ABSTRACT

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An experimental investigation of laminar smoke points of candle flames is presented. A smoke point is the flame length just before the onset of visible smoke release. Adjustable wicks with diameters of 2 – 7.6 mm were used to measure smoke points in quiescent air for 14 different waxes. The measured smoke points varied from 36 – 89 mm and increased with wick diameter. Smoke points fitted to a wick diameter of 4 mm increased from consumer-grade waxes (candelilla, carnauba, beeswax, paraffin) to alkanes (hexatriacontane, octacosane, tetracosane) to alcohols (octadecanol, docosanol, hexadecanol) to acids (stearic, palmitic, lauric, myristic). Within each wax family, a decrease in carbon number yielded an increased smoke point. Soot emission was not possible for any fuel when the wick diameter was below 1.8 mm or when wick length was below 6 mm. The results suggest new ways of producing cleaner burning candles.

LAMINAR SMOKE POINTS OF CANDLE FLAMES

By

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Nomenclature

B.P.	boiling point
d_w	wick diameter
g	gravitational constant, 9.81 m/s^2
$H_{\max}$	maximum height of wax propagation up a wick
M.P.	melting point
MW_{fuel}	molecular weight of fuel
O_2P	oxygen permeability
q	shape factor of fiber
R_v	radius of fiber
RI	Refractive index
SP	smoke point
u_o	flame velocity
V	volumetric flow rate
x_m	flame height
μ	filling
π	pi
ρ	liquid density
σ_{LG}	surface tension
τ	residence time
Θ	contact angle of liquid surface

Chapter 1: Introduction

1.1 Motivation

1.1.1 Soot

Soot is composed of carbonaceous particles that visibly appear as smoke when emitted from a flame. Soot production is composed of two processes: formation and oxidation of soot particles. Chemical formation and the growth of aromatic hydrocarbons will form into larger molecular components. Physical transitions, known as coagulation processes, evolve molecules into particles and into larger aggregates [1].

Environmental soot kills more people than any other pollutant owing to its association with respiratory illness and cancer[2]. It also contributes to global warming[3]. Soot in unwanted fires increases radiation, fire spread rates, and carbon-monoxide emissions. Ironically, soot is desired in many industrial processes; for example, it is processed into the toner used in most printers. Despite soot's importance – in both harmful and beneficial ways – it remains one of the least understood subjects in the field of combustion.

Different fuels have different propensities to form and emit soot when burned. In diffusion flames these propensities are best characterized by a flame's laminar smoke point. A laminar smoke point is the length of a diffusion flame for which a longer flame emits soot and a shorter flame does not. It is the luminous length of a laminar diffusion flame at the point of incipient sooting. Smoke points occur because an increase in fuel flow rate increases soot formation and residence time, but there is a smaller increase in soot oxidation time [4].

Smoke point measurements can yield insight into fuel effects on soot formation, soot and carbon monoxide emissions, radiation, and flame quenching. Owing to the complexity of detailed modeling of soot kinetics and transport [5,6], smoke point measurements also can be useful in computational simulations of turbulent flames [7]. To thoroughly understand sooting potential, consideration of diverse hydrocarbons must be evaluated under a standard test method. It is the intention here, in response to landmark studies of liquids, gases, and solids, to measure the smoke points of fuels of higher molecular weights. This study will carry on a broader range of hydrocarbons as past studies included smoke points of lower molecular weights. These fuels tested are of the highest molecular weights ever reported with exception of wood and polymethylmethacrylate (PMMA). Furthermore, testing should reveal the impact of wicking on combustion dynamics and smoke point.

Soot produces the yellow luminosity of candle flames and therefore, most candles contain soot. Interest has grown to develop a less sooty or cleaner burning wax. The idea of formulating a cleaner burning wax is enticing, but there are other mechanisms of candle burning that contribute to soot production. Sooting potential is a result of the following properties: C/O ratio, hydrocarbon concentration, temperature, residence time, and oxidation time [8]. Analysis of factors that may increase or decrease soot production in candle flames will be discussed as a result of experimental data. For example, this study will determine how wick size and wax type impact soot production. Results will reveal candle combustion processes relative to wicking effects and their potential impact on environmental safety and human health.

1.1.2 Candles

Candles have been used as far back as the first century to produce light [9]. Candles have also played a major role in the economy during the 1700's with the use of sperm oil from whales [9]. Industrialization saw a growth in the use of coal and gaseous fuels and a need for innovative ways to burn these new sources of energy.

The candle is a simple burning model that involves a very complex interaction of burning processes. Michael Faraday laid the foundation for candle investigations in his six lectures given in 1861 [10]. Regions of the candle flame include liquid fuel that rises up into a wick, an oxygen diffusion zone, and a blue reaction zone of C_2 and CH emissions. This region is where the flame reaches its highest temperatures. Soot formation and oxidation occur in the yellow luminous zone. These carbon particles must be consumed in this region in order for the flame to remain smokeless [11,12].

Candles are used in 70% of U.S. households and they account for $2 billion in annual sales [13]. When candles emit soot they can degrade indoor air quality and cause extensive property damage [14-16]. There is a need for more information on soot production in candle flames to quantify specific impacts on human health [17]. Soot inhalation is associated with cardiopulmonary mortality and lung cancer mortality and may have the same effects as second hand smoke [18,19]. Candles that emit soot can damage walls, ceilings, and carpets. Soot emissions inside residences should be minimized.

According to the Environmental Protection Agency (EPA), combustion from residential activities is a large source of fine particulate matter [20]. Poor ventilation causes soot accumulation, particularly in energy efficient spaces. Places of interest are homes and churches. Soot is noticeably accumulated near sources such as candles [21]. Fine particular matter is a major health concern because of its ability to reach deep into the lungs. Health problems associated with fine particulate matter are shortness of breath, aggravated asthma, coughing, painful breathing, bronchitis, and even premature death [22]. Adults breathe 13,000 L of air per day while children often consume 50% more air per pound of body weight than a typical adult [22]. Tests performed by Rezaei et al. [12 and sources within] report that after 1 hour of continuous burning of a paraffin candle, any air movement caused smoke release. Additionally, higher soot release was recorded by Krause [23] from scented paraffin candles.

Quantifying the parameters that impact soot production will lead to a better idea of how to limit particle emissions. Understanding particle emissions will help decrease human health risks and interior damage from soot. Fine et al. [15] noted that particle emissions in sooting behavior were dependent on the air flow around the flame. The amount of fine particles released during sooting conditions increased from 1e-5 to about 1e-3 μg cm^{-3}. Observations made proved that wick position affected sooting behavior. Furthermore, a sooting candle burns faster than a non-sooting candle on the order of 30 mg/min more [15].

The potential impacts on candle composition on soot emissions have not previously been explored. Rezaei et al. [12] found candle burning rates were dependent on the wick dimensions. Paraffin and soywax candles with thicker wicks created larger pools and burned at higher rates compared to candles with smaller wicks. Additional observations showed trimmed wicks burned slower than untrimmed wicks in soywax candles.

Candle holders or the typical jar may impact candle burning by interfering with air flow dynamics. Air flow that is restricted to the flame can result in soot emission. Additionally, critics of candle makers say that the demanding supply invites them to cut corners by substituting low quality wax or oils [27]. A large supply of the candles found in retail stores are made of commercial type mixtures of paraffins and natural waxes. Levels of PAH's (polycyclic aromatic hydrocarbons) in natural waxes tend to be higher than in paraffins [28].

1.2 Smoke Point Background

Past studies from Kewley [9], Minchin [29], Schalla et al. [30,31], and Schug et al. [30], have reported smoke points of gaseous and liquid fuels. Investigation of smoke points began as a method to evaluate the quality of kerosenes [9]. Tests were later expanded to include detailed analyses of the impact of a fuel's chemical structure on tendency to smoke [29]. Further evaluation by Schalla et al. [30,31] and Schug et al. [32] included analysis of fuel mass flow rates to further isolate variables of chemical complexity to identify fundamental properties that affected soot formation and smoke points [30-32]. More soot formation behavior is known about gaseous smoke points than condensed liquid and solid fuels. Heavy sooting fuels have short smoke point lengths [33].

1.3 Smoke Points for Liquids

Laminar smoke points are the most widely used measure of a fuel's sooting propensity in diffusion flames. Laminar smoke points are such good indicators that most aviation fuel sold worldwide is required to have a smoke point of 25 mm or longer [34]. American Society of Testing and Materials (ASTM) provides a standard lamp for smoke point tests of aviation fuels. Current testing for aviation fuels must comply with test standard ASTM D1322 [35]. The ASTM D1322 definition of a smoke point is the "maximum height, in millimeters, of a smokeless flame of fuel burned in a wick-fed lamp of specific design." This lamp is only suitable for liquid fuel testing.

Radiant energy from the combustion products has the strongest influence on heat transfer and can offer insight to the effects on surroundings. This effect can be related to the fuel's smoke point [35]. ASTM D1322 was developed to minimize the radiant heat transfer from the fuel to engine and combustor components [35]. Multiple lamps have been used to analyze smoke points. It is not easy to compare results of smoke point tests because the results are dependent on the testing environment. Inclusion of a wick may impact results by lowering the smoke point as a result of wick quenching. This quenching process would decrease the flame temperature causing an increase in the fuel's sooting tendency. Current analysis from testing procedures ASTM D 1322 do not account for the interaction that the wick may have on flame dynamics [35,36].

The ASTM committee notes that fuel property requirements may stray from synthetic fuels or fuels from non-conventional sources [34]. A long term goal is to revise the current standards to encompass more non-conventional fuels of different hydrocarbons. For instance, kerosene and aviation fuels tested under ASTM standards must also comply with quality standards specified by ASTM D1655 [34]. This specification details the quality necessary for fuels used in the operation of aircraft and all other civil use.

Many of the landmark studies to establish smoke points used wick lamps [29,30,37-43]. Minchin [29] compared kerosenes of different crudes to determine smoke point relationships related to aromatic and naphthalene content. Hunt et al. [39] noted an increased range of smoke points with an increase in wick diameter. This data is the only known reported tests to evaluate the effect of wick diameter relative to smoke point. However, only a limited amount of fuels were considered and only few variations of wick diameters were considered. As a result, these results are inconclusive to resolve any relationships between smoke points relative to wick diameter. Schalla et al. [30,31] varied the fuel mass flow rate by adjustment of wick height. Rakowsky and Hunt [39] observed the effects on smoke points relative to air screen height.

Ami Argand developed the first kerosene lamp in 1784 [9]. This model claimed to produce a smokeless and steady flame by regulating and directing the air supply. Design of the lamp included a glass chimney set over the flame on top of a metal platform. Fuel was supplied by a hollowed tubular wick while air was supplied within the glass tube and from the perforated metal platform. Later improvements in design included a flat wick with a flat plate above the wick to direct the air more resourcefully around the flame. Seventy years later, J.H. Austen [9 and sources therein] designed a lamp to burn coal oil called the Vienna burner. The wick was able to be raised by the movement of a lever. Air was supplied by an elliptical or cone deflector.

Several models of smoke point testing lamps have been used such as the Weber Spectro-photometer, later to be implemented by the Institute of Petroleum [39]; a wick-less lamp developed by Clarke, Hunter, and Garner [37]; a wick fed lamp by Schalla and McDonald [30,31] used to compare gaseous hydrocarbons; and the Factor Lamp [39].

The Indiana smoke point lamp [39] allowed for wick adjustment by as little as 1 mm. This was a more precise method for smoke point determination [39]. This idea for wick adjustment allowed better analysis in determining the effects of wick quenching on the smoke point. Still, these lamps are not easily adapted to testing solid fuels that occur at ambient temperature such as candles.

Investigations on the effect of fuel chemical composition and burning quality were first reported by Kewley et al. [9] in 1927. Comparisons were drawn between different paraffin crude type kerosenes. Comparing candle power, or illuminating value, from the flame was a way to determine the quality of the kerosene. Aromatic fuels tended to give off a reddish color and more smoke. Testing lamps were an important factor to consider because the same crudes would have different initial candle powers. A Hinks duplex lamp increased candle power for Mexican and East Indian kerosenes by 150 and 133%, respectively [44]. Judgment of candle power requires flames of similar sizes to compare luminosity characteristics. Trimming of the wick would be necessary, but was too difficult given the style of the lamp. Smoking tendency related to wick interaction has been apparent since the beginning of testing [9].

To overcome this problem, the Weber Spectro-photometer [39] was introduced to produce more consistent results. It was made of a cylindrical tube 130 mm × 20 mm and an adjustable 4.5 mm diameter wick. A ruler was placed within the device so height could be read. The relationship of candle power to chemical composition versus smoking tendency could be more easily evaluated. The first records of smoke points show that as the aromatic percentage composition of the paraffin increases, fuels have a higher tendency to smoke [9].

Minchin [29] conducted more in depth tests that could better quantify the effects of different hydrocarbon classes. The Weber Spectro-photometer [39] lamp was used. Comparing fuels of different crudes and mixtures, smoking tendency was found to be dependent on aromatic or naphthalene content. Indications of the effects of fuel type on smoking tendency were observed as the smoke points increased from paraffin-naphthalene mixtures to paraffin-aromatic mixtures. Minchin's [29] studies also saw that within homologous series the sooting tendency, or the inverse of the smoke point, decreased with increasing carbon number excluding paraffins.

Clarke et al. [45] found that straight chain alkanes have the highest smoke points with a decrease in smoke points as double bonds are introduced. Branching decreases the smoke point with positioning of the branches only making a small difference. The number of carbon atoms, being equivalent, played a lesser role in smoke point behavior as compared to compactness of the molecular structure. These findings were promising, but were found by burning fuel at the surface of a liquid pool where wicking effects did not play a role. Hunt [37] implemented the Factor Lamp for testing smoking tendency of hydrocarbon fuels that included a 6.35 mm diameter wick. Results show similar effects of branching and molecular structure. Increased complexity in molecular structure causes resistance to oxidation. Any chain substitution increases the resistance to oxidation. Straight chain configurations are the easiest to oxidize [37].

In tests preformed by Rakowsky and Hunt [39], alkane smoke points were affected by the testing apparatus wick diameter and air screen height. Results for wick diameter versus smoke point indicate larger wick diameters spread the smoke points of different fuel types over a larger range of heights. Wicks too large failed to obtain smoke points. Another lamp used by Rakowsky and Hunt [39] reduced the smoke point for alkanes by 14%. All components were similar in dimension other than a reduction in the air screen height. No scientific explanation was provided as to why these phenomena occurred, but the sensitivity of lamp dynamics is evident.

Efforts by Schalla and McDonald [30] investigated smoking tendency in fuels of low molecular weights. The goal of this study was to determine the impact of sooting tendency from molecular chain length, branching, unsaturation, position, and ring size. Impact of carbon bond strengths was related to the mass flow rate versus smoke point. Different devices were used for testing liquid and gaseous fuels. The liquid fuel device incorporated a wick. Results showed that the largest smoke free flames were among the *n*-paraffins and decreased with increasing chain length [30]. Branching of the chains also reduced the smoke free flame height. Cycloparaffins displayed the lowest flame heights before sooting. An important factor was the fuel's diffusion coefficient for the *n*-paraffins. Within the same homologous series, variation in the diffusion coefficients can explain differences in smoking tendency. This does not describe the smoke point behavior among fuels with different isomers or unsaturated hydrocarbons. Increased complexity in molecular structure, among fuels with the same number of carbon atoms, observes a decrease in smoke free heights. This observation gave way to the idea that increased energy in the chemical structure has a great impact on smoke height. Further explanation concluded that a dehydrogenation process may be occurring in those structures of less saturation. A saturated carbon-carbon bond may break the carbon bonds before the carbon-hydrogen bond. Soot may be more easily formed from oxidation of partially hydrogenated carbon skeletons [30].

Continuing research in 1955, Schalla et al. [31] investigated variations of smoke points in diffusion flames by pressure, fuel type, external air flow, oxygen enrichment, argon substitution, and fuel temperature. Isolation of these variables would lead to more information on the early stages of soot formation. Conclusions about the effects of fuel types were similar where smoke points increased in the order of *n*-paraffins to iso-paraffins to mono-paraffins to alkynes to aromatics. Evaluation of the remaining variables led to new findings. The appropriate fuel flow rate was achieved by adjusting the wick height [31].

Calcote et al. [46] concentrated on fuel structure and concentration relative to the onset of soot formation in premixed and diffusion flames. It was their goal to compare past data for consistency on the effects of molecular structure on sooting involving wick fed and non–wick fed lamps. Results of this investigation demonstrated that normalizing the TSI (threshold sooting index) values for each set of comparison data showed consistency in TSI values relative to molecular structures. Calcote et al. [46] minimized the error between the data sets by fitting each set into a least squares fit correlation for reported TSI values [46].

Glassman [4] suggested that incipient soot particle formation is controlled by the initial rate of ring formation. This is an important step in the chemical mechanisms that produce soot because it dictates the soot volume fraction of the flame. Larger soot concentrations require longer oxidation times. Initial soot growth processes for fuels are the same for premixed and diffusion flames. Fuels with large aromatic structures are more likely to form soot than fuels without. Fuels that do not have aromatic structure will undergo the growth process to form initial rings. Thus, for aromatic fuel structures, where rings are already present, soot will form faster and tend to have lower smoke points.

Glassman [4] found that the most influential parameter on soot formation was temperature. The initiation of soot formation will begin around 1400 K and stops under 1300 K. Milliken [47] confirmed for diffusion flames, where there is no oxidative attack on the precursors of soot formation, increased flame temperature increased the pyrolysis and soot formation rate.

1.4 Gaseous Smoke Points

Smoke points for gaseous fuels are measured by injecting fuel upward through a round burner tube into coflowing or quiescent oxidizer [4,32,36,48 and references therein]. Laminar smoke points of gaseous fuels are simple and fundamental; they are highly repeatable and are nearly independent of burner diameter.

Schalla and McDonald [30,31] used prevaporized liquid pentane and pentene-1 burning as gas jets. They reported only a 2% difference between smoke points measured with a wick flame and in their prevaporized burner. Tewarson [49] also used prevaporized liquids burning as gas jets, but found significant discrepancies with wick lamp measurements.

Laminar diffusion flame studies of gaseous hydrocarbons by Schug et al. [32] included investigations to determine the mechanisms that influence soot production such as additives and the effect on temperature. For cylindrical flames the flame height was strictly dependent on the fuel flow rate. Additives that would either reduce or induce a fuel's sooting tendency did not change the fuel flow rate. Different types of soot reducing additives such as, Helium (He), Argon (Ar), Nitrogen (N_2), Carbon-dioxide (CO_2), water (H_2O), and Sulfur-dioxide (SO_2) maintained constant fuel flow rates compared to the fuels tested without additives. Similar results were found for soot inducing additives [32]. Results further demonstrated, for diffusion flames, sooting behavior is dominated by temperature effects that influence initial fuel pyrolysis. Initial soot growth begins with the absence of oxidizing radicals. Increasing the temperature increases the pyrolysis rate over the oxidation rate, therefore, increasing tendency to soot. Additionally, results showed that fuel structure had a great impact on sooting behavior, but the addition of hydrogen did not play a dominant role in sooting tendency [32].

1.5 Solid Smoke Points

There have been very few studies that reported smoke points for solid fuels. Chemical mechanisms that govern the behavior of soot formation are highly complex processes of kinetic transport. The process of soot production becomes increasingly complex for solid fuels with the break down of the more rigid crystalline structure [50]. Three smoke point studies on nonwicking solids were completed by Tewarson [49], De Ris [49], and Delichatsios [52,53]. Smoke points for solid fuels have been conducted using laser induced pryolization. Flame heights were recorded consequent to smoke release.

Tewarson [49] performed smoke point studies on 82 aromatic and aliphatic hydrocarbons and other polymers. Some were of high molecular weights. Carbon composition of specimens used varied from $C - C_{21}$. There were a limited number of fuels in solid form. Solid species tested were octadecene and triamylbenzene with 18 and

21 carbon atoms, respectively. Most cases were liquids with carbon numbers between C_5 – C_{17}. Conclusions of this study were that the reactivity of combustion for normal saturated hydrocarbons decreases with increasing molecular weight. The reactivity parameter is defined by a ratio of alkane, alkene, and H_2 yields to alkyne, diene, arene and butylenes yields. Still, conclusions are limited to mainly gaseous and liquids samples.

De Ris et al. [51] produced smoke points for charring and non-charring fuels that were studied in “candle-like” conditions. Tests directed a laser beam down onto a solid sample to pyrolize the material. Diffusion flames rose through stabilizing screens to prevent oscillations. This study interpreted the smoke point data differently, defining the smoke point where the core flame tip merges with the soot wings and begins to release a detectable amount of smoke. “Equal wing” conditions are dependent on the ambient oxygen concentration. Larger ambient oxygen concentrations tend to produce soot wings much earlier, while lower concentrations see more convergence of soot wings at the smoke point [51]. There was a fine line for transition between diffusion and momentum controlled burning. Results from this smoke point definition may be difficult to repeat due to the effects of turbulence. It was concluded that heat release rates and thermal radiation of turbulent diffusion flames are strongly related to the fuel’s laminar smoke point. This measurement could provide flammability characteristics [54]. No further analysis was completed with consideration to chemical and physical properties of the fuels.

Delichatsios [52,53] proposed a global soot formation model based on the idea that the gaseous burning process controls soot formation [52,49,51,53]. Other tests of solid fuels performed by Delichatsios [52,53] tested wood and PMMA. These flames resembled turbulent, not laminar jets. Cooling of the flame in either study was only a result of radiation loses. The different fuel types produced different amounts of particles at a soot inception temperature between 1300 – 1650 K.

Higher soot concentrations are found at lower temperatures because the soot is not being oxidized. Temperature of the flame is reduced along the centerline as a result of air diffusion and radiative looses. As the temperatures falls with increasing height, soot burnout becomes less dependent on oxygen diffusion. Temperature becomes the dominant factor as it falls below the soot inception temperature. Different fuel types, nonetheless, do produce different amounts of particles at this temperature and therefore output different amounts of soot during the formation and coagulation processes [4,52,55]. Soot formation for higher hydrocarbon fuels such as solids and liquids can be estimated from the laminar relationships of gaseous smoke point behaviors. This stems from the idea that soot forming mechanisms are dependent on the gaseous burning of the solids and liquids [55].

1.6 Molecular Structure

Molecular structure is very important in governing soot behavior. Fuels with similar flame temperatures may vary in TSI values and are closely related to the fuel hydrogen content [41]. Fuels with complex molecular structures require greater soot oxidation times than those of simple structure [7]. Pyrolysis rates and oxidation rates increase with temperature, but the pyrolysis rate increases faster [4]. The higher the flame temperature, the greater the tendency to soot in diffusion flames because there is no initial oxidative attack on the fuel as compared to premixed flames [4]. The possibility for incomplete combustion increases if the oxygen supply is limited from the environment and the flame cannot maintain stoichiometric requirements. However, adiabatic flame temperatures calculated for waxes of known chemical formulas prove to have temperatures on the same order ranging slightly from 2290 K – 2370 K [56]. In addition to temperature, other chemical and physical properties that govern observed sooting behaviors must be interacting.

The ranking of wax groups from most to least sooty generally does not depend on wick diameter. Strong carbon bonds increase the ability of the dehydrogenation process to take place, which could be responsible for the smoking variations in fuels. Saturated fuels contain the maximum amount of hydrogen bonded to the carbon elements. There are no double or triple bonds [57]. Figure 1.1 illustrates a saturated alkane structure.

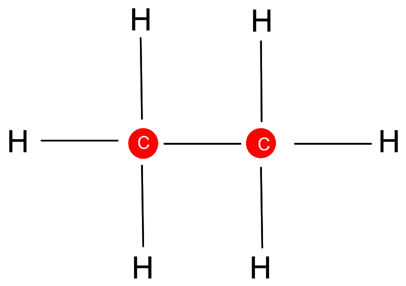

Figure 1.1: Saturated alkane structure

Fuels unsaturated with hydrogen will have greater strength among the carbon bonds and are more likely to break hydrogen bonds. Carbon bond strengths correlate to C-C = 80, C-H = 100, C=C = 150, C≡C = 200 in units of kcal/mol. Flames at higher temperatures can more readily break such bonds and encourage the dehydrogenation process with the breakdown of carbon-hydrogen bonds. Examples of this behavior are evident in Schalla and McDonald [31] experiments where butane-1, propene, and cyclopropane were subject to addition of oxygen and argon. Oxygen and argon enrichment lead to increased flame temperatures and smoking tendency for these fuels increases. The importance of the dehydrogenation process is demonstrated which leaves partial carbon skeletons that will tend to form smoke. For fuels of higher smoke points, the single C-C bonds may be more than or proportional to the breakdown of C-H bonds and therefore will have a lower smoking tendency [31]. It takes less energy to break down fuels of complex chains of large carbon amounts because they are likely made up of single carbon bonds.

Although carbon number is a strong factor relative to smoke point behavior, it does not describe the molecular structure in its entirety. Alcohols and acids contain OH and O_2, respectively. The oxidation process is different from that in normal alkanes that only contain carbon and hydrogen. More soot will be consumed with the reaction of oxygen radicals [58]. Fuels with higher soot volume fractions are more likely to lose heat from radiation. Flame cooling is increased and leads to quenching and reduction in soot oxidation.

1.7 Wick Dynamics

Capillary action of a cotton wick allows liquid wax to propagate upward instantaneously with the combustion of the gaseous wax. It forms a balance against gravity so that the top of the wick may be deficient in molten wax. The projected maximum height of wax propagation proposed by Wiener [59] for fibrous materials is given by:

$$H_{\max} = \frac{2\sigma_{LG}\mu(1+q)\cos\Theta}{R_v g\rho(1-\mu)} \tag{1.1}$$

Maximum height (H_{max}) is a function of surface tension (σ_{LG}), liquid density (ρ), filling (μ), radius of fiber (R_v), shape factor of fiber (q), contact angle of liquid surface (Θ), and gravity (g). Determining H_{max} from dependence on fiber radius, R_v, shows that decreasing the radius will increase the height that the wax is allowed to travel up the wick. This height, however, is also determined by the surface tension of the liquid and its interaction with the cotton fiber porosity. Wick lengths for smaller diameters are longer than for wicks of larger diameters. Wax may not be able to propagate up the full length of wicks with small diameters. The lack of wax in this region will not undergo the cooling process from wax evaporation and leaving charred cotton material. Less char is seen for wicks of large diameter because they may utilize available wick height more efficiently [59]. If wick length is constant, wicks with larger diameters have a greater amount of surface area for fuel supply.

1.8 Applications to Fire Protection Engineering

Candles are an open flame source. A sooting candle is a potential fire hazard as it is uncontrolled. Statistics show that many residential fires are a result of candles; however, exact ignition scenarios are debated [24]. Aherns [25] reports that in 2002 candles caused 18,000 fires and 130 deaths. Aherns [25] shows the percentages of materials that are ignited by candle flames:

Table 1.8: Candles as ignition source for various materials. [25]

Type	%
Decorations	53
Curtains	36
Cabinetry	21
Linens	18
Paper	13
Toys/Games	12

Unfinished fabrics	11
Mattress/Bedding	10
Upholstered Furniture	9
Christmas Trees	8
Floor coverings	7
Appliance casing	7
Interior wall coverings	7
Clothing (worn)	6
Box/Bags	6
Clothing (loose)	5

Proposed ignition theories from the Candle Fire Safety Task Group [26] regarding candle flames identified causes such as excessive flame height of 76 – 95 mm, pool flashover, secondary ignition, end of life, and instability.

Soot yields of waxes likely play an important role in fire behavior. Wax is not only burned as candles, but it is used for many surface finishes such as polishes, furniture and floor finishes, cosmetic products, food thickeners, and food coatings. Data gathered in this experiment should identify less sootier, or safer waxes that can be applied to the uses for many of the products found in households. Property damage from soot accumulation on walls and ceilings can be observed in churches and some homes where candles are burned. The interaction with soot on flame spread to surroundings and smoke production is an important concern for fire simulations and human safety.

Combustion of simple hydrocarbons is a necessary input into computational fire dynamics (CFD) modeling in order to calculate more complex and detailed reactions [50]. Models for simple laminar flame structures are the principle foundations for soot formation in practical systems and turbulent flames [1]. Tewarson [60] provided a vivid demonstration of the value of laminar smoke points in predicting fire behavior. He correlated smoke points of gaseous, liquid and solid fuels with measurements in turbulent fires of combustion efficiency, carbon-monoxide generation efficiency, and smoke generation efficiency. The correlations are successful, but they were limited by the small available number of smoke points of solid fuels.

Lautenberger et al. [7] point out that CFD simulations of practical fires cannot afford the computational cost of detailed models of soot formation and oxidation. They introduced a new method of modeling soot kinetics in fires based in part on the laminar smoke points of solid fuels. They assumed that soot formation and oxidation rates were functions only of mixture fraction, temperature, and laminar smoke point. This novel approach shows great promise for fire modeling. However until more measurements of laminar smoke points of solids are available, this model cannot be applied with confidence to fires burning solids.

CFD modeling currently lacks the ability to accurately calculate soot evolution through a flame envelope. Current models are in need of experiments to validate soot yields. Modeling now tends to predict soot based on the oxidation rate proportional to the soot surface area [62]. However, soot production is controlled by the diffusion of O_2 into the flame's oxidation zone [7]. Limitations may arise from an inadequate understanding of soot formation in turbulent flames [43].

1.9 Objectives

Despite extensive past work in smoke points of gaseous, liquid, and nonwicking solid fuels, no previous study has examined smoke points of candles. It is the purpose of this research to develop new test methods to measure smoke points of candles to contribute to the understanding soot formation. The measurements will furnish laminar smoke points of pure fuels with the highest molecular weights examined to date. The objectives of this study are to:

1) develop a method for measuring smoke points of candles;
2) measure smoke points of diverse waxes with various wick diameters;
3) rank the waxes according to their sooting propensities; and
4) identify wick diameter and length requirements for smoke-free conditions.

Chapter 2: Wax Selection

2.1 Wax Selection

Fourteen different waxes tested were supplied by Sigma-Aldrich [61]. They are shown in Table 2.1 and categorized here into four different families: commercial, alkanes, aliphatic alcohols, and carboxylic acids. Each family differs in chemical make up. These differences are important because they allow comparison to the effects in soot formation and smoke point heights.

Table 2.1 Summary of waxes tested. [a][63], [b][57], [c][15].

Family	Name	Formula	Carbons	MW[a] g/mol	MP[a] °C	BP[a] °C
commercial	beeswax		31[b]		63	
	candelilla		31[b]		72	240
	carnauba		45[c]		82.5 – 83.3	
	paraffin		27[c]		65.8	
alkanes	tetracosane	$C_{24}H_{50}$	24	339	49	391
	octacosane	$C_{28}H_{58}$	28	395	59	278[1]
	hexatriacontane	$C_{36}H_{74}$	36	507	75	265[2]
aliphatic alcohols	hexadecanol	$C_{16}H_{34}O$	16	242	49 – 50	190[3]
	octadecanol	$C_{18}H_{38}O$	18	271	58	210[1]
	docosanol	$C_{22}H_{46}O$	22	327	65 – 72	180[4]
carboxylic acids	lauric acid	$C_{12}H_{24}O_2$	12	200	44 – 46	225[5]
	myristic acid	$C_{14}H_{28}O_2$	14	228	54	250[5]
	palmitic acid	$C_{16}H_{32}O_2$	16	256	62	271.5[5]
	stearic acid	$C_{18}H_{36}O_2$	18	284	69.6	361

[1] B.P. at 15 mm Hg
[2] B.P. at 1 mm Hg
[3] B.P. at 10 mm Hg
[4] B.P. at 0.22 mm Hg
[5] B.P. at 100 mm Hg

2.2 Commercial Waxes

The waxes most commonly used in consumer candles are paraffin, beeswax, vegetable based waxes and stearic acid [13]. Consumer candle waxes are typically a mixture of various hydrocarbons, color esters, and scents. Commercial waxes selected here include beeswax, candelilla, carnauba, and paraffin. The exact chemical make ups of these waxes are not known. Chemical analysis relative to carbon and hydrogen composition in sooting behavior becomes more complex compared to species with specific chemical formulas because their carbon to hydrogen ratios cannot be quantified. Donhowe et al. [64] noted that studies from Tolluch [65,66], Findley and Brown [67], and Bennet [68] were able to break down chemical structures of beeswax, candelilla, and carnauba waxes into percent compositions to investigate oxygen permeability. A summary of their analyses is given in Table 2.2.

Beeswax is an animal wax produced by the abdominal glands of honeybees. Beeswax quality varies depending on the purity and type of flowers that the honey was gathered from. It must be rendered of impurities before it is used as candle wax [57].

Candelilla wax originates in Northern Mexico. It is derived from a small plant by boiling the leaves and stems and diluting it with sulfuric acid [57]. Melting and boiling points can be seen in Table 2.1.

Carnauba wax is produced from the carnauba palm native to Northern Brazil. The leaves are beaten to extract the wax then it is refined and bleached [57]. Smoke points for each fuel are seen to increase with wick diameter with the exception made to carnauba candles. Deviation from other smoke point trends may be attributed to carnauba's high melting point between 82.5 – 83.3 °C. This melting point is the highest among all tested waxes by 8 degrees.

Table 2.2: Natural waxes. Ref. [64]

Wax	Hyrdocarbons %	Wax esters %	Fatty alcoh. %	Fatty acids %	Uniden. %	Moist./ inorgan. subst. %	O_2P 10^{-14} g/msPa	RI
Beeswax	15	71		8	6		1.54	0.34
Candelilla	57	29	14				0.29	0.65
Carnauba	1	82	11	5.5		0.5	0.26	0.41

Paraffin is a common name for the alkane hydrocarbons with carbon number greater than 20. Most paraffin candles available to the consumer are a mixture of various wax solids. The boiling point for these wax types are estimated in literature over a broad range of values. Sigma-Aldrich, estimates a melting point greater than 65˚C, but does not give a value for a boiling point [57,63].

2.3 Alkanes

The alkanes selected for testing included tetracosane, octacosane, and hexatriacontane. Alkanes are also known as paraffin hydrocarbons, with a general formula C_nH_{2n+2}. Molecular structure may consist in normal (*n*-alkanes), branched (*i*-alkanes), or cyclic. They form a normal configuration when the carbon chain is straight [69]. Only linear alkanes were considered for this study. For melting and boiling points refer to Table 2.1.

2.4 Aliphatic Alcohols

Hexadecanol, octadecanol, and docosanol were selected from the family of aliphatic alcohols. They contain a hydroxyl group and have general formula $C_nH_{2n+1}OH$.

They are used not only as wax, but as thickeners and emulsifiers in the food industry. Melting and boiling point ranges are available from Table 2.1. Aliphatic alcohols are saturated fatty molecules that contain carbon, hydrogen and the attachment of an OH (hydroxyl) group. The hydroxyl group is the most reactive site for this family even though the oxygen-hydrogen bond strength (O—H) is much greater than the other carbon-carbon/hydrogen bonds [69].

2.5 Carboxylic Acids

Four carboxylic acids were selected for testing: lauric, myristic, palmitic, and stearic. Iso-alkanes with six or fewer carbon atoms will react with oxygen to form carboxylic acids [44]. The parent hydrocarbon group is made up of two other functional groups: a hydroxyl (C—H) and carbonyl (C=O). A general composition formula is $C_nH_{2n-2}(OH)_2$. The melting and boiling points can be found in Table 2.1.

2.6 Melting and Boiling Point Properties

Melting (M.P.) and boiling points (B.P.) are measurement of the strength of intermolecular forces. Boiling point typically increases with molecular weight, but melting point cannot be so easily explained. Melting points are more sensitive to size and shape of the molecule than boiling point. Solid crystalline structure is uniform and more resistant to disruption of bonds. Boiling points are relative to the liquid state where molecules are less constrained to intermolecular movement [69].

Melting points of *n*-alkanes increase more rapidly for even carbon chains than odd [69]. Alkanes with even numbers of carbon atoms are arranged in a more uniform structure, which is more resistant to breaking forces between bonds. Similar conclusions can be made relative to the aliphatic alcohols, e.g. a decrease in melting point is seen between docosanol and hexadecanol. Melting and boiling points increase as the size of the acid increases; however, this trend is not always true for acids. Melting points for acids of greater molecular weight can decrease with increased size depending on the difference between the intermolecular forces of the crystalline state [69]. Unbranched acids will have a higher melting point for an even number of carbons atoms as opposed to similar structured acids with an odd number of carbons. The number of bonds within the structure is responsible for this behavior [69].

2.7 Oxygen Permeability

Results of an oxygen permeability (O_2P) study help explain smoke point behavior for these complex fuels and the dependence on molecular structure. O_2P is the ability of a material to diffuse oxygen. The O_2P for beeswax is about five times greater than that of candelilla and carnauba waxes [64]. Refer to Table 2.1.

2.8 Relative Intensity Ratios

To understand the composition of the complex structures for these waxes, Greener and co-workers [64] used diffraction scans over thin films of the waxes. Derived relative intensity ratio (RI) values from the diffraction scans are a good indication of the waxes' crystalline structures. Decreasing RI values indicate a greater amount of hexagonal crystals as compared to orthorhombic crystals. Candelilla wax shows the greatest RI values at 0.65 followed by carnauba and beeswax wax at 0.41 and 0.34, respectively. The greater fraction of orthorhombic crystals in candelilla wax creates denser packing of hydrocarbon chains as opposed to hexagonal structures. Therefore, there are smaller intercrystalline pathways and a greater resistance to O_2P. This limitation of oxygen to the surface of candelilla wax may cause incomplete combustion and is more likely to create a low smoke point [64].

Chapter 3: Experimental

3.1 Candle Formation

The candles were formed using granular wax. Wax was placed in a 50 mL beaker. A resistively heated hot plate was heated to medium heat. The amount of heat was watched carefully to keep the wax from boiling. A metal stirrer was used to keep uniformity during the melting process. Once the wax melted fully, it was removed from the hot plate. After a few minutes it was placed in a freezer at -10 °C for rapid cooling. After complete solidification, each candle was removed from the freezer.

Removal from the beakers was difficult for some waxes. If the candle pulled away from the sides of the glass, forceful pounding of the beaker against a flat surface would suffice to slide the candle out. If it was not able to pull away from the glass, the beaker was wrapped in cloth and placed in a bag. Taps with a hammer shattered the glass and the candle was carefully removed from the bag. Formed candles were drilled on center. The drilled holes of the candles were slightly bigger than the wick diameter.

3.2 Wick Preparation

Braided cotton wicks of 1.8 – 7.6 mm diameter were obtained from study contributor, Jeb Head, of Atkins and Pearce. Wicks sizes were selected in this range because wicks smaller than 1.8 mm were unable to produce a smoke point while wicks of 7.6 mm were the largest available. Wicks were cut to a 10 cm length. They were stiffened by the addition of melted wax matching that of their intended candles. They were longer than the candles and slightly smaller than the drilled holes so that their height could be adjusted from beneath during the burn tests.

3.3 Testing Apparatus

The testing apparatus was constructed of a horizontal 30 × 30 × 1 cm aluminum plate. The plate had a 38 mm hole drilled on center to hold the candles. Three screws secured the candles, which were inserted flush with the plate's upper surface.

Draft protection for the flame was a 305 mm cubed clear acrylic box. It was placed over the candle during burning. A piece of black paper was fitted to the back of the cube to obtain clear pictures of the candle flame. A piece of white paper was fitted to the cube opposite the observer. This step helped the observer easily see the smoke point. A vertical ruler was placed in the camera view.

3.4 Camera Set Up

Images were taken with a Nikon D100^{TM} digital single-lens reflex color camera with a 60 mm lens, a shutter speed 0.15 s, and 8*f*. Focus was manually adjusted by the camera's focal lens. The camera was set on a vertical pedestal placed slightly above the horizontal of the top of the candle. A view of the burning wax pool will help obtain a better view of the candle's liquid pool. The camera was leveled. Figure 3.4 provides a sketch of apparatus set up.

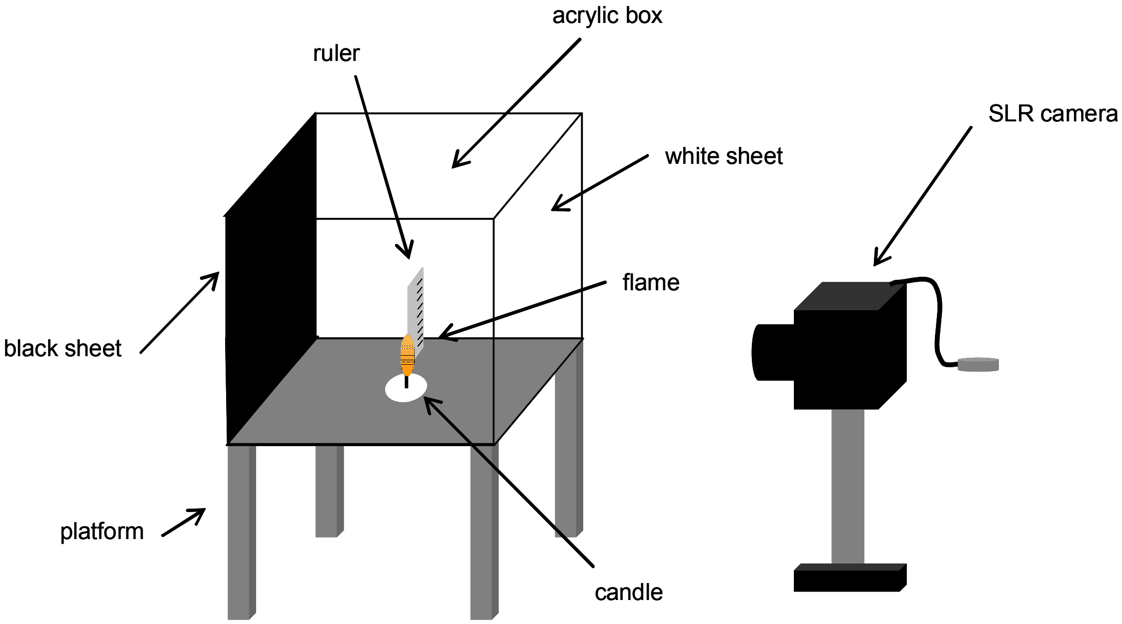

Figure 3.1: Apparatus set up.

Images were recorded and transferred into Nikon Picture Project. This software was able to take the recorded raw picture format, Nikon Enhanced Format (NEF), and convert it to a RGB (red-green-blue) format. Raw picture formats are the highest quality images available. However, these image formats are not compatible with NASA's analysis software, *Spotlight 16* edition. The images are exported into Spotlight in an RGB format. RGB format differs from the raw image because it only reads colors values as red, green, or blue with no combinations [57]. The RGB color filters create an image of lower quality, but do not damage the image enough to bias analysis.

3.5 Smoke Point Identification and Test Procedure

Each candle was loaded into the candle holder of the testing apparatus. The wax upper surface was set flush with the aluminum plate. The wick was ignited. Free burning in the open environment was allowed until the pool of liquid wax was roughly the size of a quarter. Excess wick strands or charred cotton were cut to remove any part of the wick for a uniform shape. Charred cotton does not contain liquid wax and may interfere with the flame.

The wicks were slowly adjusted from underneath until the smoke point was visually identified because erratic movement of the wick can negatively impact the stability of the flame. As slight movements were made, a small waiting period was needed to determine the effect on the movement of the flame. Although time was allowed for the flame to adjust to wick lengths, test times with the cover in place were limited. Control of the flame length generally was finer while decreasing wick length than while increasing it. Care was taken to prevent that the internal chamber conditions were not affecting the smoke point. Most of the smoke points in this study were found within 10 seconds after placing the acrylic box over the flame. A limiting time was calculated at 3 minutes. At the smoke point, a picture was taken. Each trial was re-ventilated to insure proper combustion conditions within the box. Trials were repeated 4 – 7 times.

The flame surface of an axisymmetric flame will close at the top when there is enough oxygen supply and heat for stoichiometric requirements [70]. Combustion products in the form of soot will break through the luminous zone when conditions lack oxygen to consume the carbon. This reaction also requires a sufficient amount of heat to oxidize the particles. Kent et al. [55], Delichatsios et al. [52], and Glassman [4] report this temperature requirement is between 1300 – 1650 K. Soot wings (see Fig. 3.2) are defined as a good indication of soot because of the intense particle formation at this point [4]. The visual identification process is then illustrated in Fig. 3.2.

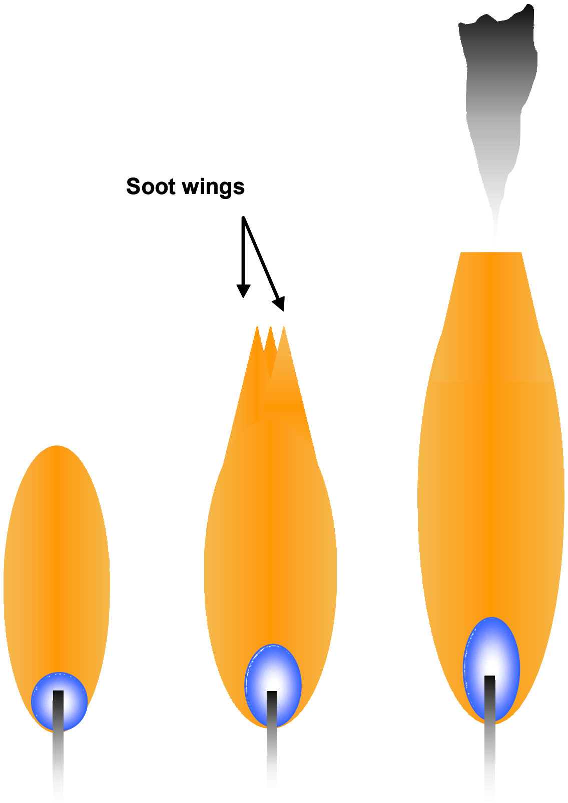

Figure 3.2: Illustration of smoke point for a laminar candle flame.

Wicks between diameters 5.26 and 7.60 mm were tested. Soot wings were not evident at the smoke points in these tests. Increased residence time in these flames results in a slow soot formation rate, which can oxidize all the soot before radiative heat losses can decrease the flame temperature below the soot inception temperature. The flame tip opens at the smoke point because of the large concentrations of soot particles [51]. Potentially, soot concentrations did not become great enough in these candle flames to break the apex, but were kept from emitting visible soot.

3.6 Image Analysis

Five measurements were made from each image: flame height with respect to wax pool (i.e., smoke point), wick height with respect to wax pool, wick diameter, flame width, and standoff height. A pixel conversion factor from the image was determined to calculate actual length in millimeters. Spatial resolution of the images were 0.031 mm/pix.

One point was chosen on each digital image at the meniscus of the wax pool and candle wick. This point served as a base to measure wick and flame lengths relative to the pool. Standoff was measured from the first base point of the wax pool to the bottom edge of the flame. The bottom edge of the flame was where the blue gas burning zone became visible. Wick height was measured from the base of the wax pool to the tip of the wick. Wick diameter was measured from each endpoint of the cotton. Wick diameters varied slightly with position, particularly for wicks with large diameters. In these cases, minimum and maximum wick diameters were measured and averaged. Flame width was measured relative to the greatest horizontal span of the flame. This point usually occurred near the top of the wick. Line endpoints were placed at the faintest visible blue edges of the flame. Smoke points were measured relative to the wax pool and terminated at the flame tip. The flame tip was chosen from luminosity values measured by Spotlight. Luminosity values occur in between 0 and 1. The black background of the image represented a luminosity of 1 while the flame zone took a value of 0. A value of 0.5 was chosen to distinguish the flame tip at the smoke point. This method produced consistent results among all wax types relative to the luminosity at the smoke point.

3.7 Uncertainty Analysis

Uncertainty in the measurements arises from wicks that were not perfectly cylindrical, and the inherently transient nature of the measurements. Further considerations to error pertain to the image analysis where actual flame boundaries can be difficult to determine. Uncertainties reported here are estimated as follows: wick diameter ± 5%; wick length at smoke point ± 10%; smoke point ± 10%; fitted smoke point ± 10%; flame width ± 5%.

Chapter 4: Results and Discussion

Figure 4.1 shows a candle of paraffin wax burning at its smoke point. The six images show flame growth to smoke point where soot wings are identified. Typical of the flames in this study, these are non-flickering and quasi-steady. The smoke point occurred when the soot wings were at the same height as the flame centerline, similar to behavior in gas jet flames [32].

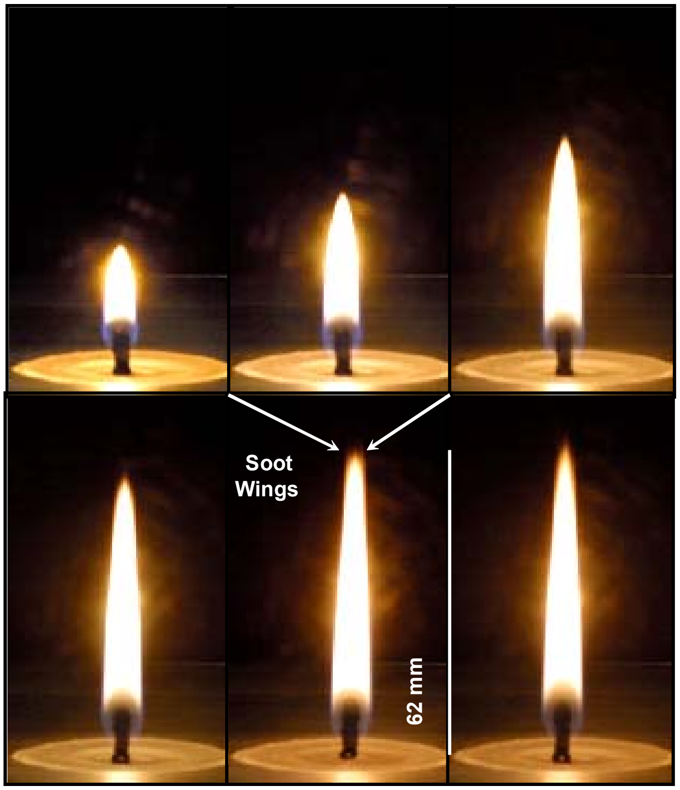

Figure 4.1. Color images of a paraffin candle flame growth to the laminar smoke point. Luminous length is 62 mm and the wick diameter is 2.7 mm.

Figure 4.2 is a representation of a beeswax candle at its smoke point identified by the appearance of soot wings.

Figure 4.2 Color image of a candle flame at the laminar smoke point. The fuel is candelilla, wick diameter is 2.1 mm, and the luminous length is 38.3 mm.

Figure 4.3 shows the measured laminar smoke points for the 14 waxes of Table 1. Each symbol represents mean smoke points and wick diameters from 4 – 7 images. The range of values for smoke points varies between 36 – 89 mm. Fig. 4.3 follows similar behavior that was seen in wick lamp tests where variations of smoke point are observed with changing wick diameter [30]. The increase may arise from wick quenching affects.

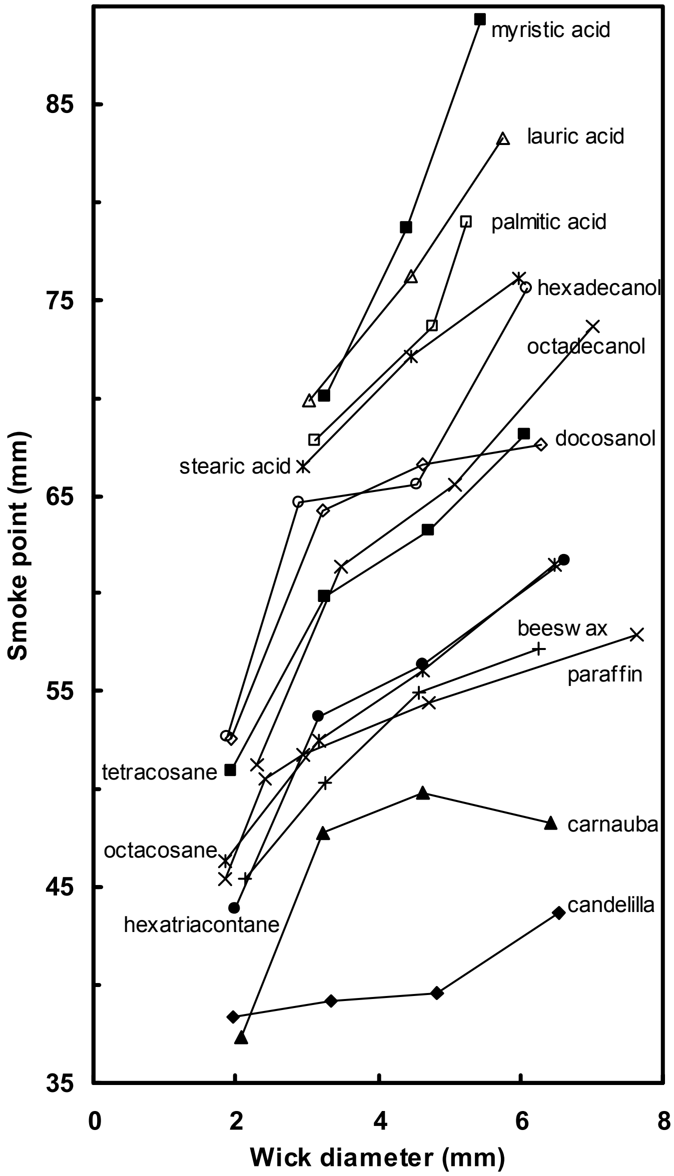

Figure 4.3: Smoke point as a function of wick diameter for the waxes of Table 2.1.

Figure 4.3 reveals the present smoke points to increase from commercial waxes to alkanes to alcohols to acids. A more detailed ranking is given below. Fig. 4.3 reveals the minimum wick diameters that can result in soot emission under these testing conditions. For acids, the minimum diameter needed to produce a smoke point is larger than for the other fuels.

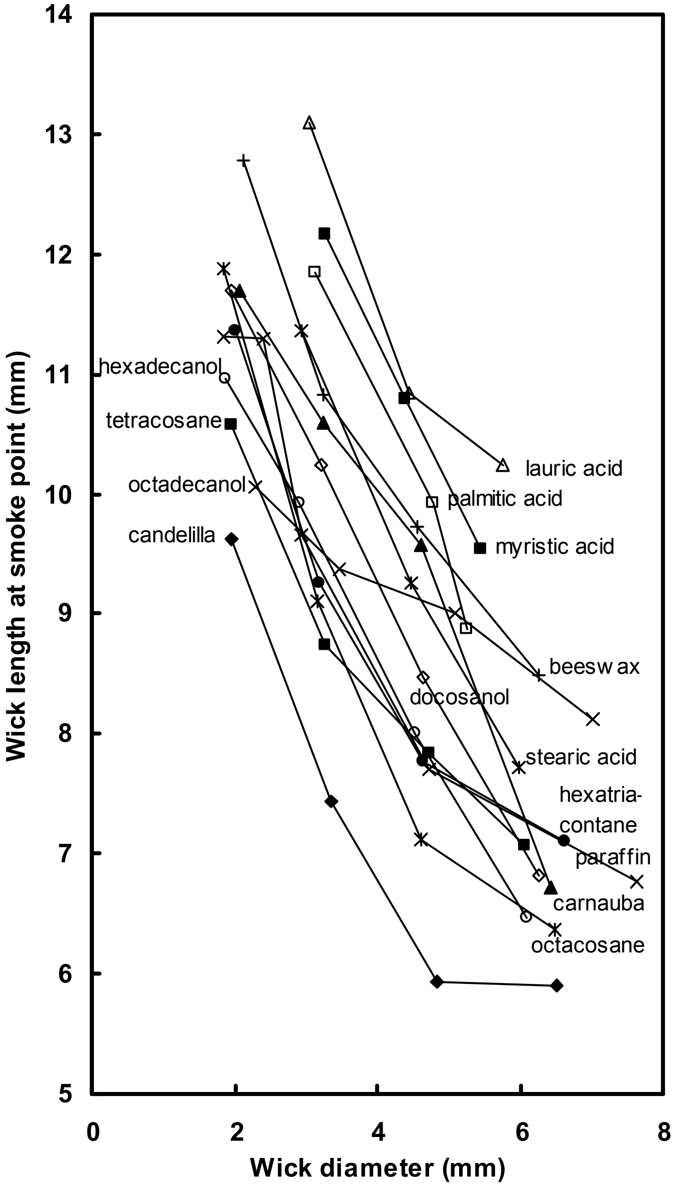

Figure 4.4: Wick length at smoke point as a function of wick diameter for the waxes of Table 2.1.

Figure 4.4 shows measured wick length at smoke point as a function of wick diameter. At the smoke point, as wick diameter increases, wick length decreases. This indicates that candle wicks of smaller diameters can sustain a longer length to avoid sooting and as a result require less trimming.

Longer wicks of smaller diameter are observed to result in shorter smoke points for otherwise matched conditions owing to flame quenching effects. This arises because long wicks can act as heat sinks near the flame centerlines. Figs. 4.3 and 4.4 suggest that the decrease in smoke point for smaller wick diameters may be attributable to flame quenching from longer wicks.

The variation of smoke point with wick diameter, evident in Fig. 4.3, requires additional consideration prior to a quantitative ranking of sooting propensities of these fuels. The approach followed here is to fit the measurements of Figs. 4.3 and 4.4 to a wick diameter of 4 mm using least squares linear fits. A linear slope ($m_{S.P.}$) was calculated among each smoke point data set along with an intercept ($int_{S.P.}$). These values were used to produce a relationship relative to equation 1.2:

$$S.P._{d_w=4mm} = m_{S.P.}(d_w = 4) + \text{int}_{S.P.} \tag{1.2}$$

This wick diameter was chosen because it is close to the mean diameter considered for each fuel. Wicks of large diameters did not consistently produce soot wings.

The resulting fitted results are shown in Fig. 4.5. Fuels are ordered according to increasing fitted smoke point from 40 – 76.1 mm. It is not possible to match both wick diameter and wick length in smoke point tests of multiple fuels. Figure 4.5 shows that wick diameters of 4 mm require wick lengths of 7.5 – 12 mm at smoke points. If wick length variations in Fig. 4.4 could be accounted for this would be unlikely to change the fuel rankings shown. Possible exceptions are beeswax and paraffin, whose smoke points are close but whose wick lengths vary.

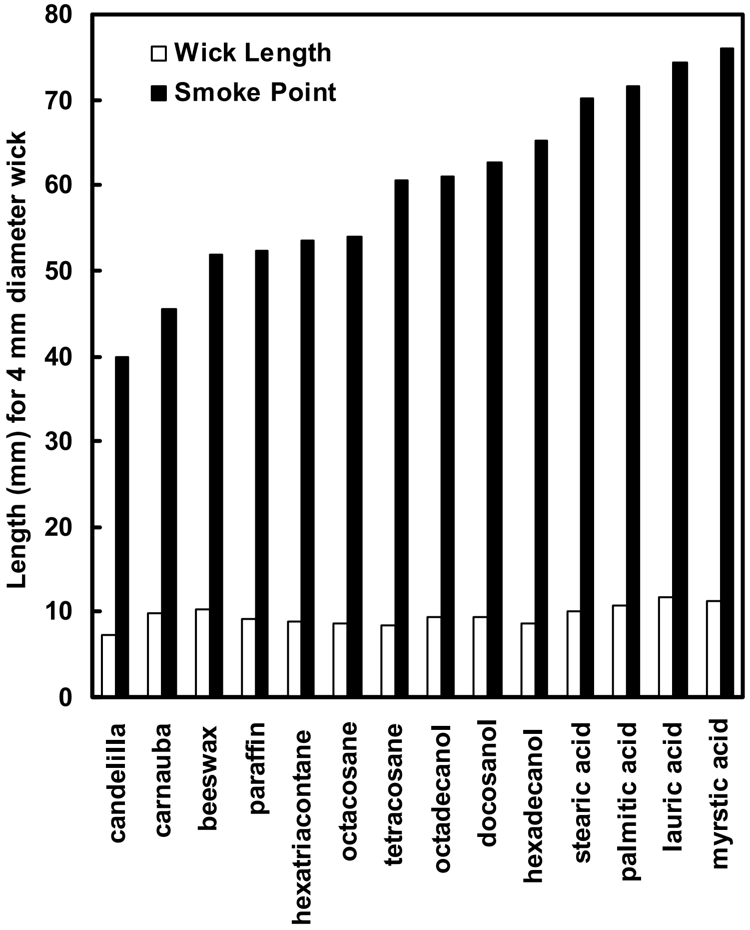

Figure 4.5: Smoke point and wick length at smoke point, both normalized to a 4 mm diameter wick for the waxes in Table 2.1.

Figure 4.5 indicates that commercial waxes have the lowest fitted smoke points. Waxes with greater oxygen numbers tend to have higher smoke points. Hydrocarbon paraffins contain no oxygen, while alcohols and acids have one and two O atoms, respectively. Acids have been found to have the highest smoke points. Oxygen content is unknown for the commercial waxes.

Fig. 4.6 shows the fitted smoke points of Fig. 4.5 plotted versus carbon number. Carbon numbers are estimated for commercial waxes in Table 2.1. Within the acids, alcohols, and alkanes, normalized smoke points decrease with increasing carbon number.

Smoke points increase with increasing oxygen number. While these trends may arise from gas-phase processes, they also may be associated with liquid properties such as boiling point, viscosity, and surface tension.

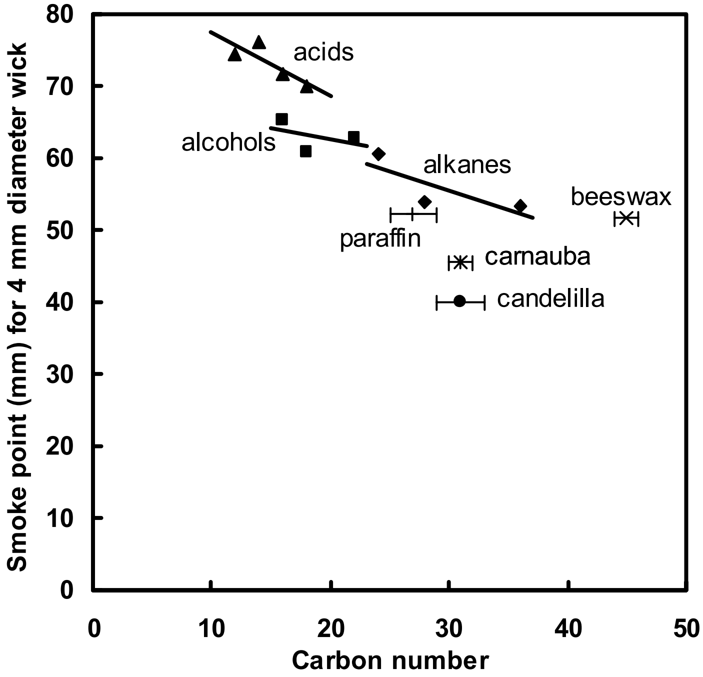

Figure 4.6: Smoke point normalized to a wick diameter of 4 mm as a function of carbon number for the waxes in Table 2.1.

Chapter 5: Conclusions

Adjustable wicks with diameters of 2 – 7.6 mm were used to measure smoke points in quiescent air for 14 different waxes. Laminar smoke points were measured for in quiescent air. This work has led to the following conclusions:

1) Candle smoke points increase with wick diameter and, for the fuels and wicks considered, vary from 36 – 89 mm.
2) When fitted to 4 mm diameter wicks, smoke points were found to increase from commercial waxes to alkanes to alcohols to acids.
3) Smoke points of acids were found to decrease with increasing carbon number. Similar behavior was observed for alcohols and alkanes.
4) Smoke point wick length was found to decrease with increasing wick diameter. Thus candles with larger wick diameters require shorter wick trimming to prevent soot emission.
5) Smoke points increase with fuel oxygen content.
6) For wick diameters tested, a typical consumer grade candle will have a laminar smoke point ≤ 55 mm.
7) There are no smoke points for wick diameters less than 1.8 mm or wick lengths less than 6 mm.

These are the first known measurements of candle smoke points. The results here show similar trends to previous testing while providing insight to new relationships.

These relationships should be evaluated in further testing. Further research resulting from this study could encompass more wax types and wick diameters. Relevant information to candle manufactures can be extracted to possibly create a more efficient burning candle. These tests could be expanded to include more explicit analysis concerning mass loss rates and flame temperatures. Moreover, this data could provide a database of inputs in future computer models. More extensive research regarding the impact of wax type coatings and materials should be correlated to soot yields and the impact in large scale fires.

Appendix A: Color images of representative smoke-point flames

A.1: Beeswax
d_w: 2.14 mm
SP: 45.3 mm

A.2: Beeswax
d_w: 3.26 mm
SP: 49.8 mm

A.3: Beeswax
d_w: 4.61 mm
SP: 54.8 mm

A.4: Beeswax
d_w: 6.26 mm
SP: 56.9 mm

A.5: Candelilla
d_w: 2.05 mm
SP: 38.5 mm

A.6: Candelilla
d_w: 3.01 mm
SP: 39.5 mm

A.7: Candelilla
d_w: 4.65 mm
SP: 40.0 mm

A.8: Candelilla
d_w: 6.43 mm
SP: 43.7 mm

A.9: Carnauba
d_w: 2.13 mm
SP: 37.8 mm

A.10: Carnauba
d_w: 3.23 mm
SP: 47.2 mm

A.11: Carnauba
d_w: 4.69 mm
SP: 50.2 mm

A.12: Carnauba
d_w: 6.55 mm
SP: 48.2 mm

A.13: Paraffin
d_w: 1.83 mm
SP: 45.4 mm

A.14: Paraffin
d_w: 2.36 mm
SP: 49.7 mm

A.15: Paraffin
d_w: 2.94 mm
SP: 51.6 mm

A.16: Paraffin
d_w: 4.68 mm
SP: 53.7 mm

A.17: Paraffin
d_w: 7.01 mm
SP: 57.2 mm

A.18: Tetracosane
d_w: 1.86 mm
SP: 51.6 mm

A.19: Tetracosane
d_w: 3.33 mm
SP: 60.0 mm

A.20: Tetracosane
d_w: 4.82 mm
SP: 63.5 mm

A.21: Tetracosane
d_w: 6.06 mm
SP: 68.7 mm

A.22: Octacosane
d_w: 1.75 mm
SP: 46.1 mm

A.23: Octacosane
d_w: 3.29 mm
SP: 52.3 mm

A.24: Octacosane
d_w: 4.87 mm
SP: 56.1 mm

A.25: Octacosane
d_w: 6.12 mm
SP: 62.8 mm

A.26:
Hexatriacontane
d_w: 2.08 mm
SP: 43.9 mm

A.27:
Hexatriacontane
d_w: 3.23 mm
SP: 53.3 mm

A.28:
Hexatriacontane
d_w: 4.73 mm
SP: 56.7 mm

A.29:
Hexatriacontane
d_w: 6.72 mm
SP: 61.5 mm

A.30:
Hexadecanol
d_w: 1.93 mm
SP: 52.9 mm

A.31:
Hexadecanol
d_w: 2.74 mm
SP: 63.2 mm

A.32:
Hexadecanol
d_w: 4.59 mm
SP: 65.1 mm

A.33:
Hexadecanol
d_w: 6.13 mm
SP: 74.0 mm


A.34: Octadecanol
d_w: 2.38 mm
SP: 51.2 mm


A.35: Octadecanol
d_w: 3.42 mm
SP: 61.3 mm


A.36: Octadecanol
d_w: 5.09 mm
SP: 65.7 mm


A.37: Octadecanol
d_w: 7.27 mm
SP: 70.5 mm


A.38: Docosanol
d_w: 1.90 mm
SP: 52.7 mm


A.39: Docosanol
d_w: 3.24 mm
SP: 63.8 mm


A.40: Docosanol
d_w: 4.54 mm
SP: 66.4 mm


A.41: Docosanol
d_w: 6.34 mm
SP: 67.9 mm


A.42: Lauric Acid
d_w: 2.85 mm
SP: 69.5 mm


A.43: Lauric Acid
d_w: 4.54 mm
SP: 76.2 mm


A.44: Lauric Acid
d_w: 5.94 mm
SP: 84.8 mm

A.45:
Myristic Acid
d_w: 3.21 mm
SP: 70.2 mm

A.46:
Myristic Acid
d_w: 4.41 mm
SP: 78.8 mm

A.47:
Myristic Acid
d_w: 5.36 mm
SP: 89.2 mm

A.48:
Palmitic Acid
d_w: 3.26 mm
SP: 67.8 mm

A.49:
Palmitic Acid
d_w: 5.03 mm
SP: 73.5 mm

A.50:
Palmitic Acid
d_w: 5.38 mm
SP: 80.2 mm

A.51: Stearic
Acid
d_w: 2.92 mm
SP: 66.3 mm

A.52: Stearic Acid
d_w: 4.44 mm
SP: 71.5 mm

A.53: Stearic Acid
d_w: 6.00 mm
SP: 76.0 mm

Appendix B: Mean Data Summary

WAX	Wick Width mm	Wick Height mm	Smoke Point mm	Flame Width mm	Stand-off mm
Beeswax	2.1	12.8	45.4	6.5	3.9
	3.2	10.8	50.4	8.1	2.2
	4.6	9.7	54.9	8.9	2.5
	6.3	8.5	57.2	10.4	2.8
Candelilla	2.0	9.6	38.3	6.9	1.6
	3.4	7.4	39.2	7.5	1.9
	4.8	5.9	39.6	8.6	1.9
	6.5	5.9	43.7	9.9	2.1
Carnauba	2.1	11.7	37.3	7.0	3.2
	3.2	10.6	47.7	8.3	2.2
	4.6	9.6	49.8	8.7	3.2
	6.4	6.7	48.3	9.9	2.6
Paraffin	1.9	45.4	6.7	11.3	3.4
	2.4	50.5	6.8	11.3	3.7
	2.9	51.7	7.6	9.7	3.0
	4.7	54.4	9.0	7.7	2.8
	7.6	57.9	12.2	6.8	2.4
Tetracosane	1.9	50.9	7.1	10.6	3.6
	3.3	59.9	8.4	8.7	2.6
	4.7	63.3	9.7	7.8	3.0
	6.1	68.1	11.0	7.1	3.0
Octacosane	1.9	46.3	6.9	11.9	3.5
	3.2	52.5	7.5	9.1	2.9
	4.6	56.0	8.6	7.1	2.6
	6.5	61.5	10.3	6.4	3.0
Hexatriacontane	2.0	43.9	6.4	11.4	3.1
	3.2	53.7	8.0	9.3	2.0
	4.6	56.4	9.2	7.8	2.7
	6.6	61.7	11.5	7.1	2.6
Hexadecanol	1.9	52.6	7.1	11.0	2.8
	2.9	64.6	8.6	9.9	2.8
	4.5	65.6	9.7	8.0	2.6
	6.1	75.6	11.2	6.5	2.3
Octadecanol	2.3	51.2	7.8	10.1	2.7
	3.5	61.3	8.8	9.4	2.8
	5.1	65.6	9.9	9.0	3.3
	7.0	73.6	12.0	8.1	2.6
Docosanol	1.9	52.6	7.4	11.7	3.6
	3.2	64.3	8.4	10.3	2.4
	4.6	66.6	9.9	8.5	2.9
	6.3	67.6	11.4	6.8	2.7

Lauric Acid	3.0	69.9	8.8	13.1	3.4
	4.5	76.2	10.4	10.8	4.3
	5.8	83.2	11.3	10.2	4.9
Myristic Acid	3.3	70.1	9.0	12.2	3.3
	4.4	78.7	10.1	10.8	3.5
	5.5	89.3	12.0	9.5	3.5
Palmitic Acid	3.12	67.8	8.76	11.84	2.92
	4.78	73.7	9.91	9.93	2.74
	5.26	79.0	11.18	8.87	3.19
Stearic Acid	2.9	11.4	66.5	8.1	3.1
	4.5	9.3	72.1	10.3	3.8
	6.0	7.7	76.1	12.1	3.0

Appendix C: Candle Trial Data Summary

Beeswax					
Figure No.	**Wick Width mm**	**Wick Height mm**	**Smoke Point mm**	**Flame Width mm**	**Standoff mm**
A.1	2.13	12.82	44.12	6.43	4.12
	2.04	12.49	44.58	6.43	3.92
	2.14	12.85	45.30	6.59	4.09
	2.14	13.34	47.22	6.56	3.92
	2.19	12.42	46.00	6.59	3.56
A.2	3.21	10.12	47.45	8.01	2.24
	3.26	10.97	49.88	8.17	2.14
	3.23	10.21	49.39	8.24	1.78
	3.23	11.17	51.96	8.11	2.21
	3.29	11.63	53.21	7.97	2.54
A.3	4.61	9.46	54.89	8.80	2.54
	4.50	9.82	55.19	9.23	2.64
	4.50	10.25	55.82	8.80	2.54
	4.61	9.39	53.44	8.80	2.50
	4.65	9.69	55.16	8.80	2.31
A.4	6.29	8.04	56.97	10.41	2.34
	6.29	9.09	57.40	10.35	3.29
	6.23	8.80	57.53	10.44	3.03
	6.26	8.17	56.97	10.41	2.67
	6.29	8.34	56.94	10.51	2.67

Candelilla					
Figure No.	**Wick Width mm**	**Wick Height mm**	**Smoke Point mm**	**Flame Width mm**	**Standoff mm**
A.5	1.73	9.31	37.0	6.87	1.35
	2.05	9.85	39.5	6.94	1.66
	2.05	9.58	38.5	6.80	1.69
	2.00	9.54	37.6	6.77	1.46
	2.01	9.85	39.0	6.97	1.66
A.6	3.45	6.97	38.4	7.41	1.69
	3.45	7.55	39.6	7.48	1.86
	3.01	7.88	39.5	7.55	2.00
	3.42	7.61	39.9	7.45	1.96
	3.42	7.14	38.8	7.48	1.90
A.7	4.65	5.85	40.0	8.43	1.90
	4.89	6.02	39.2	8.63	1.96
	4.67	6.46	41.3	8.80	2.00
	4.99	5.65	38.2	8.56	1.86
	4.99	5.72	39.4	8.66	1.73
A.8	6.58	6.02	45.3	10.02	2.03
	6.40	5.65	42.9	9.64	2.00
	6.51	6.33	44.2	9.85	2.27
	6.43	6.02	43.7	9.61	2.23
	6.72	5.52	42.6	10.22	1.93

Carnauba

Figure No.	Wick Width mm	Wick Height mm	Smoke Point mm	Flame Width mm	Standoff mm
	2.06	11.34	36.1	6.97	2.64
	2.03	11.84	36.6	6.84	3.45
	1.98	11.20	37.9	7.04	3.05
A.9	2.13	11.95	37.8	7.21	3.18
	2.13	12.18	38.0	7.04	3.86
A.10	3.23	10.59	47.2	7.88	2.27
	3.21	9.61	45.7	9.24	2.06
	3.21	10.46	48.7	8.12	1.83
	3.28	11.74	48.0	7.92	3.38
	3.23	10.56	49.1	8.19	1.56
	4.60	11.10	51.4	8.66	4.81
	4.57	10.29	50.4	8.76	3.93
	4.53	8.09	48.1	8.66	1.83
A.11	4.69	9.81	50.2	8.70	3.28
	4.70	8.60	48.9	8.83	1.93
	6.50	6.73	48.4	10.25	2.06
	6.43	7.07	48.3	9.95	2.77
	6.43	6.57	47.4	9.81	2.34
	6.29	7.45	49.0	9.85	2.98
A.12	6.55	5.75	48.2	9.75	2.84

Paraffin					
Figure No.	**Wick Width mm**	**Wick Height mm**	**Smoke Point mm**	**Flame Width mm**	**Standoff mm**
	1.88	11.24	45.4	6.61	3.21
	1.83	11.24	45.0	6.61	3.37
	1.77	12.10	44.9	6.71	4.40
A.13	1.83	11.04	45.4	6.68	3.11
	1.95	10.91	46.5	6.64	2.94
	2.98	10.12	52.6	7.57	3.37
	2.89	9.22	51.0	7.67	2.71
A.14	2.94	9.26	51.6	7.57	2.38
	2.94	9.39	51.0	7.54	2.88
	2.99	10.35	52.4	7.60	3.47
	4.68	7.47	52.8	9.09	2.91
A.15	4.68	7.57	53.7	8.96	2.68
	4.84	6.88	53.3	8.76	2.51
	4.74	7.97	56.7	8.99	2.84
	4.64	8.63	55.7	9.09	3.17
	9.54	6.08	54.4	12.07	1.98
	7.39	6.84	56.2	12.20	2.68
	7.22	7.04	61.6	12.40	2.64
	7.06	7.01	60.0	12.50	2.38
A.16	7.01	6.84	57.2	11.97	2.38
A.17	2.36	12.56	49.7	6.74	4.53
	2.30	11.40	49.4	6.91	3.31
	2.36	11.90	52.3	6.98	3.54
	2.36	8.00	49.5	6.68	3.24
	2.36	12.60	52.0	6.81	4.03

Tetracosane

Figure No.	Wick Width mm	Wick Height mm	Smoke Point mm	Flame Width mm	Standoff mm
A.18	1.94	9.87	49.0	7.06	2.81
	1.92	9.47	48.1	6.96	2.74
	1.86	10.64	51.6	7.06	3.72
	1.94	11.68	52.9	7.10	4.62
	2.06	11.18	52.9	7.23	4.22
A.19	3.31	8.37	57.8	8.27	2.64
	3.33	8.94	60.0	8.33	2.78
	3.20	9.10	61.1	8.30	2.78
	3.18	8.64	61.2	8.40	2.48
	3.28	8.64	59.3	8.47	2.31
A.20	4.85	7.90	62.8	9.77	3.01
	4.38	8.20	65.0	9.51	3.21
	4.77	7.83	60.6	9.84	3.01
	4.82	7.43	63.5	9.77	2.85
	4.79	7.83	64.4	9.81	2.78
A.21	6.03	7.67	67.5	10.95	3.38
	5.99	7.23	69.1	10.95	3.21
	6.11	6.63	67.6	11.11	2.64
	6.06	7.16	68.7	11.11	2.98
	6.18	6.63	67.7	11.11	2.78

Octacosane

Figure No.	Wick Width mm	Wick Height mm	Smoke Point mm	Flame Width mm	Standoff mm
A.22	1.75	10.08	46.08	6.83	3.15
	1.93	12.45	45.55	7.11	3.56
	1.68	11.76	44.24	6.74	3.03
	2.06	13.26	49.45	7.05	4.09
A.23	3.03	9.16	51.66	7.33	3.16
	3.19	9.35	54.38	7.55	2.72
	3.29	9.23	52.29	7.52	2.97
	3.16	8.69	51.69	7.61	2.72
A.24	4.39	7.39	56.49	8.53	2.50
	4.68	6.67	54.38	8.53	2.27
	4.55	7.33	57.16	8.72	2.88
	4.87	7.08	56.05	8.63	2.88
A.25	6.12	7.11	62.75	11.17	2.62
	6.61	6.80	64.77	9.55	3.00
	6.55	5.93	57.54	10.23	3.56
	6.68	5.62	60.94	10.36	2.68

Hexatriacontane					
Figure No.	**Wick Width mm**	**Wick Height mm**	**Smoke Point mm**	**Flame Width mm**	**Standoff mm**
A.26	2.08	11.80	43.9	6.27	3.60
	2.00	11.43	44.2	6.50	3.00
	2.02	11.50	43.2	6.60	3.07
	1.95	10.87	43.8	6.33	2.70
	1.95	11.23	44.5	6.40	2.93
	3.22	10.10	55.7	7.97	2.27
	3.25	9.47	55.0	8.00	2.23
A.27	3.23	8.80	53.3	8.07	1.67
	3.08	9.33	53.2	8.00	2.07
	3.10	8.57	51.5	7.97	1.63
	4.52	8.17	55.4	9.20	2.97
	4.52	8.23	57.3	9.27	2.93
	4.58	7.93	57.1	9.20	2.93
A.28	4.73	7.43	56.7	9.10	2.37
	4.82	7.10	55.5	9.17	2.40
	6.72	6.67	61.1	11.77	2.47
A.29	6.72	6.67	61.5	11.50	2.27
	6.53	7.30	61.3	11.37	2.63
	6.58	7.40	63.4	11.17	2.57
	6.55	7.47	61.0	11.47	2.97

Hexadecanol					
Figure No.	**Wick Width mm**	**Wick Height mm**	**Smoke Point mm**	**Flame Width mm**	**Standoff mm**
A.30	1.88	10.69	51.5	6.97	2.54
	1.93	10.56	52.9	7.14	2.50
	1.98	11.84	54.4	7.04	3.52
	1.79	11.10	52.3	7.04	2.98
	1.79	10.59	52.1	7.17	2.61
A.31	2.99	10.02	66.0	8.60	2.57
	3.01	9.34	63.0	8.76	2.20
	2.91	10.59	65.7	8.56	3.32
	2.74	9.68	63.2	8.53	3.11
	2.86	10.02	65.2	8.46	3.01
A.32	4.59	8.02	65.1	9.71	2.77
	4.57	8.32	66.8	9.81	2.67
	4.57	7.72	66.1	9.78	2.44
	4.48	8.36	66.5	9.75	2.54
	4.50	7.58	63.4	9.54	2.61
A.33	6.13	6.43	74.0	11.07	2.27
	6.06	6.46	73.1	11.07	2.37
	6.09	6.43	76.9	11.37	2.40
	6.09	6.40	77.6	11.34	2.37
	6.09	6.63	76.2	11.37	2.10

Octadecanol

Figure No.	Wick Width mm	Wick Height mm	Smoke Point mm	Flame Width mm	Standoff mm
A.38	2.38	10.68	51.19	7.80	2.66
	2.22	9.83	51.16	7.61	2.85
	2.25	9.64	50.27	7.70	2.85
	2.38	10.08	52.33	8.02	2.76
A.39	3.51	9.49	60.92	8.81	2.84
	3.42	9.21	61.17	8.81	2.87
	3.42	9.43	61.26	8.84	2.78
	3.53	9.34	61.98	8.77	2.78
A.40	5.09	9.95	65.67	10.36	3.87
	5.06	8.43	67.99	9.60	3.11
	5.12	8.87	63.71	10.02	3.36
	5.06	8.78	65.01	9.95	2.95
A.41	7.27	8.05	70.52	12.01	1.97
	6.85	8.08	75.12	12.11	2.66
	6.97	8.21	75.29	11.98	3.33
	6.93	7.89	68.24	11.38	2.47

Docosanol

Figure No.	Wick Width mm	Wick Height mm	Smoke Point mm	Flame Width mm	Standoff mm
A.34	2.00	11.62	52.1	7.35	3.71
	1.99	12.09	52.1	7.48	3.94
	1.95	12.15	53.3	7.45	3.97
	1.90	11.22	52.7	7.31	2.90
	1.90	11.42	52.8	7.25	3.27
A.35	3.17	11.09	66.1	8.45	2.67
	3.24	9.92	63.8	8.48	2.14
	3.27	10.05	65.2	8.35	2.40
	3.22	10.58	62.7	8.25	2.77
	3.17	9.62	63.4	8.35	2.17
A.36	4.54	8.85	66.4	9.95	3.17
	4.64	8.15	65.9	9.92	2.57
	4.71	9.28	67.1	9.82	3.47
	4.57	7.98	65.9	9.92	2.60
	4.74	8.15	67.7	9.85	2.84
A.37	6.34	6.98	67.9	11.39	3.01
	6.39	6.74	66.7	11.42	2.50
	6.28	6.88	69.1	11.45	2.37
	6.18	6.78	66.5	11.29	2.70
	6.18	6.71	67.9	11.25	2.84

Lauric Acid

Figure No.	Wick Width mm	Wick Height mm	Smoke Point mm	Flame Width mm	Standoff mm
A.42	2.85	12.99	69.5	8.84	3.05
	3.25	13.15	71.2	8.97	3.05
	3.18	13.46	68.2	8.77	4.38
	2.98	12.05	68.6	8.74	2.54
	2.95	13.86	71.8	8.87	4.22
	4.12	12.96	78.7	10.19	6.53
	4.35	10.79	77.5	10.23	4.07
	4.63	10.79	75.6	10.42	3.80
	4.63	10.00	73.2	10.74	3.80
A.43	4.54	9.68	76.2	10.28	3.47
	5.67	10.29	85.4	11.34	5.31
	5.67	10.34	85.7	11.52	3.99
	5.67	7.57	78.6	11.29	2.54
	5.85	10.88	81.6	11.20	5.90
A.44	5.94	12.11	84.8	11.34	6.76

Myristic Acid

Figure No.	Wick Width mm	Wick Height mm	Smoke Point mm	Flame Width mm	Standoff mm
	3.34	12.05	68.7	8.85	3.21
	3.34	11.99	70.7	9.15	3.21
	3.21	12.62	69.6	8.95	4.17
A.45	3.21	11.89	70.2	9.08	2.44
	3.21	12.29	71.1	8.98	3.44
	4.27	11.05	80.1	10.22	3.24
	4.31	10.08	79.3	10.12	3.11
	4.52	10.58	74.9	9.98	4.07
A.46	4.41	11.45	78.8	10.12	3.87
	4.47	10.82	80.4	10.12	3.44
	5.54	10.14	89.3	11.94	3.38
	5.50	9.46	89.9	11.85	3.60
	5.41	8.92	87.5	12.07	3.56
A.47	5.36	9.59	89.2	11.85	3.78
	5.45	9.59	90.3	12.12	3.20

Palmitic Acid

Figure No.	Wick Width mm	Wick Height mm	Smoke Point mm	Flame Width mm	Standoff mm
A.48	3.26	11.48	67.8	8.86	3.05
	3.15	12.35	67.6	8.76	3.09
	3.02	11.04	66.9	8.69	2.42
	3.14	13.15	69.8	8.83	3.59
	3.05	11.17	66.9	8.66	2.45
A.49	4.90	9.90	72.2	9.83	2.75
	5.03	9.90	73.5	10.03	2.92
	4.83	9.93	73.0	9.90	2.85
	4.87	10.13	74.3	10.00	2.82
	4.24	9.80	75.5	9.77	2.35
A.50	5.32	9.44	78.3	11.10	3.53
	5.20	8.86	79.9	11.23	3.12
	5.16	8.86	77.8	11.23	3.49
	5.24	9.36	78.5	11.27	3.24
	5.38	7.86	80.2	11.06	2.54

Stearic Acid

Figure No.	Wick Width mm	Wick Height mm	Smoke Point mm	Flame Width mm	Standoff mm
A.51	2.97	9.52	64.3	7.86	2.25
	2.92	9.89	66.3	7.77	2.39
	2.90	14.02	65.6	8.23	4.74
	2.92	12.41	69.2	8.51	3.68
	3.01	10.99	67.0	8.18	2.44
A.52	4.44	9.43	71.5	9.84	3.77
	4.48	9.29	74.2	9.93	3.77
	4.53	9.20	74.4	12.00	3.86
	4.53	9.10	70.1	9.84	3.68
	4.37	9.29	70.3	9.84	3.68
A.53	5.89	8.64	76.8	12.41	3.68
	6.25	7.45	76.8	11.77	2.85
	6.00	8.23	76.0	12.00	3.63
	5.89	6.30	73.6	12.23	1.98
	5.84	7.95	77.3	12.05	2.90

Appendix D: Average Smoke Points for Waxes Tested

Table D.1: Average Smoke Points

WAX	Avg. Smoke Pt
candelilla	40.0
carnauba	45.6
beeswax	51.8
paraffin	52.2
hexatriacontane	53.2
octacosane	54.0
tetracosane	60.5
octadecanol	60.9
docosanol	62.7
hexadecanol	65.3
stearic acid	70.1
palmitic acid	71.6
lauric acid	74.4
myristic acid	76.1

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