*Combust. Sci. and Tech.*, 181: 800–811, 2009

ISSN: 0010-2202 print/1563-521X online
DOI: 10.1080/00102200902935512

# LAMINAR SMOKE POINTS OF WAX CANDLES

**Kathryn M. Allan,[1] John R. Kaminski,[1] Jerry C. Bertrand,[2] Jeb Head,[3] and Peter B. Sunderland[1]**
[1]*Department of Fire Protection Engineering, University of Maryland, College Park, Maryland, USA*
[2]*CW Group, Menlo Park, California, USA*
[3]*Atkins and Pearce, Inc., Covington, Kentucky, USA*

***An experimental investigation of laminar smoke points of candle flames is presented. Adjustable wicks with diameters of 1.7–7.3 mm were used to measure smoke points in quiescent air for 14 different waxes. The measured smoke points increased with wick diameter. Smoke points interpolated to a wick diameter of 4.5 mm varied from 41–80 mm and increased from commercial waxes (candelilla, carnauba, beeswax, paraffin) to normal alkanes (hexatriacontane, octacosane, tetracosane) to primary alcohols (octadecanol, docosanol, hexadecanol) to carboxylic acids (stearic, palmitic, lauric, myristic). Wax smoke points decreased with increasing carbon number. Alkane and alcohol smoke points decreased with increasing fuel C/H ratio and correlated with past measurements of liquid fuels and polymers. Soot emission was not possible for any fuel when wick diameter was below 1.7 mm or when wick length was below 5.9 mm.***

***Keywords***: Combustion; Diffusion flames; Laminar flames; Soot; Wicks

## INTRODUCTION

A reliable indication of the propensity of a fuel to produce and emit soot requires a combustion test. For premixed flames, the relevant test is the sooting limit. This test identifies the critical equivalence ratio at the point of the first appearance of yellow luminosity in a premixed flame (e.g., Takahashi & Glassman, 1984). For diffusion flames, the most widely used test is the laminar smoke point test. Note that a fuel's sooting propensity relative to other fuels may be different in sooting-limit and smoke-point tests (Calcote & Manos, 1983; Glassman, 1988).

A laminar smoke point is the length of a gas jet or wick-fed diffusion flame at the point of incipient soot emission. Smoke points occur because an increase in fuel flow rate increases soot formation time but yields a smaller increase in soot oxidation time (Glassman, 1988).

Received 5 September 2007; revised 1 April 2008; accepted 9 April 2008.

This research was supported by a Minta-Martin award from the College of Engineering at the University of Maryland. Helpful discussions with John L. de Ris and David L. Urban are acknowledged.

Address correspondence to Peter B. Sunderland, Department of Fire Protection Engineering, University of Maryland, 3104 J.M. Patterson Building, College Park, MD 20742, USA. E-mail: pbs@umd.edu

Laminar smoke points have been found to correlate with soot volume fractions (Kent, 1987) and radiative loss fractions (Markstein, 1984) of turbulent diffusion flames. Yang et al. (2007) found gas turbine soot emissions to be well correlated with a threshold sooting index (TSI) based on fuel molecular weight divided by laminar smoke point. Laminar smoke point measurements can be helpful in computational combustion simulations (Lautenberger et al., 2005) because they are central to the important phenomena of soot formation, soot and CO emissions, radiation, and flame quenching. Detailed models of soot kinetics and transport (e.g., Singh et al., 2006; Smooke et al., 2005) are currently too expensive for use in turbulent flames or fires.

The commercial impact of laminar smoke points is most significant in aviation. Most aviation jet fuel sold worldwide is required to have a laminar smoke point in a standard wick lamp (ASTM, 2002) of at least 25 mm (or at least 18 mm when naphthalene content is 3% by volume or below) (ASTM, 2003). Yan et al. (2005) pointed out the importance of matching smoke points when selecting surrogate fuels. A related study of effects of smoke points on surrogate fuel selection was presented by Aksit and Moss (2005).

The first laminar smoke point tests involved kerosenes in a wick lamp (Kewley & Jackson, 1927). Many notable later studies also used wick lamps (Aksit & Moss, 2005; Gülder, 1989; Marsh et al., 2007; Olson et al., 1985; Rakowsky & Hunt, 1956; Schalla & McDonald, 1955; Yan et al., 2005). The largest number of fuels considered was in Olson et al. (1985), which reported laminar smoke points of 42 liquid fuels.

Laminar smoke points of gas-fueled flames have been measured and reported in dozens of peer-reviewed papers (e.g., Berry & Roberts, 2006; Glassman, 1988; Markstein, 1986; Schug et al., 1980; Sunderland et al., 1994; Urban et al., 2000). These measurements are made by injecting fuel upward through a round tube into coflowing or quiescent oxidizer. Laminar smoke points of gaseous fuels are simple and fundamental; they are highly repeatable and are nearly independent of burner diameter.

Laminar smoke points of fuels that are solid at room temperature have only been reported in two studies, covering just six fuels. Tewarson (1986) examined five polymers, which were prevaporized and burned as gas jets. de Ris and Cheng (1994) measured smoke points of polymethylmethacrylate and particle board in an apparatus that involved sample heating with a $CO_2$ laser. Smoke points have never previously been reported for candles or for waxes.

A recent alternative to smoke point measurements was developed by McEnally and Pfefferle (2007). This involves doping a methane laminar diffusion flame with 400 ppm of a test fuel. Peak soot volume fraction is measured with laser-induced incandescence. To date, carbon numbers of up to 30 have been tested. This method holds great promise, especially for heavily sooting fuels and fuels with limited availability. However, it involves low fuel concentrations and testing different fuels along fixed trajectories of temperatures, times, and radical concentrations, which may not fully capture the sooting behavior of flames of pure fuels, such as candle wax or aviation fuel.

Candles are used in 70% of U.S. households and account for $2 billion in annual sales (National Candle Association, 2007). Soot emissions from candles can threaten human health and property. These concerns have been discussed in *The Wall Street Journal* and elsewhere (Fine et al., 1999; Huynh et al., 1991; Tejada, 1999).

Wax candles have received relatively little attention in peer-reviewed combustion literature, partly owing to experimental and analytical difficulties. Candles were one of the first combustion configurations tested in space (Dietrich et al., 2000). A detailed computational model of candle flames was presented by Alsairafi et al. (2004) and Raju and T'ien (2008). Several fire hazards of candles were considered by Hamins et al. (2005). Similarities between candle flames and gas-jet flames were examined by Takahashi (2009).

Given the above background, the objectives of this study are as follows:

- develop a method for measuring smoke points of candles;
- measure and correlate the smoke points of diverse waxes;
- consider the effects of wick diameter and length;
- rank the waxes according to their sooting propensities; and
- identify wick diameter and length requirements for smoke-free conditions.

This manuscript presents the results of an experimental study of laminar smoke points of candles and waxes. The experimental methods are described, followed by results and conclusions. Recommendations are provided for candle manufacturers and consumers and for those who administer and interpret aviation fuel smoke-point tests.

## EXPERIMENTAL SETUP

Fourteen waxes were tested, as identified in Table 1. These were obtained from Sigma-Aldrich in granular form. The commercial waxes are not monomers and have

**Table 1** Summary of waxes tested

| Family | Wax[*] | Formula | MW, g/mol | MP, °C[†] | BP, °C[‡] |
|---|---|---|---|---|---|
| Commercial | Beeswax | | | 63 | |
| | Candelilla | | | 72 | |
| | Carnauba | | | 83 | |
| | Paraffin | | | 66 | 350–430 |
| Normal alkane | *n*-tetracosane | $C_{24}H_{50}$ | 339 | 50.4 | 391.3 |
| | *n*-octacosane | $C_{28}H_{58}$ | 395 | 61.1 | 431.6 |
| | *n*-hexatriacontane | $C_{36}H_{74}$ | 507 | 75.8 | $298.4^{3}$ |
| Primary alcohol | 1-hexadecanol | $C_{16}H_{34}O$ | 242 | 49.2 | 312 |
| | 1-octadecanol | $C_{18}H_{38}O$ | 270 | 57.9 | 335 |
| | 1-docosanol | $C_{22}H_{46}O$ | 327 | 72.5 | $180^{0.22}$ |
| Carboxylic acid | Lauric acid | $C_{12}H_{24}O_2$ | 200 | 43.8 | 299.2 |
| | Myristic acid | $C_{14}H_{28}O_2$ | 228 | 54.2 | 318 |
| | Palmitic acid | $C_{16}H_{32}O_2$ | 256 | 62.5 | 353.8 |
| | Stearic acid | $C_{18}H_{36}O_2$ | 284 | 69.3 | 370 |

[*] Additional details are as follows: beeswax, refined, yellow; candelilla, natural; carnauba number 1, yellow, refined.

[†] Melting points sources are as follows: commercial waxes (Sigma-Aldrich, 2007), all others (Lide, 2007).

[‡] Boiling points are at 760 mm Hg except where a different pressure is shown in superscript. Sources are: paraffin (Reed, 1997), alkanes and aliphatic alcohols (Lide, 2007), carboxylic acids (Speight, 2005).

unknown or uncertain thermal properties, but were considered here owing to their widespread use in candles and other commercial products. The other waxes were certified to be monomers with purities of 98% or higher. Beeswax, candelilla, and carnauba were opaque yellow, paraffin was translucent white, and all other waxes were opaque white. Chemical formulas of the alkanes, alcohols, and acids are, respectively, $C_nH_{2n+2}$, $C_nH_{2n+2}O$, and $C_nH_{2n}O_2$, where $n$ is the carbon number. Where properties are available, chemical formula, molecular weight (MW), melting point (MP), and boiling point (BP) are shown in Table 1.

Waxes were placed in 50 mL glass beakers, melted on a hotplate, and allowed to cool. The beakers were placed in a freezer to facilitate wax removal. The candles were then removed from the beakers, which sometimes required breaking the beakers. Holes were drilled on axis to admit wicks. Braided round cotton wicks with diameters of 1–7.3 mm were obtained from Atkins and Pearce. Wicks were stiffened by the addition of melted wax matching that of their intended candles. The wicks were longer and slightly narrower than the drilled holes to allow adjustment of their heights from beneath during the burn tests.

Each candle was secured in a 38 mm hole in a horizontal 30 × 30 × 1 cm aluminum plate. A flame of 40 mm was established until the melt pool reached a diameter of about 20 mm. The wick was then made as straight and vertical as possible and, when necessary, was trimmed again with scissors. A 300 mm cube clear acrylic box with one open side was then placed over the candle to eliminate drafts. The acrylic box was left in place for no longer than 30 s and was flushed with fresh air between tests. The wick was adjusted by hand from below until a quasi-steady smoke point was visually identified. An image of this condition was then captured by the color camera.

There was a delayed response of flame length to changes in wick length. Because this delay was shorter (typically 2 s) for reductions in wick length, most smoke points were obtained while gradually reducing wick length. Flicker was sometimes observed, particularly for long flames, but could be eliminated by temporarily reducing wick length. Measurements reported here are associated with nonflickering conditions.

White paper was placed on the inner wall of the acrylic box opposite the observer, which allowed visual identification of soot emissions with good sensitivity. The inner wall opposite the camera was covered with black fabric for image clarity, particularly near the flame tip. This arrangement prevented observations of soot emissions in the camera images. Color images were recorded with a Nikon D100™ digital single-lens reflex camera with a 60 mm lens at 8*f* and a shutter speed of 0.15 s. These settings resulted in saturation in the brightest flame regions, but yielded good resolution of the pool, wick, and flame tip. Spatial resolution in the images was 0.04 mm or better.

Three measurements were obtained from each digital image: flame height (i.e., laminar smoke point), wick height, and wick diameter. The datum for flame and wick height was a horizontal line passing through the midpoint of the liquid wax meniscus at the wick base. The flame tips were not sharply defined in most images, but rather involved a transition from bright yellow to black across an axial distance of 2–5 mm. Flame height was thus measured to the point where the centerline greyscale was midway between these yellow and black regions. This helped reduce the sensitivity of measured flame height to camera exposure conditions. Wick diameters varied slightly with position, particularly for wicks with large diameters. In these cases, minimum and maximum wick diameters were measured and averaged.

Uncertainty in the measurements arises primarily from two factors: the difficulty of detecting small quantities of soot emitted from flames slightly longer than their smoke points, and unsteadiness associated with the delayed response of flame length to changes in wick length. In addition, the wicks were not perfectly cylindrical and vertical, and some oxygen vitiation within the enclosure was unavoidable. Measured smoke points, wick lengths, and wick diameters were repeatable within ±5%. Uncertainty in these measurements is estimated at ±10%.

## RESULTS AND DISCUSSION

Representative color images of four candle flames at their smoke points are shown in Figure 1. These images are for tetracosane with wick diameters of 1.9–6.2 mm. No smoke point could be obtained for tetracosane with a wick diameter of 1.7 mm or below. Visible in each image is a melt pool and the meniscus it forms at the wick base. The wicks are not obscured by flame luminosity. They are charred for heights above the flame standoff height and uncharred below. The base region of each flame is blue, with its widest point coinciding with the wick tip. Soot first appears in an annulus and crosses this blue region. Past work in normal-gravity gas-jet flames found the stoichiometric (blue) flame to be about 50% as long as the luminous (yellow) height at the smoke point (Lin et al., 1999). The yellow luminous regions of the present flames generally taper inward with increased height owing to inward buoyant flows and, low in the flames, thermophoresis.

Interesting behavior is evident in the smoke-point flame tips of Figure 1. Annular soot layers, called soot wings, appear near the flame tips except in the case involving the widest (6.2 mm) wick. Schug et al. (1980) found laminar smoke points of gas-jet flames to occur when soot wings are equally high as the flame centerline.

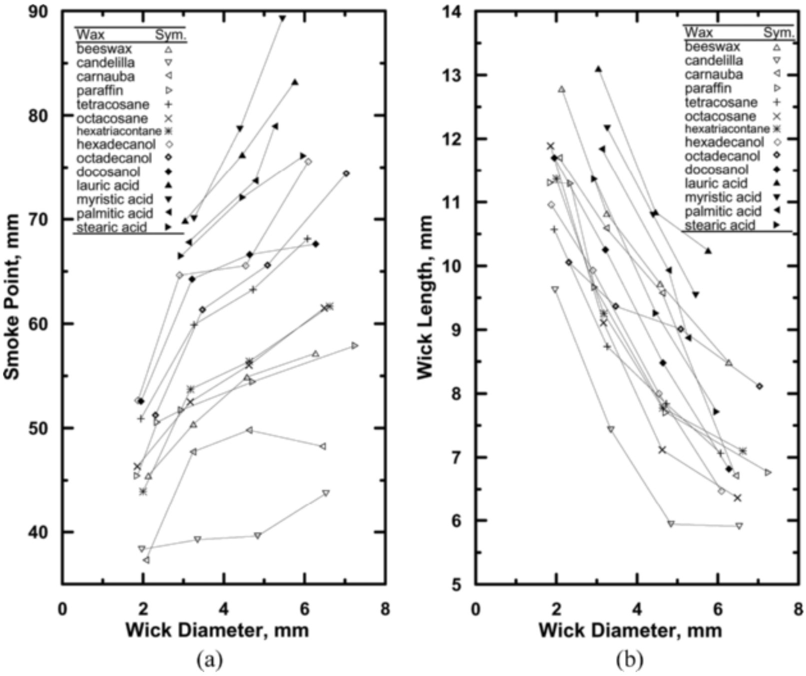
**Figure 1** Color images of tetracosane candle flames at their smoke points. Smoke points are, from left to right, 51.6, 60.0, 65.0, and 67.7 mm. Wick lengths are 10.6, 8.9, 8.2, and 6.6 mm. Wick diameters are 1.9, 3.3, 4.4, and 6.2 mm. These dimensions are slightly different from the mean values for tetracosane reported elsewhere in this paper.

In contrast, Markstein (1986) found that gas-jet smoke points could occur when soot wings were longer or shorter than the flame centerline. Soot wings are visible in most of the smoke-point flames for the waxes considered here. Their prominence diminishes or disappears for increasing smoke-point length. In general, present smoke-point flames with lengths below 50 mm have soot wings that are equally high as the centerline region, while those with lengths longer than 65 mm do not have soot wings.

It is expected that the equal-wings smoke points have their first soot emissions in an annulus, whereas the other smoke points have their first emissions on the centerline. Markstein (1986) observed similar behavior. Two modes of smoke points also were observed in microgravity flames by Urban et al. (2000), closed tip and open tip, with the open-tipped flames partially extinguished. The possibility that normal-gravity smoke points are associated with local flame extinction warrants further study.

Figure 2a shows the measured laminar smoke points for the 14 waxes of Table 1, plotted with respect to wick diameter. Each symbol represents mean smoke points and wick diameters from 4–7 tests with a single wick. The mean wick diameters and smoke points vary from 1.9–7.3 mm and 37–89 mm, respectively. Smoke points for each fuel are seen to increase with wick diameter. Rakowsky and Hunt (1956) also reported variations in smoke point with wick diameter for liquid fuels, but their measurements were limited, and their trends with respect to wick diameter were inconclusive.

Figure 2a reveals that, for fixed wick diameter, the present smoke points generally increase from commercial waxes to alkanes to alcohols to acids. The ranking of wax smoke points generally does not depend on wick diameter. Wick diameters



(a) (b)

**Figure 2** (a) Measured laminar smoke points versus wick diameter; (b) measured wick lengths at the laminar smoke points versus wick diameter.

smaller 1.7 mm were unable to result in soot emissions under quiescent conditions; for the carboxylic acids, this limit was 2.9 mm.

Figure 2b shows measured wick length at the smoke point as a function of wick diameter. Each symbol in Figure 2b corresponds to a symbol in Figure 2a. The wick lengths vary from 5.9–13.1 mm. At the smoke point, as the wick diameter increases, the wick length decreases, reflecting the approximate proportionality between burning rate and wick surface area. No smoke points could be obtained for wick lengths below 5.9 mm for any wax. For the carboxylic acids, the shortest wick length at a smoke point was 7.7 mm.

The increase in smoke point with increasing wick diameter (Figure 2a) is attributed to increased heat losses from the flame base to the wick and the wax pool. This decreases temperatures in the soot formation region, thus reducing soot-emitting tendency. Markstein (1986) also found smoke points to increase with increased heat loss at the flame base for gas-jet flames. For otherwise matched conditions, increased wick length can also reduce temperatures in the soot formation region. Thus, it is important to report wick diameter and length when smoke-point lengths are reported for wick-fed flames.

The variation of smoke point with wick diameter, evident in Figure 2a, requires additional consideration prior to a quantitative ranking of sooting propensities of these fuels. The approach followed here is to interpolate the measurements of Figure 2 to a wick diameter of 4.5 mm using a least-squares linear fit for each wax.

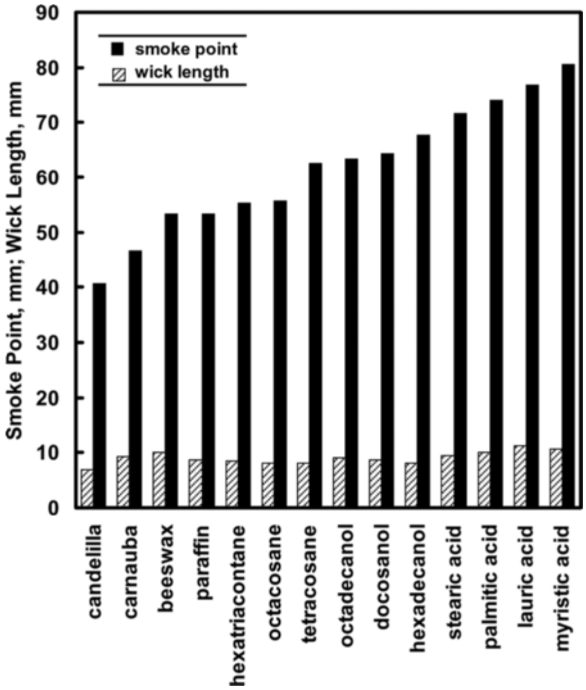


**Figure 3** Measured laminar smoke points and wick lengths at smoke points, both interpolated to a 4.5 mm-diameter wick.

This wick diameter was chosen because it is close to the diameter of one of the present wicks and is close to the mean wick diameter of the measurements of Figure 2. It also is comparable to the size of wick used in the ASTM (2002) tests, found under burning conditions in this laboratory to have a rectangular cross-section with dimensions of 5.0 × 6.1 mm (i.e., a hydraulic diameter of 5.5 mm).

The resulting interpolated results are shown in Figure 3. Fuels are ordered according to increasing interpolated smoke point, which vary from 41–80 mm. Figure 3 indicates that the commercial waxes have the highest sooting propensities of the waxes tested. The alkanes have the next higher smoke points, followed by the alcohols and the acids. It is unfortunate that paraffin and beeswax have some of the shortest smoke points, as these are widely used in candle manufacture (National Candle Association, 2007). Stearic acid, also widely used in candles, has one of the longest smoke points of the waxes tested.

It is not possible to match both wick diameter and wick length in smoke point tests of different fuels. Figure 3 shows that wick diameters of 4.5 mm required interpolated wick lengths of 7.0–11.3 mm at smoke points. Because of heat losses discussed above, some of the increase in smoke points from left to right in Figure 3 may be a result of increasing wick lengths.

Figure 4 shows the interpolated smoke points of Figure 3 plotted with respect to carbon number. Carbon number has been used extensively in past correlations of sooting propensity (Calcote & Manos, 1983; McEnally & Pfefferle, 2007; Olson et al.,

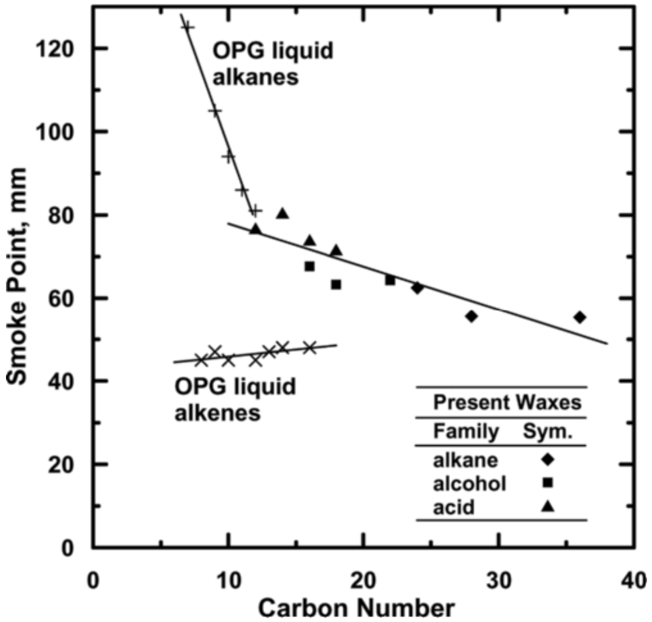


**Figure 4** Measured laminar smoke points versus fuel carbon number. Values for waxes are interpolated to a wick diameter of 4.5 mm. Values for liquids come from OPG (Olson et al., 1985) and involve a wick diameter of approximately 5.5 mm. The least-squares linear fits have these equations: $y = -1.03x + 88.3$ (present waxes); $y = -9.04x + 187$ (OPG liquid alkanes); $y = 0.341x + 42.4$ (OPG liquid alkenes).

1985; Schalla & McDonald, 1955). Commercial waxes could not be included here because their representative carbon numbers are unknown. A reasonable correlation with carbon number is obtained for the present waxes, with smoke points decreasing with increasing carbon number. The present carboxylic acids fall above the correlation, owing to increased fuel oxygen content.

Also included in Figure 4 are smoke points for liquid alkanes and alkenes, measured in a wick lamp with forced co-flow by Olson et al. (1985). Neither that study nor any other past study has reported smoke points or sooting propensities of alcohols or acids. The present measurements for alkanes extend the upper limit of carbon number for which smoke points are available from 12 to 36. The Olson et al. (1985) alkane smoke points decrease more quickly with carbon number than the wax alkanes do. This is probably because smoke points approach infinity as carbon number approaches zero. The Olson et al. (1985) alkenes have increasing smoke points with carbon number because in these fuels, the ratio of C-C double bonds to single bonds decreases with increasing carbon number.

The smoke-point data of Figure 4 is plotted in Figure 5 with respect to fuel C/H ratio. These axes allow inclusion of the two alkane polymer measurements of Tewarson (1986). Like carbon number, C/H ratio has been used in past correlations of sooting propensities (Calcote & Manos, 1983; Schug et al., 1980). Figure 5 shows that sooting propensity generally increases with increasing C/H ratio, as expected. This plot collapses the alkanes, alkenes, and alcohols into a single correlation, such as the power law shown. This correlation captures the expected behavior as carbon

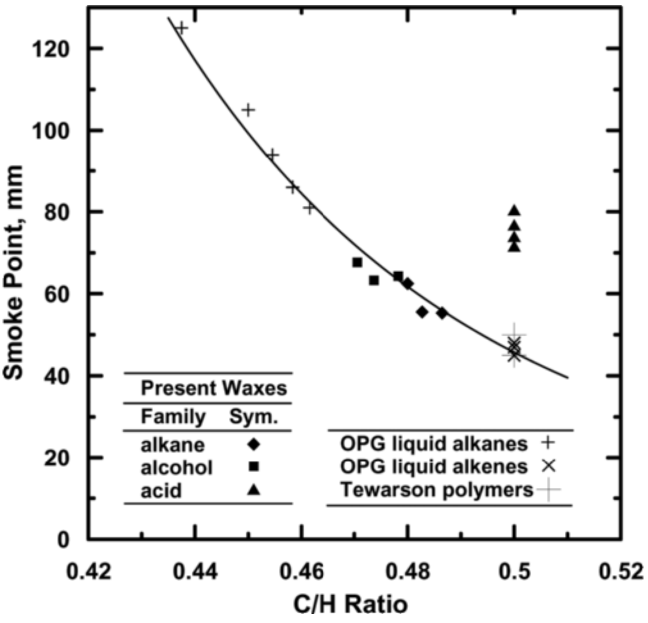


**Figure 5** Measured laminar smoke points versus fuel C/H ratio. Values for waxes are interpolated to a wick diameter of 4.5 mm. Values for liquids come from OPG (Olson et al., 1985) and involve a wick diameter of approximately 5.5 mm. Values for alkane polymers come from Tewarson (1986). The least-squares fit is for all measurements except the acids and has the equation $y = 0.279x^{-7.36}$.

number approaches zero, which facilitates a single correlation of both the liquid and wax alkane smoke points.

The alkanes, alkenes, alcohols, and acids in Figure 5 have C/H ratios of $n/(2n+2)$, 0.5, $n/(2n+2)$, and 0.5, respectively, where $n$ is carbon number. For a given carbon number, alcohols and alkanes have identical C/H ratios and similar smoke points, and thus are correlated by the same fit. The curve fit in Figure 5 also captures the increased C/H ratio and decreased smoke points of liquid alkenes. The acids, with their low sooting propensities and high C/H ratios, are not correlated by this fit. The C-O double bond in each acid molecule increases C/H ratio and moves acids well to the right of the fit in Figure 5.

While the smoke-point trends observed for waxes arise largely from gas-phase processes, they also may be associated with liquid properties such as melting point, boiling point, viscosity, and surface tension. These complex aspects of wick-fed flames are not present in gas-jet flames. Thus, the present findings are most relevant to the burning of waxes in candles and may require further confirmation before they are applied to other flame systems such as pool fires.

## CONCLUSIONS

Laminar smoke points of 14 waxes were measured in candles burning in quiescent air. Wick diameters were 1.7–7.3 mm. These are the first measurements of smoke points or other sooting propensities of candles, waxes, alcohols, or acids. This study increases from 6 to 20 the number of compounds that are solid at room temperature and for which smoke points are available and extends to 36 the fuel carbon number for which sooting propensities are available. This work has led to the following conclusions:

- Candle smoke points increase with wick diameter and, for the fuels and wicks considered, vary from 37–89 mm. It is important to include wick diameter and length when reporting smoke points of wick-fed flames.
- Smoke points could not be obtained for any wax with wick diameters less than 1.7 mm or wick lengths shorter than 5.9 mm. Candles with larger wick diameters require shorter wick trimming to prevent soot emission.
- When interpolated to 4.5 mm diameter wicks, the present smoke points were found to increase from commercial waxes to alkanes to alcohols to acids and to vary from 41–80 mm. For the common candle waxes, it was found that paraffin and beeswax had high sooting propensities and stearic acid had a low sooting propensity.
- Smoke points of the present waxes were found to be correlated with carbon number and to decrease with increasing carbon number.
- C/H ratio was found to accurately correlate the smoke points of alkane and alcohol waxes, alkane and alkene liquids, and alkane polymers. Smoke points for these fuels decreased with increasing C/H ratio. Smoke points of carboxylic acids were not correlated by C/H ratio.

These findings are significant for their importance in the manufacture of cleaner burning candles and for revealing the importance of considering wick diameter and length effects during testing of smoke points of liquid fuels such as aviation fuel.

## REFERENCES

Aksit, I.M., and Moss, J.B. 2005. Model fuels to reproduce the sooting behaviour of aviation kerosene. *Fuel*, **84**, 239.

Alsairafi, A., Lee, S.-T., and T'ien, J.S. 2004. Modeling gravity effect on diffusion flames stabilized around a cylindrical wick saturated with liquid fuel. *Combust. Sci. Technol.*, **176**, 2165.

ASTM. 2002. Standard test method for smoke point of kerosine and aviation turbine fuel. Standard D1322. ASTM International, West Conshohocken, Pa., pp. 527–533.

ASTM. 2003. Standard specification for aviation turbine fuels. Standard D1655. ASTM International, West Conshohocken, Pa., pp. 614–619.

Berry, T.L., and Roberts, W.L. 2006. Measurement of smoke point in velocity-matched coflow laminar diffusion flames with pure fuels at elevated pressures. *Combust. Flame*, **145**, 571.

Calcote, H.F., and Manos, M. 1983. Effect of molecular structure on incipient soot formation. *Combust. Flame*, **49**, 289.

de Ris, J., and Cheng, X.-F. 1994. The role of smoke-point in material flammability testing. *Fire Safety Science, Proceedings of the Fourth International Symposium*, 301.

Dietrich, D.L., Ross, H.D., Shu, Y., Chang, P., and T'ien, J.S. 2000. Candle flames in non-buoyant atmospheres. *Combust. Sci. Technol.*, **156**, 1.

Fine, P.M., Cass, G.R., and Simoneit, B.R.T. 1999. Characterization of fine particle emissions from burning church candles. *Environ. Sci. Technol.*, **33**, 2352.

Glassman, I. 1988. Soot formation in combustion processes. *Proc. Combust. Instit.*, **22**, 295.

Gülder, Ö.L. 1989. Influence of hydrocarbon fuel structural constitution and flame temperature on soot formation in laminar diffusion flames. *Combust. Flame*, **78**, 179.

Hamins, A., Bundy, M., and Dillon, S.E. 2005. Characterization of candle flames. *J. Fire Prot. Eng.*, **15**, 265.

Huynh, C.K., Savolainen, H., Vu-Duc, T., Guillemin, M., and Iselin, F. 1991. Impact of thermal proofing of a church on its indoor air quality: The combustion of candles and incense as a source of pollution. *Sci. Tot. Environ.*, **102**, 241.

Kent, J.H. 1987. Turbulent diffusion flame sooting-relationship to smoke-point tests. *Combust. Flame*, **67**, 223.

Kewley, J., and Jackson, J.S. 1927. The burning of mineral oils in wick-fed lamps. *J. Instit. Petrol. Technol.*, **13**, 364.

Lautenberger, C.W., de Ris, J.L., Dembsey, N.A., Barnett, J.R., and Baum, H.R. 2005. A simplified model for soot formation and oxidation in CFD simulation of non-premixed hydrocarbon flames. *Fire Safety J.*, **40**, 141.

Lide, D.R. (Ed.) 2007. *CRC Handbook of Chemistry and Physics*, CRC Press, New York, pp. 3-224–3-472.

Lin, K.-C., Faeth, G.M., Sunderland, P.B., Urban, D.L., and Yuan, Z.-G. 1999. Shapes of nonbuoyant round luminous hydrocarbon/air laminar jet diffusion flames. *Combust. Flame*, **116**, 415.

Markstein, G.H. 1984. Relationship between smoke point and radiant emission from buoyant turbulent and laminar diffusion flames. *Proc. Combust. Inst.*, **20**, 1055.

Markstein, G.H. 1986. Radiant emission and smoke points for laminar diffusion flames of fuel mixtures. *Proc. Combust. Inst.*, **21**, 1107.

Marsh, N.D., Preciado, I., Eddings, E.G., Sarofim, A.F., Palotas, A.B., and Robertson, J.D. 2007. Evaluation of organometallic fuel additives for soot suppression. *Combust. Sci. Technol.*, **179**, 987.

McEnally, C.S., and Pfefferle, L.D. 2007. Improved sooting tendency measurements for aromatic hydrocarbons and their implications for naphthalene formation pathways. *Combust. Flame*, **148**, 210.

National Candle Association. 2007. http://www.candles.org

Olson, D.B., Pickens, J.C., and Gill, R.J. 1985. The effects of molecular structure on soot formation II. Diffusion flames. *Combust. Flame*, **62**, 43.

Raju, M.P., and T'ien, J.S. 2008. Development of direct multifrontal solvers for combustion problems. *Numerical Heat Transfer B*, **53**, 189.

Rakowsky, F.W., and Hunt, R.A., Jr. 1956. Variables in lamp design that affect smoke point. *Anal. Chem.*, **28**, 1583.

Reed, R.J. (Ed.). 1997. *North American Combustion Handbook*, North American Mfg. Co., Cleveland, Ohio, p. 285.

Schalla, R.L., and McDonald, G.E. 1955. Mechanism of smoke formation in diffusion flames. *Proc. Combust. Inst.*, **5**, 316.

Schug, K.P., Manheimer-Timat, Y., Yaccarino, P., and Glassman, I. 1980. Sooting behavior of gaseous hydrocarbon diffusion flames and the influence of additives. *Combust. Sci. Technol.*, **22**, 235.

Sigma-Aldrich. 2007. http://www.sigmaaldrich.com

Singh, J., Patterson, R.I.A., Kraft, M., and Wang, H. 2006. Numerical simulation and sensitivity analysis of detailed soot particle size distribution in laminar premixed ethylene flames. *Combust. Flame*, **145**, 117.

Smooke, M.D., Long, M.B., Connelly, B.C., Colket, M.B., and Hall, R.J. 2005. Soot formation in laminar diffusion flames. *Combust. Flame*, **143**, 613.

Speight, J.G. (Ed.). 2005. *Lange's Handbook of Chemistry*, McGraw-Hill, New York, pp. 2.162–2.233.

Sunderland, P.B., Mortazavi, S., Faeth, G.M., and Urban, D.L. 1994. Laminar smoke points of nonbuoyant jet diffusion flames. *Combust. Flame*, **96**, 97.

Takahashi, F. 2009. Candle and jet diffusion flames: Mechanisms of combustion under gravity and microgravity conditions. In Jarosinski, J., and Veyssiere, B. (Eds.), *Combustion Phenomena: Selected Mechanisms of Flame Formation, Propagation and Extinction*. Boca Raton, Fla.: Taylor and Francis, pp. 170–177.

Takahashi, F., and Glassman, I. 1984. Sooting correlations for premixed flames. *Combust. Sci. Technol.*, **37**, 1.

Tejada, C. 1999, March 31. Incensed by soot: Decorative candles ignite a crusade. *Wall Street Journal*, p. 1.

Tewarson, A. 1986. Prediction of fire properties of materials, part 1: Aliphatic and aromatic hydrocarbons and related polymers. NIST Report GCR-86-521.

Urban, D.L., Yuan, Z.-G., Sunderland, P.B., Lin, K.-C., Dai, Z., and Faeth, G.M. 2000. Smoke-point properties of non-buoyant round laminar jet diffusion flames. *Proc. Combust. Instit.*, **28**, 1965.

Yan, S., Eddings, E.G., Palotas, A.B., Pugmire, R.J., and Sarofim, A.F. 2005. Prediction of sooting tendency for hydrocarbon liquids in diffusion flames. *Energy and Fuels*, **19**, 2408.

Yang, Y., Boehman, A.L., and Santoro, R.J. 2007. A study of jet fuel sooting tendency using the threshold sooting index (TSI) method. *Combust Flame*, **149**, 191.