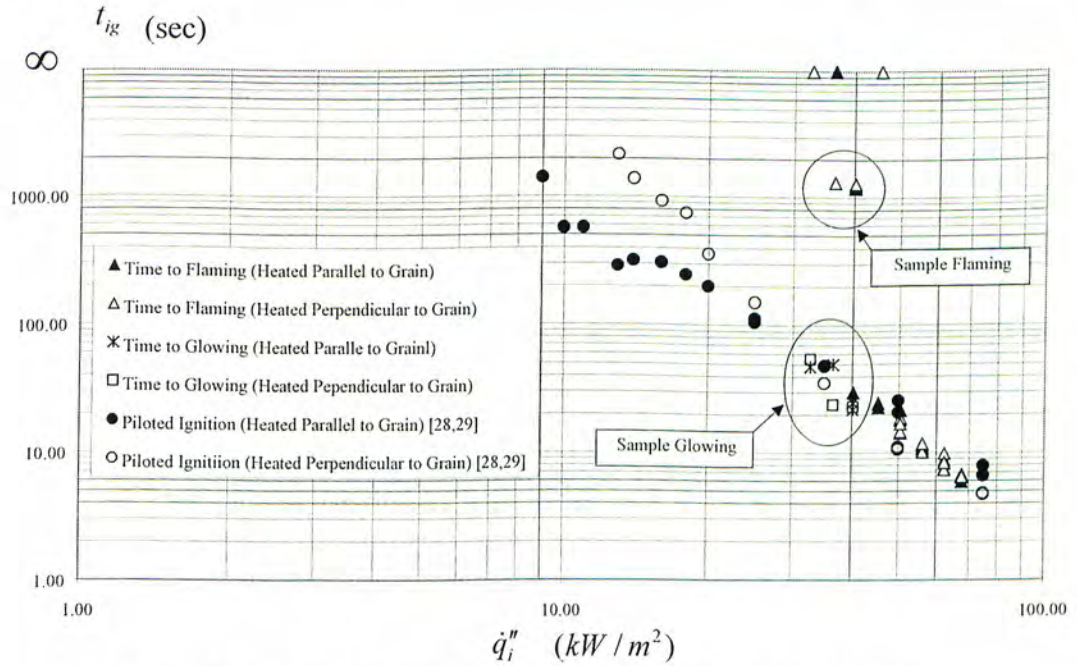


Figure 4.1: The plot of ignition time against incident heat flux.

The auto-ignition time data plotted against the incident heat flux is shown in Figure 4.1. We found that for the high incident heat flux, the sample was flaming almost immediately after exposed to the incident heat flux. However, for the low incident heat

flux, the sample would be glowing before flaming ignition. Therefore, we would like to define two definitions of ignition time here: (1) time to flaming, and (2) time to glowing. We define the time to flaming as the duration of time after the sample is exposed to an incident heat flux until it ignites to produce a visible flame. This time can be obviously observed from the experiment by eye. We define the time to glowing as the time when the surface temperature of the sample is greater than the corresponding surface temperature of the insulator, which is inert. This is based on the assumption that, in general, we might expect for two materials that have different thermal inertia ($k\rho c$), when they are exposed to the same incident heat flux, the surface temperature of the material with lower thermal inertia should be greater than the other one with higher thermal inertia. The thermal inertia is the product of thermal conductivity, density and specific heat capacity. The specific heat capacity of wood is approximately the same as the insulator. The thermal conductivity is proportional to the density; therefore, thermal inertia of wood and insulator can be inferred from their thermal conductivity. We can say that the material with higher thermal conductivity will have a lower surface temperature if both materials are inert. However, a high thermal conductivity material that undergoes a chemical reaction (surface oxidation) can have surface temperature greater than a material with low thermal conductivity and inert. The thermal conductivity of the sample (red wood) is approximately 0.1 W/m.K [27], while the thermal conductivity of the insulator (Kaowool PM board) is 0.073 W/m.K. The thermal conductivity of the sample is greater than the insulator; therefore, the surface temperature of the sample should be lower than for the insulator, if the sample is inert. However, the plot of surface temperature time history (see Figure 4.3) shows that the

surface temperature of the sample is greater than the corresponding insulator. Consequently, we can deduce that the greater surface temperature of the sample results from surface oxidation.

Figure 4.1 also shows a comparison between the time to flaming for auto-ignition and for pilot ignition [28,29]. At high incident heat flux ($>40.2 \text{ kW/m}^2$), the flaming auto-ignition time merge to the pilot ignition times. The sample was ignited and a visible flame could be noticed almost immediately (within 30 seconds) after exposed to the incident heat flux. For low incident heat flux ($< 40.2 \text{ kW/m}^2$), the flaming auto-ignition time prominently diverges from the piloted ignition times. The longer flaming ignition time for auto-ignition results since there are no external heat sources promote the ignition process; while for piloted ignition, a small pilot flame or an electrical arc will help the ignition process. However, the time to glowing for the low heat flux auto-ignition data still follows the trend of the time to flaming ignition for the high heat flux data. The study found that at low heat flux some samples started glowing up to 20 minutes before a visible flame was noticed.

4.2 Surface Temperature

A typical surface temperature time history is shown in Figure 4.2 for the high incident heat flux case ($> 40.20 \text{ kW/m}^2$) and Figure 4.3 for the low incident heat flux case ($<40.2 \text{ kW/m}^2$). At the high incident heat flux (see figure 4.2), the sample ignited almost immediately after it was exposed. The surface temperature rose gradually until the sample ignited which is indicated by the jump of surface temperature. From the surface

temperature time history and observation, the sample did not flash before ignition like it sometimes does in the piloted ignition [3,4,31].

For the low incident heat flux (see Figure 4.3), the surface temperature gradually increased and reached a constant value of approximately 700 C. The sample started glowing, which we defined as when the sample surface temperature was greater than the corresponding insulator surface temperature. However, the surface temperature plotted in the graph was the average surface temperature over the exposed sample area. Some local glowing of hot spots on the sample surface may occur before the average surface temperature of the sample started to be greater than the corresponding surface temperature of the insulator.

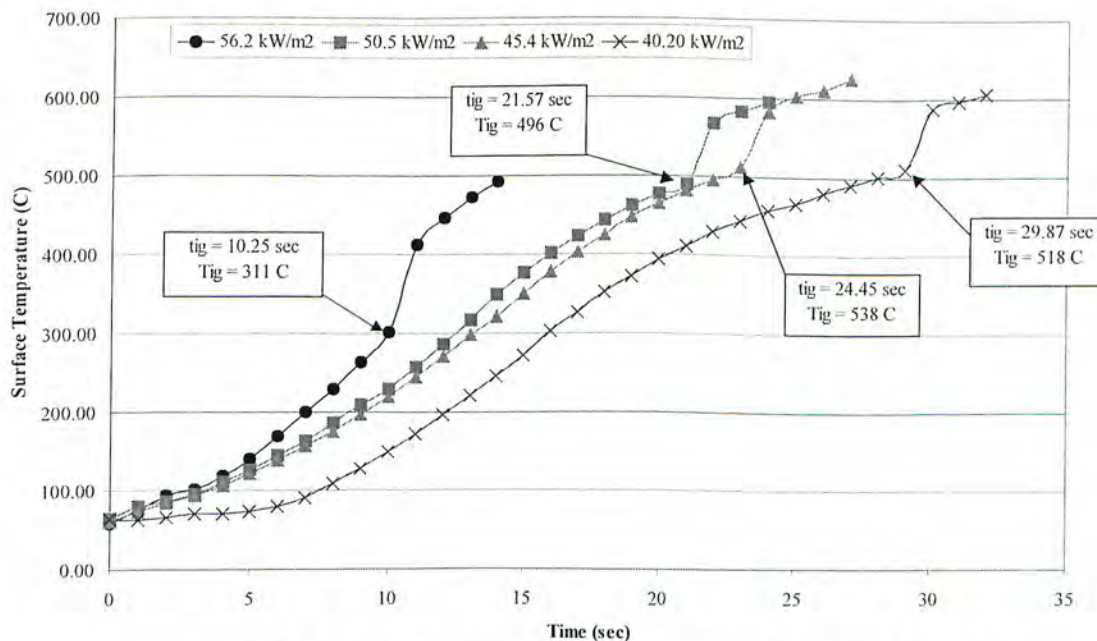


**Figure 4.2: Surface temperature history (High incident heat flux).
(Heated parallel to grain)**

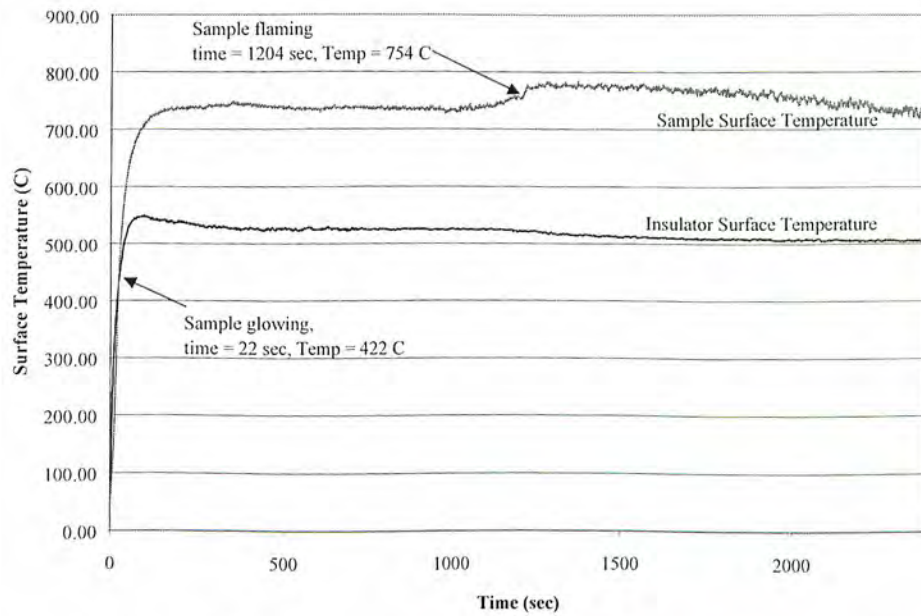


**Figure 4.3: Surface temperature history (Low incident heat flux).
(Heated perpendicular to grain: 40.2 kW/m²)**

4.3 Mass Loss and Mass Loss Rate (Mass Flux)

A typical mass loss rate (mass flux) time history is shown in Figure 4.4 for the high incident heat flux case and Figure 4.5 for the low incident heat flux case. The sample started to produce pyrolysis product when its temperature reached the pyrolysis temperature of approximately 300 C [2]. We can divide the pyrolysis behavior of solid material into two types: non-charring material and charring material. Non-charring materials burn completely leaving no-residue such as a flammable liquid. Charring materials leave significant amounts of residue when they burn. Wood is a charring material; however, before the char layer builds up, the mass loss rate of the sample behaves like a non-charring material. The mass loss rate increases with time. Once the char layer is formed on the surface, it blocks the release of pyrolysis product from the

sample resulting in a decrease of the mass loss rate. After the char layer formed, the mass loss rate decreased and then remained constant (approximately 8 g/sm^2) until the back effect occurred. When the thermal wave reached the back of the sample, the mass loss rate increased again, which could be noticed from the plot. The whole sample became charred and then the mass loss rate decreased again due to a depletion of the sample. The sample was almost gone after 40 minutes.

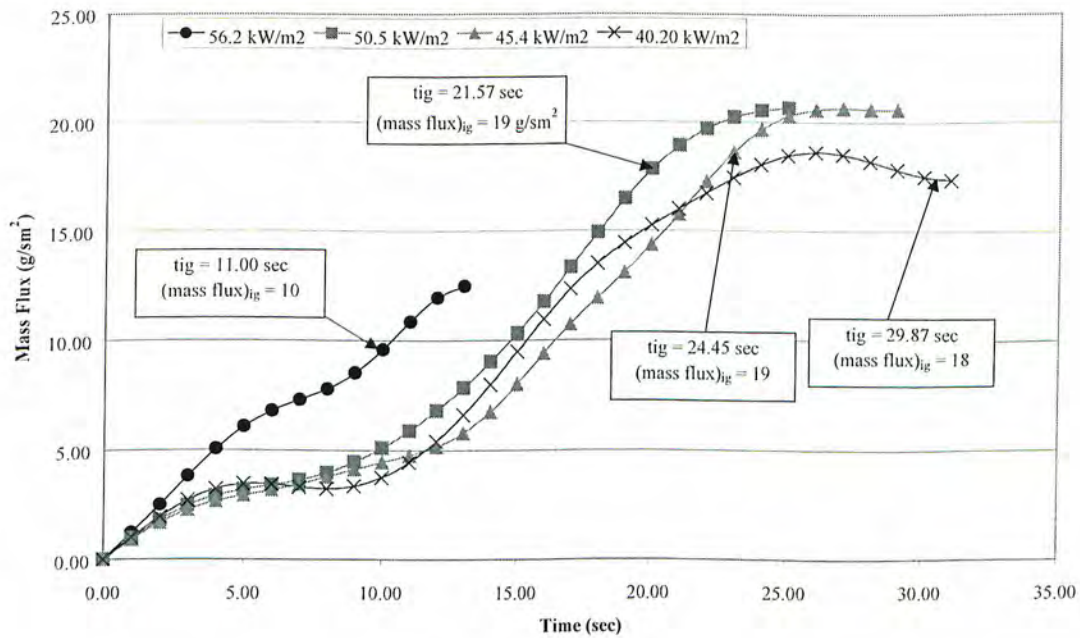


Figure 4.4: Mass flux history (High incident heat flux).
(Heated parallel to grain)

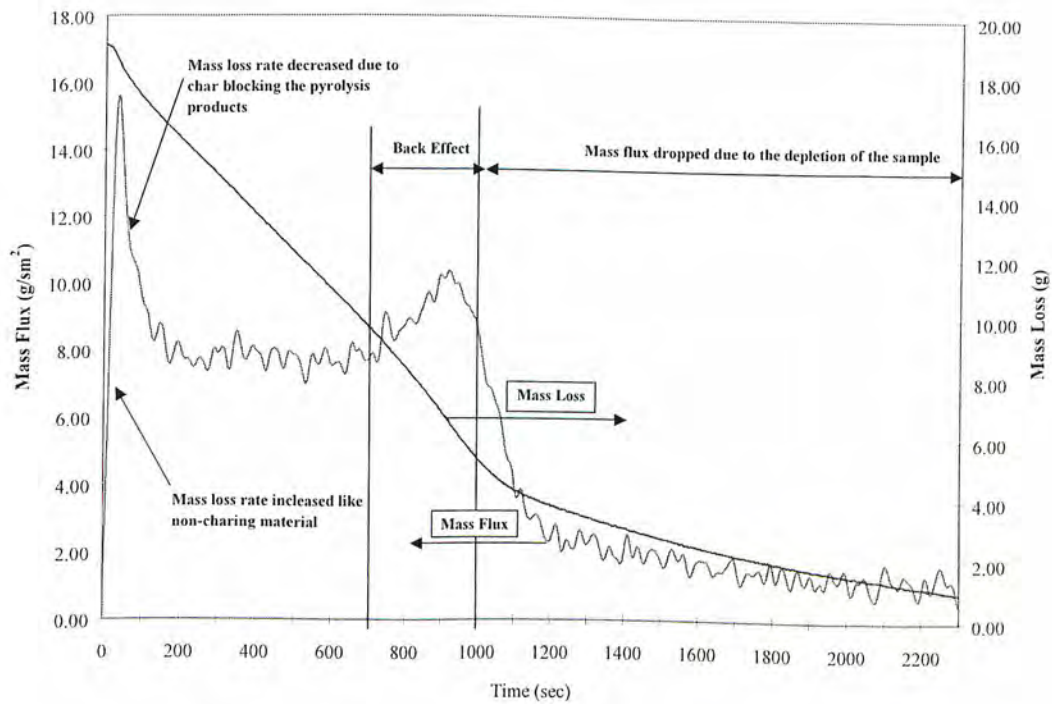


Figure 4.5: Mass flux history (Low incident heat flux).

(Heated parallel to grain: 40.2 kW/m²)

4.4 Flaming Ignition and Glowing Ignition

From carefully observing the auto-ignition behavior, we found that a sample was flaming ignition when it was exposed to a high incident flux ($> 40 \text{ kW/m}^2$) while the sample started glowing before flaming ignition when exposed to a low incident heat flux ($< 40 \text{ kW/m}^2$). As suggested by Martin [21], he categorized the ignition behavior of cellulosic material into three regions: convection-controlled, diffusion-controlled, and ablation-controlled. Spearpoint & Quintiere [28] interpreted Martin's work as (1) convection-controlled (very low heat flux): Ignition time controlled by diffusion of oxygen into vaporized fuel and hot surface; (2) diffusion-controlled: Ignition time

controlled by thermal (diffusion) conduction;(3) ablation-controlled: Ignition time controlled by the time to vaporize the surface fuel. In this study we found that the ignition of the sample fell into two regions: diffusion-controlled (flaming ignition) and convection-controlled (glowing ignition).

Flaming ignition occurred when the sample was exposed to a high incident heat flux. The pyrolysis products emanated from a sample mixing with fresh air producing a boundary layer of combustible mixture. The boundary layer near the sample surface was laminar; however, when the combustible mixture traveled further away from the surface, it became turbulent. Once the combustible mixture reached a lower flammable limit and the conditions were suitable, the auto-ignition of the sample was achieved. The flame first appeared in the gas phase above the sample surface and then propagated back to the sample surface (see Figure 4.6 and Figure 4.7). This ignition behavior is consistent with the observations of Simms [25].

For the low incident heat flux cases (i.e. $<40.2 \text{ kW/m}^2$), the sample started glowing before flaming ignition. The heated sample surface became black as it turned to char and then local glowing indicated by red spots, started from the bottom edge of the sample and propagated up all over the surface. By observation from the video record, we found that in the case of flaming ignition success, the flame first appeared near the glowing surface (see Figure 4.8). The location of the first appearance of the flame for the low incident heat flux case is different from the high incident heat flux case, in which the first flame occurred relatively far away from the sample surface.

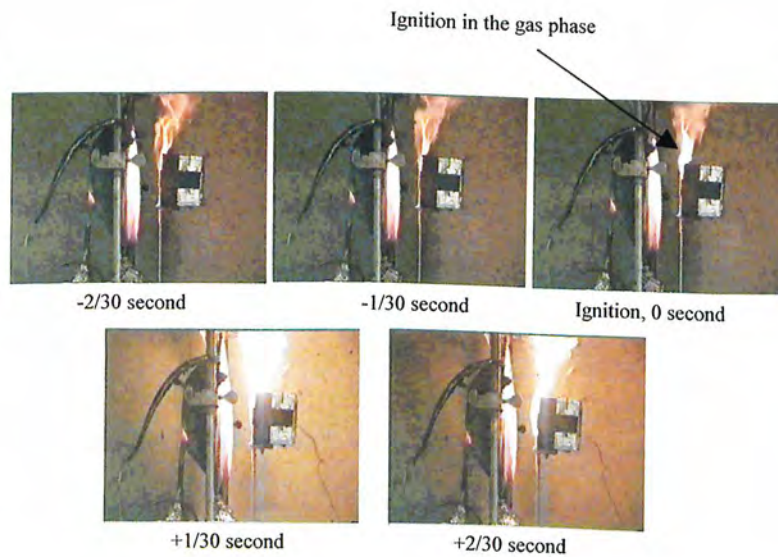


Figure 4.6: Flaming ignition process of redwood (Side view).
(Heated parallel to grain: 67.8 kW/m^2)

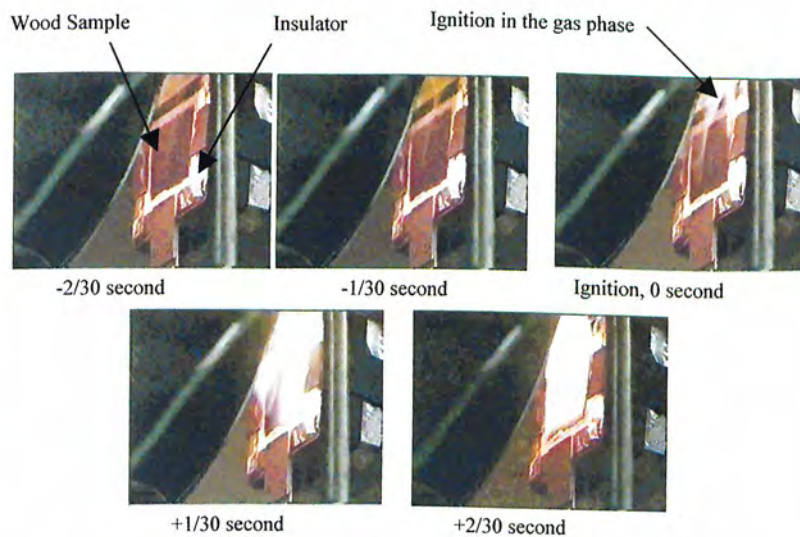


Figure 4.7: Flaming ignition process (Front view)
(Heated parallel to grain: 50.5 kW/m^2)

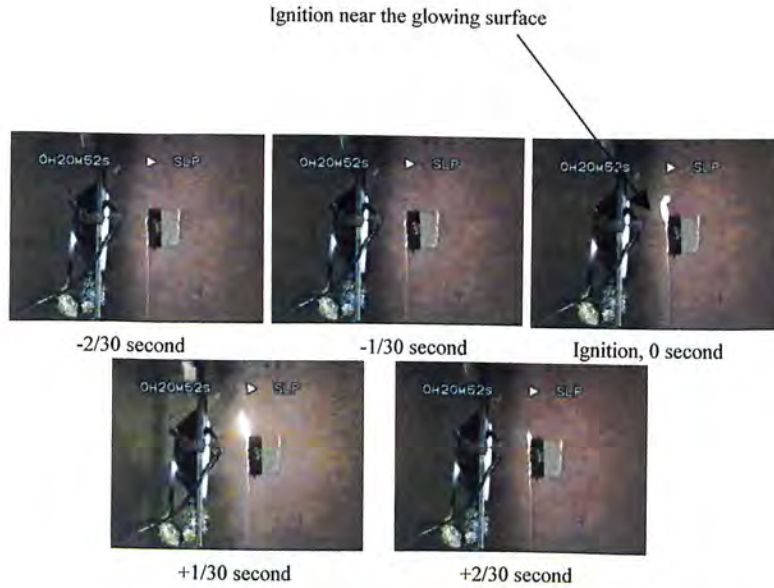


Figure 4.8: Glowing ignition process (Side view)
(Heated perpendicular to grain: 40.2 kW/m^2)

The infrared surface images are shown in Figure 4.9. In these pictures, the sample was heated parallel to the grain with an incident heat flux of 40.20 kW/m^2 . The surface of the sample was heated causing isothermal lines, which correspond to the grain alignment. The small square frame indicates the sample area while it was wrapped by an insulator. The local glowing on the sample surface can be noticed from the red spots on the bottom edge of the sample (i.e. at 20 seconds). The temperature of those area were approximately 650 C ; however, in this case the average surface temperature of the sample was still lower than the corresponding insulator. As the time proceeded, the average surface temperature of the sample became greater than the corresponding insulator (i.e. at 100 seconds). This was due to the surface oxidation over the sample

surface. The crossed lines shown on the sample area indicated cracks on the wood surface.

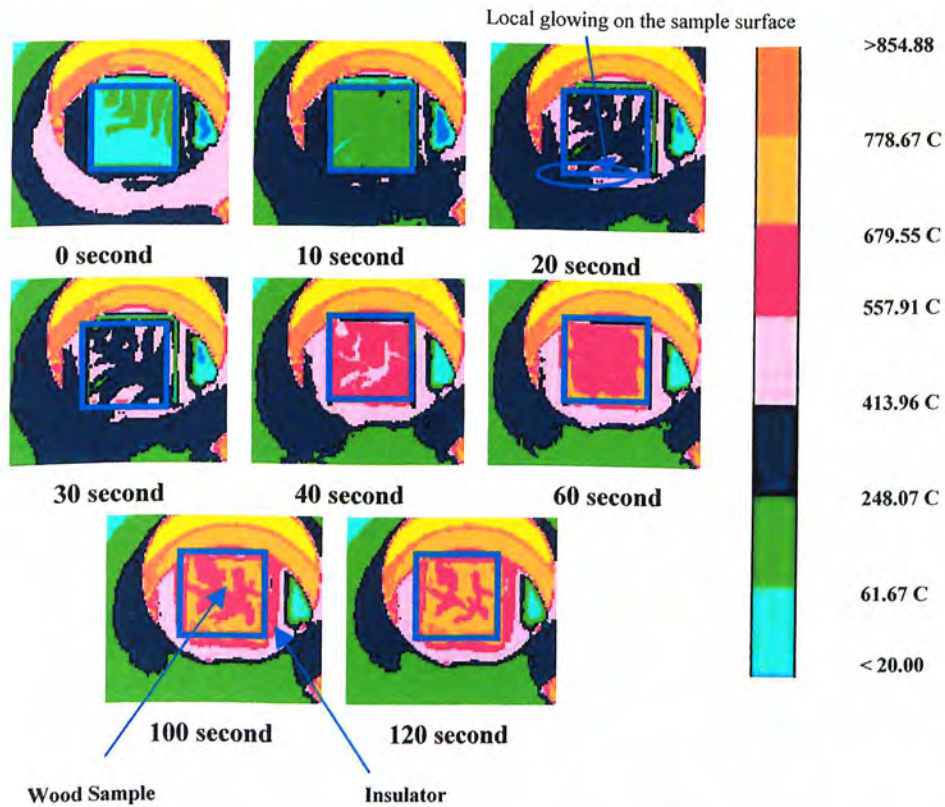


Figure 4.9: The surface temperature of the sample captured by infrared camera.

(Heated parallel to grain: 40.2 kW/m²)

$$\dot{q}''(t) = \alpha \dot{q}_i'' - \varepsilon \sigma (T_s^4 - T_0^4) - \bar{h} (T_s - T_0) \quad (5.1)$$

The emissivity ε and the absorptivity α of the sample change with time; however, we assume them to be unity since the sample surface will become dark when it is heated.

Therefore, equation (5.1) can be reduced to

$$\dot{q}''(t) = \dot{q}_i'' - \sigma (T_s^4 - T_0^4) - \bar{h} (T_s - T_0) \quad (5.2)$$

Introducing a dimensionless heat flux parameter β , which is defined as the ratio of the heat losses at the surface due to radiation and convection to the incident heat flux where

$$\beta = \frac{\sigma (T_s^4 - T_0^4) + \bar{h} (T_s - T_0)}{\dot{q}_i''} \quad (5.3)$$

Equation (5.2) can be rewritten in term of β as

$$\dot{q}''(t) = \dot{q}_i'' (1 - \beta) \quad (5.4)$$

The conservation of energy for the control volume in figure 5.1 can be written as

$$\frac{d}{dt} \iiint_{CV} \rho u dV + \iint_{CS} \rho h (\bar{v} - \bar{w}) \bar{n} dS = \dot{Q}_{add} + \dot{W}_{shaft} + \iint p \bar{n} dS \quad (5.5)$$

Since there is no shaft work or pressure work and the heat addition per unit area to the control volume is equal to $\dot{q}''(t)$, equation (5.5) will reduce to

$$\frac{d}{dt} \iiint_{CV} \rho u dV + \iint_{CS} \rho h (\bar{v} - \bar{w}) \bar{n} dS = \dot{q}''(t) \quad (5.6)$$

Assuming the thermal properties (density ρ and thermal conductivity c) of the sample are constant during the heating time, and the thermal penetration moves at velocity $\frac{d\delta}{dt}$

in the x-direction, equation (5.6) becomes

$$\rho c \frac{d}{dt} \int_0^\delta T(x) dx + \rho c T_0 \left(-\frac{d\delta}{dt} \right) = \dot{q}''(t)$$

$$\text{or} \quad \rho c \left(\frac{d}{dt} \int_0^\delta T(x) dx - T_0 \left(\frac{d\delta}{dt} \right) \right) = \dot{q}''(1 - \beta) \quad (5.7)$$

The LHS of equation (5.7) can be rewritten as

$$\begin{aligned} \rho c \left(\frac{d}{dt} \int_0^\delta T(x) dx - T_0 \left(\frac{d\delta}{dt} \right) \right) &= \rho c \left(\frac{d}{dt} \int_0^\delta T(x) dx - T_0 d \int_0^\delta \frac{dx}{dt} \right) \\ &= \rho c \left(\frac{d}{dt} \int_0^\delta T(x) dx - d \int_0^\delta T_0 \frac{dx}{dt} \right) \\ &= \rho c \left(\frac{d}{dt} \int_0^\delta T(x) dx - d \int_0^\delta T_0 \frac{dx}{dt} \right) \\ &= \rho c \left(\frac{d}{dt} \int_0^\delta T(x) dx - \frac{d}{dt} \int_0^\delta T_0 dx \right) \\ &= \rho c \left(\frac{d}{dt} \int_0^\delta (T(x) - T_0) dx \right) \end{aligned} \quad (5.8)$$

Thus, from equation (5.7) and (5.8), the final energy equation can be expressed as

$$\rho c \left(\frac{d}{dt} \int_0^\delta (T(x) - T_0) dx \right) = \dot{q}''(1 - \beta) \quad (5.9)$$

The boundary conditions of equation (5.9) are

- i) $x = 0$, $\dot{q}''(t) = \dot{q}''(1 - \beta) = -k \left(\frac{dT}{dx} \right)$, Where k is thermal conductivity.
- ii) $x = \delta$, $T = T_0$
- iii) $x = \delta$, $\frac{dT}{dx} = 0$ (No heat loss).

Spearpoint and Quintiere [29] suggested that the temperature profile that satisfies these boundary conditions could be given as

$$T(x) - T_0 = \frac{\dot{q}''(t)}{2k} \delta \left(1 - \frac{x}{\delta}\right)^2$$

(5.10)

or in term of dimensionless heat flux parameter β as

$$T(x) - T_0 = \frac{\dot{q}_i''(1 - \beta)}{2k} \delta \left(1 - \frac{x}{\delta}\right)^2$$

(5.11)

Substituting the temperature profile, equation (5.10), back into equation (5.9) and solving for thermal penetration depth δ we get

$$\delta^2 = \frac{6 \frac{k}{\rho c} \int_0^t \dot{q}''(t) dt}{\dot{q}''(t)}$$

(5.12)

The term $\int_0^t \dot{q}''(t) dt$ can be estimated in term of average heat flux from duration time $t =$

0 to $t = t$ or

$$\int_0^t \dot{q}''(t) dt = \left(\frac{\dot{q}''(t) + \dot{q}''(0)}{2} \right) t$$

(5.13)

Substituting equation (5.13) into equation (5.12) and since at $t = 0$, $\dot{q}''(0) = \dot{q}_i''$, then equation (5.12) becomes

$$\delta^2 = 3 \frac{k}{\rho c} \left(\frac{\dot{q}''(t) + \dot{q}_i''}{\dot{q}''(t)} \right) t$$

This can be written in term of the dimensionless heat flux parameter β as

$$\delta^2 = 3 \frac{k}{\rho c} \left(\frac{2 - \beta}{1 - \beta} \right) t \quad (5.14)$$

Rearranging the temperature profile equation (5.11) for δ , we get

$$\delta = \frac{2k(T(x) - T_0)}{\dot{q}_i''(1 - \beta)(1 - \frac{x}{\delta})^2}$$

or
$$\delta^2 = \frac{4k^2(T(x) - T_0)^2}{[\dot{q}_i''(1 - \beta)]^2(1 - \frac{x}{\delta})^4}$$

(5.15)

Equating equation (5.14) to (5.15), and rearranging for t, we get

$$t = \frac{4}{3} \left(\frac{k\rho c(T(x) - T_0)^2}{\dot{q}_i''^2(1 - \beta)(2 - \beta)(1 - \frac{x}{\delta})^4} \right) \quad (5.16)$$

At the moment of ignition we have conditions at the sample surface ($x = 0$) as follows:

- i) $t = t_{ig}$
- ii) $T(x) = T(0) = T_s = T_{ig}$
- iii) $\beta = \beta_{ig} = \frac{\sigma(T_{ig}^4 - T_0^4) + \bar{h}(T_{ig} - T_0)}{\dot{q}_i''}$

Substituting those conditions back into equation (5.16) the ignition time can be presented as

$$t_{ig} = \frac{4}{3} \left(\frac{k\rho c}{(1 - \beta_{ig})(2 - \beta_{ig})} \right) \left(\frac{T_{ig} - T_0}{\dot{q}_i''} \right)^2 \quad (5.17)$$

In order to evaluate this equation, we need to know (1) critical heat flux for auto-ignition ($\dot{q}_{cr}''$), (2) ignition temperature (T_{ig}), and (3) thermal inertia ($k\rho c$). These values can be calculated from the experimental data, which will be discussed in the following sections.

5.2 Critical Heat Flux

The critical heat flux ($\dot{q}_{cr}''$) is the minimum heat flux that the auto-ignition can achieve. It is more reasonable to calculate the critical heat flux considering only the long time ignition data (i.e. glowing ignition case), since the critical heat flux is the heat flux that takes the ignition time goes to infinite. We can estimate the critical heat flux from the ignition time data by extrapolating the linear regression line of the plot of $\frac{1}{\sqrt{t_{ig}}}$ against an incident heat flux $\dot{q}_i''$ fit to the low heat flux data (see Figure 5.2 and Figure 5.3).

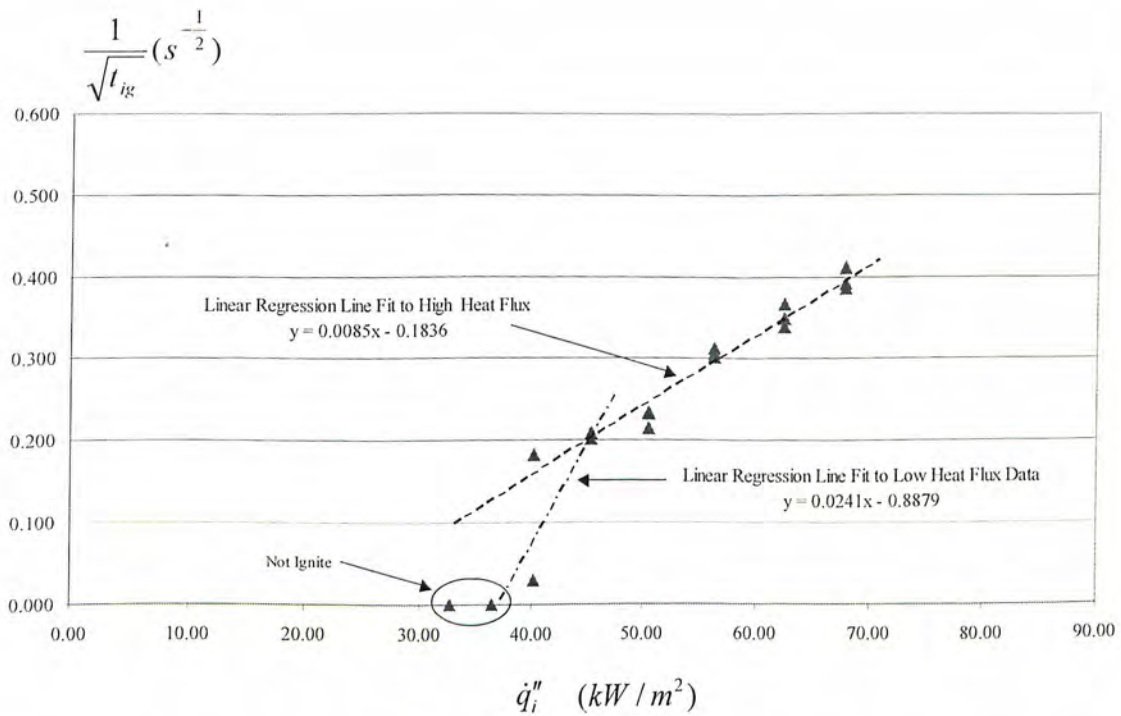


Figure 5.2: Linear regression fit to low and high incident heat flux ignition time data (Heated parallel to grain).

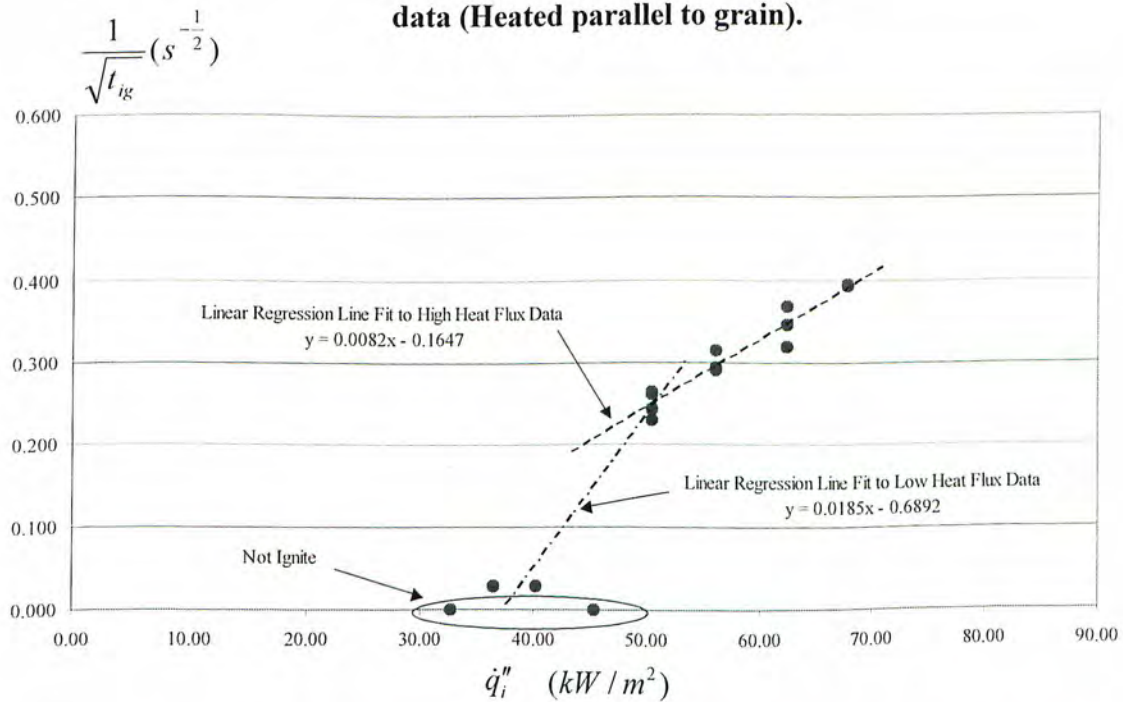


Figure 5.3: Linear regression fit to low and high incident heat flux ignition time data (Heated perpendicular to grain).

Computing the value of the interception point on x axis of the linear regression line fit to the low incident heat flux ignition time data, we obtained the values of 37 kW/m² for heated parallel to grain scenario and 35 kW/m² for heated perpendicular to grain scenario. The critical heat flux from this study is higher than the values obtained from other researchers shown in Table 5.1. The reason is that the mode of ignition here is auto-ignition while the others are piloted ignition.

Table 5.1: Comparison of critical heat flux

Heating Configuration	Extrapolating (Auto-Ignition) (kW/m²)	Spearpoint& Quintiere [28,29] (Piloted Ignition) (kW/m²)	Janssen [12] (Piloted Ignition) (kW/m²)	Tran&White [15] (Piloted Ignition) (kW/m²)
Parallel to Grain	37	5.9	-	-
Perpendicular to Grain	35	15.5	14	12.4

5.3 Ignition Temperature

Figure 5.4 shows the plot of ignition surface temperature as a function of incident heat flux. The 10 % error bar represents the error due to the calibration factor of the infrared camera. It is obvious that the auto-ignition temperature varies with an incident heat flux. The auto-ignition surface temperature increases when the incident heat flux decreases. An increase of ignition surface temperature is due to the high surface temperature from the forming of char on the sample surface when the incident heat flux is low. Figure 5.4

also shows the effect of grain orientation to the ignition surface temperature. The higher ignition surface temperature occurs when heated perpendicular to grain than when heated parallel to grain cause form the difference of the thermal conductivity depend on the grain orientation. This is due to that the thermal conductivity of wood is greater when the heat flows parallel to grain than when the heat flows perpendicular to the grain yielding that more heat will accumulate at the surface for heated perpendicular to grain before it ignited.

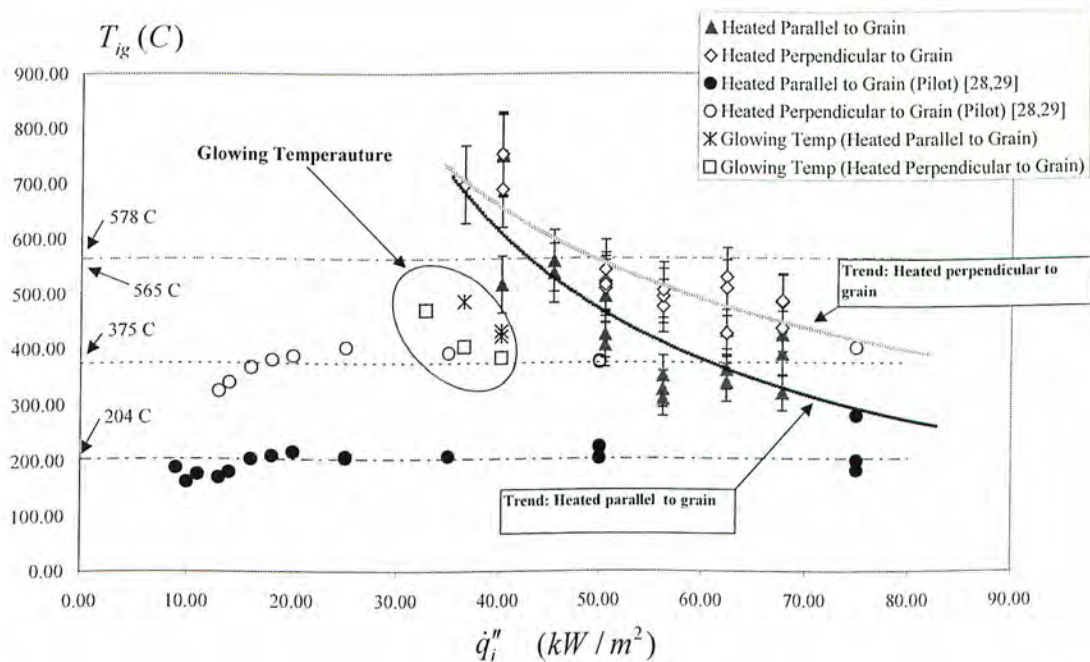


Figure 5.4: The plot of ignition surface temperature against incident heat flux.

The glowing temperature plots in Figure 5.4 indicate the temperature at which the surface temperature of the sample overtook the corresponding surface temperature of the insulator. This glowing temperature ranges from 383 C up to 487 C depending on

the incident heat flux. However, the surface temperature of the sample when the surface oxidation occurred could achieve up to 700 C.

Apparently the auto-ignition surface temperature is greater than the piloted ignition temperature. The reason is due to that for auto-ignition, the ignition occurs by itself; therefore more energy will be required to promote the ignition indicating from a high surface temperature. Kashiwagi [18] commented that there are two necessary conditions that have to be satisfied for achieving auto-ignition. First, sufficient amounts of fuel and oxygen must be available in the gas phase. Second, gas phase temperatures must be high enough to accelerate the chemical reaction. However, for piloted ignition, only first condition has to be met since the external heat source will provide the energy for the second condition. For these reasons, the auto-ignition temperature will normally be higher than the piloted ignition temperature.

Nevertheless, if we consider the trend lines of the auto-ignition surface temperature, as incident heat flux increases the auto-ignition temperature decrease and it seems to be approach the same average ignition temperature for piloted ignition. We may imply from these trends that if an incident heat flux is large enough, the auto-ignition temperature will be the same as the piloted ignition temperature. We can estimate the average ignition temperature for the low incident heat flux case (i.e. $q_i'' \rightarrow \dot{q}_{cr}'', \beta_{ig} \rightarrow 1$) based on the assumption that when the ignition time is very long the heat loss at the sample surface is only due to convection and radiation loss, which can be written as

$$\dot{q}_{cr}'' = \bar{h}(T_{ig} - T_0) + \sigma(T_{ig}^4 - T_0^4) \quad (5.18)$$

The average convective heat transfer coefficient ($\bar{h}$) needs to be evaluated in order to calculate the ignition temperature (T_{ig}). The boundary layer of pyrolysis product near the sample surface can be considered as a laminar boundary layer [1]. We will use a correlation of the Nusselt number for a constant surface temperature for a vertical flat plate for laminar flow to evaluate the convective heat transfer coefficient. The Nusselt number is given as [3]

$$\bar{Nu} = \frac{\bar{h}L}{k} = 0.59 Ra^{1/4} \quad (5.19)$$

The variation of $\bar{h}$ to the ignition temperature is not significant as shown in Figure 5.5; therefore, we assumed that $\bar{h}$ is constant for each grain orientation. We obtained the average value of $\bar{h}$ as 13.55 W/m²K for heated parallel to grain configuration and 13.39 W/m²K for heated perpendicular to grain configuration.

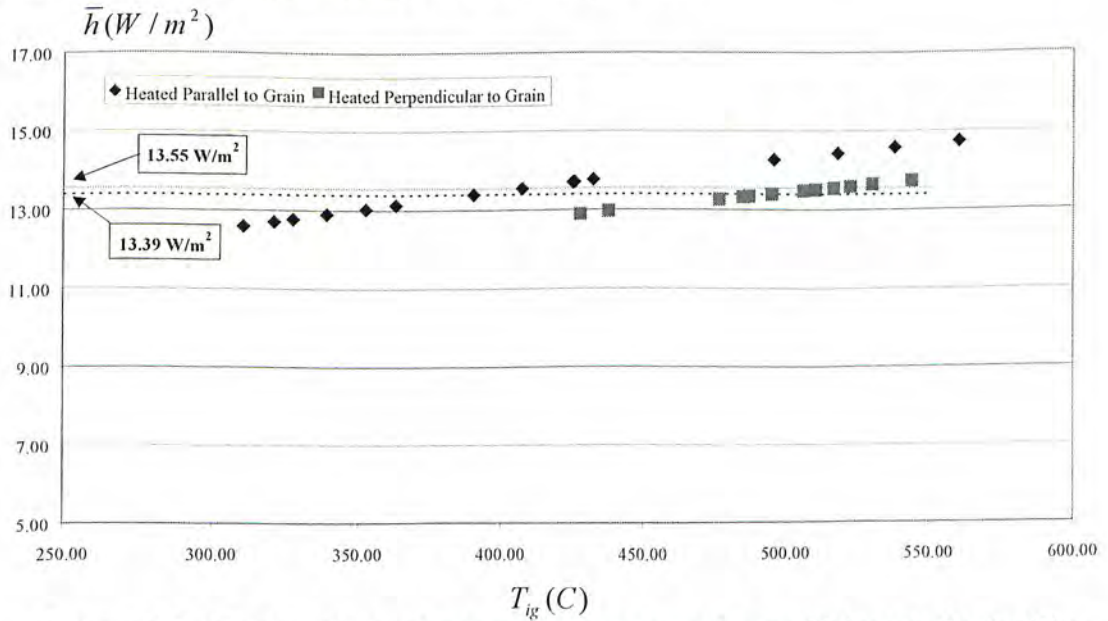


Figure 5.5: The variation of convective heat transfer coefficient to the ignition temperature.

Solving equation (5.18), we obtain the average ignition temperature of 578 C for heated parallel to grain and 565 C for heated perpendicular to grain. These values fall within in the range of auto-ignition temperatures measured from the experiment. However, as we discuss above, the average auto-ignition temperatures are higher than the average ignition temperature of piloted ignition, which are 375 C for heated perpendicular to grain and 204 C for heated parallel to grain [28,29].

Many researchers suggested that the critical ignition temperature does not depend on an incident heat flux. Simms [25] gave the critical ignition temperature as 525 C. These fixed-critical ignition temperatures seem to contradict this study as we found that the ignition temperatures vary with the incident heat flux.

5.4 Thermal Inertia

Since thermal inertia is temperature dependent, it will change when the wood is heated. Therefore, it is more reasonable to use the apparent thermal inertia derived from the experimental data for the calculation purposes. When the incident heat flux is large, the value of $\frac{1}{\sqrt{t_{ig}}}$ varies linearly with the incident heat flux. Consider equation (5.17) and

rearrange as

$$\frac{1}{\sqrt{t_{ig}}} = \left(\frac{4}{3} k \rho c \left[\frac{1}{(2 - \beta_{ig})(1 - \beta_{ig})} \right] \right)^{-1/2} \left(\frac{\dot{q}_i''}{T_{ig} - T_0} \right) \quad (5.20)$$

For large incident heat flux, $\beta_{ig} \rightarrow 0$, then equation (5.20) can be reduced to

$$\frac{1}{\sqrt{t_{ig}}} = \sqrt{\left(\frac{3}{2(k\rho c)} \right)} \left(\frac{\dot{q}_i''}{T_{ig} - T_0} \right) \quad (5.21)$$

We assume that $\frac{1}{\sqrt{t_{ig}}}$ varies linearly with incident heat flux ($\dot{q}_i''$), therefore the slope of

equation (5.21) can be expressed as

$$slope = \sqrt{\left(\frac{3}{2k\rho c}\right)\left(\frac{1}{T_{ig} - T_0}\right)} \quad (5.22)$$

Rearranging equation (5.22) to get $k\rho c$, the apparent thermal inertia will be

$$k\rho c = \frac{3}{2} \left(\frac{1}{slope(T_{ig} - T_0)} \right)^2 \quad (5.23)$$

Using equation (5.23), we obtained the apparent thermal inertia of $0.068 \text{ kJ}^2\text{m}^{-4}\text{K}^2\text{s}^{-1}$ for heated parallel to grain and $0.076 \text{ kJ}^2\text{m}^{-4}\text{K}^2\text{s}^{-1}$ for heated perpendicular to grain. Many researchers have quoted the values of thermal inertia. A comparison is shown in Table 5.2.

Table 5.2: Comparison of apparent thermal inertia.

Heating Configuration	Derived from Experiment Data (Auto-Ignition) ($\text{kJ}^2\text{m}^{-4}\text{K}^2\text{s}^{-1}$)	Spearpoint & Quintiere [28,29] (Piloted Ignition) ($\text{kJ}^2\text{m}^{-4}\text{K}^2\text{s}^{-1}$)	Janssen [12] (Piloted Ignition) ($\text{kJ}^2\text{m}^{-4}\text{K}^2\text{s}^{-1}$)	Tran & White [30] (Piloted Ignition) ($\text{kJ}^2\text{m}^{-4}\text{K}^2\text{s}^{-1}$)
Parallel to Grain	0.068	2.070	-	-
Perpendicular to Grain	0.076	0.220	0.141	0.073

Spearpoint and Quintiere [28,29] calculated the thermal inertia for piloted ignition of redwood as $2.070 \text{ kJ}^2\text{m}^{-4}\text{K}^2\text{s}^{-1}$ for heated paralleled to grain and $0.220 \text{ kJ}^2\text{m}^{-4}\text{K}^2\text{s}^{-1}$ for

heated perpendicular to grain. Janssen [12] obtained the value of $0.141 \text{ kJ}^2\text{m}^{-4}\text{K}^2\text{s}^{-1}$ for heated perpendicular to grain while Tran and White [30] calculated from their experiments obtained the value of $0.073 \text{ kJ}^2\text{m}^{-4}\text{K}^2\text{s}^{-1}$ for heated perpendicular to grain. The thermal inertia from Tran and White's experiment can be comparable to the value obtained from this study. However, the significant differences of thermal inertia from Spearpoint and Quintiere's values may be due to from many factors; the ignition mode is piloted ignition or auto-ignition, the experiment is conducted in vertical or horizontal configuration, the samples were oven dry or before the test, and the different in nature of the wood sample. Since the values are computed from ignition data, the principal reasons are the high ignition temperatures and the effect of char on auto-ignition.

Tran and White suggested that the thermal inertia at ignition temperature is approximately 1.8 times greater than the value obtained at ambient temperature. They quoted the thermal inertia for redwood at ambient temperature as $0.045 \text{ kJ}^2\text{m}^{-4}\text{K}^2\text{s}^{-1}$. Janssen suggested that the thermal inertia is 2.3 to 2.5 times greater when the wood is heated. Using the ambient thermal inertia given by Tran&White, the thermal inertia for this study is greater than the ambient value by approximately 1.7 times for heated perpendicular to grain, which is consistent with Tran and White suggestion.

5.5 Predicted Ignition Time

Once we have the needed parameters, critical heat flux, average ignition temperature, and apparent thermal inertia, we can evaluate the predicted ignition time from the integral model and comparing it to the experimental ignition time. The plots of the

ignition time calculated from equation (5.20) compared with the experimental results are shown in Figure 5.6 for heated parallel to grain and Figure 5.7 for heated perpendicular to grain. A good agreement of the model and the experiment data is obtained for the high incident heat flux cases. However, for the low incident heat flux cases, a disagreement is obtained on some level. The reason may be due to the fact that the model does not account for the forming of char when the sample is heating while in the experiment the formation of the char layer on the sample surface is significant when the incident heat flux is low.

The plots also show that for the low incident heat flux the sample started glowing before flaming ignition. The time to glowing follows the linear line fit to time to flaming for the high incident heat flux data. These results may imply that if a char does not form, the ignition time would still follow the linear line fit to the high incident heat flux data. However, more experiments on the low incident heat flux cases need to be done to verify this.

Table 5.3: The summary of the needed parameters for the integral model.

Heating Configuration	Thermal inertia ($\text{kJ}^2\text{m}^{-4}\text{K}^2\text{s}^{-1}$)	Critical heat flux (kW/m^2)	Average Ignition Temperature (C)
Parallel to Grain	0.068	37	578
Perpendicular to Grain	0.076	35	565

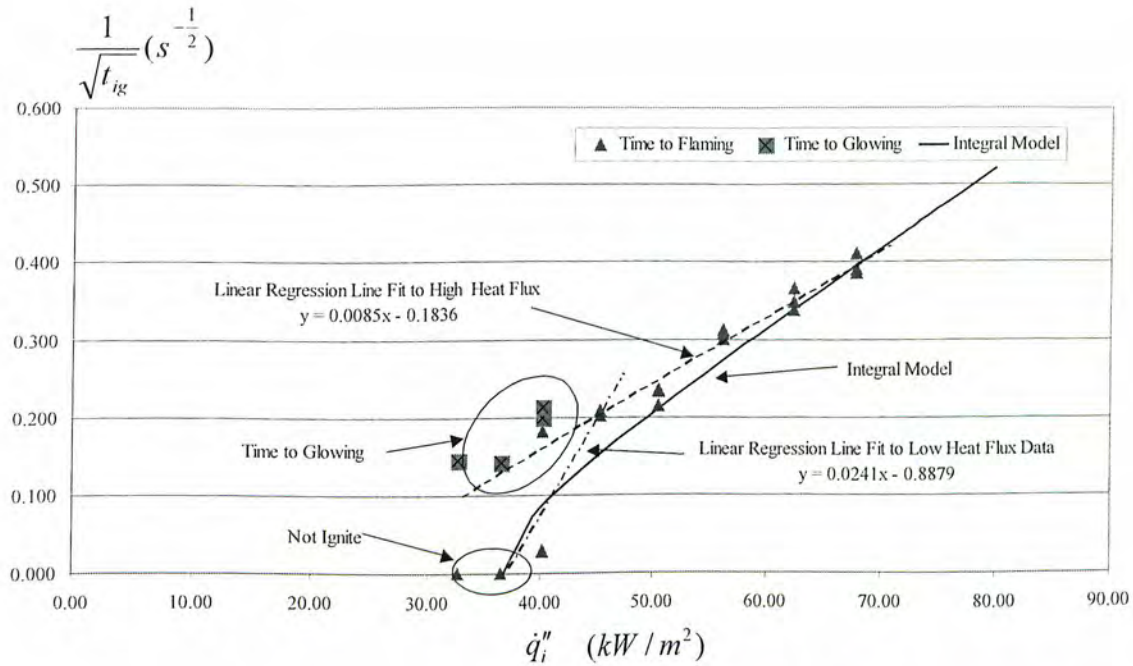


Figure 5.6: Comparison of the integral model with the experiment result

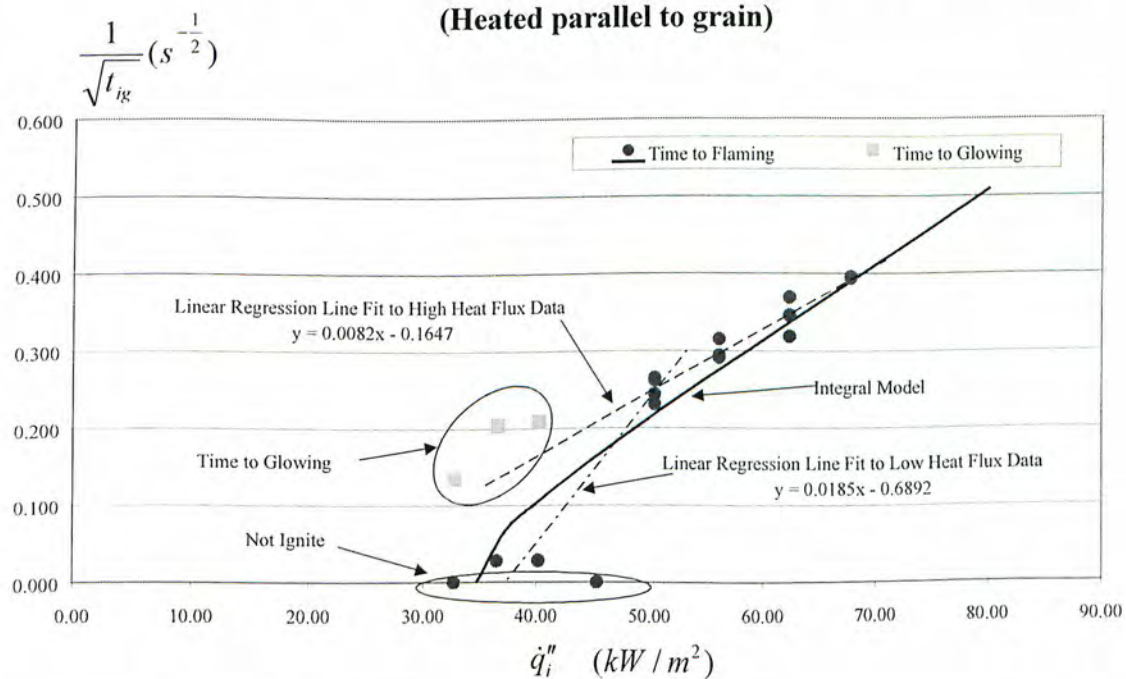


Figure 5.7: Comparison of the integral model with the experiment result.

(Heated perpendicular to grain)

5.6 Mass Loss Rate (Mass Flux)

Qualitatively examining the ignition mass flux data varying with incident heat flux (see Figure 5.8), we found that for the flaming ignition cases, the ignition mass flux increased when the incident heat flux decreased. The reason is that for the flaming ignition at high incident heat flux (i.e. $> 40 \text{ kW/m}^2$), the ignition occurred in a very short time before the forming of a char layer, thus the mass flux still increased with time. When the incident heat flux was decreased until the sample was glowing before flaming ignition. The char layer already formed and then blocked the pyrolysis products resulting in a decrease of the ignition mass flux.

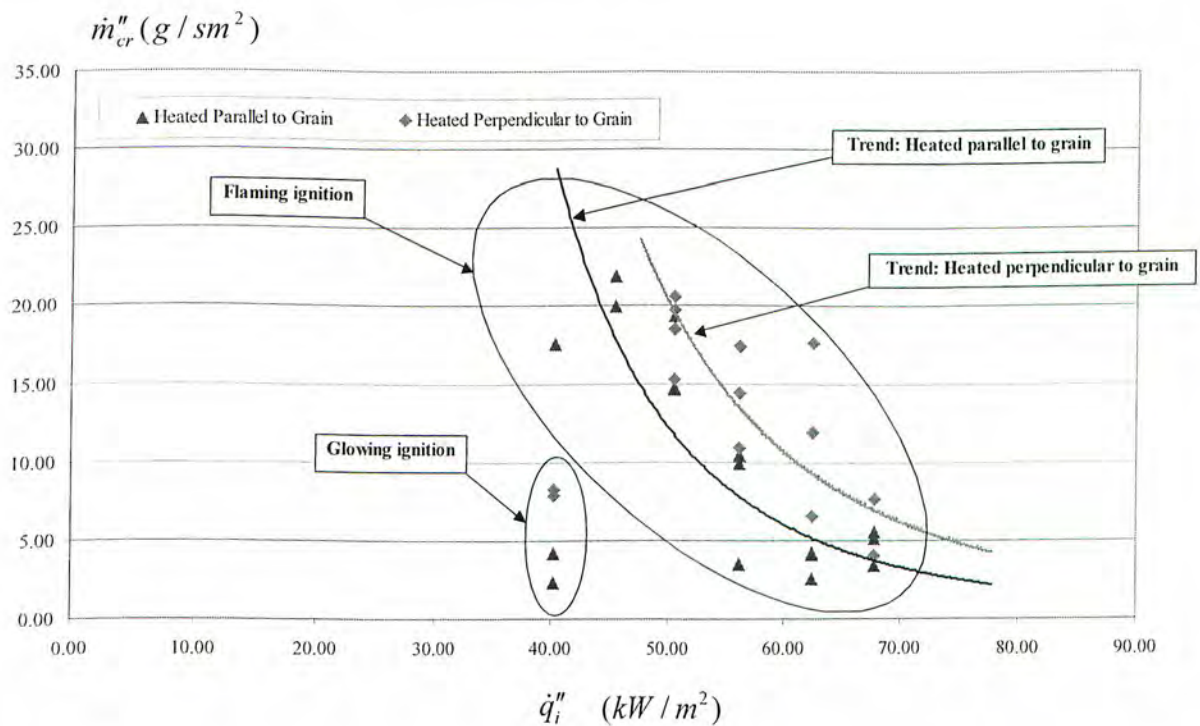


Figure: 5.8: The plot of ignition mass flux against an incident heat flux.

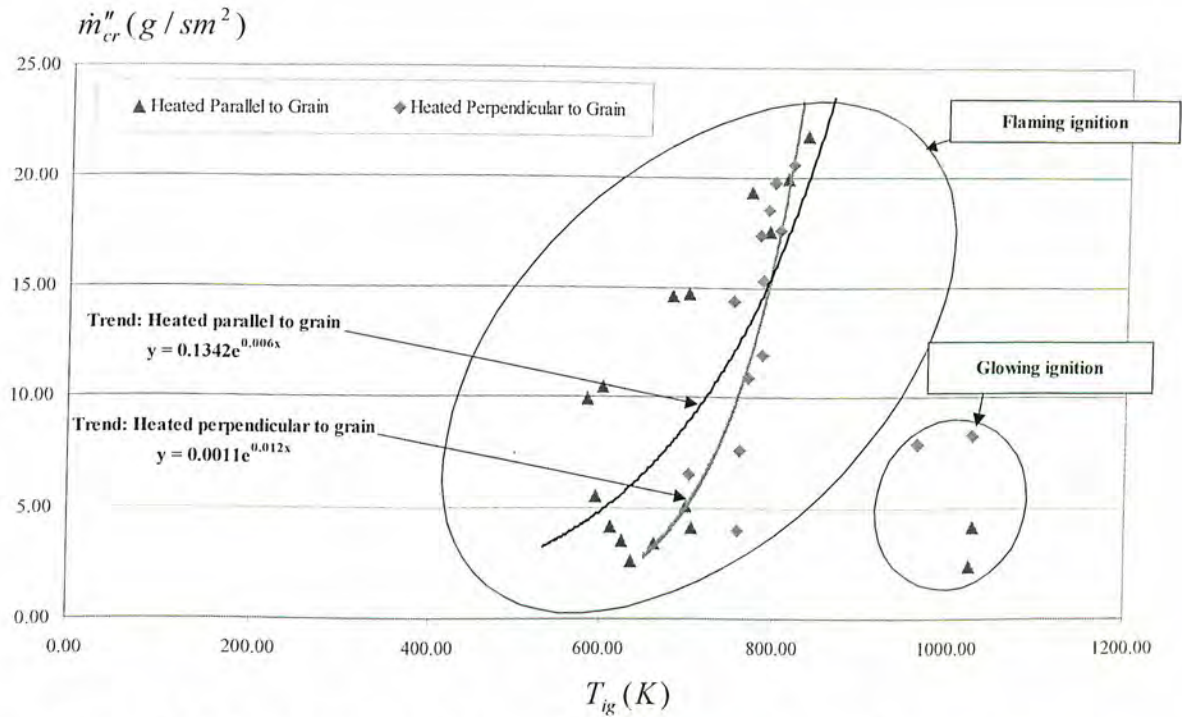


Figure 5.9. The plot of ignition mass flux against ignition surface temperature

Figure 5.9 shows the plot of flaming ignition mass flux as a function of surface ignition temperature. For the flaming ignition case, the sample ignited before a char layer formed yielding increasing ignition mass flux with increasing ignition surface temperature. For the glowing ignition case, the ignition mass flux decreased since the forming of char layer blocked the pyrolysis products. However, the ignition surface temperatures were high because of the contribution from char oxidation.

Considering only the flaming ignition case, the trend lines fit to the data are an exponential function. The ignition mass flux seems to increase exponentially with the ignition temperature, which is consistent with [3]. The relation of the ignition mass flux

appears to follow the Arrhenius reaction rate; however, more theoretical analysis is required to confirm this claim.

Many researchers have suggested that the ignition will occur only when mass flux is greater than the critical ignition mass flux. Kanury [16] suggested the value of critical mass flux as 2.5 g/sm^2 . Quoted from Kooyhar's work by Rasbash, Drysdale, and Deepeak [24], the critical ignition mass flux was a least 7 g/sm^2 . For this study the ignition mass flux ranges from 2 g/sm^2 to 22 g/sm^2 for heated parallel to grain and from 4 g/sm^2 to 21 g/sm^2 for heated perpendicular to grain. These results can be comparable with those criteria of critical mass flux.

Chapter 6. Conclusion

The auto-ignition of wood has been studied and compared with the piloted ignition. The conclusions based on the experimental results are as follows:

- The auto-ignition of wood exposed to incident heat flux ranging from 30 kW/m^2 to 70 kW/m^2 falls into two regions: (1) flaming ignition and (2) glowing ignition.
- The flaming ignition occurs when the incident heat flux is high ($> 40 \text{ kW/m}^2$). The flame first appears in the gas phase above the sample surface and then propagates back to the surface.
- The glowing ignition (surface oxidation) occurs when the incident heat flux is low ($< 40 \text{ kW/m}^2$). The glowing of the hot surface starts on the bottom edge and then propagates upward all over the surface. The case in which the glowing surface produces a visible flame, the flaming first occurs almost near the glowing surface.
- The glowing time of a sample could be indicated as when its average surface temperature was greater than the corresponding surface temperature of the insulator. This glowing temperature ranged from 383 C to 487 C depending on the incident heat flux. The glowing surface temperature could achieve up to 700 C .
- The ignition temperature is not constant. It varies inverse proportional to the incident heat flux. The ignition temperature ranges from 320 C up to 760 C . The ignition temperature is higher when heated perpendicular as compared to when heated perpendicular to the grain.

- The average ignition temperature can be estimated from the energy balance considering only the heat losses due to radiation loss and convection loss.
- The auto-ignition time merges to the piloted ignition time when the incident heat flux is high ($> 40 \text{ kW/m}^2$), but significantly diverge when the incident heat flux is low (40 kW/m^2). The glowing time of low incident heat flux still follows the same trend of auto-ignition time of high incident heat flux.
- The auto-ignition critical heat flux can be extrapolated from a linear regression line fit to the low incident heat flux data.
- The apparent thermal inertia can be estimated from a slope of a linear regression line fit to the high incident heat flux data.
- For the high incident heat flux, a good agreement of the ignition time between the predicted values by the one-dimensional integral model and the experiment data could be obtained when we chose the reasonable parameters: thermal inertia, critical heat flux, and ignition temperature.
- Before forming of a char layer, the ignition mass flux varies inverse proportional to the incident heat flux but varies in proportion to the ignition surface temperature.

Chapter 7. Future Work

The author would like to suggest possible future work in order to investigate the auto-ignition of wood as follows:

- More experiments need to be done for the low incident heat flux case in order to confirm the glowing ignition mechanism.
- Since the trend of the auto-ignition temperature varying with incident heat flux seems to converge to the piloted ignition temperature for the high heat flux; therefore, to confirm this idea, more experimental data for the incident heat flux higher than 70 kW/m^2 need to be carried out.
- In order to obtain more accuracy of predicted ignition time for the low incident heat flux, a model that includes char effects needs to be constructed.
- In order to examine the relation between the ignition mass flux and the ignition temperature, the model considering gas phase reactions has to be studied.

APPENDIX

Appendix A.: Summary tables of experimental results

Table A1: Heated parallel to grain experimental results

Test	Heating	Incident Heat Flux	t_{ig}	$\frac{1}{\sqrt{t_{ig}}}$	$\dot{m}_{ig}''$	T_{ig}	$t_{glowing}$	$\frac{1}{\sqrt{t_{glowing}}}$	$T_{glowing}$
		(kW/m ²)	(s)	(s ^{-1/2})	(g/sm ²)	(C)	(s)	(s ^{-1/2})	(C)
26	Parallel	67.80	5.91	0.411	5.55	320.91	-	-	-
29	Parallel	67.80	6.71	0.386	5.13	425.10	-	-	-
30	Parallel	67.80	6.52	0.392	3.42	389.93	-	-	-
31	Parallel	62.40	8.20	0.349	4.14	432.34	-	-	-
32	Parallel	62.40	7.45	0.366	4.22	338.83	-	-	-
33	Parallel	62.40	8.73	0.338	2.61	362.59	-	-	-
35	Parallel	56.20	11.00	0.302	10.46	327.37	-	-	-
36	Parallel	56.20	10.25	0.312	9.91	310.48	-	-	-
37	Parallel	56.20	10.66	0.306	3.54	352.21	-	-	-
38	Parallel	50.50	18.16	0.235	14.71	425.66	-	-	-
39	Parallel	50.50	18.33	0.234	14.62	407.21	-	-	-
40	Parallel	50.50	21.57	0.215	19.35	495.57	-	-	-
65	Parallel	45.40	22.95	0.209	21.91	560.15	-	-	-
66	Parallel	45.40	24.45	0.202	19.93	537.72	-	-	-
68	Parallel	40.20	29.87	0.183	17.54	517.61	-	-	-
69	Parallel	40.20	1190.00	0.0290	2.37	750.70	25.00	0.20	432.31
70	Parallel	40.20	1204.00	0.0288	4.19	754.70	22.00	0.21	422.87
81	Parallel	36.50	NI	NI	-	-	50.00	0.14	487.18
83	Parallel	32.70	NI	NI	-	-	48.00	0.14	472.11

Table A2: Heated perpendicular to grain experimental results

Test	Heating	Incident Heat Flux	t_{ig}	$\frac{1}{\sqrt{t_{ig}}}$	$\dot{m}_{ig}''$	T_{ig}	$t_{glowing}$	$\frac{1}{\sqrt{t_{glowing}}}$	$T_{glowing}$
		(kW/m ²)	(s)	(s ^{-1/2})	(g/sm ²)	(C)	(s)	(s ^{-1/2})	(C)
41	Perpendicular	67.80	6.42	0.395	4.04	484.83	-	-	-
42	Perpendicular	67.80	6.40	0.395	7.61	486.89	-	-	-
43	Perpendicular	67.80	6.46	0.393	NA	437.76	-	-	-
45	Perpendicular	62.40	7.35	0.369	6.56	427.86	-	-	-
46	Perpendicular	62.40	9.85	0.319	17.58	529.85	-	-	-
48	Perpendicular	62.40	8.35	0.346	11.95	509.76	-	-	-
51	Perpendicular	56.20	11.55	0.294	14.39	476.56	-	-	-
53	Perpendicular	56.20	10.07	0.315	10.91	494.85	-	-	-
55	Perpendicular	56.20	11.82	0.291	17.38	505.81	-	-	-
56	Perpendicular	50.50	18.75	0.231	20.61	543.72	-	-	-
58	Perpendicular	50.50	14.28	0.265	15.31	510.04	-	-	-
59	Perpendicular	50.50	14.66	0.261	19.75	522.16	-	-	-
60	Perpendicular	50.50	16.88	0.243	18.51	516.30	-	-	-
62	Perpendicular	40.20	1250.00	0.0283	8.30	753.79	23.00	0.21	383.46
63	Perpendicular	40.20	1292.00	0.0278	7.91	690.40	-	-	-
64	Perpendicular	45.40	NI	NI	-	-	-	-	-
82	Perpendicular	36.50	1320.00	0.0275	7.44	698.61	24.00	0.02	404.16
84	Perpendicular	32.70	NI	NI	-	-	55.00	0.13	470.96

Note: NI = Not Ignite

Appendix B: Graphs of mass flux and surface temperature history.

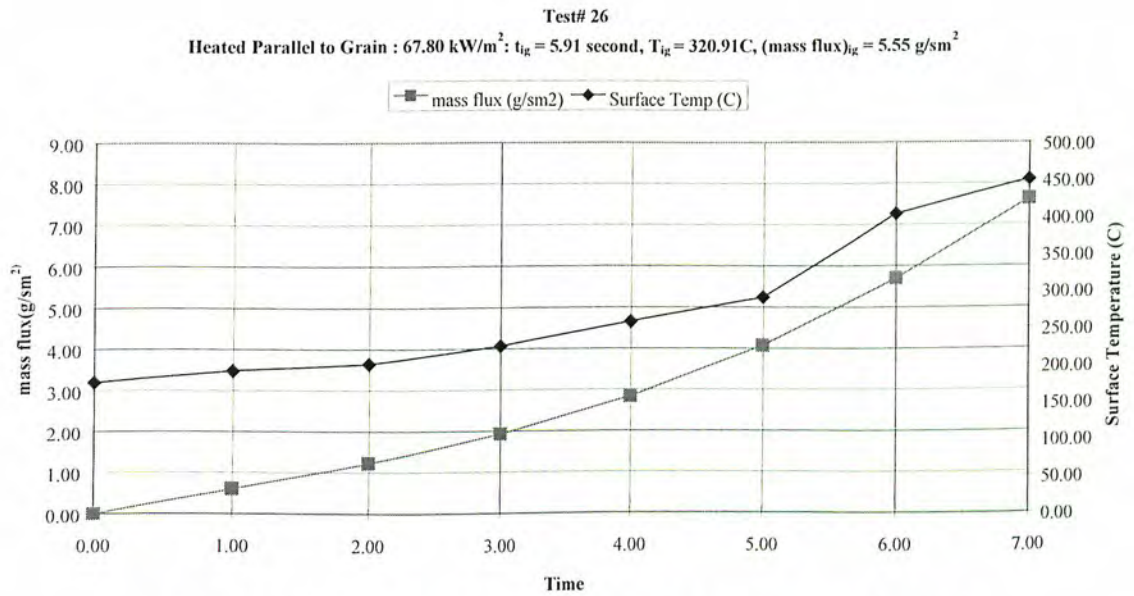


Figure B1: Mass flux and surface temperature history (test# 26).

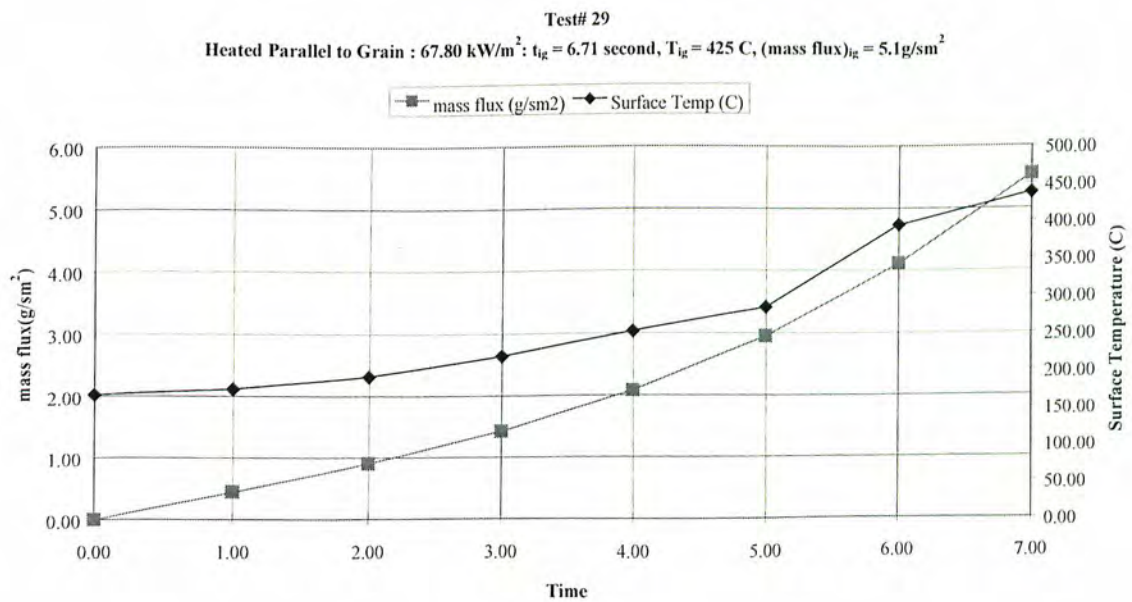


Figure B2. Mass flux and surface temperature history (test# 29).

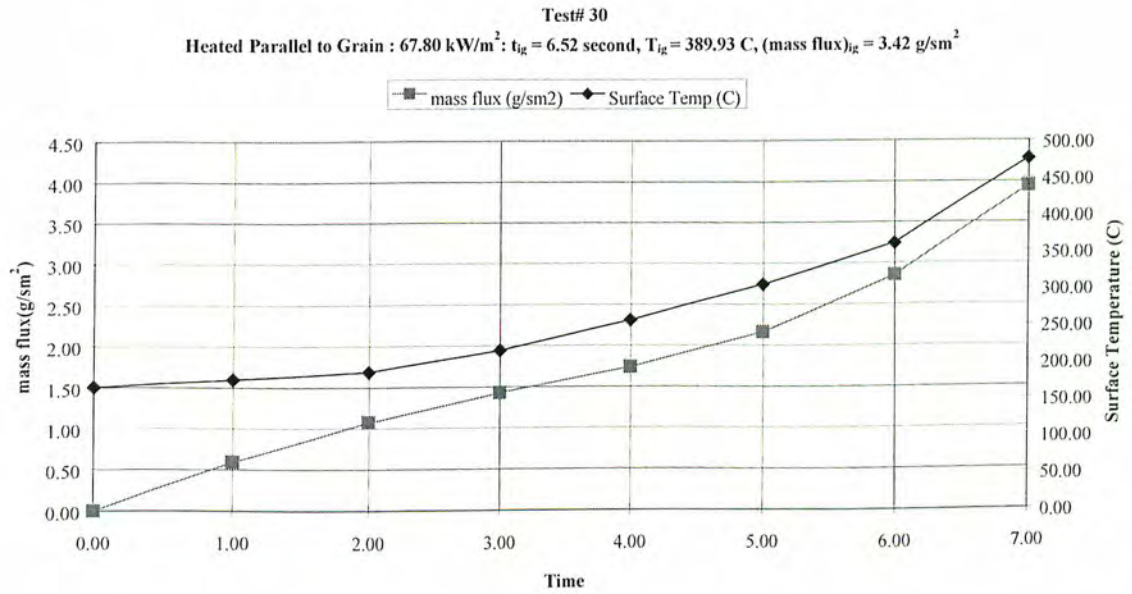


Figure B3: Mass flux and surface temperature history (test# 30).

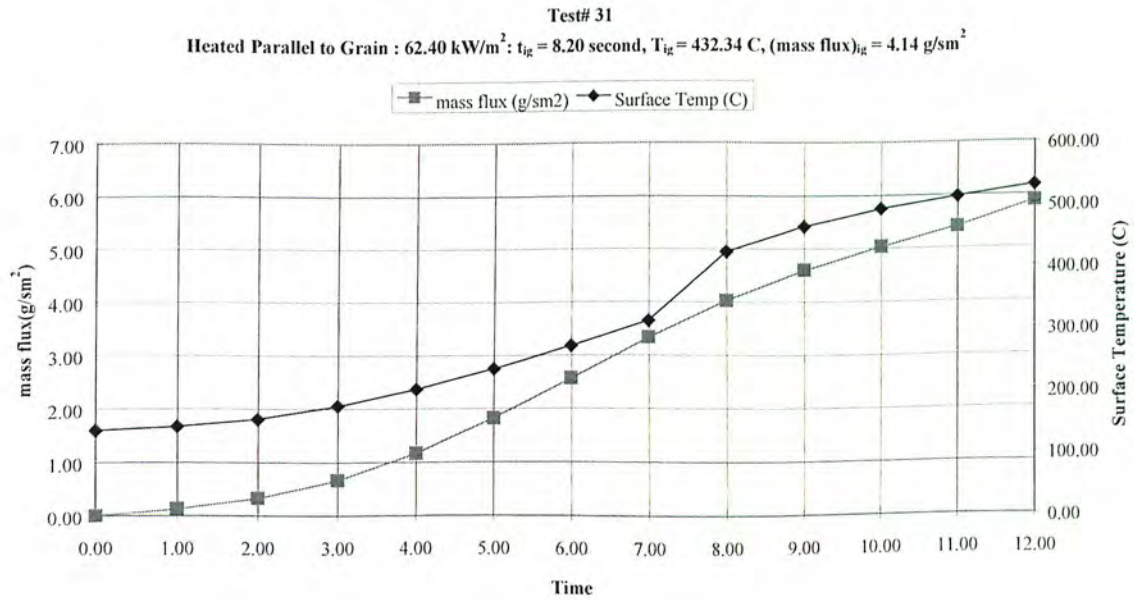


Figure B4: Mass flux and surface temperature history (test# 31).

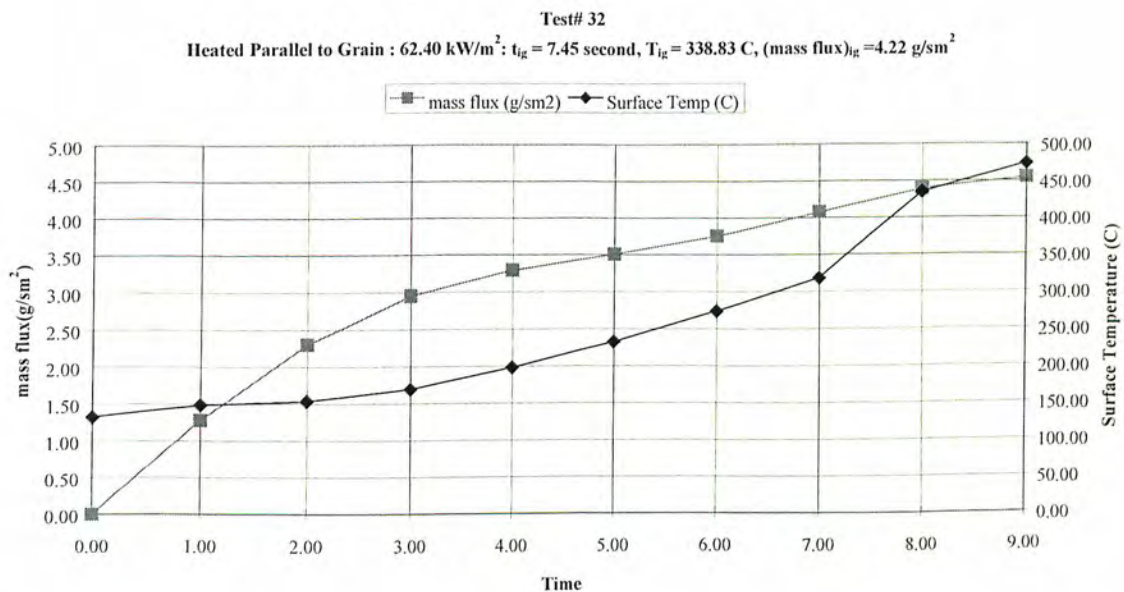


Figure B5: Mass flux and surface temperature history (test# 32).

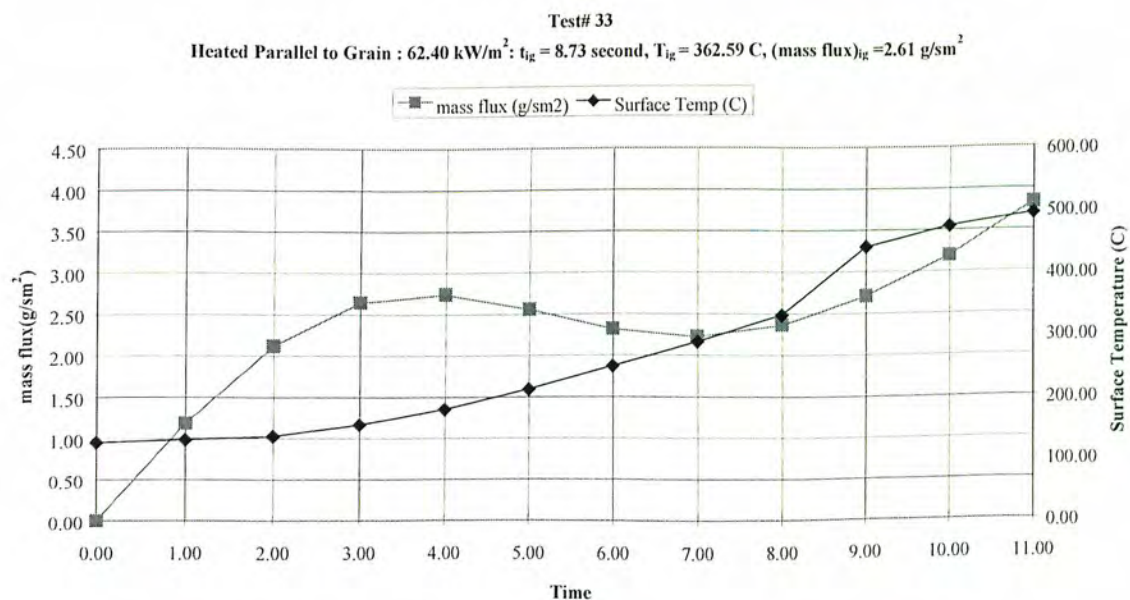


Figure B6: Mass flux and surface temperature history (test# 33).

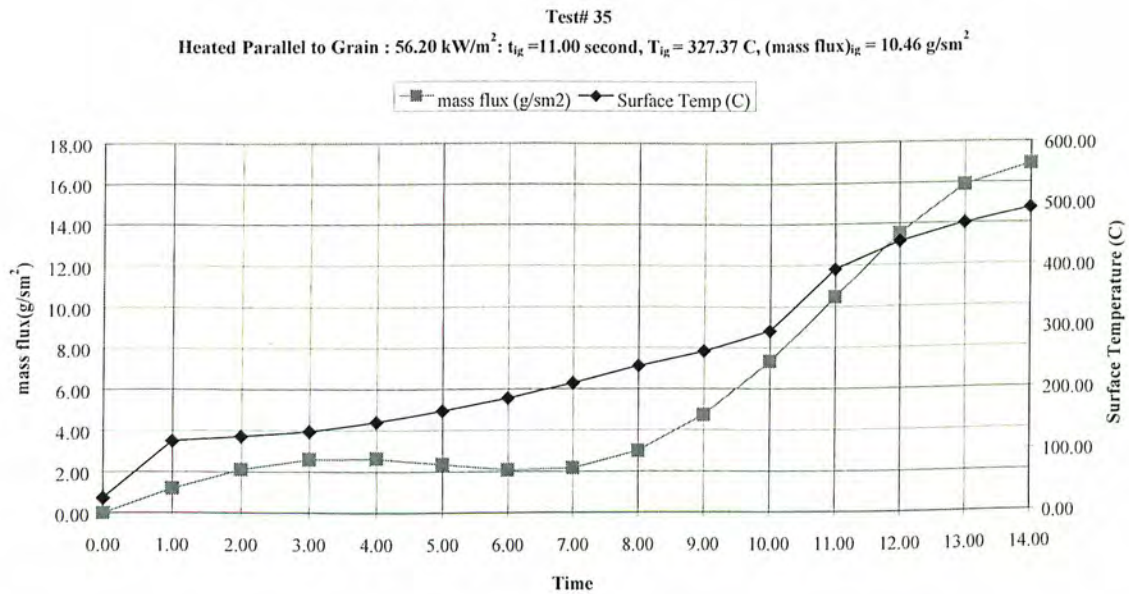


Figure B7: Mass flux and surface temperature history (test# 35).

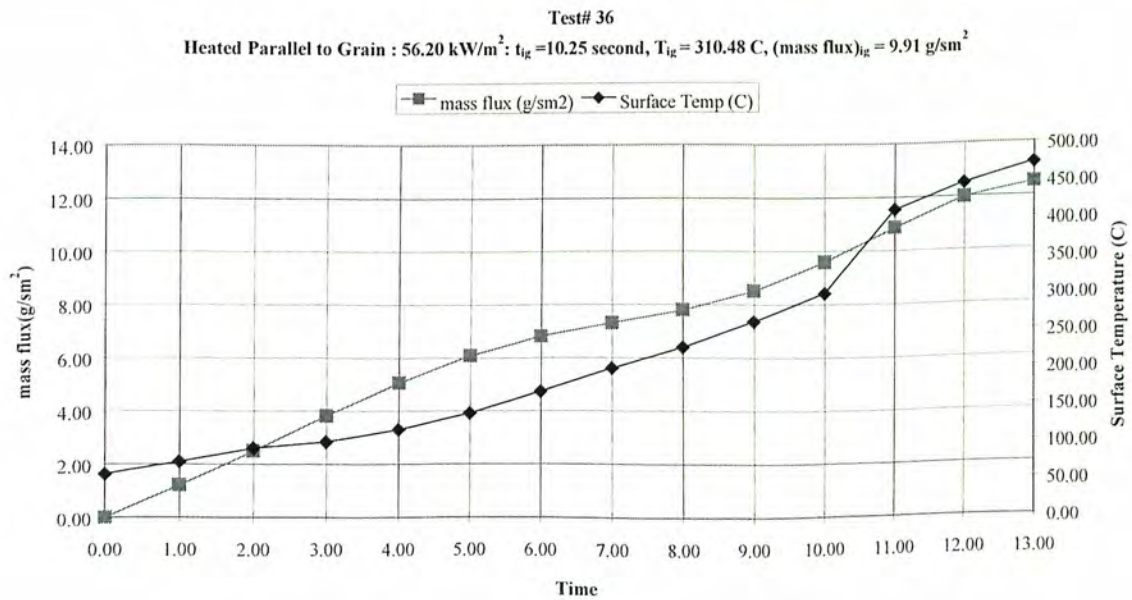


Figure B8: Mass flux and surface temperature history (test# 36).

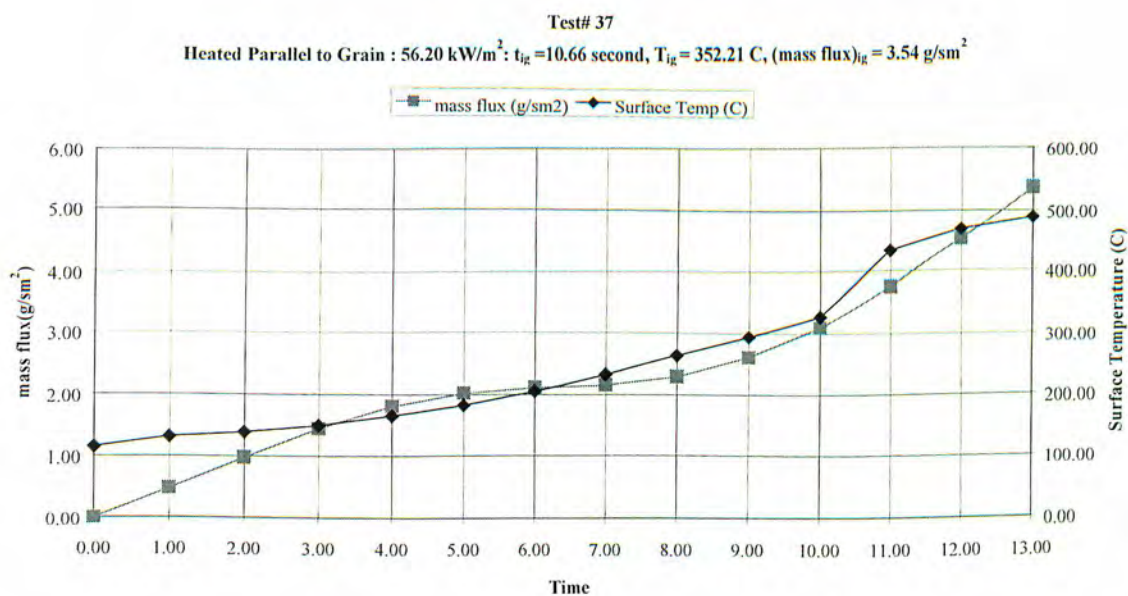


Figure B9: Mass flux and surface temperature history (test# 37).

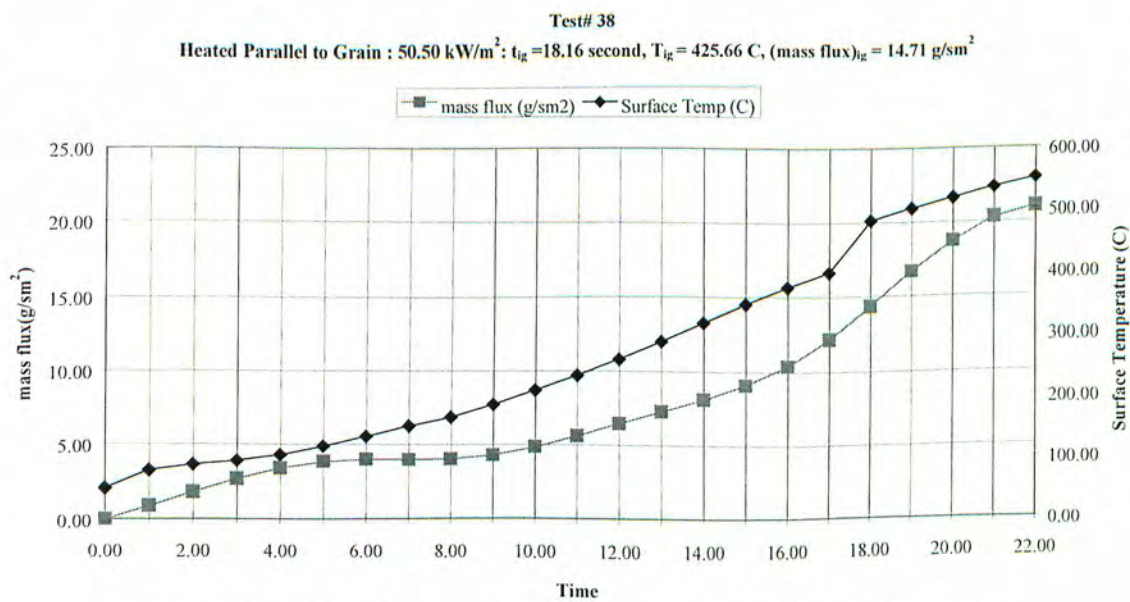


Figure B10: Mass flux and surface temperature history (test# 38).

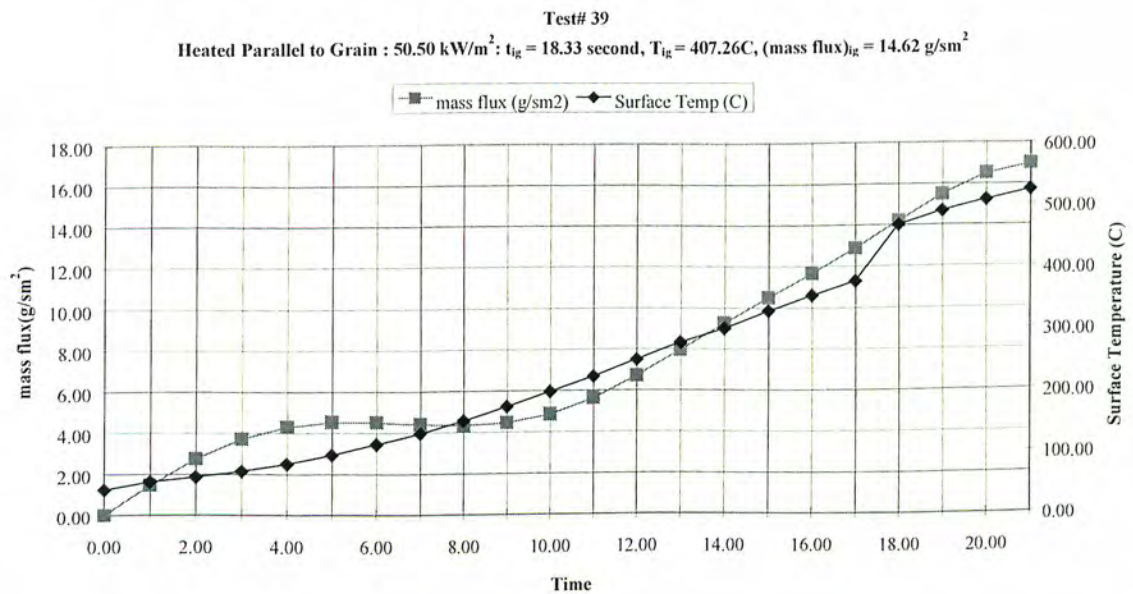


Figure B11: Mass flux and surface temperature history (test# 39).

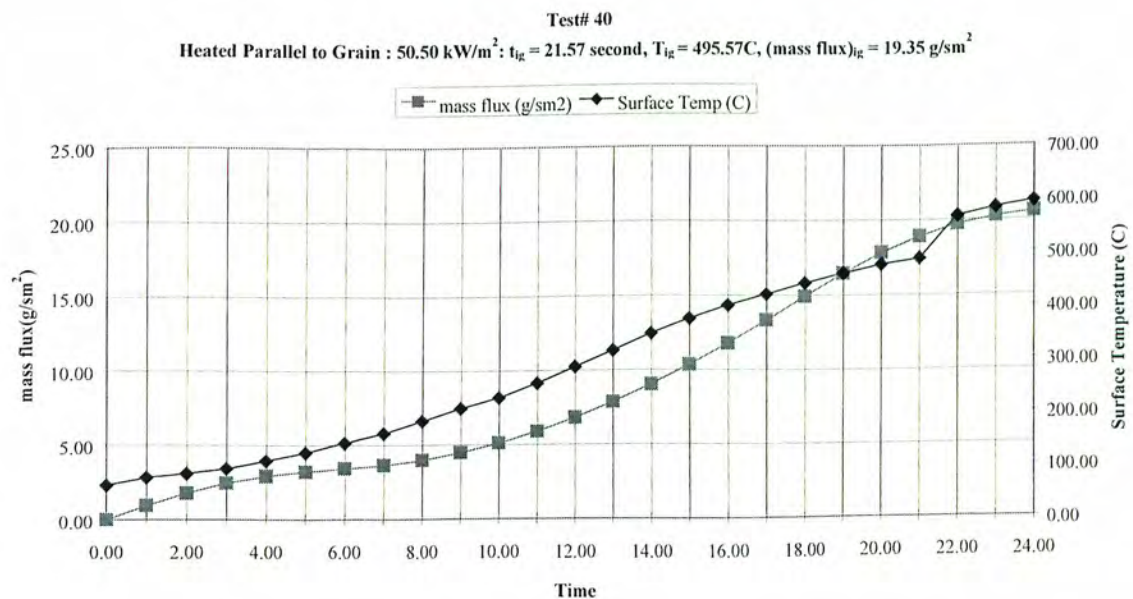


Figure B12: Mass flux and surface temperature history (test# 40).

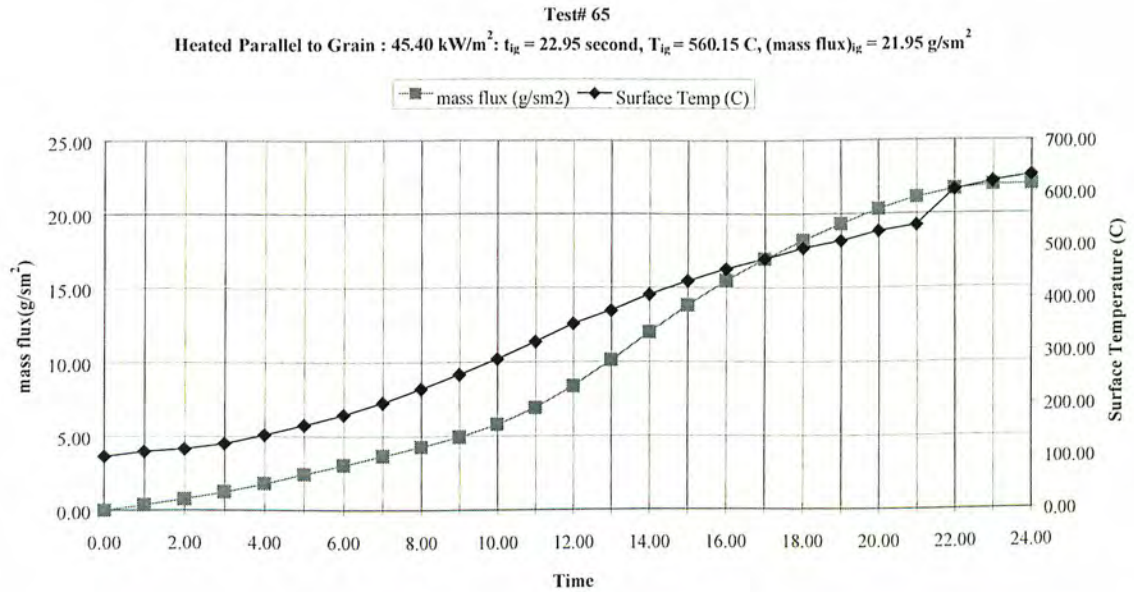


Figure B13: Mass flux and surface temperature history (test# 65).

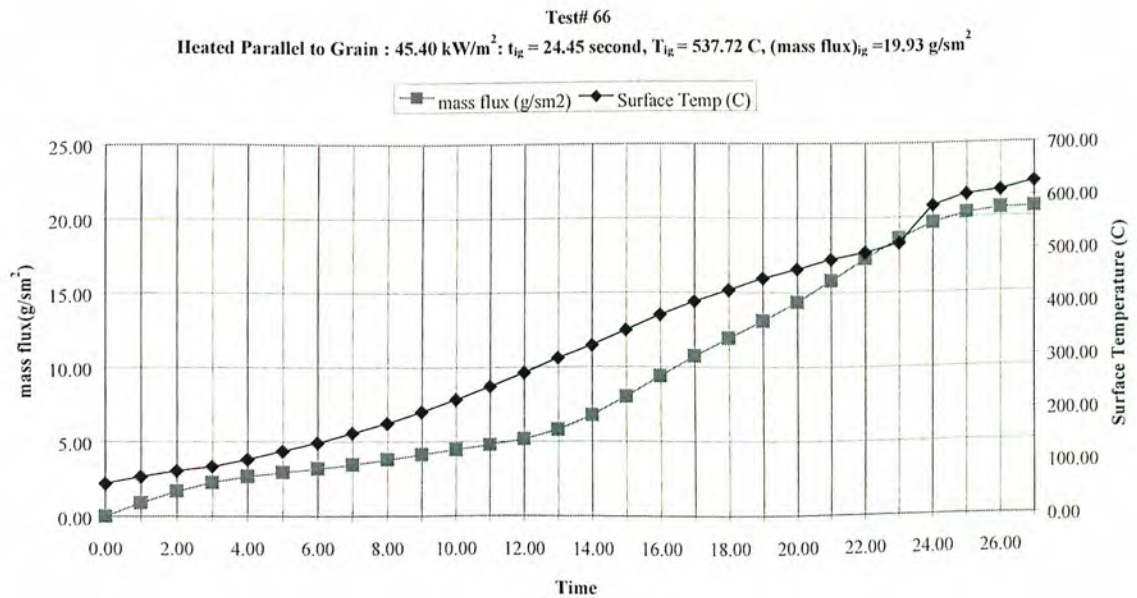


Figure B14: Mass flux and surface temperature history (test# 66).

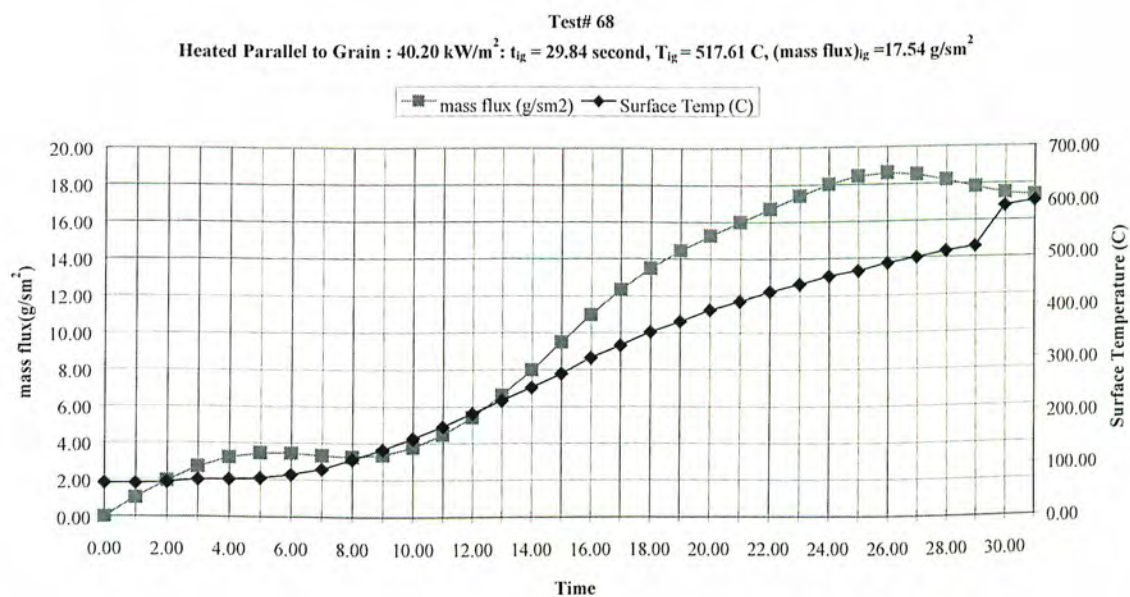


Figure B15: Mass flux and surface temperature history (test# 68).

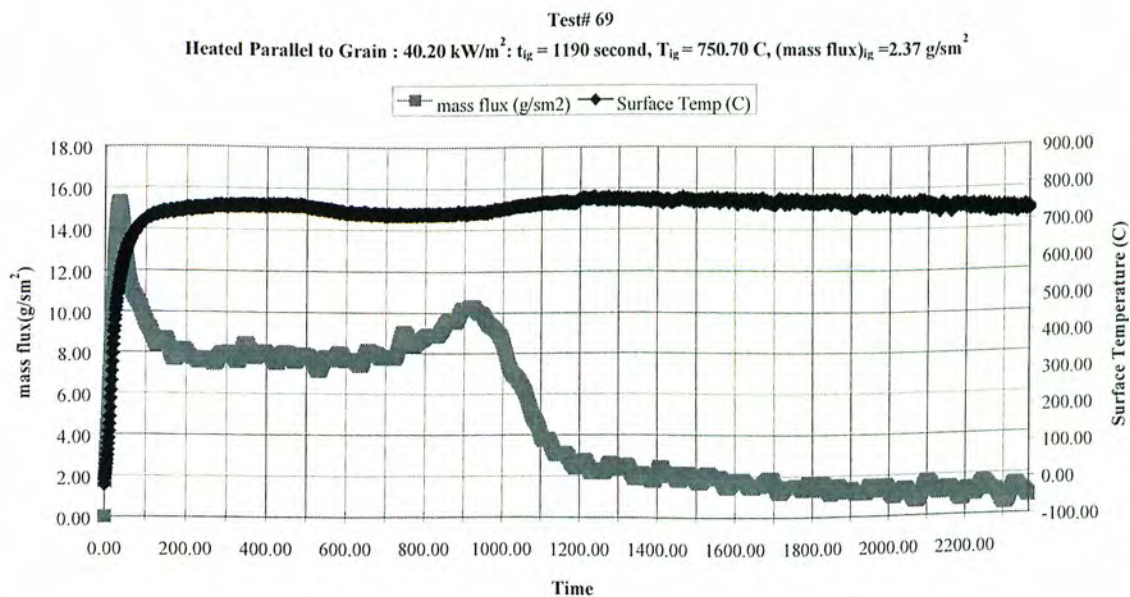


Figure B16: Mass flux and surface temperature history (test# 69).

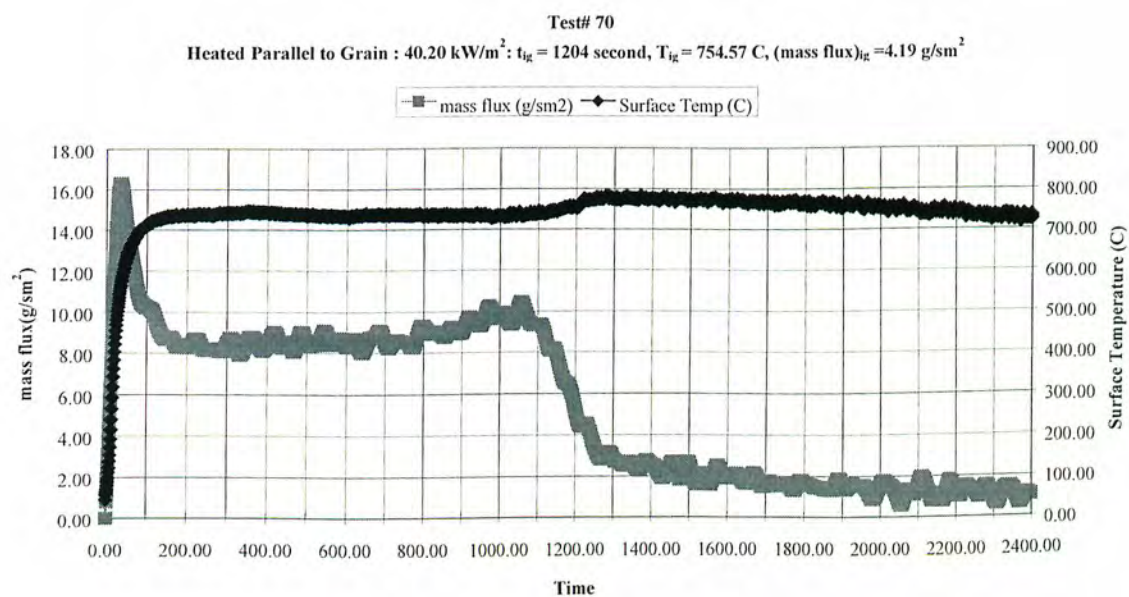


Figure B17: Mass flux and surface temperature history (test# 70).

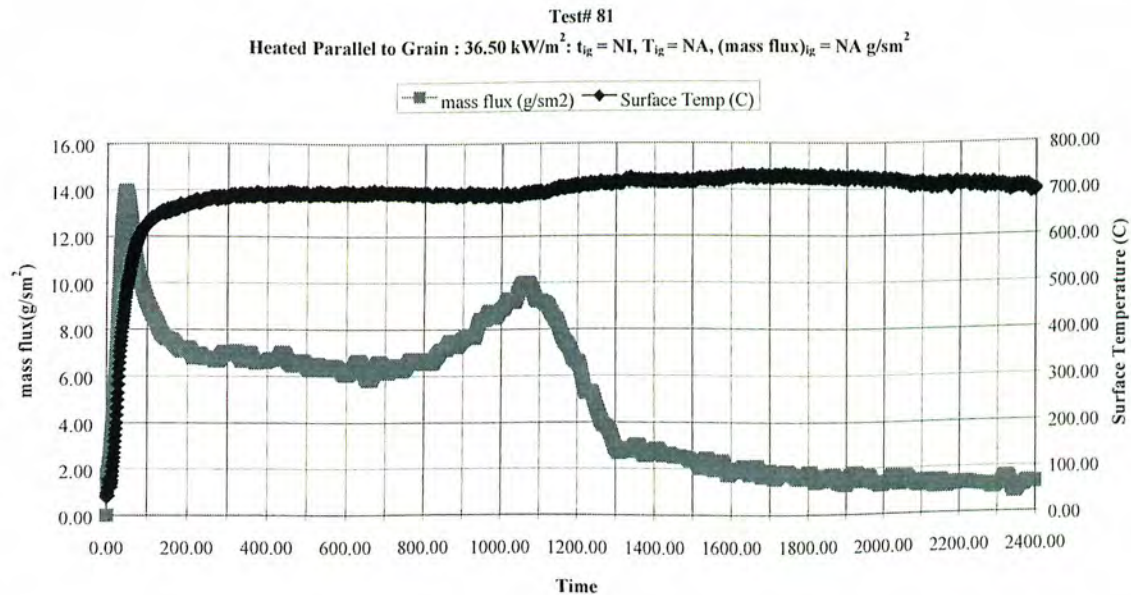


Figure B18: Mass flux and surface temperature history (test# 81).

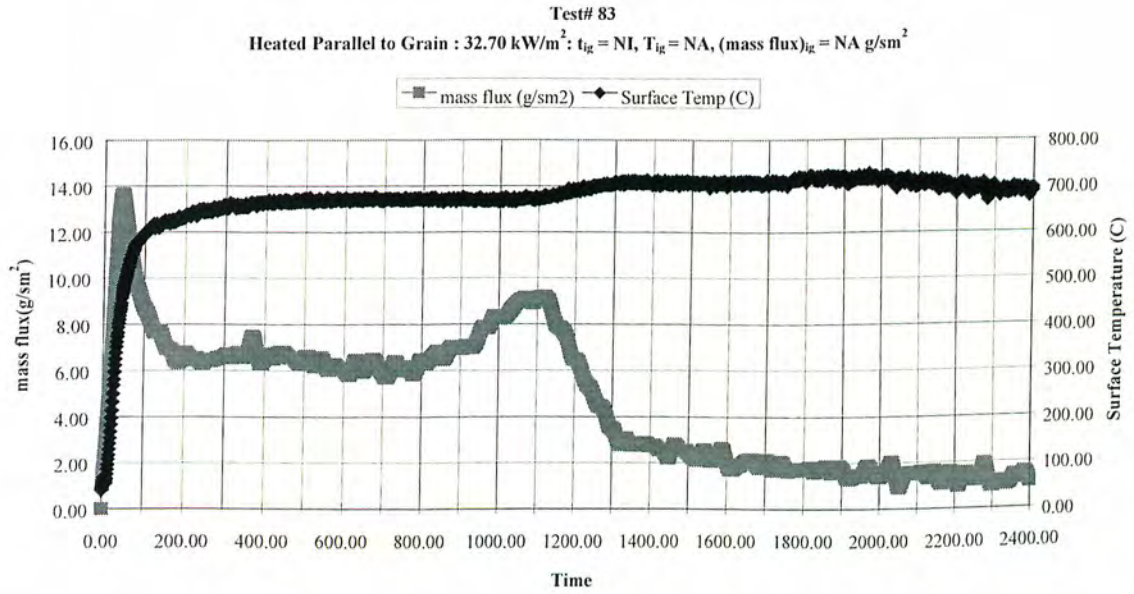


Figure B19: Mass flux and surface temperature history (test# 83).

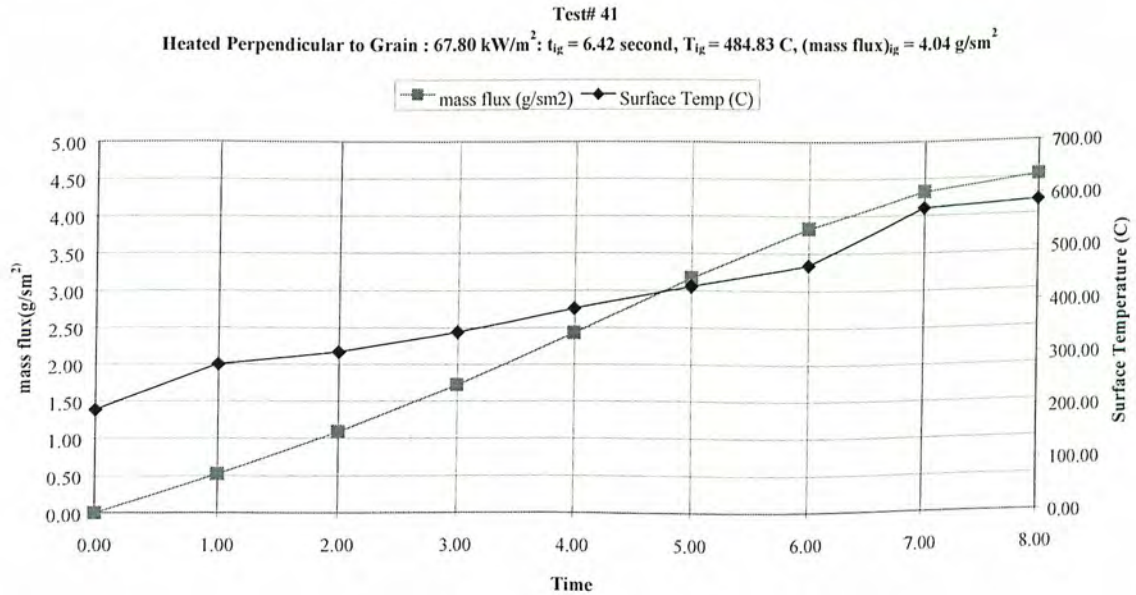


Figure B20: Mass flux and surface temperature history (test# 41).

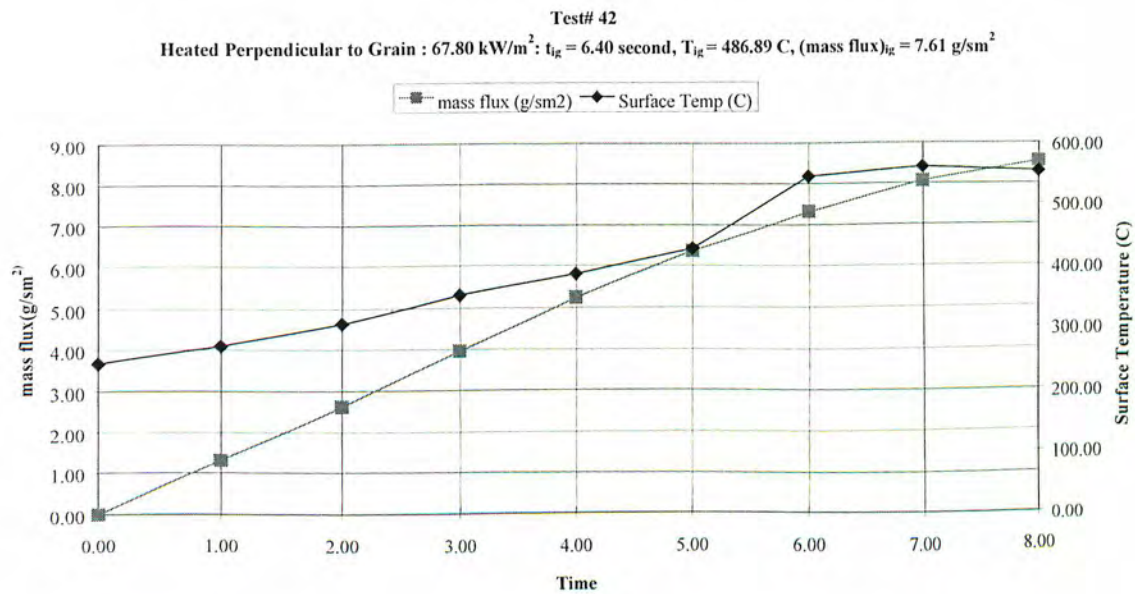


Figure B21: Mass flux and surface temperature history (test# 42).

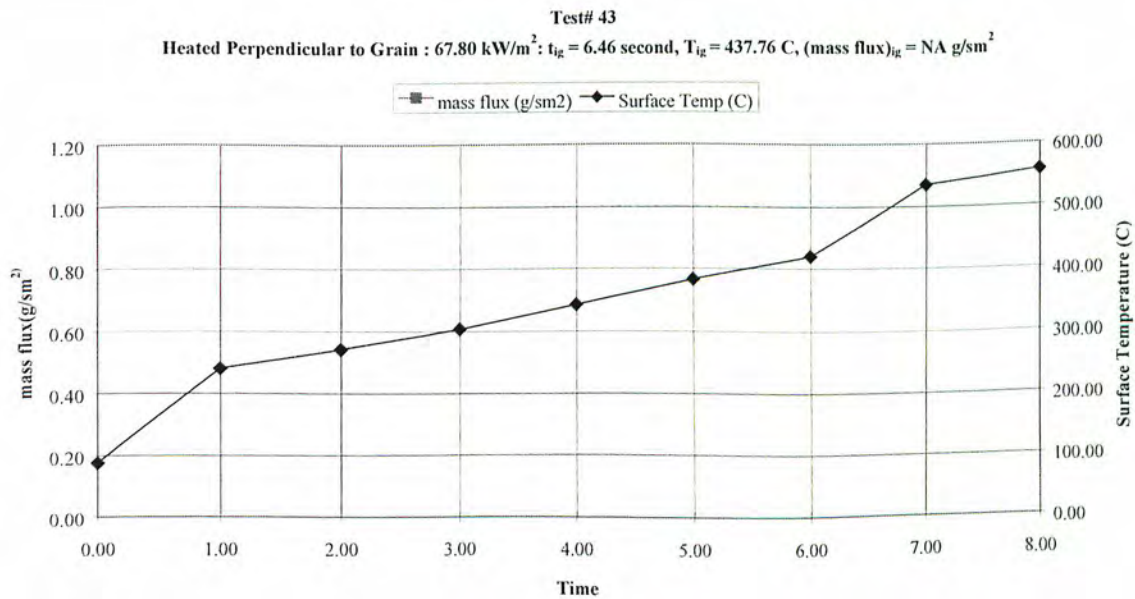


Figure B22: Mass flux and surface temperature history (test# 43).

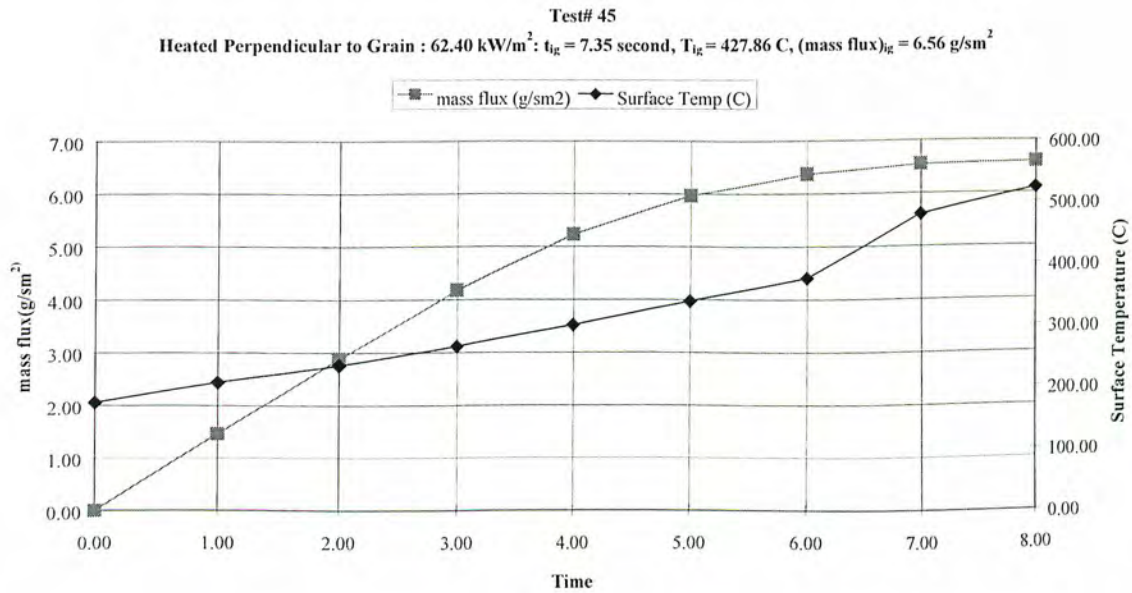


Figure B23: Mass flux and surface temperature history (test# 45).

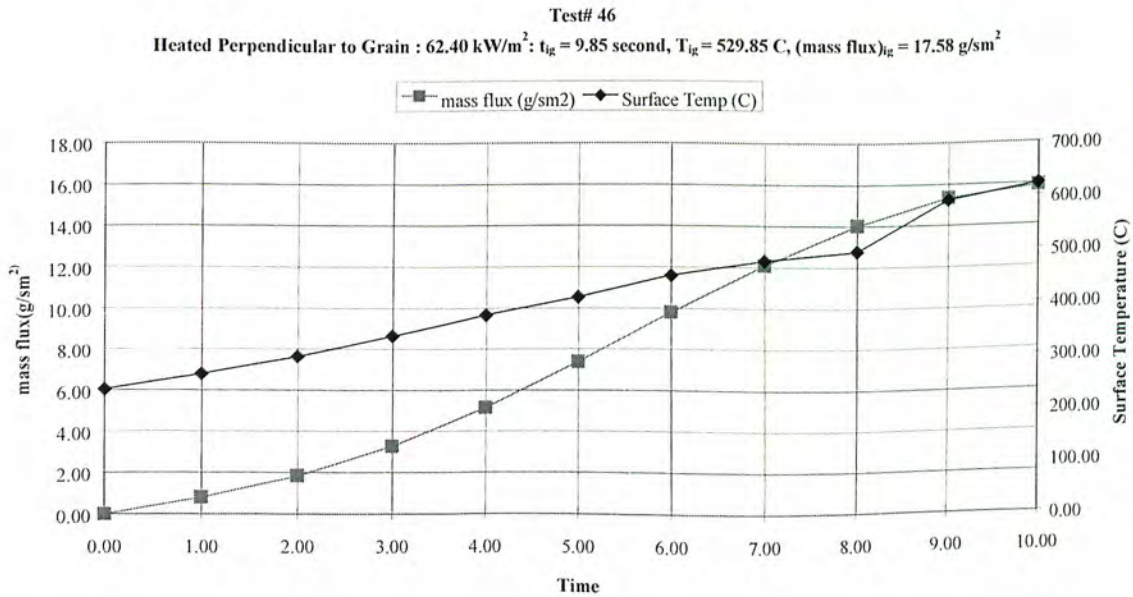


Figure B24: Mass flux and surface temperature history (test# 46).

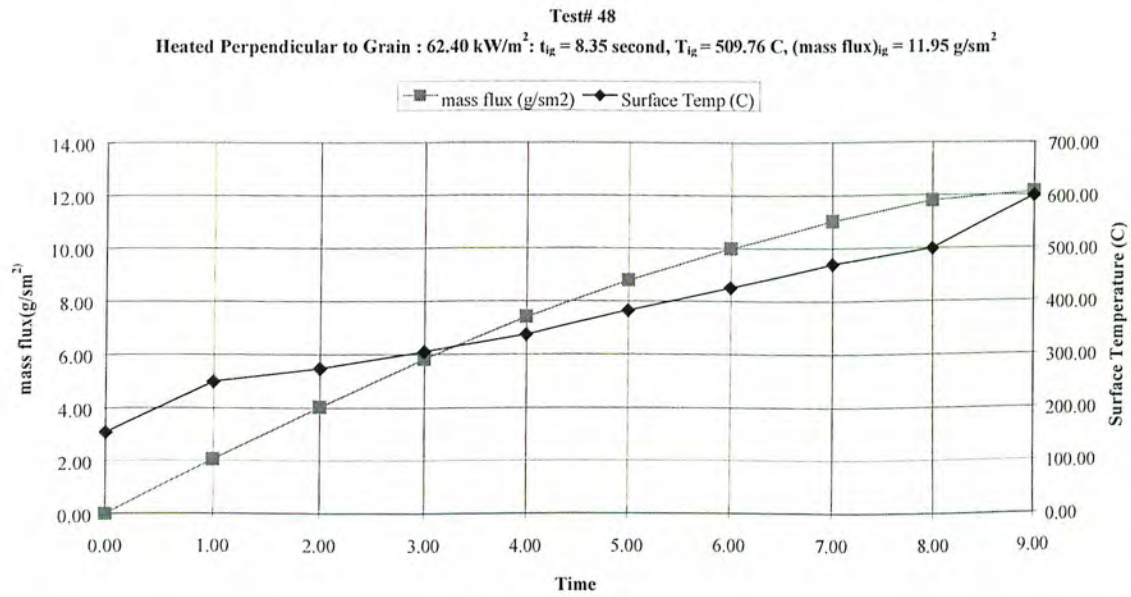


Figure B25: Mass flux and surface temperature history (test# 48).

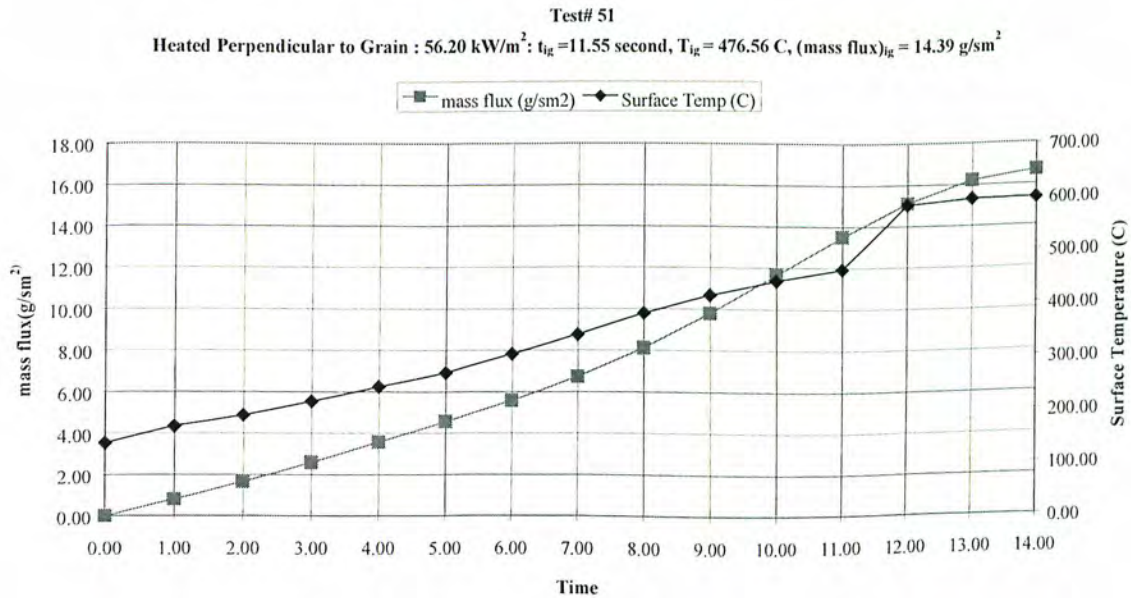


Figure B26: Mass flux and surface temperature history (test# 51).

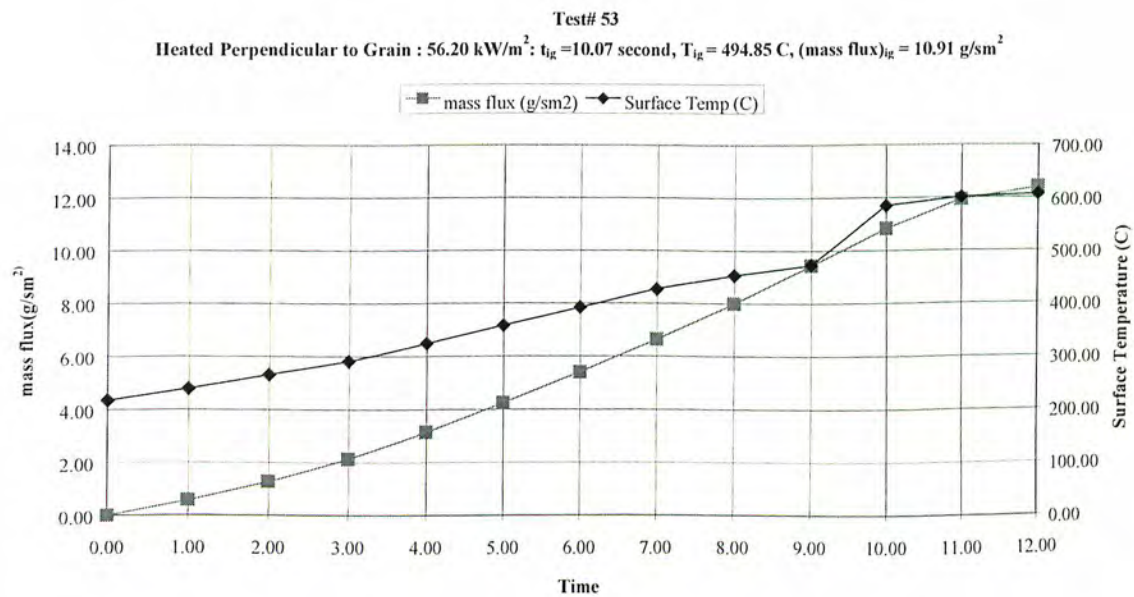


Figure B27: Mass flux and surface temperature history (test# 53).

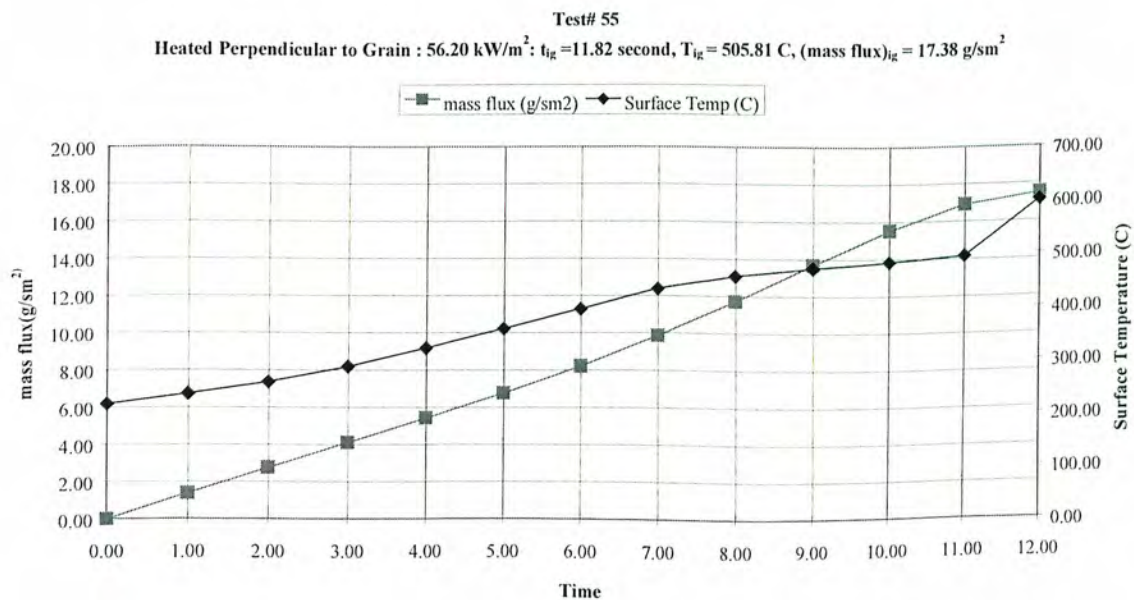


Figure B28: Mass flux and surface temperature history (test# 55).

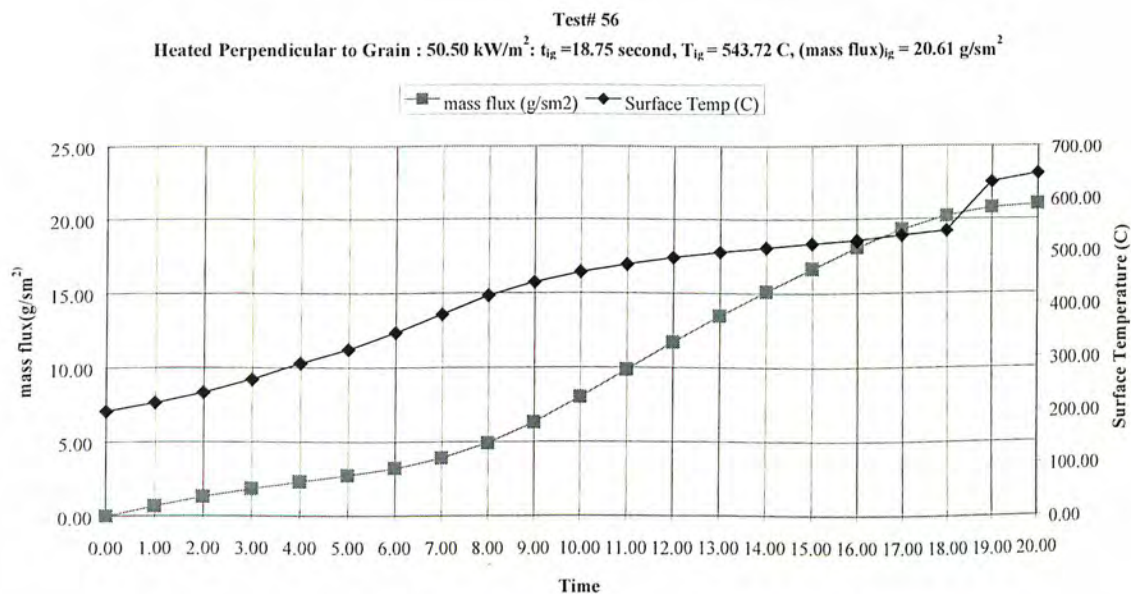


Figure B29: Mass flux and surface temperature history (test# 56).

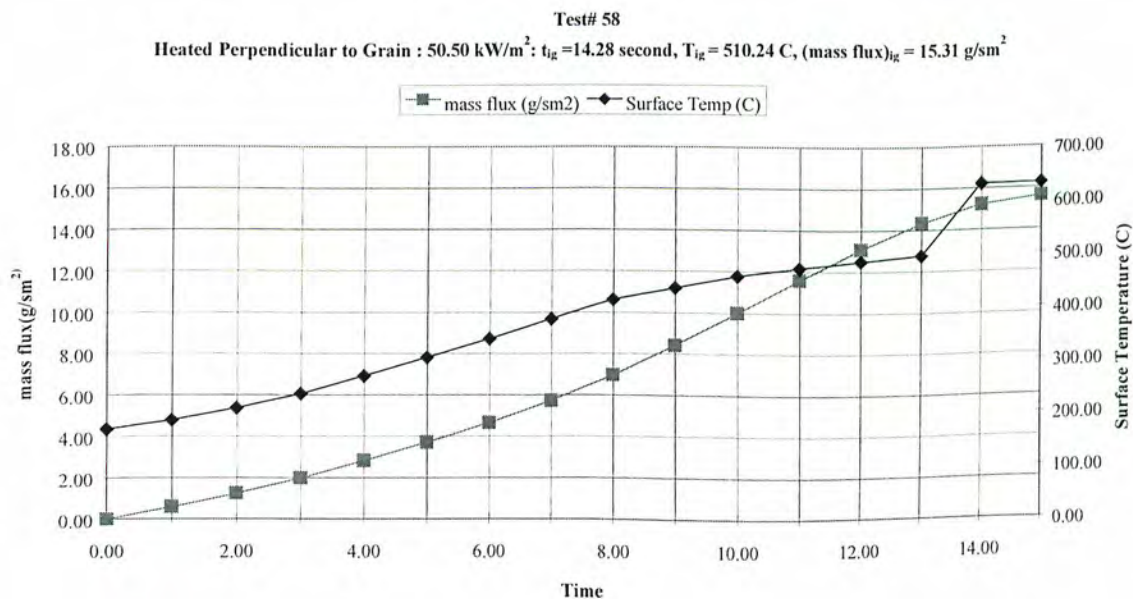


Figure B30: Mass flux and surface temperature history (test# 58).

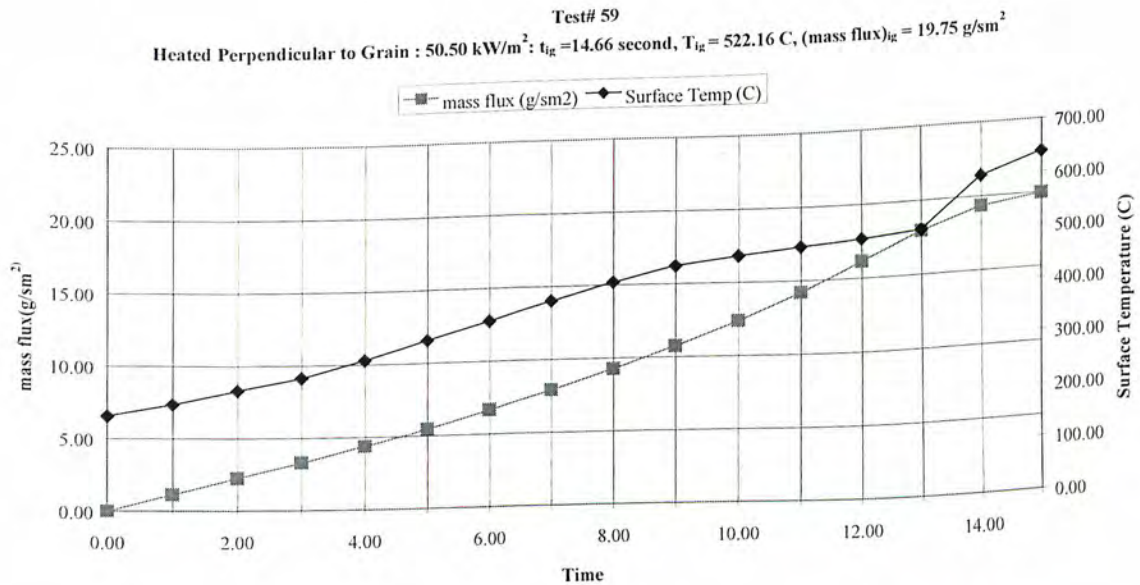


Figure B31: Mass flux and surface temperature history (test# 59).

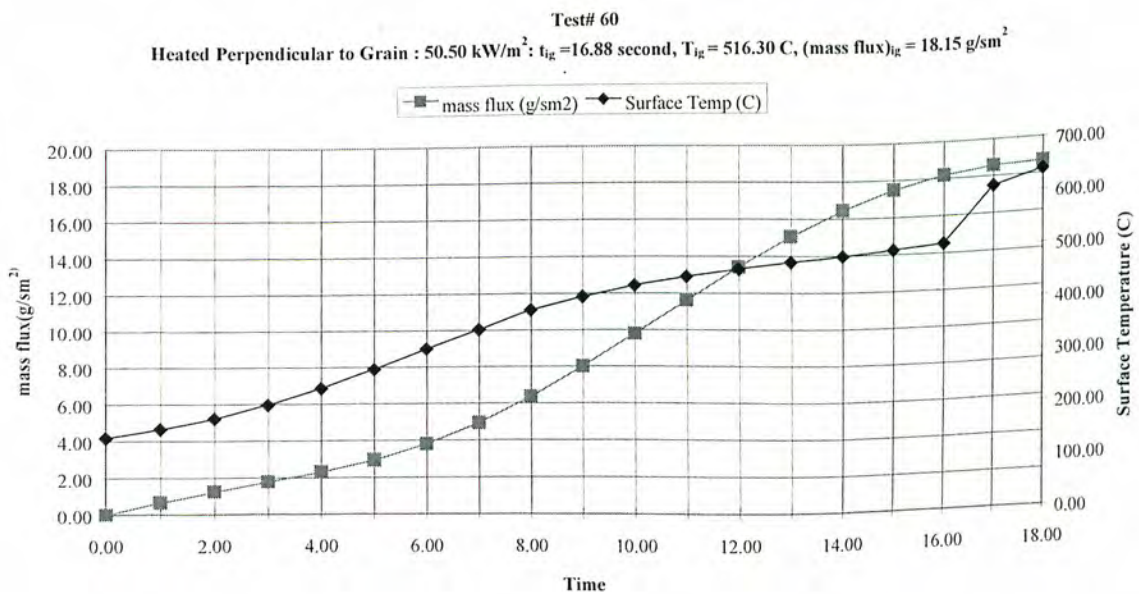


Figure B32: Mass flux and surface temperature history (test# 60).

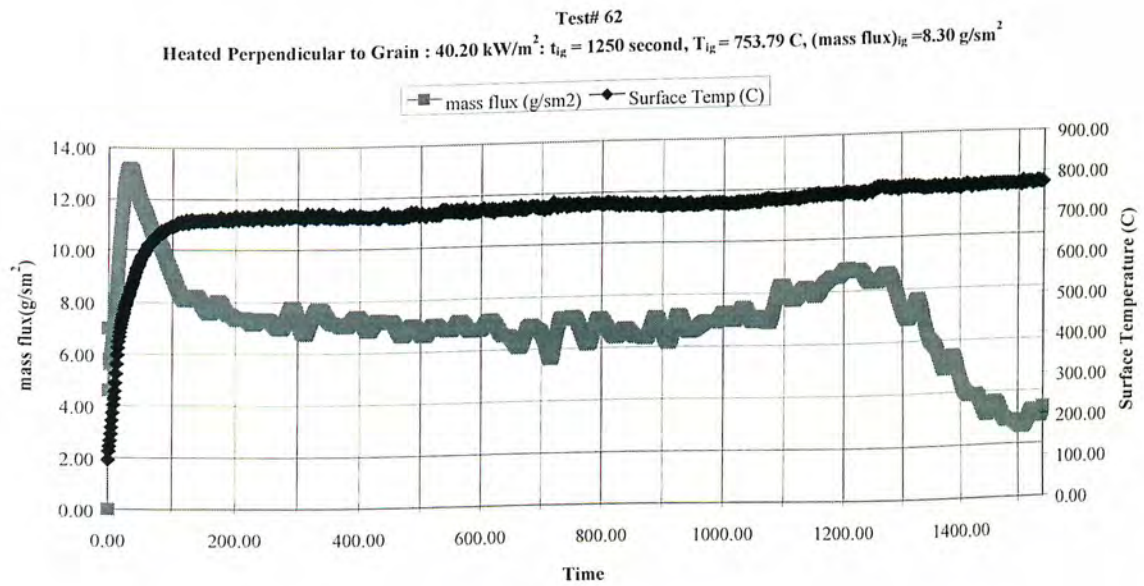


Figure B33: Mass flux and surface temperature history (test# 62).

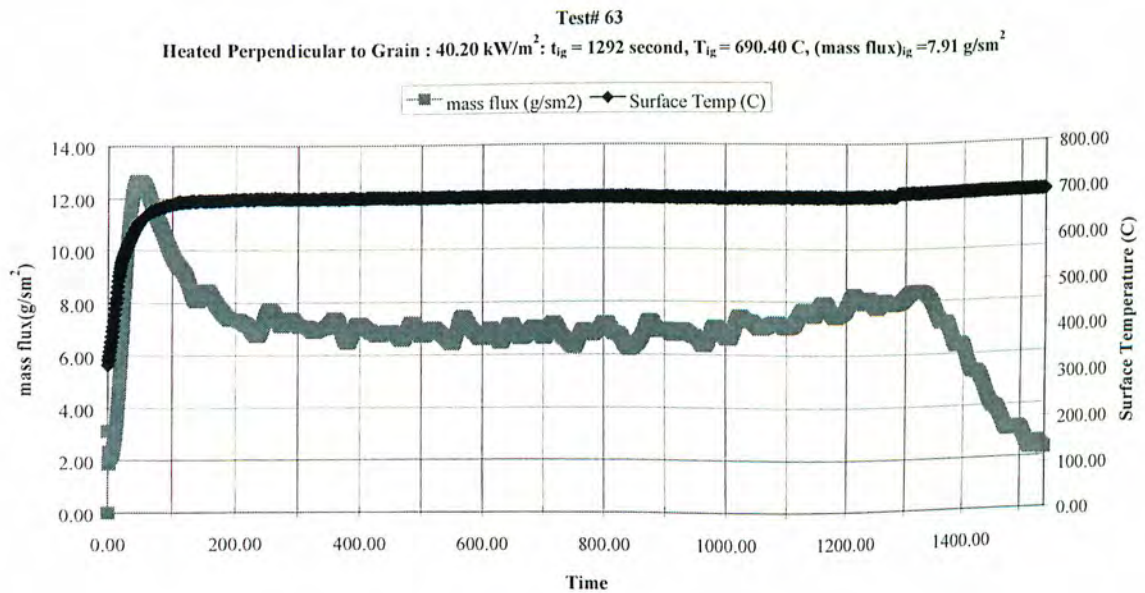


Figure B34: Mass flux and surface temperature history (test# 63).

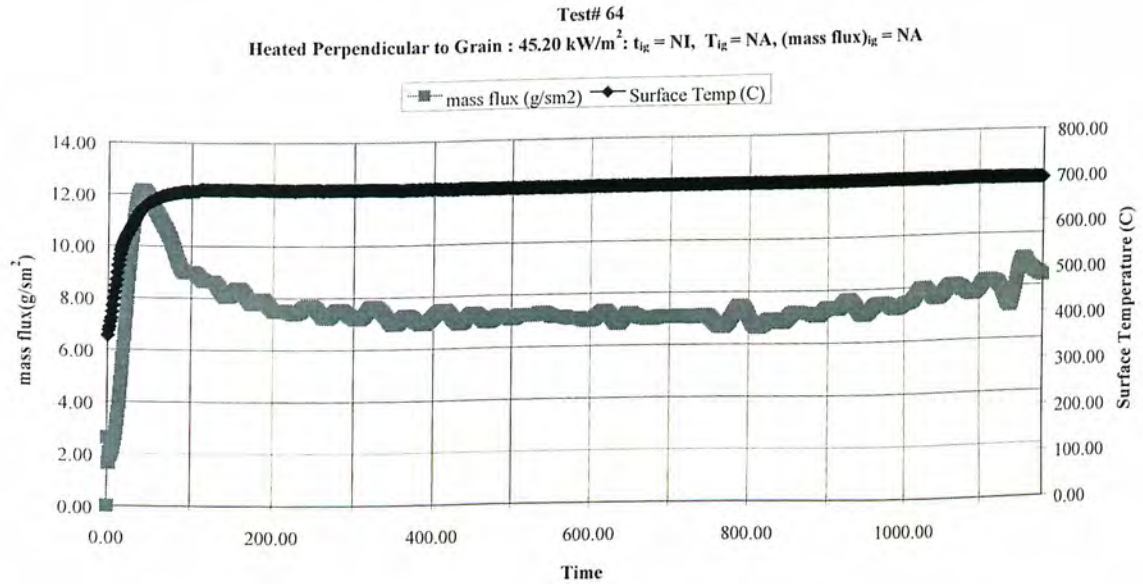


Figure B35: Mass flux and surface temperature history (test# 64).

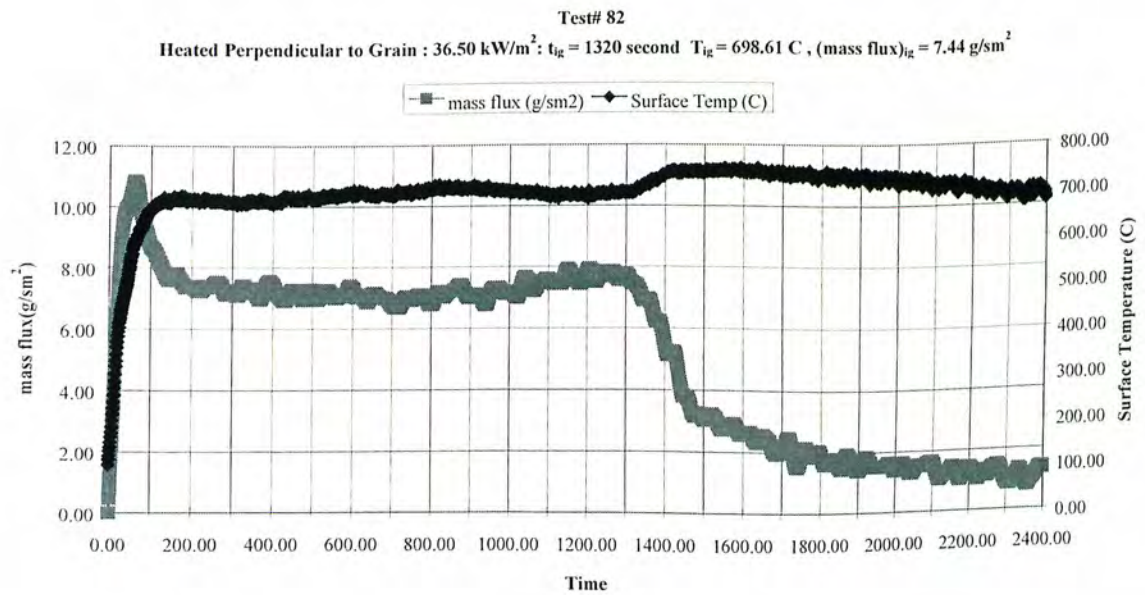


Figure B36: Mass flux and surface temperature history (test# 82).

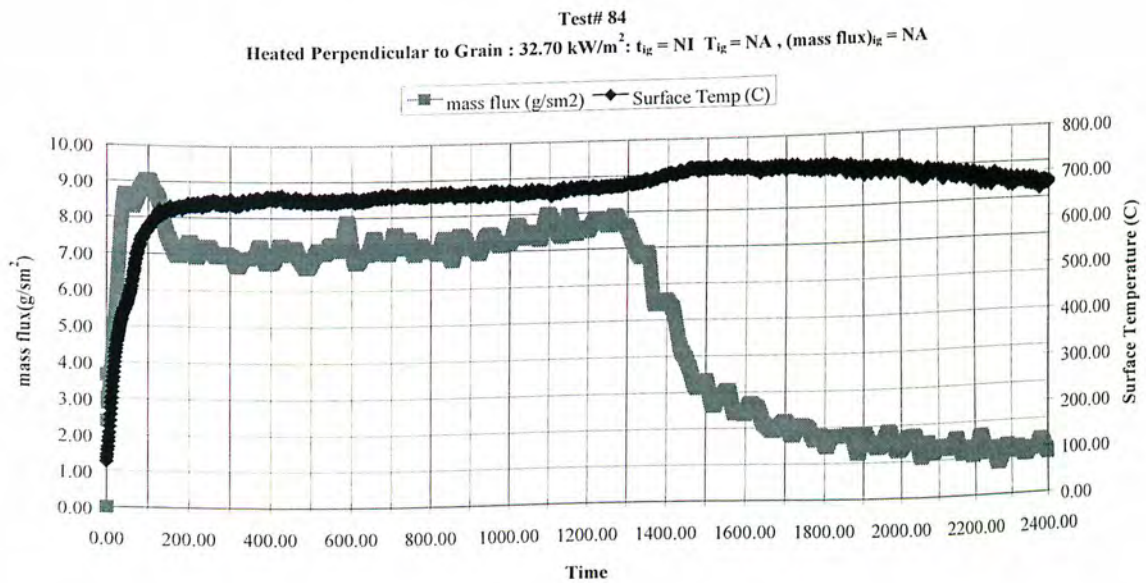


Figure B37: Mass flux and surface temperature history (test# 84).

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