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Titel: Measuring light intensity of candles of various compositions

Keywords: Candle, burning, light intensity, brightness

Summary

The aim was to determine the light intensity emitted by candles made of paraffin, beeswax, fat and stearic acid.

In order to be able to reach a conclusion regarding how effectively combustion occurs with these different candle materials, an apparatus was developed which allowed wax consumption rates and light intensity to be determined simultaneously. The relationship between these two factors (light intensity/wax consumption) can be used to provide a unit of measurement for the effectiveness of the transformation of chemical energy into light.

A comparison of averages of (specific) light intensity obtained per gram of burning material shows that beeswax and paraffin display considerably higher values than fat and stearic acid.

An apparatus to determine the critical fuel flow (hourly consumption) will be presented.

1. The role of the candle in the history of light measurement

As can be seen from the measuring unit used to indicate light intensity, the candle played an important role in the development of photometry. In astronomy for example it was the light intensity of a candle which served as a reference to define the luminosity of celestial bodies.

A basic problem was how to define a generally valid standard of light intensity. It had to stem from a light source emitting a preferably white, constant light which in addition had to provide repeatable values. In reality, many different measurement units existed, which were based on the most widely available light source at the time – candles.

The "old light unit" represents one of the first attempts to define a basic unit of measurement. This was based on the light of a 42 mm high flame of a wax candle of which 6 pieces weighed one pound (500 g).

In 1868 the "Association of German Gas and Water Experts" [1] (Verein deutscher Gas- und Wasserfachmänner) defined a paraffin candle of 20 mm diameter with a flame height of 50 mm, as the underlying reference. This was called the "German Association Candle" ("Deutsche Vereinskerze"). As in the case of the "old light unit" the weight was again defined as 6 candles amounting to one pound.

Another simple measuring unit was the “Berlin candle”. This unit was defined as a whale oil or spermaceti candle, which burned with a consumption rate of 7.77 g per hour and with a flame height of 44.5 mm. Due to the good burning properties of this candle raw material obtained from sperm whales, a similar standard was used in England and the USA from 1860.[2]

All these units had the disadvantage that the light emission of the flickering candle was not constant and was additionally influenced by factors such as air pressure, moisture and wick condition. Furthermore, the stipulated flame height could only be regulated by trimming the wick. At the same time the demands on the light intensity norm increased constantly. Whereas in the middle of the 19th century various kinds of candles were used as light intensity references, better reproducible systems were developed as measuring devices became more precise and light source engineering more advanced.

The first repeatable system for measuring light intensity was constructed in 1884 by Friedrich-Alternak Hefner[3] and was based on the light intensity of a kerosene (petroleum) lamp fueled with isoamyl acetate. The wick was 8 mm in diameter and the flame height 40 mm. This system had the advantages, that the flame size could be regulated easily and that wax consumption was defined by the apparatus itself. Furthermore formulas existed by which the measured results could be adjusted to take air pressure and humidity variations into account. The so-called Hefner candle (1 HK = 0.903 cd) [4] was been used in Germany from 1896 [5] onwards and later also in Scandinavia and Austria as the legal standard and still serves today as a nostalgic measuring unit for gas and petroleum lamps.

At the same time the “international candle” was being used as the standard in England, France and the USA. This referred to a set of carefully selected carbon-fibre filament bulbs. Due to the poor repeatability of the lamps as well as the aging properties, this unit basis never became a true primary standard. It was only in the 1940s that the development of a true norm began, which was about to replace the light of a flame as the standard. The so-called “new candle” was introduced in 1948 and was based on the emitted light intensity of a black body. Today the unit Candela is defined as a monochromatic light source of 555 nm wavelengths and a radiancy level of 1/683 Watt per steradian.

2. Candle burning and light generation

Despite the possibilities of modern light sources, candles still enjoy enormous importance in todays society. Whether it be the romantic candle–lit dinner, afternoon tea- or coffee, the festively decorated birthday table or the relaxed atmosphere of a summer evening - candles play a significant role. For such occasions candles are expected to burn with a bright flame and without visible smoke. For illumination purposes the intensity of a light source is naturally a decisive factor. Surprisingly little attention is normally paid to the light intensity of candles although this would surely be an important product characteristic.

What does the light intensity of a candle depend on? How do the types of burning materials and wax consumption per hour influence the brightness of the candle flame?

During the development of new candles the wick is carefully selected to fit the candle material and diameter. Wicks are braided in such a way that they exhibit a natural curve during burning. Thus, the tip of the wick is located in the hot border zone of the candle flame, where it can be burned away. In this way the wick regulates its length and a uniform burning behaviour can be expected. Furthermore self-trimming of the wick helps to avoid carbon deposit formation at the wick tip. Figure 1 shows the various zones of a candle flame.

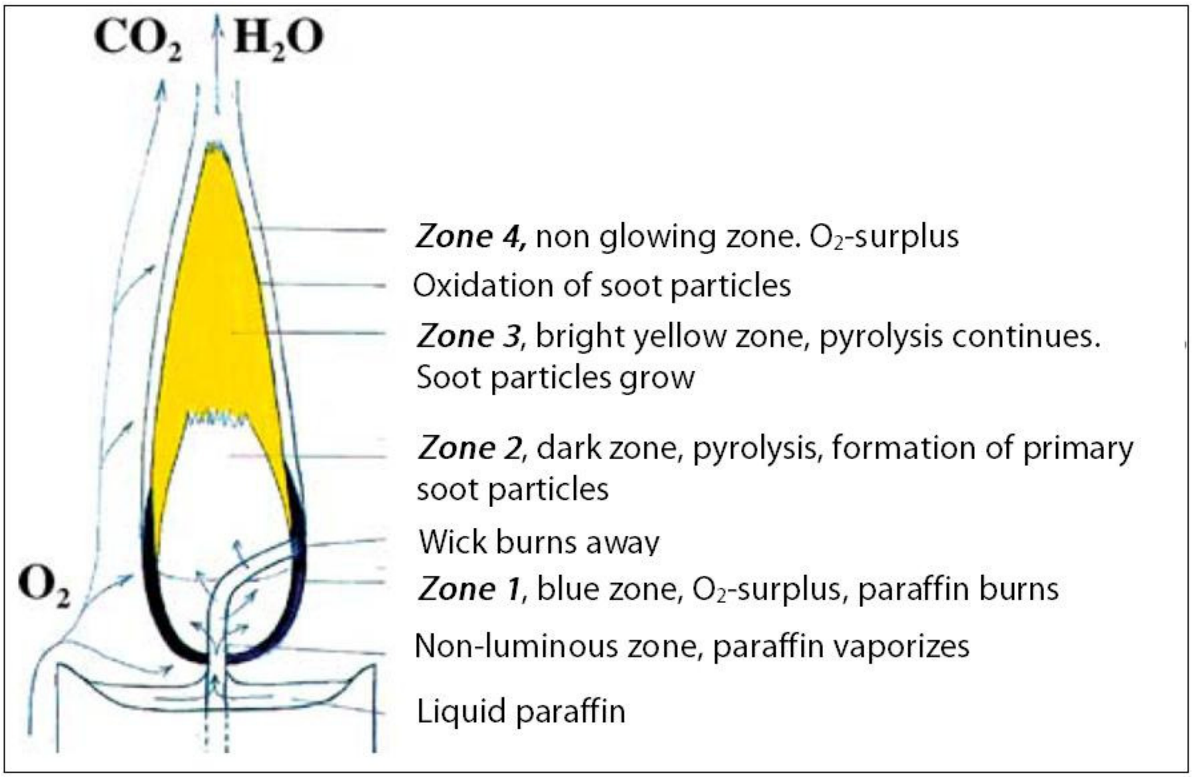

Figure 1: Zones of a candle flame [6]

Vegetable and animal fat, stearic acid, beeswax and paraffin are the main raw materials of the candle industry today. Decisive criteria for their usage are availability, price, as well as suitability for use on existing production lines. Due to good availability and universal applicability paraffin is used in 78 % of all candles. Levels for hardened vegetable or animal fats amount to approx. 12 %, stearic acid to approx. 8 % and beeswax to around 2 % (see figure 2).

Beeswax is secreted in platelet form by bees and obtains its yellow colour from the dye carotene, which is found in pollen. As a further alternative candle material, fat deserves a mention. It consists of hardened palm oil and is used due to its good fragrance binding capability in scented candle production.

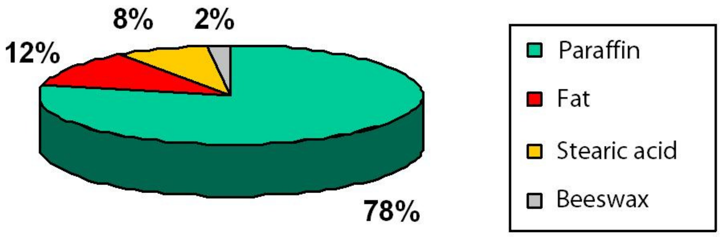

Figure 2: Proportion of different wax types used in candle production [7]

Candles made of paraffin, stearic acid, beeswax and fat with a diameter of 70 mm were tested. These candles have the advantage that the melting sphere remains within the overall diameter of the candle during burning, and so dripping which would influence the flame size does not occur. It is clear, that the light intensity of a candle depends fundamentally upon the flame size. The flame size itself is determined mainly by the amount of wax which is consumed per hour. This "hourly consumption" is basically determined by the thickness or diameter of the wick. The candles under test were produced with three different wick thicknesses per material type to allow different hourly consumption rates and flame sizes to be investigated.

For a better understanding of the parameters influencing the light generated by candles, a test apparatus for light intensity measurement was developed, taking the particular circumstances surrounding candle burning into account .

3. Basics of light measurement

Light intensity is a photometric property of a light source and specifies the emitted beam power per dihedral angle. Photometric units are based on the luminosity impression of a radiation source on the human eye, which can sense radiation (light) in the wavelength region of approx. 400 nm to 700 nm [8]. The luminosity impression not only depends on the intensity of the source but on the spectral composition as well. For example blue and red parts of light are perceived less intensively than green ones. In order to quantify the impression of a light source on the human eye and to be able to compare it, radiometric units (beam intensity) are weighted with the sensitivity curve of the eye for daylight vision (V-Lambda curve). In Figure 3 the sensitivity curves of the human eye for daylight and night vision are depicted. With appropriate filters, the photometric measuring devices are adapted to the wavelength sensitivity of the human eye.

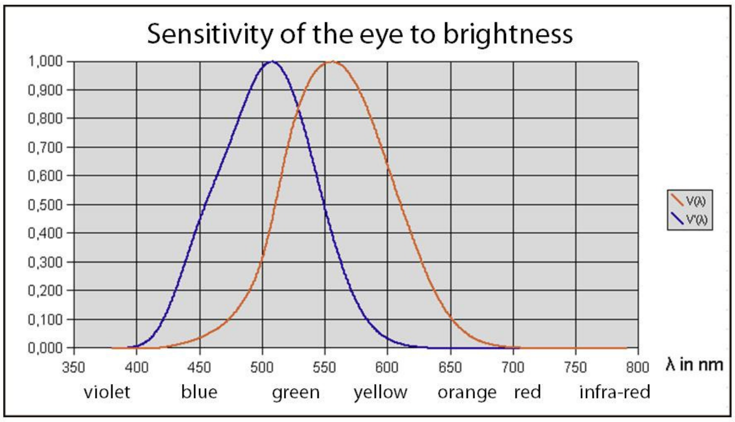

Figure 3: Sensitivity curve of a normal sighted person by day (orange) and by night (blue)[9]

Light intensity cannot be measured directly. Normally it is detected via light irradiation by means of the photometric distance law, which is given by the following equation:

$$I = E \,.\, r^2 \,.\, \cos \beta$$

Light intensity (I) is therefore dependent upon the irradiation strength (E) of the light to be measured, the distance (r) of the sensor from the source and the incidence angle (β). The level of irradiation can be directly detected with a luxmeter. For this it is assumed that a central light source emitting homogeneously in all directions is present. Real light sources however with their spatial diffusion properties cause errors which have to be taken into consideration. By increasing the distance between the light source and the sensor, real light sources can come reasonably close to the ideal source. The extent to which the accepted error is within the allowed error range is called the photometric limiting distance. This is light source dependent and is normally detected empirically. In reality the distance should be at least tenfold the largest expansion of the light source.

4. Tasks

4.1 Test apparatus and procedure

To draw a conclusion concerning the efficiency of the combustion of different wax types, a measuring apparatus was developed enabling wax consumption and light intensity to be detected simultaneously. From the ratio (light intensity/wax consumption), the efficiency of the transformation of chemical energy into light can be measured.

During the selection of a measuring system, care had to be taken to consider the special properties of the candle providing the light source . Apart from heat and soot production these are – in comparison to an electrical light source - especially the fluctuating light levels and the necessity to supply a sufficient and draft-free air flow. Particular attention had to be paid to the last point. On the one hand an oxygen deficit in the flame can lead to incomplete combustion and thereby to production of soot, on the other hand convection draughts can cause turbulence leading to flickering of the flame. Strong air currents can furthermore cool the flame down to such an extent that the complex combustion process is disturbed and carbon particles (soot) can escape un-combusted from the flame.

To fulfil the requirements for measuring the burning behaviour of a candle as far as possible, it was decided to use a luxmeter to help estimate light intensity. This calculates light intensity on the basis of the photometric distance law. The distance between the sensor and the candle flame was chosen to be in the range of 55 cm to 65 cm, to fulfil the limiting distance for all flame sizes occurring. Furthermore the sensor of the measuring device was shielded from the ambient light, the incident angle was restricted to 14 degrees. To adjust the measuring field of the sensor exactly, the apparatus was equipped with a sighting laser. To compensate the natural fluctuations of the flame, filtering and averaging procedures were incorporated into the software. The installation of a second luxmeter permitted the detection and subsequent elimination of ambient light fluctuations from the equation. For this purpose the sensor of the second measuring device was adjusted in such a manner that it only detected ambient light without registering light emitted from the candle.

Other devices for the determination of light intensity such as the integrating sphere (Ulbricht Kugel) or the gonio-photometer have only very limited use for the measurement of candles due to their form. The measurement with the integrating sphere has the advantage that the inhomogeneous character of the candle is taken into consideration, but the closed apparatus creates problems with air supply. Furthermore soot particles could decrease the reflecting properties of the integrating sphere and thereby create a high measuring error. The gonio-photometer offers a more open solution. But in order to conduct the measurement with this device it is necessary to fix the light emitter in the centre of the measuring device. The flame of the candle however represents a “living” light source, which is in constant movement due to air currents etc . This movement results therefore in an inaccurate defective light distribution curve, from which no significant result for the average light intensity can be deduced. Apart from this, the gonio-photometer does not allow for continuous measuring value detection. Furthermore the measuring procedure with this device for this type of application would be prohibitively time consuming.

For the calculation of wax consumption, highly sensitive electronic scales (d = 10 mg) were used. From the continuously decreasing weight values, the wax consumption differential was calculated (ascent).

The detected values were further processed with specially developed software (based on Labview) on a PC. This collects, processes and logs data.

The whole system used for the tests is schematically depicted in Figure 4.

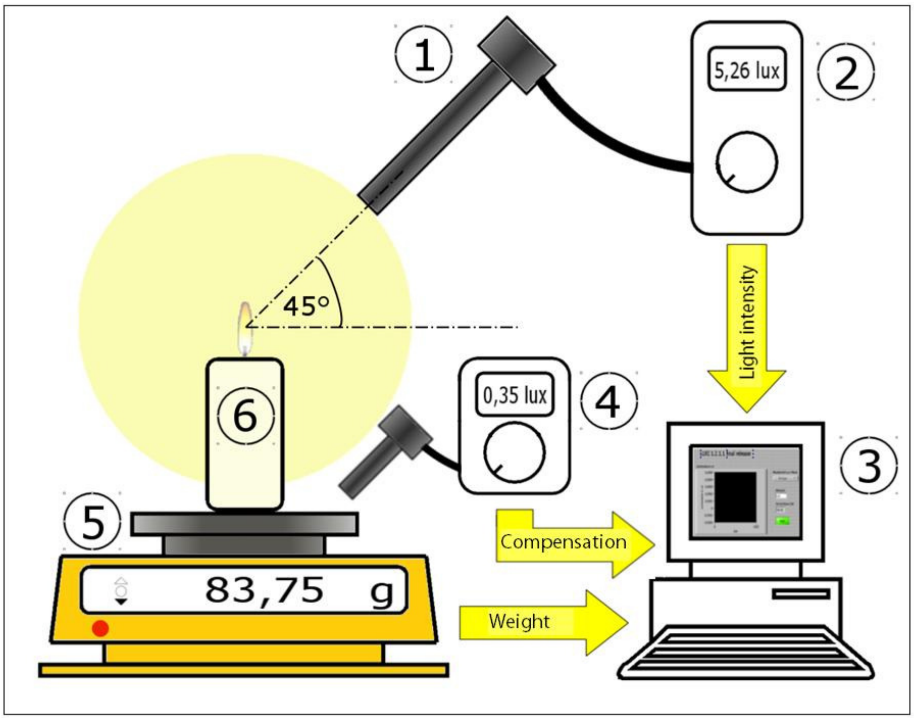

Figure 4: Sketch to show the principle of a testing apparatus comprising a light sensor with shutter (1) Luxmeter (2), PC with processing software (3), Luxmeter to compensate for ambient light (4), scales (5) and candle (6)

The wick plays a central role in the transformation of chemical energy into light energy; therefore the consistency of the wick was checked before every measurement with respect to damage and contamination e. g. carbon deposit formation. When this was clarified, the candle was ignited and after a burn-in phase of 15 minutes positioned in the apparatus. To avoid a shielding of the flame light and a deterioration of the air circulation, the candles rim was removed before starting the measurement. Within the framework of the test at least 5 sets of measurements were gathered for each combination of wax and wick type. From these the average values were calculated. The measuring duration after the burn-in phase amounted to approx. 10 to 20 minutes.

4.2 Data analysis

To display the relationship between emitted light intensity and wax consumption, the quotient of both values was depicted on the time line (Figure 5). It is obvious that this value fluctuates over time around a constant value and hence a clear coherence exists between wax consumption and intensity of light emitted .

This quotient can be interpreted as showing the efficiency of the transformation of wax into visible light. After the burn-in phase, this depends on the type of wax selected as well as on wick diameter and therefore in turn on wax consumption . The relatively constant values show, that the candle, often described as “living” still yields stable values on average . The results obtained show a standard deviation of approx. 5 %.

The graph of light intensity over time shows if the burn-in phase has been completed and if a more or less stationary state has been reached during which error free data collection is possible. It is from this data obtained from a series of tests that the average light intensity, wax consumption and efficiency was calculated. The results of the various tests are summarized in Table 1 with sorted according to material type and wick size. Each value was calculated by taking the average of at least five recorded measurements.

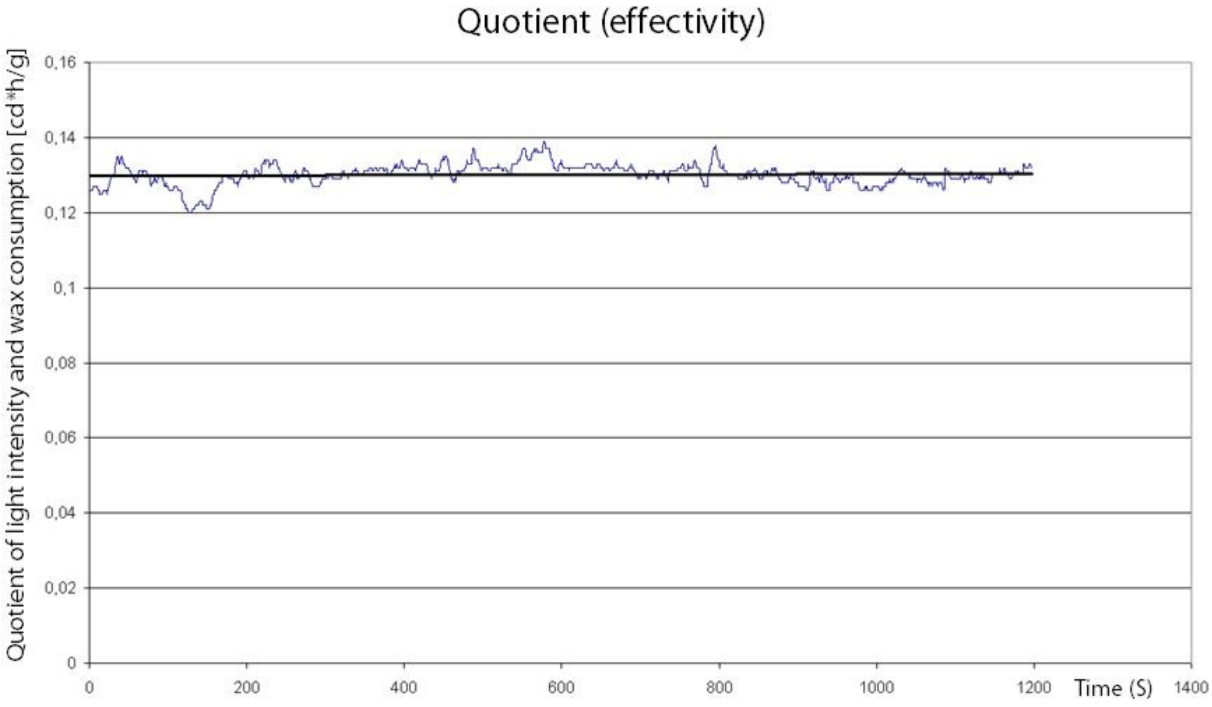

Figure 5: Progression of the quotients of light intensity to wax consumption – stearic acid, large wick

Table 1: Overview of candle parameters obtained

	Beeswax		
	small	medium	large
Wax Consumption (g/h)	4,740	6,630	7,890
Light Intensity (cd)	0,72	1,253	1,299
Light Intensity / Wax Consumption (cd*h/g)	0,152	0,189	0,165
	Fat		
	small	medium	large
Wax Consumption (g/h)	3,780	5,610	6,960
Light Intensity (cd)	0,562	0,939	1,061
Light Intensity / Wax Consumption (cd*h/g)	0,149	0,167	0,152
	Paraffin		
	small	medium	large
Wax Consumption (g/h)	2,590	4,380	6,184
Light Intensity (cd)	0,429	0,817	1,096
Light Intensity / Wax Consumption (cd*h/g)	0,189	0,187	0,177
	Stearic acid		
	small	medium	large
Wax Consumption (g/h)	5,370	8,030	11,250
Light Intensity (cd)	0,661	1,191	1,416
Light Intensity / Wax Consumption (cd*h/g)	0,123	0,148	0,126

As expected, wax consumption and therefore light intensity rises with increasing wick diameter. When we examine the quotient of light intensity and wax consumption however, there is no direct relationship to wick size. In order to determine this relationship, the values in the table were augmented by intermediate values which were determined by considering variations in wick length.

In the graph Figure 6 the values for the quotients thus obtained are depicted according to wax consumption .

A comparison of the middle value ranges of candle flame light intensity per gram of combustible material demonstrates that beeswax and paraffin have 8 % and 39 % higher values than fat and stearic acid.

Every wax type has its own specific parabolic curve which represents the dependence of burning efficiency on wax consumption. The depicted dependencies have been approximated by quadratic regression to the sets of values. The resulting standard deviations of the values of the regression function are summarized in Table 2 and fluctuate according to wax type between 2.8 % and 5.4 %. These deviations can be attributed mainly to ambient influences as well as different wick stances.

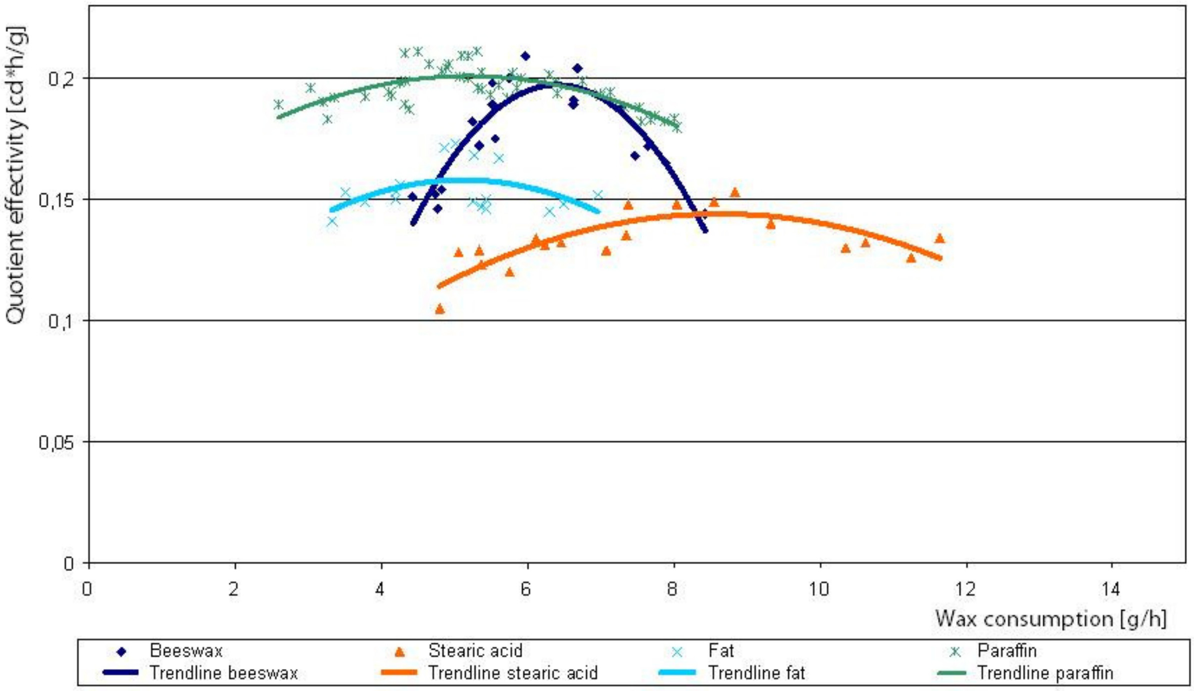

Figure 6: Effectivity of combustion in relation to wax consumption

Table 2:

Wachstype	Standard deviation
Beeswax	4,9%
Stearic acid	5,1%
Fat	5,4%
Paraffin	2,8%

Lower consumption rates result in a smaller quotient as can be seen in the diagram. This means that with smaller flames, less of the energy stored in the combustible material is transformed into visible light. This suggests that the size of the illuminating part of the flame does not increase at the same rate as the overall flame size when wax consumption increases. If we observe a candle flame, we see that the emitted light is produced in the inner part of the flame. This region is surrounded by a burning cone which is only weakly luminescent and in which soot particles and hydrocarbons are oxidized and transformed into heat. The thickness of this region is all but independent of the flame size and mainly determined by the diffusion rate of the oxygen entering the flame. Therefore this area makes up a larger part of total flame volume in small flames in comparison to large flames. Thus with increasing flame size the part of the flame which emits visible light increases.

As wax consumption increases and flames become larger, the surface/volume ratio of the flame decreases . The amount of oxygen entering the flame by diffusion and therefore the amount of energy released by the combustion process does not increase at the same rate as flame volume. The result is a decrease in flame temperature.

The emitted light of a flame is produced by hot soot particles glowing in the flame core. Therefore as the temperature falls, the energy of the single particles decreases as well. They behave like a “black body” and emit a temperature dependent light spectrum. The position of the emission maximum is, as can be seen in Equation 1, dependent on the temperature and given by “Wien’s Displacement Law”.

$$\lambda_{max} = 2897.8 / T \, [\mu mK]$$

λmax = Wavelength of the emission maximum

Equation 1: Wien’s Displacement Law

Through a decrease in flame temperature the emission spectrum of these particles is shifted from the visible to the non-visible infrared light spectrum. Hence a smaller part of the consumed energy is transformed into visible light and the quotient decreases.

Furthermore a lower flame temperature causes incomplete combustion and portions of the soot particles are not fully combusted and therefore combustible material is lost as soot .

The corresponding maximum of the curves determines the most effective combustion point, in which none of the processes mentioned before has the upper hand. At this point the combustible material is transformed into visible light most efficiently.

From the curve progression further information can be deduced. Flatter curves indicate only a small sooting tendency. This allows candle manufacturers to adjust hourly consumption rates over a wide range without creating visible soot. With more pronounced curves this range is much smaller.

5. Outlook

As seen from the data analysis, many important parameters of candle combustion can be deduced with this simple and practical apparatus. The data can be used to improve burning properties. To improve the precision and the relevance of measurements still further, an optimized apparatus as shown in Figure 7 is planned. As opposed to the previous apparatus, the wax is kept liquid during the measurement and the cotton wick is replaced by a glass fibre wick. Such wicks are height adjustable and permit a variable adjustment of the wax consumption. The improved apparatus therefore facilitates a more efficient measuring procedure, because consumption can be changed independently of wick diameter. In this manner the time-consuming adjustment of intermediary consumptions by shortening the wick and the necessary burn-in phase of candles can be omitted. A further advantage could lie in the fact that this clearly defined burning apparatus would permit comparable testing parameters to be introduced. The constant wick parameter is expected to bring about a lower scattering of the measuring values. Additionally various wax types can be tested and compared with each other under the same burning conditions .

Besides the improvement of the above measurements, the apparatus can be used to measure another important candle parameter, namely “critical fuel flow” which indicates at which wax consumption the flame starts to soot. This is of fundamental importance particularly for the production of quality candles with low-emissions.

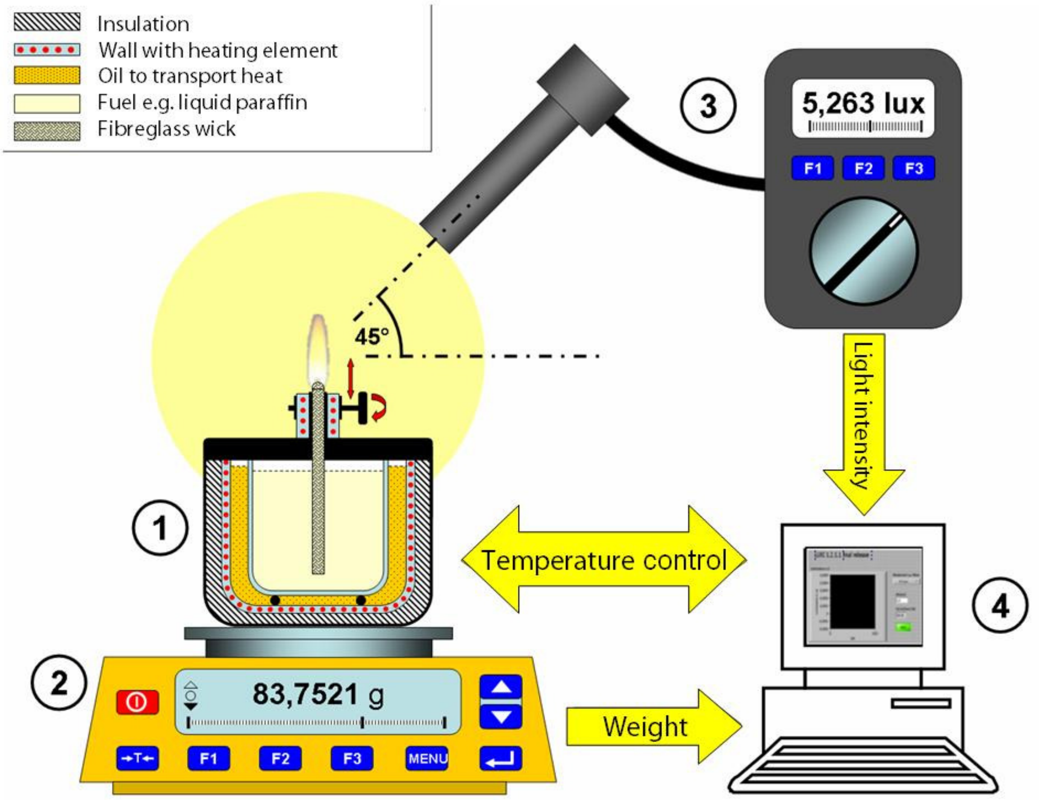

Figure 7: Sketch to show the principle of the improved measuring apparatus comprising a heated burner system (1), scales (2), luxmeter with sensor (3), PC with processing and control software (4)

Sources

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