IGNITION PROPENSITY AND HEAT FLUX PROFILES OF CANDLE FLAMES FOR FIRE INVESTIGATION

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Common household open flame and radiant ignition sources are the actual or suspected cause for many fires. Because of their popular use, fire investigators have identified candles as one of the most important of these ignition sources. In spite of this, the ignition potential from candle flames is not well characterized and the properties of paraffin wax are not easily accessible. The purpose of this ongoing research is to identify the burning behavior and properties of common candles in order to provide additional tools for use by investigators. The properties of paraffin wax were obtained from literature as well as experimentally. The candles were burned experimentally under controlled laboratory conditions in order to measure the mass burning rate, regression rate, flame height, and heat flux. Using the properties of paraffin wax and characteristics of the candles, numerous simulations were performed with the NIST Fire Dynamics Simulator (FDS) to model the burning rate and heat flux profile **of** a candle flame. The modeling results were then compared with the flame height and heat flux data obtained experimentally.

INTRODUCTION

The use of candles in the U.S. has been increasing annually since the early 1990's. According to the National Candle Association **(NCA),** candles are used in 7 out of 10 homes, and retail candle sales exceed approximately $2.3 billion annually with a growth rate exceeding 15% [1]. The increased use of candles has also resulted in a corresponding increase in the number of candle related fires. The U.S. Fire Administration (USFA) currently estimates that candles are responsible for approximately 9,400 residential fires each year, 90 fatalities, $120.5 million in property loss, and 950 civilian injuries. This accounts for more than twice the number of injuries averaged for all residential fires [2]. In 1998 the U.S. Consumer Product Safety Commission (CPSC) also estimated that there were 12,800 candle-related fires that resulted in 170 deaths and 1,200 injuries [3]. Unattended candles are the number one cause of candle related fires at 19.3%, and 19.1% are attributed to candles placed in close proximity to combustible materials. The types of materials most often ignited by candles were found to be mattresses or bedding (12.8%), cabinetry (10.1%), and curtains, blinds or draperies (8.4%), with **45%** of candle-related fires originating in the bedroom [4]. Despite the rise in candle use and candle-related fires, very little information is available to fire investigators to determine the likelihood of a candle being the cause of a fire.

The purpose of this study is to investigate common ignition sources, such as candles, and to provide data and correlations that fire investigators can use to support their investigations. Additional work is being conducted simultaneously on portable electric and gas-fueled heaters. This work is being funded by the U.S. National Institute of Justice, and is being performed collaboratively by the Bureau of Alcohol, Tobacco, and Firearms (ATF) Fire Research Laboratory (FRL) and the National Institute of Standard and Technology's (NIST) Building and Fire Research Laboratory (BFRL). The goal of the study is to develop accurate inputs to describe the fire characteristics of common ignition sources and the reaction ofmaterials exposed to these sources. The first part of the study on candles involves the characterization of burning candles including mass burning rate, heat release rate, regression rate, flame height, wick length and shape, and heat flux profiles around the flame. Additionally, the thermo-physical properties of candle wax will be studied to better define the combustion processes involved. The properties of the wax and the physical dimensions of a burning candle will become input parameters to a computational fluid dynamics model that will be used to model the candle flame. The candle flame model will be compared and validated with the experimental results. The results of the model validation will provide input procedures and properties necessary to accurately model candle flames of different geometries as well as the interaction of those flames with different target fuels, i.e. ignition.

CANDLE BASICS

A candle consist primarily of wax and a wick. The wax can be provided with additives such as dyes or pigments for color, fragrances for scent, as well as other ingredients that affect the surface finish and adhesion. The most common type of wax used in the candle making process is petroleum-derived paraffin, which has been refined to contain a low percentage of residual oil. The melting point of the paraffin wax used is determined by the manufacturer based on the candle's intended size, shape, and use. Other specialty candles can be made from beeswax, stearic acid, and clear gels. The various dyes and fragrances added to the wax are designed to not effect the burning of the candles and to produce "clean" combustion byproducts (water and carbon dioxide), however the actual effects of these additives is unclear. The wick consists of a braided or twisted fabric (usually cotton) that is designed to match the type of candle and wax it is being used with. The most common type of wick is the flat braid wick, with others being a square or cored braid [5].

The National Candle Association provides the following general descriptions for candles [5]:

- Taper – a slender candle, typically 6 to 18 inches in height, to be held securely upright by a candle holder (see Figure 0)

- Votive – a small cylindrical candle, usually about 1.5 inches in diameter and 2 or 2.5 inches high, which is placed in a "cup"(usually made of glass) to hold the liquefied wax that results from burning; originally produced as white unscented candles for religious ceremonies; they are now available in many colors and scents

- Pillar or Column – a rigid, self-standing candle that is thick in diameter, with one or more wicks

- Luminaria – an outdoor candle created by planting a 15-hour votive in a container filled with sand

- Container or Wax-filled – a candle that is poured into a special glass, tin or pottery container

- Tealight – a small cylindrical candle, usually about 1 inch in diameter and 1.5 inches high, which is filled in its own holder, typically made of metal

- Specialty – an unusually shaped or sculpted free-standing candle

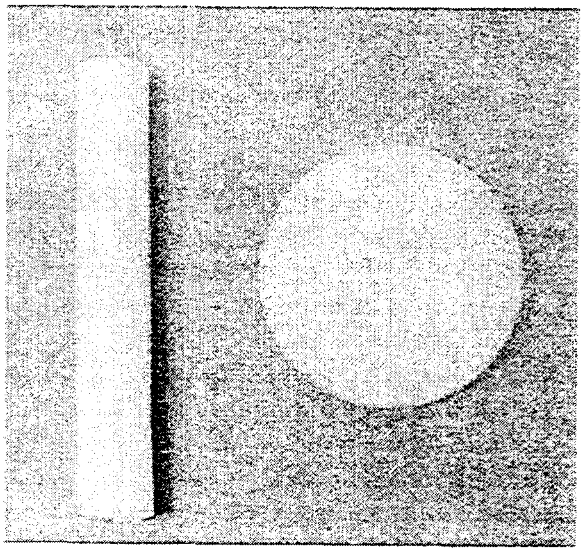

Figure 1. Paraffin Wax Candle and Cone Calorimeter Test Specimen

- Gel – a transparent-type candle typically having a rubbery-like consistency, made primarily from gelled mineral oils or gelled synthetic hydrocarbons, and poured into a container to maintain its shape

- Floating – a shallow candle with a smooth, slightly convex bottom designed specifically to float on water

Because of the various candle types and wax combinations available, the preliminary portion of this study was to focus on a single type of candle. According to the NCA, there are over 350 manufacturers of candles in the U.S., and a major manufacturer can offer 1000 to 2000 varieties of candles [13. Because of their common use, this study focuses primarily on paraffin wax candles of the taper variety, with a single column type candle investigated for comparative purposes. Early in the investigation, it was found that the burning rate and heat flux from the candle flame depends on many interdependent factors including wick length, wick shape, mass burning rate, heat release rate, flame height and paraffin wax formulation, which has a direct affect on the density, melting point, and viscosity. Therefore, a single taper-type candle became the primary focus of this preliminary burning characterization and heat flux study (see Figure 0). This allowed several repeat measurements to be made that would eliminate the various effects. Additional candle types and wand waxes are to be investigated later, based on the information obtained as part of this work.

The primary candle selected for this portion of the study is a 305-mm long white, paraffin wax, taper style candle with a diameter of 21 ± 0.5-mm over the entire length. The wick is a flat braid type, and was approximately 1 mm x 2 mm wide.

PARAFFIN WAX

The primary component of a candle is the wax. Paraffin wax is a composite material that is made up of a mixture of straight-chain hydrocarbon molecules. The molecular formula for paraffin is C_nH_{2n+2}, where the value of n ranges from 19 to 36 and the average value is 25 [7].

The characteristics of a particular paraffin wax are commonly defined by its physical properties. These properties include melting point, penetration, drop point, viscosity, oil content, color, odor, and a few others. These properties help manufacturers assess the appropriateness of a particular wax for a particular type of candle that they intend to manufacture. The most important of these properties, from a manufacturing standpoint, is the melting point which dictates the type of candle that can be produced. For instance, the recommended melt point of the paraffin used to make a taper and pillar candles ranges specifically from 59 to 65°C [8]. Heat release properties such as the effective heat of combustion are not of interest to wax producers or candle manufactures, and are therefore unavailable. A list of material properties for paraffin wax has been provided in Table 1. The properties presented represent ranges of values and due to the incompleteness of data from each reference, only limited attempts have been made to relate the dependence of these properties, i.e. the melting point with respect to flash point, density, and kinematic velocity as presented in Figure 2, Figure **3,** and Figure 4.

The heat release rate of the candle has a direct effect on the heat flux. Therefore in order to develop an accurate flux profile, the heat of combustion of the burning wax becomes extremely important. **As** Table 1 indicates, only one value for the net heat of combustion could be found [15]. Therefore the effective heat of combustion ($\Delta h_{c,eff}$) for the paraffin wax samples selected for this study were determined using the Cone Calorimeter in general accordance with ASTM E 1354 [19]. To determine $\Delta h_{c,eff}$, the candles were broken into small pieces and the wick material was removed. The wax pieces were pressed into a 8-mm thick by 75-mm diameter test specimen using a press at a temperature of 45°C and a pressure of **28** MPa (see Figure 1). The effective heat of combustion for each test specimen was calculated over the time period from ignition of the specimen to flameout.

The $\Delta h_{c,eff}$ of the primary test candle (shown in Figure 1) was determined for heat flux exposures of 10 to 40 kW/m^2. The peak heat release rate for these experiments ranged from 4,150 kW/m^2 (at an incident flux of 40 kW/m²) to 800 kW/m² (at a flux of 10 kW/m²). Nevertheless, the $\Delta h_{c,\,eff}$ for the paraffin was determined to be relatively constant with a slight inverse proportionality to the exposure flux. The average $\Delta h_{c,\,eff}$ for the paraffin wax at the various flux levels was determined to be 45.2 kW/m² with a standard deviation of 0.7 kW/m².

Table 1. Properties of Paraffin Candle Wax

Property	Value	Reference
Carbon Number, Range (C_nH_{2n+2})	19 – 36	6, 7
Carbon Number, Average (C_nH_{2n+2})	23 – 25	7
Molecular Weight (average)	350 – 420 kg/kmol	7
Melting Point	48 – 68°C	6, 7, 9, 11, 12
Congealing Point	66 – 69°C	10, 11
Flash Point	204 – 271"C	6, 7, 9, 11
Fire Point	238 – 263°C	12
Boiling Point	350 – 430°C	10
Oil Content (average)	0.1 – 0.5%	11, 12
Oil Content (maximum)	0.5 – 0.9%	11
Density (@ room temp)	865 – 913 kg/m³	10, 13
Density (@ 82°C)	766 – 770 kg/m³	14
Specific Gravity	0.82 - 0.92	9
Kinematic Viscosity (@ 100°C)	3.12 – 7.1 mm²/s	6, 11, 12
Vapor Pressure (@ 100°C)	2.67 kPa	9
Net Heat of Combustion	43.1 MJ/kg	15
Gross Heat of Combustion	46.2 MJ/kg	15
Latent Heat of Fusion	0.147 – 0.163 kJ/g	10
Specific Heat (solid @ 35 to 40°C)	2.604 kJ/kg·K	10
Specific Heat (liquid @ 60 to 63°C)	2.981 kJ/kg·K	10
Thermal Conductivity (@ room temp)	0.23 W/m·K	13
Melted Wax Temperature (average, around base of wick)	82 – 85°C	16, 17
Maximum Flame Temueerature	1400°C	18

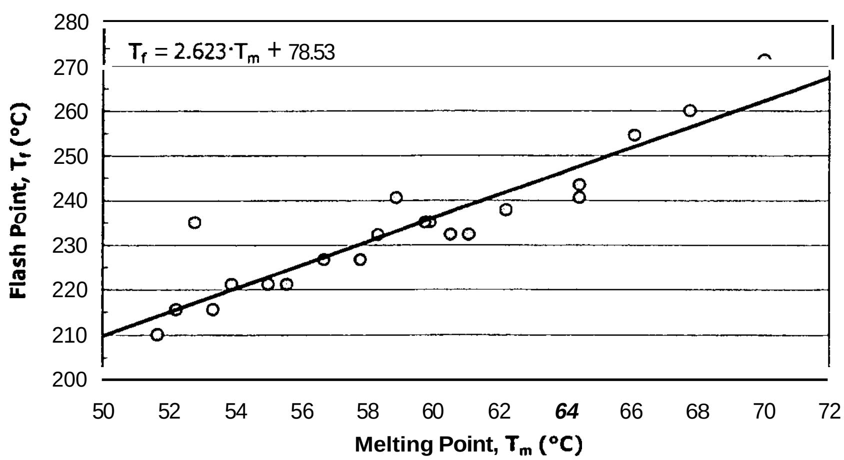

Figure 2. Temperature Dependence of the Flashpoint of Paraffin Candle Wax [6, 7, 9, 11]

Since the Ah,, eff was found to be relatively constant for one wax formulation, the $\Delta h_{c,\,eff}$ was also determined for all eight candles at an exposure flux of 10 kW/m². This flux was level was found to provide the most steady burning rate in the tests described above and was deemed to be the most consistent with actual exposure levels at the wax pool from the candle flame. The $\Delta h_{,eff}$ for the eight different wax formulations was found to be relatively constant with an average value of 45.1 kW/m² and standard deviation of 0.6 kW/m².

Therefore, the effective heat of combustion for paraffin wax is taken to be 45.2 kJ/g, which is in reasonable agreement with the net value of 43.1 kJ/g found in the literature [15]. However this value is for burning paraffin and it is unclear how the process of the liquid wax being draw into the wick by capillary action and burning affects the heat of combustion.

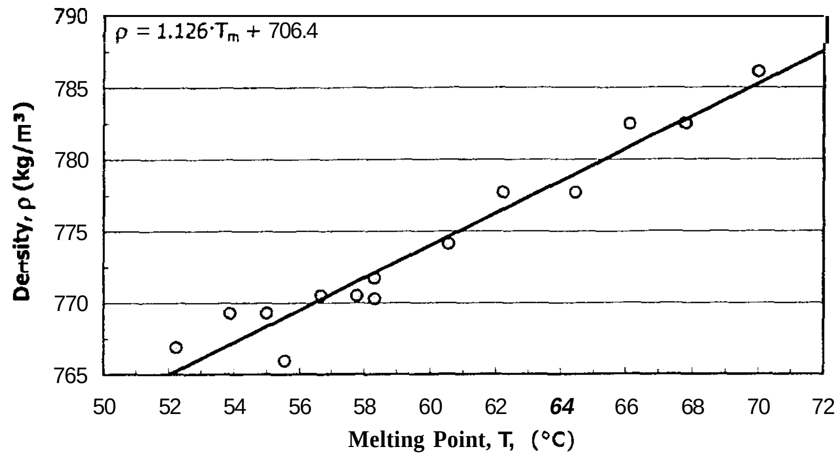

Figure 3. Temperature Dependence of the Density of Paraffin Candle Wax [11, 14]

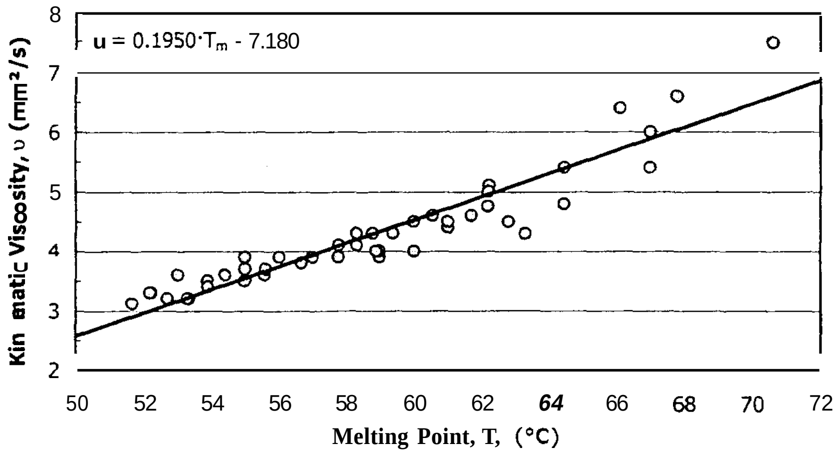

Figure 4. Temperature Dependence of the Kinematic Viscosity of Paraffin Candle Wax [6, 11, 12]

EXPERIMENTAL SETUP AND PROCEDURE

Candle tests were conducted in a 0.61 x 0.61 x 0.76-m high plexi-glass chamber to reduce drafts and provide a truly laminar flame. The chamber was raised 20 mm off of the supporting surface, and the bottom surface was provided with 44 uniformly spaced 6-mm diameter holes around the perimeter to allow fresh air to enter the chamber without producing unwanted drafts. A 150-mm diameter hole, with a 150-mm high plexi-glass chimney was provided at the top of the chamber to allow heat and combustion products to vent from the chamber. One side of the chamber was hinged and provided with two latching closures to allow access to the inside of the chamber for specimen placement, ignition, and platform adjustment during tests.

The candles were supported in the vertical orientation on a load cell within the chamber (see Figure 3). The load cell was located on a jack stand that allowed the entire assembly to be raised or lowered during a test in an absolute vertical direction. *An* array of Schmidt-Boelter heat flux transducers was mounted in a rigid frame either horizontally above the candle specimen as shown in Figure *3*, or in a vertical orientation, depending on the flux measurements to be recorded. The transducers used were water cooled with a 25-mm diameter copper body. Each transducer contained one 9.5-mm diameter total heat flux sensor as well as one 7.5-mm diameter radiant heat flux sensor located 13-mm apart. The water supplied to the transducers was heated to 77°C in order to eliminate condensation formation on the surfaces of the transducers. **A** thermocouple was positioned in the flow of the water exiting the transducers to ensure that the flux from the candle flame did not produce a temperature increase in the transducer. Additional thermocouples were positioned at the top and bottom of the chamber to monitor the test conditions. The voltage output of the transducers and thermocouples was recorded digitally by a data acquisition system every **3** to 5 seconds.

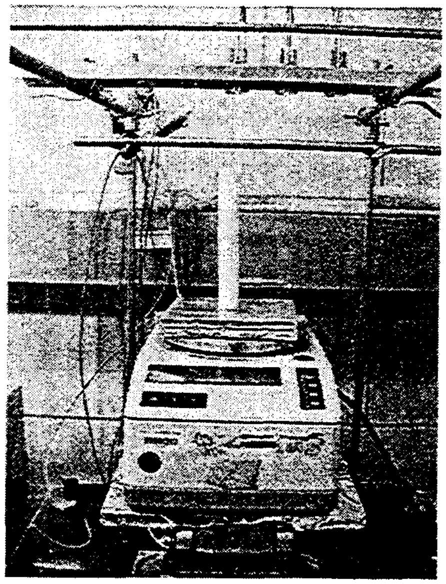

Figure *5*. Test Setup

Prior to each test, the position of the candle in relation to the heat flux meters was verified. This was often difficult and could be simplified by conducting each test with a candle that had been pre-burned for 20 to 30 minutes and allowed to cool. Burning the candle allowed the natural curvature of the wick to become obvious, which then allowed the position of the candle flame to be more accurate since it was recognized that the tip of the flame is generally centered above the center of the curved wick. If an unburned candle was positioned based on the center of the wick, the direction of curvature could move the candle flame away from the expected location and reduce the accuracy of the flux measurements.

A digital camera was mounted on a jack stand just outside the wall of the test chamber. Close-up digital photographs of the top portion of the burning candle were taken approximately every 1 to **2** minutes over the entire test duration. The photographs were used to determine the flame and wick heights as well as the height of the candle with respect to time. **A** metal ruler with 1-mm demarcations was positioned directly next to the candle, at the centerline, which allowed measurements to be made based on physical comparison.

Most tests were conducted for several hours in order to get a representative sampling of heat flux measurements with respect to the relative height of the flame. However, due to the slow burning rate of the candles, the overall distance between the candle and the heat flux transducers would be adjusted by lowering or sometimes raising the platform of the jack stand. An additional metal ruler was positioned vertically next to the stand to allow the platform height to be adjusted to within ± 0.5 mm.

EXPERIMENTAL RESULTS

The mass burning rate (expressed as the mass loss rate), candle regression rate, and flame height are expressed graphically in Figures 6, 7, and **8,** respectively. Each graph represents data obtained from a number of separate tests (either *3* or 5 as indicated). The purpose of these measurements is to understand the actual burning behavior of the candle. As each of the graphs indicates, after ignition of the wick it takes approximately 12 to 15 minutes for burning to reach equilibrium, after which there is very little change in the behavior. The time to reach equilibrium was found to be about 5 minutes shorter for the pre-burned candles, due to the previous formation of the wax pool. Each graph has been provided with a correlation for the measured mass loss rate, regression rate and flame height with respect to time.

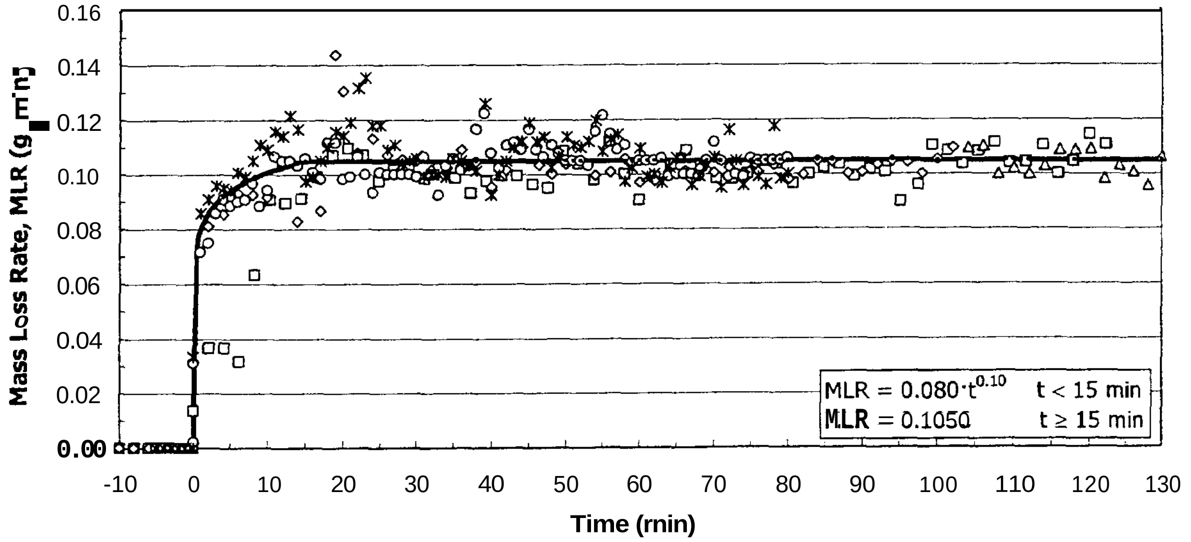

Figure 6. Mass Loss Rate of 21-mm Diameter Candle (5 Tests)

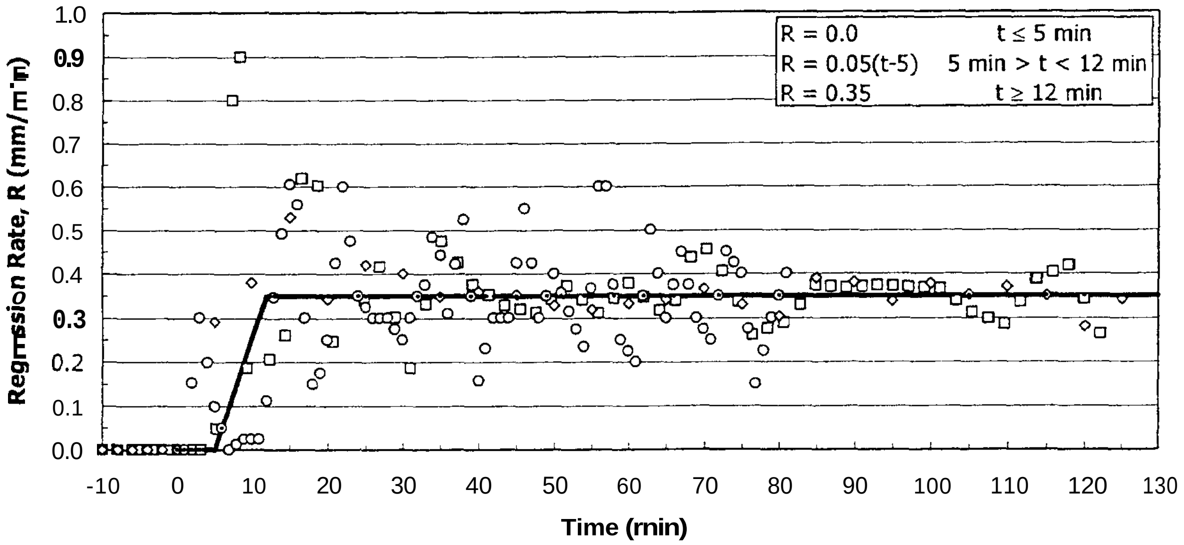

Figure 7. Regression Rate of 21-mm Diameter Candle (3 Tests)

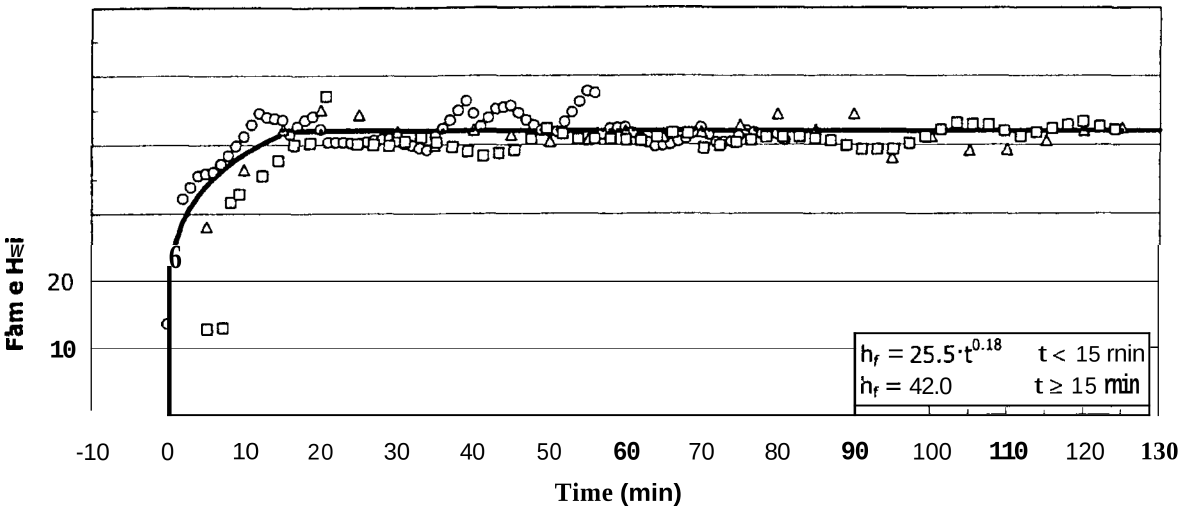

Figure 8. Flame Height of 21-mm Diameter Candle (3 Tests)

Total and radiant heat flux measurements from the candle flames were made in both the horizontal and vertical directions in varying radial distances from the center of the flame. The heat **flux** measurements with respect to the height above the base of the flame and at various radial distances from the center of the flame are presented in Figures **9,** 10, and 11. It was observed that for most cases, once equilibrium had been established, the base of the flame is consistent with the top lip of the candle within approximately 1 to 2 mm. Figure **9** represents the flux directly above the flame tip at a distance of 56 mm above the top of the candle (base of the flame). Because the flame height for this particular candle has a steady burning height of 42 mm, as shown in Figure 8, the heat flux transducers could only be brought to within approximately 50 mm of the top of the candle. At closer distances, the presence of the heat flux transducer significantly affected the height of the flame. Experimental measurements were made at this radial position in four different tests for heights ranging from 50 to 260 mm above the top of the candle. Above 260 mm, the average flux is on the order of only 10 kW/m² and large fluctuations in the measurements can be seen. It is unclear what the cause for the discrepancy is between the data above 150 mm. The data that is represented by the circle and the diamond show good agreement, but the data represented by the square is significantly lower. Because of the consistency between the data from two of the tests, the lower values are believed to be erroneous. Two correlations for the heat flux versus height have been provided since the true nature of the heat flux at these positions is not completely understood, and both correlations give similar agreement below 150 mm.

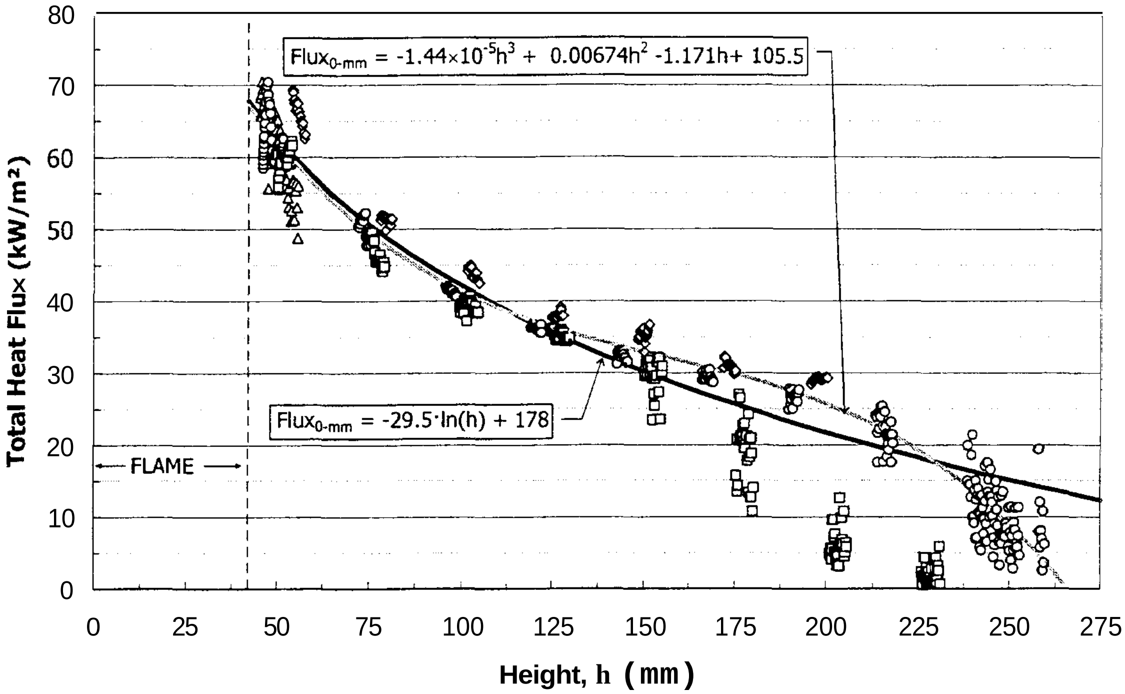

Figure 9. Total Heat Flux in the Vertical Direction vs. the Height Above the Base of the Flame – at Centerline of the Flame (4 Tests)

Correlations for the other radial positions (3 to 13 mm) are also provided within the figures. Different correlations were examined, and it was found that a logarithmic expression consistently provided the best representation for all of the data. Measurements at radial distances greater than 13 mm produced no significant heat flux measurements. However, this is likely due to the configuration of the heat flux transducers and their relatively large size as compared to the flame—the body of each transducer is larger than the diameter of the candle being burned most likely produced disturbing effects on to the buoyant flow field. For example, experiments conducted with the candle positioned at the midpoint between two transducers (only 50 mm apart) produced low heat flux levels with a large amount of fluctuation. These fluctuations are directly attributed to the turbulent disturbance of the buoyant plume.

Radiant fluxes in the vertical direction are presented in Figure 9, which shows the measurements recorded directly above the tip of the flame at 56 mm above the base of the flame. The peak radiant flux that was measured was 5.0 kW/m² and the flux is consistently less than approximately 7% of the total heat flux that was measured.

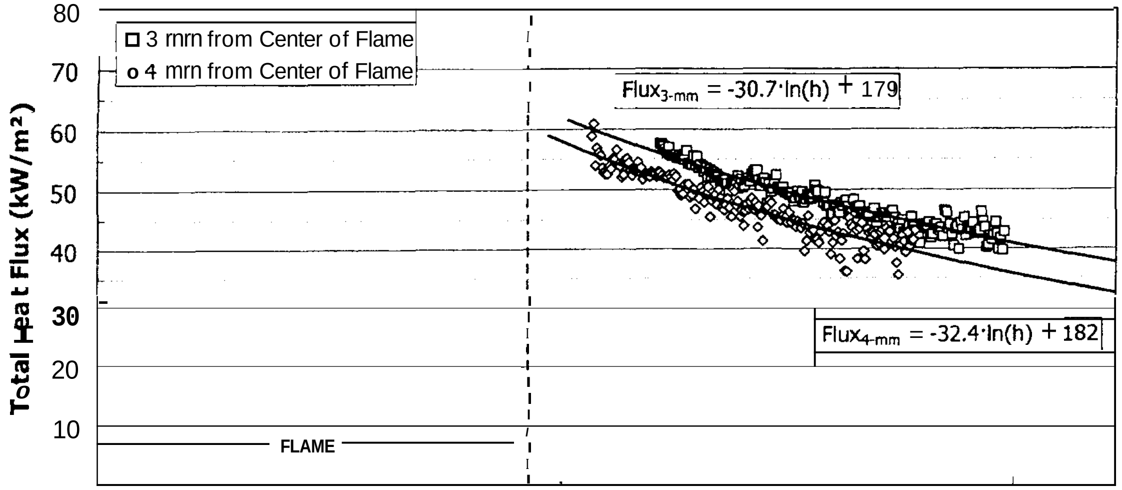

Figure 10. Total Heat Flux in the Vertical Direction vs. the Height Above the Base of the Flame – at 3 and 4 mm from the Centerline of the Flame

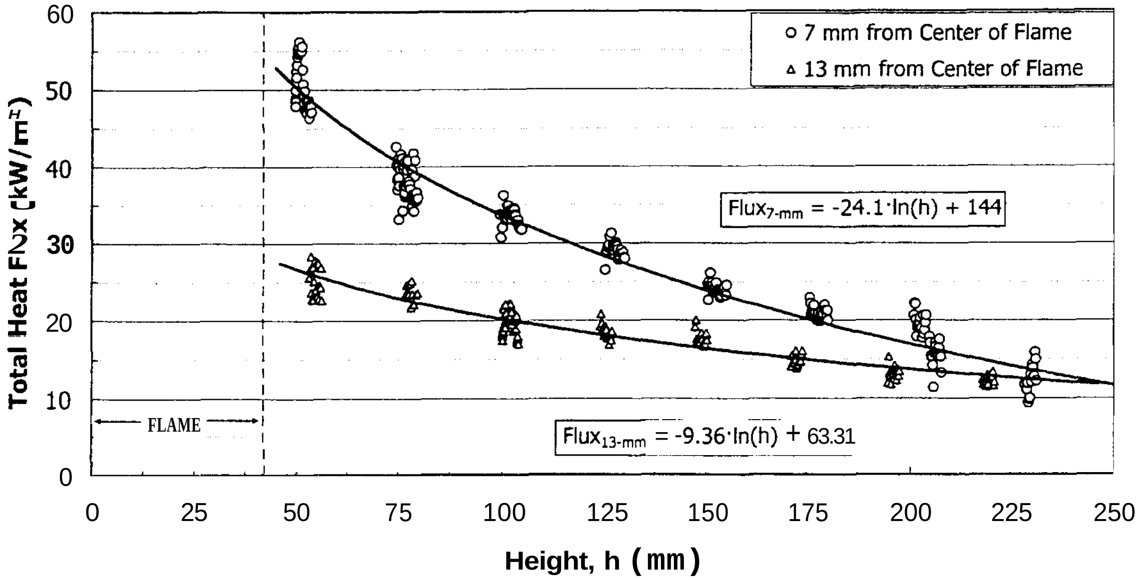

Figure 11. Total Heat Flux in the Vertical Direction vs. the Height Above the Base of the Flame – at 7 and 13 mm from the Centerline of the Flame

CFD MODELING

In order to determine heat flux exposures from candle flames at different positions and the reaction of target materials, the candle flame was modeled using the NIST Fire Dynamic Simulator (FDS), Version 3.0. To validate the model, the candle was input as simplistically as possible with the input parameters being as realistic and intuitive as possible. During validation several simulations were computed and the results of the model were initially evaluated based on (1) the accurate visual depiction of the flame height by Smokeview and on (2) a comparison of the calculated and measured flux directly above the flame tip at a height of 56 mm from the top of the candle. Input parameters were adjusted to better meet these two criteria and once they were sufficiently met, the additional output parameters were evaluated and compared with the experimental values.

For the initial modeling simulations, a 48 x 48 x 80 mm high domain was created around the top 20 mm of the virtual candle. The grid sizing used was 1 x 1 x 2 mm high around the candle and expanded to 2 x 2 x 2 near the edges of the domain using the FDS linear grid transformation algorithm. This resulted in a total of 51,840 cells. The wax portion of the candle of the candle was modeled as a solid inert material, however the geometry of the candle, including the circular shape and the curved wax pool, were represented as detailed as the modeling grid would allow in order to provide realistic air flow to the flame. Preliminary models using a simple square shape produced noticeable effects on the air flow to the flame and on the heat flux to the surfaces above the flame.

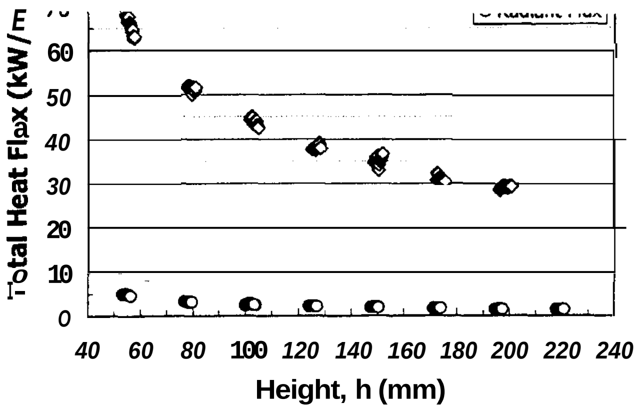

Figure 12. Total vs. Radiant Heat Flux

The wick was represented realistically based on measurements made from actual burned candles except that in order to maintain simplicity, the curvature of the wick was not provided. The wick was simply modeled as a 1 x 1 x 16 mm straight vertical piece with the lower 4 mm being non-burning, with all of the heat being released over the top 12 mm. The heat release per unit area from all four sides and the top surfaces of the wick were input as 1465.9 kW/m². This heat release rate was based on the average measured mass burning rate of the candle (0.105 g/min), heat of combustion value measured in the Cone Calorimeter experiments (45.2 kJ/g), and the surface area of the burning wick (49 mm²). Attempts to vary the wick height and heat release rate per unit area failed to produce flame height or heat flux values more consistent with the experimentally measured and observed values.

The calculations also require information on the stoichiometry of the fuels and the radiative fraction. The properties of the burning wax were based on $C_{24}H_{50}$, which is a reasonable approximation for paraffin wax as seen in Table 1. To test the sensitivity of the result to fuel properties, calculations were also performed using the properties of n-heptane (C_7H_{16}) and methane (CH_4), which is the default fuel in FDS. The stoichiometry is defined by the molecular composition. The radiative heat loss fraction to the surroundings was originally estimated as 10%. Calculations were also performed for values of 20 % and 30 %. Very little difference was observed in either the calculated flame height or heat flux values for the different fuel types, but the radiative fraction was found to be critical to the heat flux exposures and a value of 20% was found to be more appropriate.

Visual representations of one of the FDS simulations are presented in Figure 13b and 13c with an image of an actual burning candle specimen presented in figure 13a. A representation of the iso-surface of the stoichiometric mixture fraction is typically used in Smokeview to represent the location of the flame sheet. The input parameters used in FDS provided the iso-surface presented in Figure 13c, which indicates a flame height of approximately 30 mm with a flame shape that is inconsistent with the actual flame. However, representation of the same flame using an iso-surface of temperature equal to 1100°C provides a flame height of 42 mm and a better representation of the flame shape.

Comparisons of the vertical and horizontal heat flux values predicted by FDS are compared with the experimental measurements in Figures 14 and 15. The model provides a prediction of the total heat flux 56 mm above the base of the flame within 5%; however the flux at 76 mm is under predicted by 16% (see Figure 14). The remainder of the heat flux predictions show similar under predictions of 15 to 40% up to 15 mm from the center of the flame after which FDS predicts higher fluxes than the experiments. However these higher values farther from the center are due to the flat-surfaced target that was used in FDS to evaluate the heat flux. As Figure 5 shows, the experimental set up had the heat flux transducers descending down from the frame structure. The transducers were not installed such that the face was flush with a horizontal surface. Similarly, the FDS predictions of the heat flux laterally, 11 mm from the edge of the candle, were over predicted by more than 100% (see Figure 15).

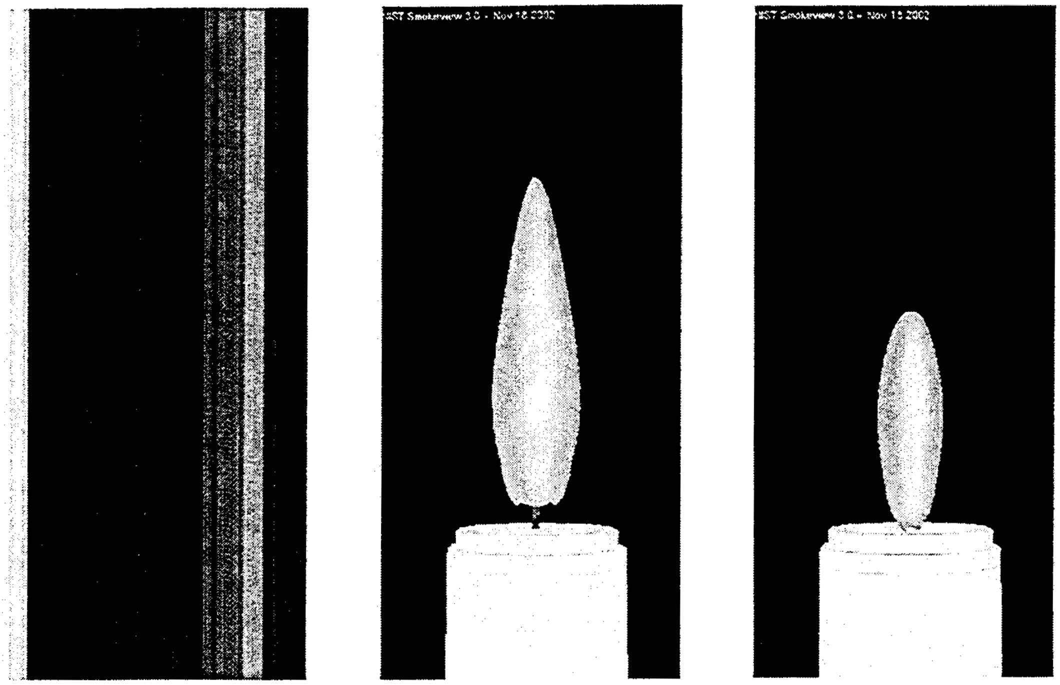

Figure 13. (a) Image of the Burning of a 21-mm Diameter Candle. (b) FDS Simulation of a Burning Candle − Iso-Surface of Temperature = 1100°C. (c) Stoichiometric Iso-Surface.

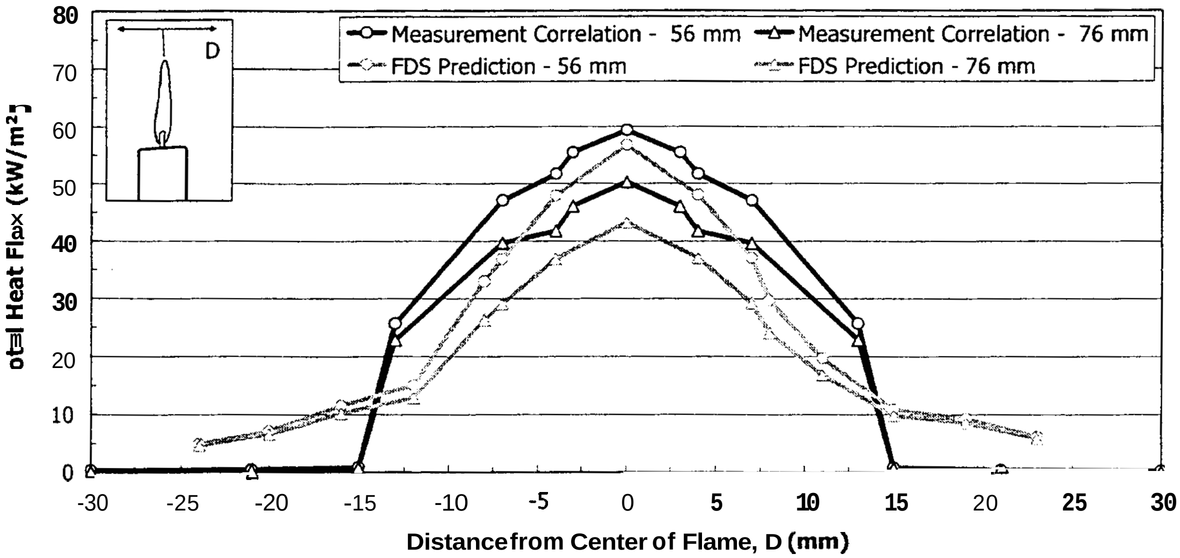

Figure 14. Vertical Heat Flux Profile at 56 and 78 mm Above the Base of the Flame.

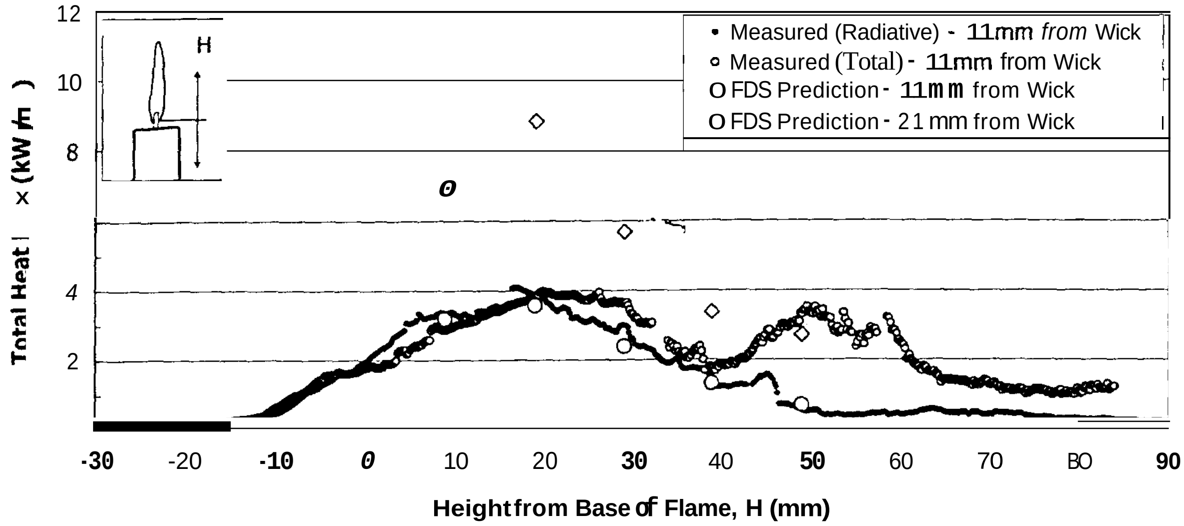

Figure 15. Vertical Heat Flux Profile at 11 and 21 mm from the Center of Candle Flame.

ADDITIONAL WORK

This study is ongoing and based on the information that has been learned as part of this initial candle characterization, the following additional areas need to be researched:

- The experimental work needs to be replicated using less disruptive sensors. Smaller heat flux meters need to be used in order to (1) reduce the impact of the presence of the meter on the flow field and (2) to provide a smaller area over which the heat flux is to be measured. The meters used in this study had a diameter of 9.5 mm which is on the same order of magnitude as the diameter of the candle flame. Several 3-mm diameter Schmidt-Boelter gauges have been obtained, and will be used for follow-up testing.

- The candle flame needs to be better defined within the model. Although the flame shape and heat flux at a few locations can be well defined, the complete flux profile is not yet completely understood.

- The properties of different wax types needs to be investigated and compared with those now available for paraffin.

- The ignition of real materials needs to be investigated. Several representative materials are to be obtained and exposed to the candle flames in various orientations. The experiments will be modeled using the input parameters and procedures outlined here, and the times to ignition will **be** validated.

- Information provided by the CPSC [3] indicates that many candle-related fires are due to causes other than unattended candles, close proximity to combustibles, or negligence. These include candle flare-up, candles that exploded, low wax level, shattered containers, flammable containers, candle reignition, and tip-over. These types of events will be investigated as **part** future studies for this project.

CONCLUSIONS

Fires caused by candles are occumng at an increasing rate every year. Despite this fact, there is **a** lack of available information that fire investigators can use to help accurately determine the likelihood of potential ignition from a candle. Through this initial study, an attempt has been made to bridge this gap and provide tools that can be used by investigators. Through the initial part of this study the basic properties of paraffin wax have been compiled, measurements and correlations of the burning characteristics of a particular paraffin wax candle have been presented, and the input parameters necessary to model that candle flame have been provided, along with a comparison of predicted and measured values.

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