Effect of Moisture on Ignition Time of Cellulosic Materials

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ABSTRACT

The effect of equilibrium moisture content (ranging from 4 to 12.5% moisture, corresponding to 20 to 90% relative humidity) on piloted ignition times of single wall and tri-wall corrugated paperboard samples has been measured over a range of external radiant heat flux (10 to 60 kW/m^2) in the Fire Propagation Apparatus (ASTM E-2058). It has been shown for heat fluxes up to 50 kW/m^2 corrugated paperboard samples behave as thermally thin solids and satisfy a simple fundamental equation based on energy required for ignition: $(\dot{q}''_e - \chi\,\dot{q}''_{cr})t_{ig} = \alpha(1+\gamma\, m_w)$

where α and γ are: $\alpha = c_{pc} m''_{dry}(T_{ig} - T_0)$ and $\gamma = \dfrac{c_{pw}(T_b - T_0) + L_w}{c_{pc}(T_{ig} - T_0)}$

This thermally thin model provides the piloted ignition time for a given net radiant heat flux and at a specific moisture content, consistent with experimental data. The value of dimensionless, γ is predicted to be 5.14 for corrugated samples initially at 23^{o}C, whereas, the measured value is 5.0. Measurements of the tested tri-wall and single wall corrugated paperboard yield α = 332 kJ/m^2 and 230 kJ/m^2, respectively. Based on moisture dependent property values obtained from the literature, the model has been extended to piloted ignition under thermally thick conditions.

KEYWORDS: ignition measurement, ignition time, thermally thin, thermally thick, moisture content

NOMENCLATURE LISTING

c	specific heat of solid (kJ/kg-K)
c_0	specific heat of dry wood (kJ/kg-K)
c_{pc}	specific heat of dry corrugated (kJ/kg-K)
c_{pw}	specific heat of water (kJ/kg-K)
d	thickness (m)
k	thermal conductivity of solid (kW/m-K)
k_0	thermal conductivity of dry wood (kW/m-K)
L_w	heat of vaporization of water (kJ/kg)
m_{wet}	mass wet (kg)
m_{dry}	mass dry (kg)
m''_{dry}	mass of dry corrugated per unit area (kg/m^2)
m_w	fractional added mass of water in the sample
$\dot{q}''_e$	incident heat flux (kW/m^2)
$\dot{q}''_{cr}$	critical heat flux for ignition (kW/m^2)
T_b	boiling point of water (K)
T_{ig}	surface ignition temperature (K)
T_0	ambient temperature (K)
t_{ig}	time to piloted ignition (s)
Greek	
α	$= c_{pc} m''_{dry}(T_{ig} - T_0)$ (kJ/m^2)
χ	average heat loss as a fraction of $\dot{q}''_{cr}$
γ	non-dimensional (see Equation 10)
ρ	density of solid (kg/m^3)
ρ_0	density of dry wood (kg/m^3)
τ_{th}	thermal diffusion time (s)
σ	Stephan-Boltzmann constant (5.67 x 10^{-11} kW/m^2-K^4)

INTRODUCTION

Cellulosic materials, such as wood, paper products, etc. are inherently hygroscopic in nature. The variation of moisture content in cellulosic material is expected to have an effect on the ignition delay time and rate of

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flame spread. The effect of moisture content in relation to fire growth tests has long been recognized. However, few researchers have addressed this issue and test methods generally do not account for its importance. Simms and Law [1] conducted piloted and auto ignition tests on specimens of different wood materials with 20 to 60% moisture contents and measured the ignition times over a wide range of radiation intensities. They found that ignition times increase with increasing moisture content. They attributed this increase to the increase in thermal properties (thermal conductivity, specific heat and density), and the effects of moisture vaporization and moisture migration. Atreya and Abu-Zaid [2] also reached the same conclusion while working with wood materials with moisture contents in the range of 11 to 27%. Recently, Moghtaderi et el. [3] also concluded that 15 to 30% moisture content in wood materials significantly delays the thermally thick ignition times as a function of external heat flux and substantially alters the thermo-physical properties of the materials. All the above studies were made for wood under thermally thick conditions. Researchers have yet to investigate the effect of moisture for materials under thermally thin conditions or for moisture contents less than 11%. When wood materials are inside buildings, their moisture contents are usually between 5% and 15% [4]. The difficulty in controlling moisture contents at lower relative humidity is the possible reason why the above experiments were not conducted in the range of lower moisture contents.

In this study, the effect of moisture content (4 to 12.5% corresponding to 20 to 90%RH) on ignition behavior has been determined for corrugated paperboard samples, generally used for packaging purposes. Compared with wood, corrugated paperboard has a lower moisture content for a given relative humidity. The Fire Propagation Apparatus (FPA) (ASTM E 2058) allows one to control its atmosphere and was, therefore, used for the experiments. We designed and developed a suitable humidity control and delivery system to measure piloted ignition times as a function of external radiant heat flux under various relative humidity cases (20% to 90%RH in air stream).

HUMIDITY CONTROL AND DELIVERY SYSTEM

In this study, a humidity control and delivery system for the FPA was designed and assembled from different components. The hardware was selected to work with a flow through system such as the FPA, whose flow rate is typically 200 liters/min (3.3 x 10^{-3} m^3/s).

Figure 1 presents a schematic of the humidity control and delivery system for the FPA. A syringe pump is used to inject water at a known flow rate (0 - 4.5 ml/min). Two 300 watt coil heaters are wrapped tightly around a 12.5 mm copper tube into which water is injected from a small 3 mm stainless steel tube supplied by the syringe pump. The coil heaters are regulated to 225-300^{o}C to convert the water into steam. Inside the 12.5 mm copper tube, a coiled 3 mm copper tube (not shown in Fig. 1) is introduced connecting the 3 mm stainless steel tube of the syringe pump. This coiled arrangement of 3 mm copper tube increases the residence time for water to completely vaporize before entering the 12.5 mm copper mixing chamber where it mixes with the dry air flowing at a volume flow rate of 200 l/min. The resulting humid air is passed through a 12.5 mm stainless steel tube before delivery into the air distribution box of the FPA (shown in Fig. 2) at a flow rate of 200 l/min at ambient temperature (23^{o}C $\pm$ 1^{o}C) and pressure (101 kPa).

A humidity measuring probe (accuracy $\pm$ 1% R.H. range 0 – 90% at 15 – 25^{o}C) is used to measure the relative humidity inside the air distribution chamber, close to the sample location in the FPA (Fig. 2). The absolute pressure inside the air distribution chamber is monitored by a digital readout during the experiment. Two syringes are used in the syringe pump in order to allow for longer test duration time. The water flow rate from the syringe pump as well as the temperature of the coil heaters are adjusted to provide a fixed relative humidity in the FPA.

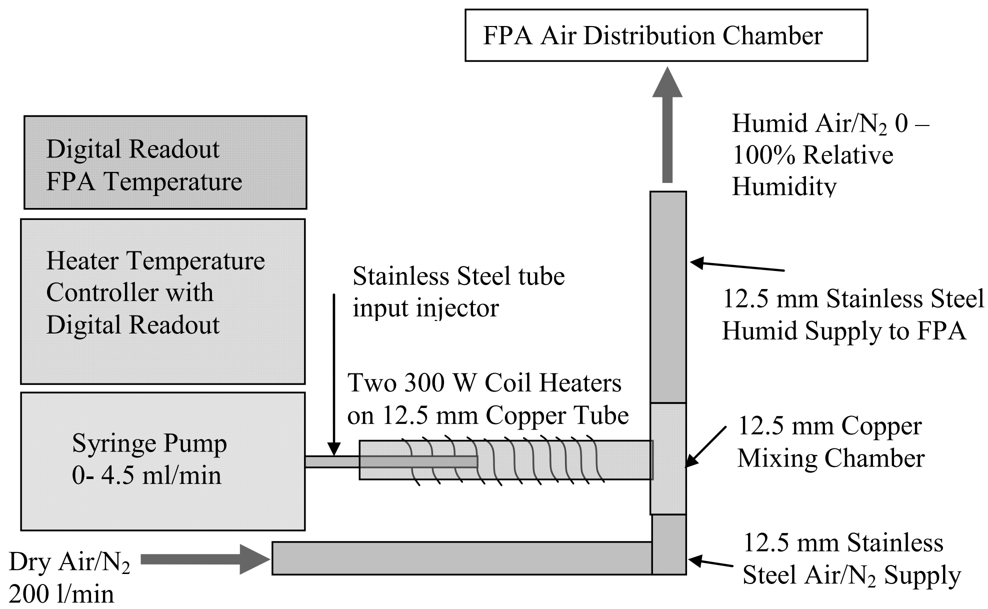

Fig. 1. Humidity Control and Delivery System for the Fire Propagation Apparatus.

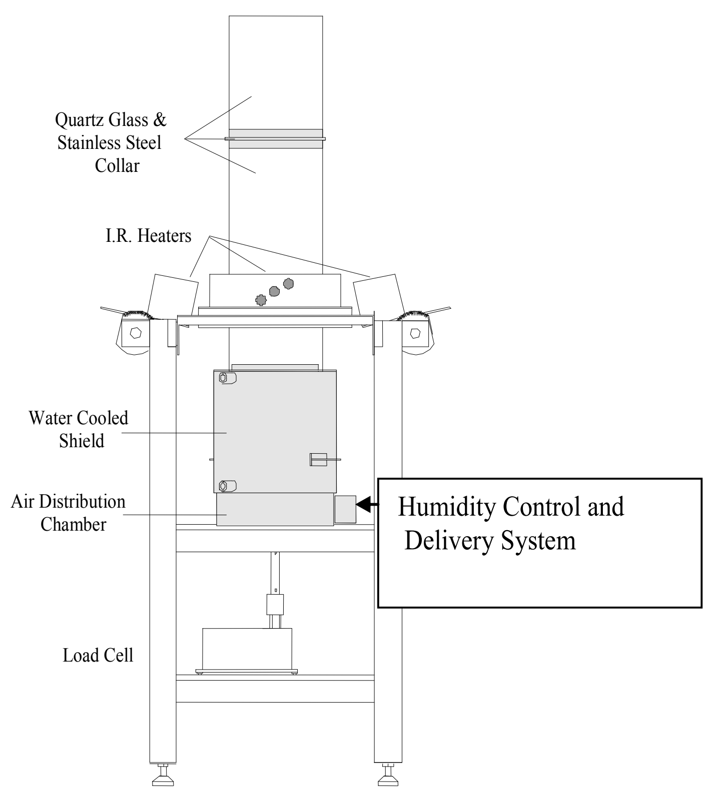

Fig. 2. Fire Propagation Apparatus.

EXPERIMENTAL APPROACH

Sample

Single-wall (~3.175 mm overall thickness) and tri-wall (~15.875 mm overall thickness) corrugated paperboard samples were tested in this study.

Sample Conditioning

Circular samples (9.8 cm diameter) in standard insulated sample holders [5] are first conditioned in a vacuum oven at 105°C for 24 hours to completely remove moisture (bone dry). Subsequently, these samples along with the sample holders are placed in a desiccator and transported to environmental chambers for 24 hours conditioning at 23°C at various values of relative humidity (RH%). The relative humidity in the environmental chambers was set equal to the values for ignition testing in the FPA, which was also performed at 23°C $\pm$ 1°C .

Ignition Experiment

While in the environmental chamber, samples in their sample holder [5] were put into individual polyethylene (PE) bags and immediately transferred in a desiccator which was transported to the laboratory for ignition testing. Another sample (2.54 cm x 2.54 cm size) was taken out of the environmental chamber in a PE bag for moisture content measurement. Moisture contents were measured on a dry mass basis: Moisture Content, MC = $\frac{(m_{wet} - m_{dry}) \times 100}{m_{dry}}$ where m_{wet} = mass wet; m_{dry} = mass dry. (1)

Figure 3 presents the moisture content in corrugated paperboard samples as a function of relative humidity. The dashed line in Fig. 3 is a trend line.

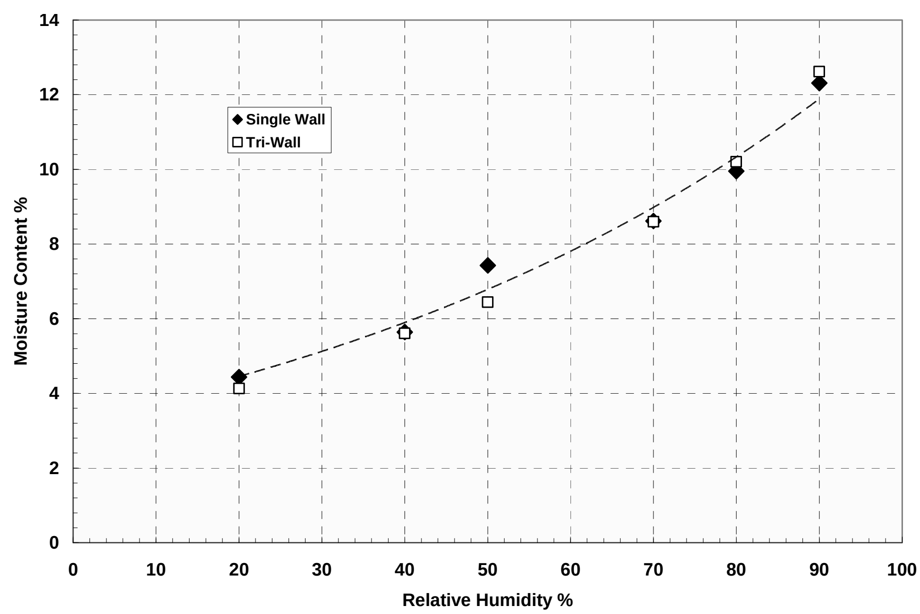

Fig. 3. Moisture Content as a function of relative humidity.

As previously mentioned, the FPA is set to the same RH% as the RH% of the environmental chamber. The sample together with its sample holder is removed from its PE bag and quickly placed on the sample platform near the IR heaters in the FPA (Fig. 2). Carbon black powder is evenly applied on the sample surface in order to make sure that all the imposed radiant heat is absorbed by the material. A 10-mm long premixed ethylene-oxygen pilot is lighted. Then the FPA quartz tube is placed around the sample and sample holder to control the environment. This procedure takes about 30 seconds to 1 minute. At this point, the water-cooled radiation shield is raised for protecting the sample as the radiant heaters are turned on for a specific heat flux value. After stabilizing the radiant heaters for 30 seconds, the water-cooled shield is dropped to expose the sample and then the time to piloted ignition is observed and recorded. Piloted ignition experiments are conducted under 20%, 40%, 50%, 70%, 80% and 90% RH conditions and at various values of radiant heat flux up to 60 kW/m^2 (limit of the present FPA). Ignition experiments are repeated three times for each radiant heat flux and moisture content. The maximum variation of repeated ignition time measurements is found to be ~14% in the lower radiant heat flux region (10 to 20 kW/m^2) close to the critical heat flux for ignition. The maximum variation in measurements is within 8% in the heat flux range of 30 to 60 kW/m^2. All repeated ignition times are presented in the Results and Discussion section.

THEORETICAL ANALYSIS OF IGNITION

When a solid material is exposed to a heat flux, it behaves either as thermally thin or thermally thick, depending on its material properties, dimensions and the magnitude of the incident heat flux. Materials typically behave as thermally thick at high heat fluxes (i.e., at high heating rates); and behave thermally thin at low heat fluxes (i.e., at low heating rates) near their critical heat flux for ignition. A thermally thick material is one having its physical thickness always greater than the depth of thermal diffusion at the time of ignition, while a thermally thin sample has its physical thickness less than the depth of thermal diffusion at ignition.

The equation for piloted ignition time of solids under thermally thick conditions is based on conduction theory given by Carslaw and Jaeger [6]:

$$t_{ig(thick)} = \frac{\frac{\pi}{4} k\rho c\,(T_{ig} - T_0)^2}{(\dot{q}''_e - \chi\,\dot{q}''_{cr})^2} \tag{2}$$

where, $t_{ig(thick)}$ is the time to piloted ignition (s); *k*, ρ and *c* are thermal conductivity (kW/m-K), density (kg/m^3) and specific heat (kJ/kg-K) of the solid; T_{ig} and T_0 are the surface ignition temperature (K) and ambient temperature (K); $\dot{q}''_e$ and $\dot{q}''_{cr}$ are the incident heat flux (kW/m^2) and the critical heat flux for ignition (CHF) (kW/m^2); and χ is the average heat loss as a fraction of the critical heat flux. The square root of the term in the numerator of the right hand side of Eq. 2 is sometimes referred to as the Thermal Response Parameter [7]:

$$\text{TRP} = \left(\frac{\pi}{4} k\rho c\right)^{1/2} (T_{ig} - T_0) \tag{3}$$

Under thermally thin conditions for solids of thickness *d* (m), the time to piloted ignition is based on the energy required to heat the material to its ignition temperature assuming a uniform temperature:

$$t_{ig(thin)} = \frac{\rho c d\,(T_{ig} - T_0)}{\dot{q}''_e - \chi\,\dot{q}''_{cr}} \tag{4}$$

T_{ig} in Eqs. 2 and 4 is evaluated here such that $\dot{q}''_{cr} = \sigma(T_{ig}{}^4 - T_0{}^4)$ for a black surface, where σ is the Stephan-Boltzmann constant (5.67 x 10^{-11} kW/m^2-K^4).

The value of χ in Eq. 2 approximates the effect of heat losses during heat up of the solid. It was first recommended by Delichatsios et al [8] for thermally thick conditions assuming the surface re-radiation losses close to $\dot{q}''_{cr}$ are dominant. Delichatsios et al, assuming only radiative losses, recommended setting

χ =0.64 for solids being rapidly heated under thermally thick conditions. After analyzing various materials, and considering both radiant and convective losses we propose a single value for χ =1.0 for both thermally thin and thermally thick solids. CHF is obtained empirically by plotting the inverse of time to ignition against several low incident heat fluxes and interpreting the intercept on the heat flux axis by a best fit line.

We define a thermal diffusion time, τ_{th} (s), to demarcate the transition between a thermally thick response and a thermally thin behavior as [9]:

$$\tau_{th} = \frac{4\rho c d^2}{\pi k} \tag{5}$$

Using Eqs. 2 and 5, the relationship between thick to thin is given by,

$$t_{ig(thin)} = (\tau_{th} t_{ig(thick)})^{1/2} = \frac{(\frac{\pi}{4} k\rho c)^{1/2} (T_{ig} - T_0)}{\dot{q}''_e - \chi \dot{q}''_{cr}} \left[\frac{4\rho c d^2}{\pi k}\right]^{1/2} = \frac{\rho c d (T_{ig} - T_0)}{\dot{q}''_e - \chi \dot{q}''_{cr}} \tag{6}$$

A generalized form applicable to both thermally thick and thin behavior is

$$t_{ig(thick/thin)} = \left[\left(\frac{\dot{q}''_e - \chi \dot{q}''_{cr}}{(\frac{\pi}{4} k\rho c)^{1/2} (T_{ig} - T_0)} \right)^4 \frac{1}{\tau_{th}{}^2} + \left(\frac{\dot{q}''_e - \chi \dot{q}''_{cr}}{(\frac{\pi}{4} k\rho c)^{1/2} (T_{ig} - T_0)} \right)^8 \right]^{-1/4} \tag{7}$$

The exponents ¼, 4 and 8 above provide a good fit to an exact numerical solution for transition between thermally thin and thick behavior [10]. In Eq. 7, if t_{ig} is less than τ_{th} the response of the material becomes thermally thick; whereas, if t_{ig} is greater than τ_{th} the response becomes thermally thin. Thus τ_{th} provides the transition between thermally thin and thermally thick behaviors.

Thermally Thin Condition

Using Eq. 7, both types of corrugated paperboard samples are found to behave as thermally thin solids for incident heat fluxes up to 50 kW/m^2, as discussed in a later section. Based on thermally thin condition in Eq. 4, the net energy received by the surface of the sample equals the energy required for ignition:

$$(\dot{q}''_e - \chi \dot{q}''_{cr})\, t_{ig} = \alpha\,(1 + \gamma\, m_w) \tag{8}$$

Here $\gamma\, m_w$ is the normalized increase in energy needed to heat up and vaporize the moisture. m_w is the fractional added mass of water in the sample (i.e., fractional moisture content), i.e., $m_w = \dfrac{m_{wet} - m_{dry}}{m_{dry}}$; α and γ are defined by:

$$\alpha = c_{pc} m''_{dry} (T_{ig} - T_0) \tag{9}$$

$$\gamma = \frac{c_{pw}(T_b - T_0) + L_w}{c_{pc}(T_{ig} - T_0)} \tag{10}$$

where c_{pc} is the specific heat of the dry corrugated paperboard (kJ/kg-K); m''_{dry} is the mass of the dry corrugated paperboard per unit surface area (kg/m^2); c_{pw} is the specific heat of water (kJ/kg-K); T_b is the boiling point of water (K) and L_w is the heat of vaporization of water (kJ/kg). Equation 8 provides the combined effect of net external radiant heat flux and moisture content (in the material) on the piloted ignition time under thermally thin conditions. Equation 8 simply assumes that all the moisture in the thin sample must be vaporized.

Thermally Thick Condition

As we know, Eq. 2 provides ignition time under thermally thick conditions. The properties k, ρ and c all increase with the increase in moisture content, as discussed by Simms and Law [1]. Ignoring moisture migration and the small heat of desorption of water, the specific heat increases by approximately $c = c_0(1+5m_w)$; while the thermal conductivity increases by approximately $k = k_0(1+2.1m_w)$; and the density increases by $\rho = \rho_0(1+m_w)$. Combining these moisture effects, they correlated piloted ignition data on wet wood with thermal inertia, $k\rho c$ after adjusting the thermal properties for the small value of moisture, m_w:

$$k\rho c = k_0\rho_0 c_0[(1+5\,m_w)(1+2.1m_w)(1+m_w)] \geq k_0\rho_0 c_0(1+8.1\,m_w) \tag{11}$$

where k_0, ρ_0 and c_0 are thermal conductivity, density and specific heat of dry wood. It will be seen that the value of 8.1 in Eq. 11 is almost twice the value for thermally thin conditions (as given in Eqs. 12a and 12b below). Thus one expects a greater effect of moisture under thermally thick conditions. Indeed, the data of previous investigators [1-3] suggest the same to be true.

RESULTS AND DISCUSSION

Thermally Thin Condition

There should be little effect of moisture on the thermal diffusion times, τ_{th}. Therefore, we assume that the thermal diffusion time, τ_{th} in Eq. 7 remains invariant with increasing moisture content for our measurements (MC from 4 to 12.5%). By using a readily available optimization technique (Solver in Excel), one can simultaneously evaluate TRP and τ_{th} for piloted ignition data using Eq. 7 for each moisture content. The χ value was found to be very close to 1.0 (0.95 – 0.97) by the best match of theory (Eq. 7) with the actual experimental ignition data. Figures 4a and 4b present the ratio of thermal diffusion time to piloted ignition time as a function of net incident heat flux. Best fit lines are shown for each moisture content data series. In some cases, because of overlaps, lines are not drawn for the sake of clarity. These figures reveal that indeed the samples behave as thermally thin solids for incident heat flux up to 50 kW/m^2.

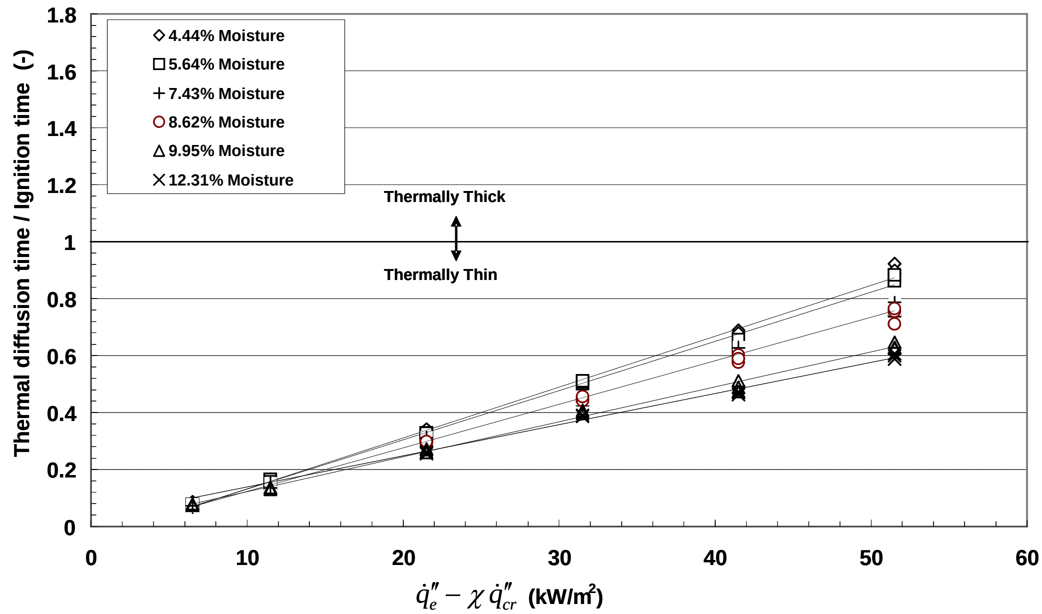

Fig. 4a. The ratio of thermal diffusion time to ignition time as a function of net external heat flux at various moisture contents (for single wall corrugated paperboard).

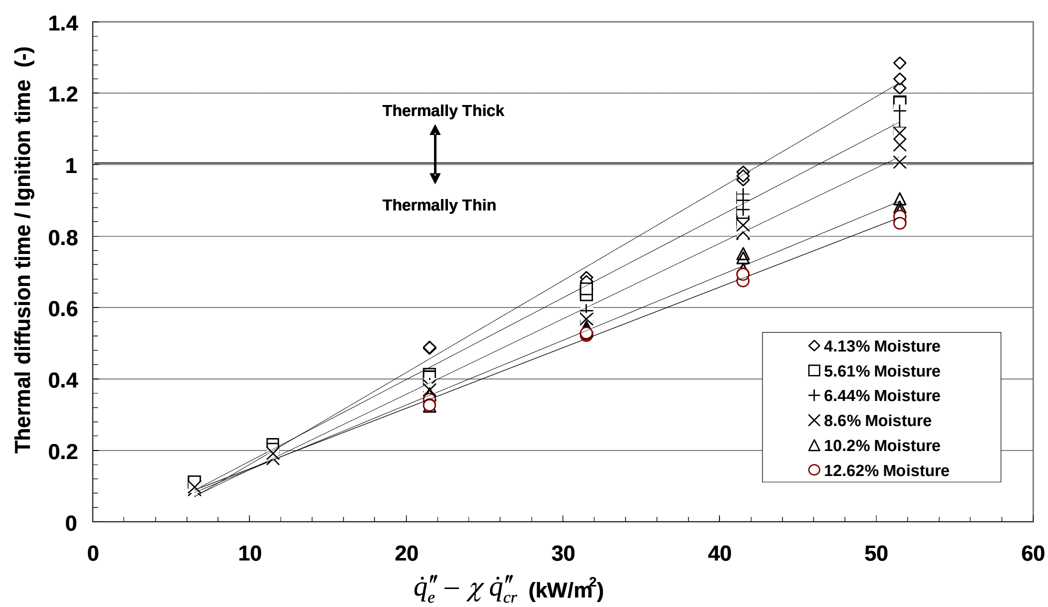

Fig. 4b. The ratio of thermal diffusion time to ignition time as a function of net external heat flux at various moisture contents (for tri-wall corrugated paperboard).

Critical Heat Flux (CHF)

The critical heat flux, $\dot{q}''_{cr}$ (CHF) is obtained (as previously discussed) from Figures 5a and 5b for single wall and tri-wall corrugated paperboard, respectively.

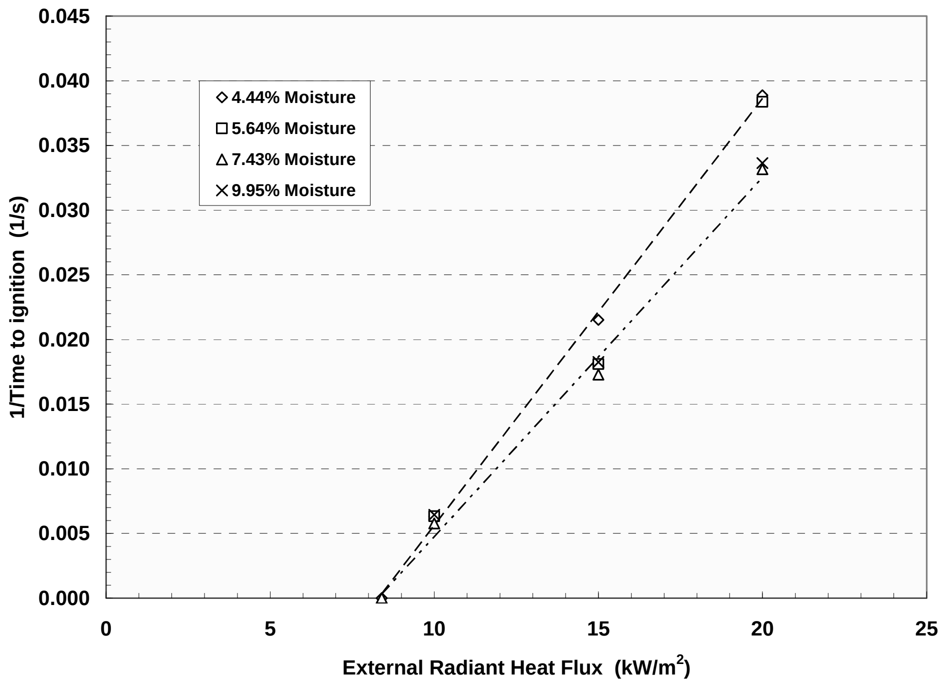

Fig. 5a. Critical heat flux for single wall corrugated paperboard.

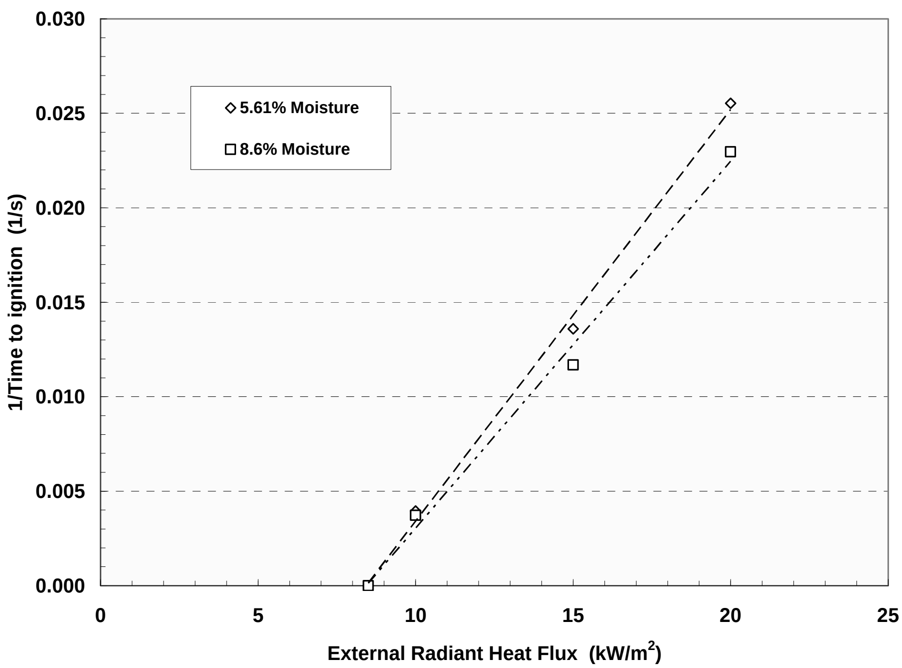

Fig. 5b. Critical heat flux for tri-wall corrugated paperboard.

The CHF from the intercept on the heat flux axis by the best fit lines is found to be about 8.5 kW/m^2 for both single and tri-wall samples regardless of the moisture content. This is due to the fact that, at slow heating rates, the sample heats slowly and dries out prior to ignition.

Effect of Moisture on Ignition Time

In order to demonstrate the combined effects of net external heat flux (setting $\chi = 1.0$) and moisture content on piloted ignition time, Eq. 8 is plotted in Figs. 6a and 6b for single and tri-wall samples, respectively. The data in the two figures indicate that the overall agreement of theory and experiment is very good. The slight reduction in time to ignition at high heat fluxes suggests the beginning of thermally thick response. The best fit lines to the data are as follows:

$$t_{ig} = \frac{230.0\,(1+5.0\,m_w)}{\dot{q}''_e - \chi\,\dot{q}''_{cr}} \quad \text{for single wall corrugated paperboard,} \qquad (12a)$$

and

$$t_{ig} = \frac{331.63\,(1+5.0\,m_w)}{\dot{q}''_e - \chi\,\dot{q}''_{cr}} \quad \text{for tri-wall corrugated paperboard,} \qquad (12b)$$

Based on Eqs. 12a and 12b, one can predict the time to piloted ignition for a given net radiant heat flux, thermal properties and a specific moisture content.

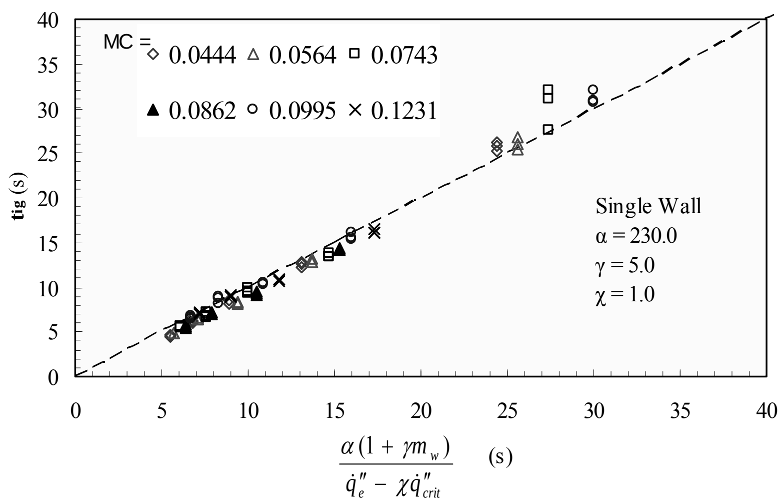

Fig. 6a. Measured piloted ignition time vs. theoretical ignition time for single wall corrugated paperboard at various moisture contents.

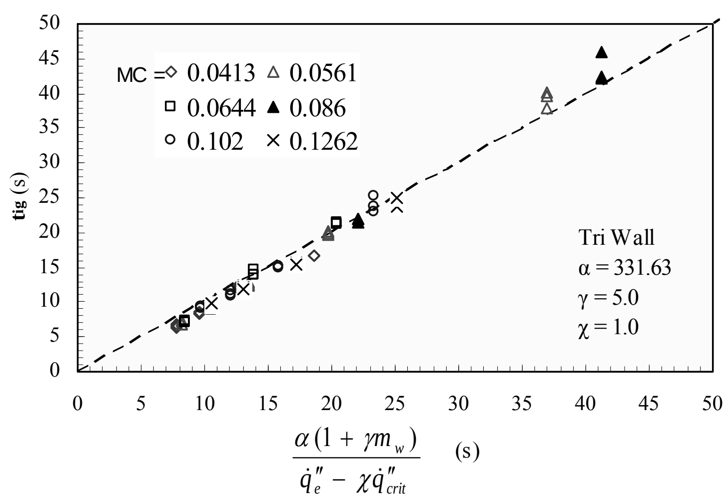

Fig. 6b. Measured piloted ignition time vs. theoretical ignition time for tri-wall corrugated paperboard at various moisture contents.

Table 1. Corrugated paperboard properties

Assumed Properties	
Corrugated Paperboard:	
Specific Heat, c_{pc}	1.52 kJ/kg-K
Ignition Temperature, T_{ig}	623 K (calculated from CHF)
Ambient Temperature, T_0	293 K
Water:	
Specific Heat, c_{pw}	4.2 kJ/kg-K
Heat of Vaporization, L_w	2260 kJ/kg

By using the properties from Table 1 in Eq. 8, we find the predicted value of γ =5.14 for corrugated paperboard samples (initially at 20°C), which is very close to the measured value (5.0) in Eqs. 12a and 12b. Using the measured values of α (kJ/m^2) from Eqs. 12a and 12b, one can find the corresponding value of m''_{dry} in Eq. 9 for single and tri-wall corrugated paperboard, which are 0.46 kg/m^2 (94 lb/1000 ft^2) and 0.66 kg/m^2 (135 lb/1000 ft^2), respectively. These values are about 3.5 and 1.5 times the mass per unit area of the outer sheet (i.e. linerboard) of the corrugated paperboard materials having respectively mass per unit area 0.127 kg/m^2 (26 lb/1000 ft^2) for single and 0.44 kg/m^2 (90 lb/1000 ft^2) for tri-wall. These results appear to be quite reasonable given the density of the linerboard materials of the finished corrugated products.

The results also suggest that, under thermally thin conditions, the piloted ignition times for a known external heat flux increase by about 40% for the increase in moisture content from 4 to 12.5%.

Effect of Moisture on Fire Growth Rate

Characteristic fire growth times are fundamentally related to the ignition delay times. As mentioned previously, the corrugated paperboard samples behave as thermally thin solids for incident heat fluxes up to 50 kW/m^2 with ignition time given by Eq. 8. Thus the effect of moisture content on the characteristic fire growth times will follow Eq. 8 for thermally thin conditions

$$t_{ig\,(thin)} = \frac{\rho_0\, c_0 (1+\gamma m_w) d\; (T_{ig}-T_0)}{\dot{q}''_e - \chi\, \dot{q}''_{cr}} \qquad (13a)$$

For greater heat fluxes, that is above 60 kW/m^2, the corrugated paperboards presumably would behave as thermally thick solids for which the characteristic fire growth times are given by

$$t_{ig\,(thick)} = \frac{\frac{\pi}{4} k\rho c (T_{ig}-T_0)^2}{(\dot{q}''_e - \chi\, \dot{q}''_{cr})^2} \geq \frac{\frac{\pi}{4} k_0 \rho_0\, c_0 (1+8.1 m_w)(T_{ig}-T_0)^2}{(\dot{q}''_e - \chi\, \dot{q}''_{cr})^2} \qquad (13b)$$

This has a considerably greater dependence on moisture content.

CONCLUSIONS

1. In this study, a humidity control and delivery system was designed and developed for the Fire Propagation Apparatus FPA (ASTM E 2058). It is capable of producing 20 to 90% relative humidity conditions close to the sample location. This is the first time a standard material flammability apparatus has included humidity control. The present results show that such control is necessary for testing cellulosic materials.

2. A simple thermal model (Eq. 8) was developed for thermally thin conditions. It provides the energy required for ignition for a given net energy delivered to the surface of the sample. This model predicts the time to piloted ignition for a given net heat flux, thermal properties and moisture content.

3. The effect of moisture content (4 to 12.5%) on piloted ignition times for both single wall and tri-wall corrugated paperboard samples has been measured over a range of external radiant heat flux (10 to 60 kW/m^2) in the FPA. The measured value of γ was 5.0 and the predicted value was 5.14. These results suggest that, under thermally thin conditions, the piloted ignition times increase by about 40% for the above increase in moisture content.

4. Based on moisture dependent property values obtained from the literature, the model has been extended to piloted ignition under thermally thick conditions. The effect of moisture is expected to be considerably greater under thermally thick conditions (i.e. heat fluxes greater than 60 kW/m^2 to the present corrugated paperboard).

5. Piloted times apply to the characteristic fire growth times for corrugated paperboard. Due to heat flux limitations of the FPA it was not possible to evaluate these times for thermally thick conditions. However, the theoretical model indicates the effect would be more pronounced in this latter case.

6. The critical heat flux for ignition is found to be about 8.5 kW/m^2 for both single and tri-wall corrugated paperboard regardless of the moisture content.

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