Measurement of Luminaire Thermal Factor

A White Paper: A Study of F80TFHO Lamps

It is well known that fixtures using the T5 lamp can exhibit total photometric luminaire efficiencies in excess of 100%. The lumen output of T5 lamps is rated by the manufacturers at both 25°C and 35°C surrounding air temperatures. The lamp's maximum optical output occurs when the temperature of air surrounding the lamp cold spot is about 35°C.

Consider a one-lamp luminaire. Relative photometry of a luminaire measures a bare lamp, and a luminaire with the same lamp. The total photometric efficiency is, simplistically, the ratio of the total luminous flux of the luminaire containing a lamp to the total luminous flux of the same bare lamp. Measurements of relative photometry do not typically access temperatures internal to the luminaire, but rather control the ambient temperature of the room to be 25°C—for both the bare lamp and the luminaire measurements. Heat flow from the hot lamp within the luminaire to the cold room produces a steady-state temperature gradient. This temperature gradient causes the temperature environment internal to the luminaire to be different than the temperature environment external to the luminaire. The bare lamp, on the other hand, is completely immersed in the external environment. Thus, for a typical photometric measurement of a luminaire, the lamp within the luminaire is immersed in a different temperature than is the same lamp measured bare.

In discussing this thermal behavior, it is important to assess two different temperature measurements. The room temperature is the ambient temperature environment in which the luminaire (or bare lamp) is immersed. This is the temperature which an end-user would measure or specify. We typically speak of a room temperature of 25°C for fluorescent, though it may be much different for a target application.

The second temperature of importance is the ***lamp-surround temperature***. This is the temperature of the air surrounding the lamp cold spot. It corresponds to the manufacturers' published data of lumens vs. temperature (for example, footnote 4, p 5). The lamp-surround temperature results from the temperature gradient between the hot internals of the luminaire, and the external environment. It is, thus, always higher than or equal to room temperature. An example is shown in Figure 1, on page 2.

Finally, a ***thermal factor,*** $F_T(T)$, of a luminaire operating in an environment of some room temperature, T, may then be defined as the ratio of lumens of a lamp in the luminaire to lumens of the bare lamp at a room temperature of 25°C. That is, $F_T(T)$ = Lamp-Lumens $_{\text{luminaire}}$ (T) / Lamp-Lumens $_{\text{bare-lamp}}$ (25).

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The thermal factor is defined solely in terms of room temperature, which may be measured or specified by an end user or by a lighting designer. It is unique for each luminaire design, in that the relationship of lamp-surround temperature to room temperature is dependent on luminaire design and consequent heat flow. It is the lamp-surround temperature which more nearly controls the lumens produced by the lamp within the luminaire.

If, in relative photometry, a bare T5 or T5HO lamp is measured at a 25°C room temperature, the lamp-surround temperature is near 25°C. If the same lamp is then operating within a luminaire which produces a 35°C lamp-surround temperature (when the luminaire is immersed in a 25°C room temperature), the thermal factor of the system, FT(25°C), will exceed 1.0. That is, the lumens produced by the lamp within the luminaire will be greater than the lumens produced by the bare lamp because of the increased lamp-surround temperature.

As discussed below, the total photometric efficiency is the product of the optical efficiency of the luminaire, and the thermal factor of the luminaire. A luminaire designer should have tools to separate these effects as part of the design process. Since the luminaire efficiency depends, in part, on lamp-surround temperature, it is desirable to determine the degree of optimization of a design, considering the thermal characteristics of the lamp and the targeted lighting application. Thus, the luminaire designer should require the lamp to engage an optimum lamp-surround temperature within the luminaire for the target application room temperature – i.e., control the heat flow between the luminaire and the outside environment.

We utilize the F80T5HO lamp in a non-recessed 1-lamp luminaire. In addition to its high lumens/meter (about 10% more than F54T5HO), we note that economies may result with 5' or 10' fixtures, rather than the conventional 4' or 8' fixtures, which have their origin in grid ceilings.

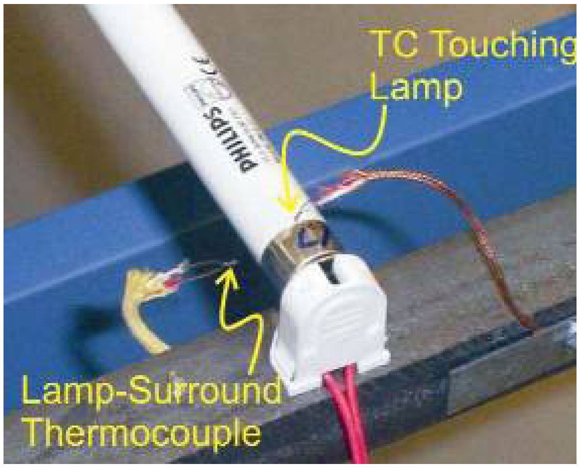

Figure 1 Thermalcouples on Bare Lamp

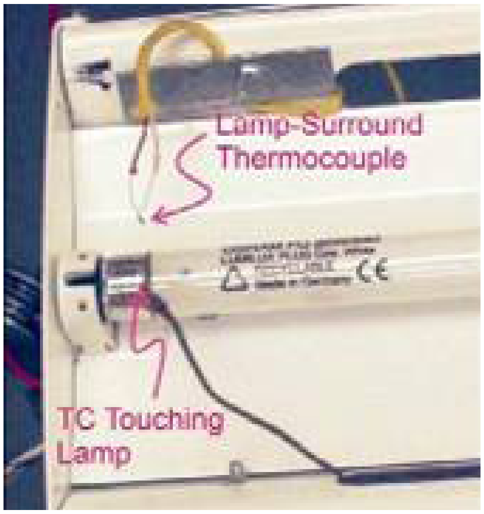

Figure 2 Thermalcouples on Luminaire Lamp

The thermal factor, FT(T), of a commercial luminaire (utilizing a F80T5HO lamp and commercial electronic ballast) is measured for various room temperatures, T. Presented for this range of room temperatures are relative lumen output measurements for the luminaire, as well as lamp-surround temperatures. As a baseline bare lamps are measured under identical conditions. Room temperatures range from 25°C to 50°C.

The bare lamp measurements presented here generally reflect published curves. Lumen and temperature measurements indicate the degree of optimization of the lamp-surround temperature within the commercial luminaire. This experimental technique enables a luminaire designer to determine the temperature near the lamp cold spot (lamp-surround temperature), and thus the thermal factor of the luminaire. Moreover, while lumens change predictably with temperature, the lumens per watt (LPW) is found to be relatively constant over a wide range of temperatures.

Experimental setup

The measurements were made in two 8'l x 8'w x 9'h thermal chambers, certified by UL for temperature control and proper air flow (less than 30 fpm at exit portals of 72 sq. ft.). Temperature control is a thermostatic contactor (not proportional control). Thermal measurements were made by three thermocouples. One was touching the lamp at the intersection of the metal cap and glass on the cold end. The second was in air about 9 mm from this point, perpendicular to the lamp axis (measuring the lamp-surround temperature). The third was in about 20 ml of mineral oil for the room temperature measurement. Thermal soak times were typically 25 minutes for a 2°C ambient temperature change. Time-temperature logs of all thermocouples show that equilibrium was reached after this time. Initial turn-on equilibrium occurred overnight for the lamp and fixtures. The thermocouple locations near the cold end of the lamp are shown in Figures 1 and 2 (on page 2).

Luminaires were suspended 4 feet from the floor—about half-way between floor and ceiling. The luminaires consisted of a 20" x 5' frame surrounding a bare lamp (Figure 3) and a commercial lighting fixture (Figure 4). In all cases, the lamps were horizontal. For each room temperature measured, three illuminance measurements were made on the floor using a Minolta T-1 meter: directly below either end of the lamp, and directly below the middle of the lamp. It is asserted here that these illuminance measurements are directly proportional to lamp lumens (for a given fixture), since all optical properties of the thermal chamber were constant. Reported relative lumens for a data set (lumens vs. temperature) are derived from the sum of these three illuminance measurements, normalized to 100%. Comparison of lumens between different lamps and fixtures was not performed.

Input VAW were measured with calibrated transducers, and automatically recorded, along with time and temperatures. High frequency lamp voltage, frequency, and current were hand-measured with a Fluke 8060a, and Pearson model 2877 current monitors.

Lamp Selection

Four lamps were chosen from a distribution of 32 lamps, 12 from type (CCT) 841 and 20 from 830, from two manufacturers. The lamps were aged and photometered for total flux and measured for input watts. The goal was to reject lamps on the extreme of the distribution. The estimated deviation of total input watts was less than 1W. The estimated deviation of LPW was 1 LPW for the 841 lamps, and 1.8 LPW for the 830 lamps. The average LPW and estimates of standard deviations were used to select two lamps from each manufacturer that was within 0.3 deviations of LPW from center. In both cases, lamps were chosen on both sides of center. These are labeled L830-4, L830-12, L841-1, and L841-11. Thus the matrix of data acquisition is four lamps each as bare lamp, and in the commercial luminaire. Two ballasts (Philip Advance Mark 7™ model VZT-180) were used with the dimming leads left open.

Figure 3

For each data point, the RMS lamp current and voltage was measured. The lamp current data are summarized here. These ballasts are nearly constant current devices relatively independent of temperature over the range of the experiment. They had a variation of <1% over all lamps for a lamp-surround temperature range of 28–57°C for the bare lamp, and a variation of <2% over all lamps for a lamp-surround temperature range of 31–60°C in the commercial luminaire. Ballasts were attached to the fixtures, and were not varied in temperature independently, nor were they swapped between luminaires.

Figure 4

Consistency checking

In acquiring data, it is desirable to examine consistency. Here, consistency is investigated between data sets, and with commercially published data by Philips Lighting Company (Footnote 4, p 5). In Figures 5 – 8 are line plots of relative lumens vs. lamp-surround temperature for each of the bare lamps, and for each of the lamps in the commercial fixtures. Also plotted is relative lamp voltage for the same lamps. While the match with published data (general T5/T5HO) data, not specific to F80T5/HO, is lss than perfect, the curves do indicate reasonable consistency.

It is noted that the thermocouples measuring lamp-surround temperature are in air, have minimal thermal capacity, and thus respond very quickly to minor fluctuations in air temperature. This is contrasted to the room temperature measurement, which is moderated by a small amount of mineral oil to add thermal capacity (UL specified). It is further noted that the thermal capacity of the lamp is considerably greater than that of the thermocouple, so that the thermocouple on the lamp responds less to minor fluctuations than does the thermocouple in air *near* the lamp.

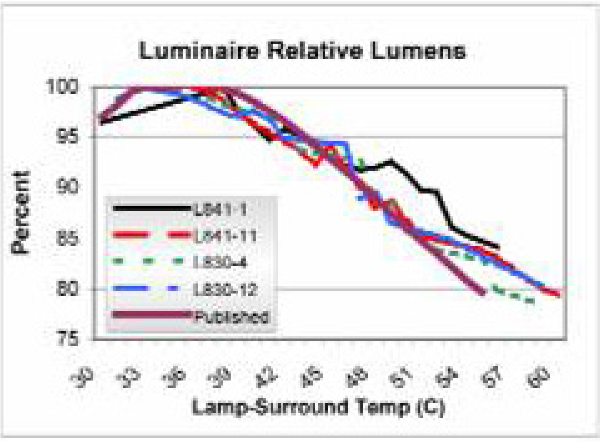

Figure 5

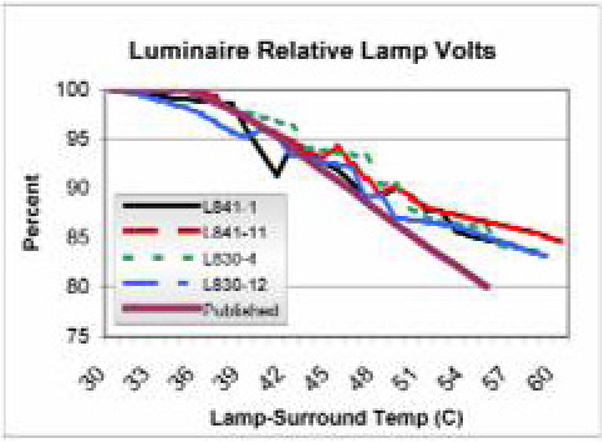

Figure 6

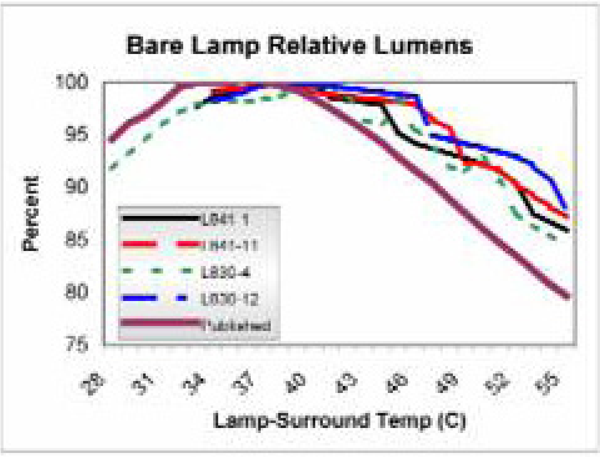

Figure 7

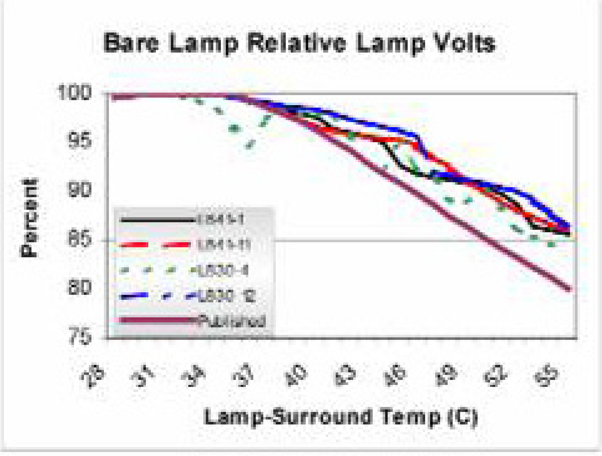

Figure 8

The lamp-surround temperature was 4.6°C 1.5°C above the room ambient for the bare lamp, and 7.2°C 1.8°C for the luminaire. These averages and deviations are over 50 data points for the bare lamp, and 50 for the luminaire. The measurement of this lamp-surround temperature was critical to correlating the data with manufacturers' published data. Zhang and Ngai[1] indicate a significant discrepancy with manufacturers' data, and attribute it to lamp orientation. The measurement of the lamp-surround temperature appears to alleviate this concern.

Another potential measurement point is the thermocouple on the glass, at the intersection of the glass tube and the cold end cap. The thermocouple is on the bottom of the tube (see Figures 1 and 2 on page 2). The thermal capacity of the glass is somewhat higher than air, so some thermal averaging should occur, giving more stability. This is attributed to the higher thermal capacity (and consequently less measurement noise) of the lamp glass. Moreover, this same averaging should affect the actual cold spot within the lamp. Philips has published[2] a curve for a temperature near this point. It shows lumen output vs. the temperature on the cap. This provisional publication is somewhat vague about where on the cap the temperature is measured. The thermocouple used here is at an easily repeatable place on the lamp to measure. Shown in Figure 5 and 7 is the relative lumen output of both the bare lamps and luminaires. The corresponding temperature differences between this thermocouple and room ambient was 6.5°C 1.0°C (bare lamp), and 12.8°C 1.2°C (luminaire).

Thermal Factor

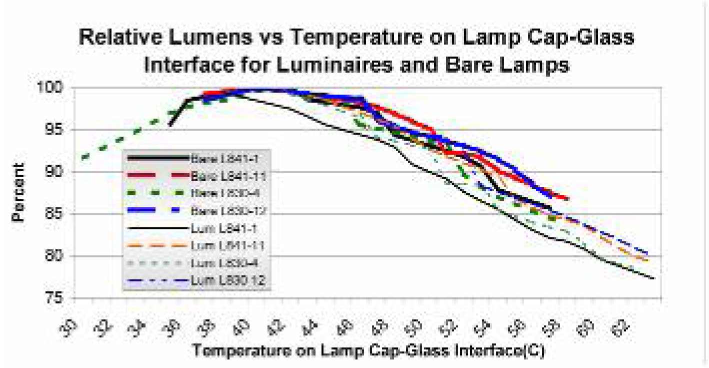

Figure 9

The Lumen output curve published[3] by Philips Lighting shows an increase of lumens of 13.8% (87.9% to 100% relative) between 25°C and 35°C for general T5 and T5HO. This is the published curve shown above in Figures 5 – 8. The product catalogs of Philips[4] and OSI[5] show an increase for the F80T5HO lamp from 6150 lumens at 25°C to 7000 lumens at 35°C (also 13.8%). These temperatures refer to the lamp-surround temperature, of course. Thus, knowing the lamp-surround temperature of a luminaire design at a particular room temperature, permits a designer to estimate this thermal factor. Moreover, the curves in Figures 5 – 8 indicate that a reasonable estimate of the thermal factor at a given room temperature may be made with a single lamp-surround temperature measurement in the luminaire, while referring to the published lumen-temperature curve. To estimate the thermal factor over a range of temperatures, only two measurements need be completed. Three measurements (an extra hour or two of lab time) yield not only the desired data, but a consistency measurement, as well. These measurements yield lumens vs. room temperature, as shown in Figure 10. Knowing the thermal factor can help us estimate the optical efficiency from a photometric test.

More specifically, the total luminaire efficiency, $E_L(T)$, is a product of the Thermal Factor, $F_T(T)$, and the temperature independent Optical Efficiency, E_O: $E_L(T) = F_T(T) \times E_O$, where T is room temperature. The total luminaire efficiency, EL(25C) is measured by photometry; and the thermal factor, FT(25C), may be measured as demonstrated above. Thus the optical efficiency, EO, may be determined.

$$E_O = E_L(25C) / F_T(25C).$$

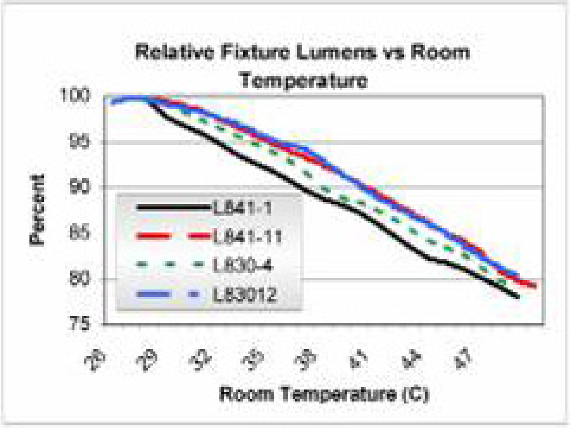

Figure 10

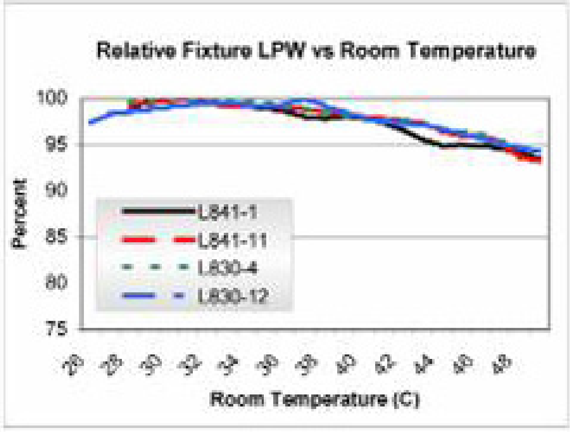

Figure 11

For example, the luminaire used here has a total photometric test efficiency, E_L(25°C), of 107%[6], including optical efficiency, E_O, and thermal factor, FT(25°C). From Figure 10 in the previous page, we can estimate the lamp-surround temperature in the luminaire to be optimum at approximately 27-28°C room ambient. From the published curve noted above in Figure 5 (and in footnote 4, p. 7), at 2-3 degrees below optimum, the lamp will produce 99.5% of the 7000 lumens (6965 lumens). The 25°C bare lamp, according to the manufacturers, produces 6150-6160 lumens. Thus, the thermal factor (FT) of the fixture is about 1.13 (6965/6160). If the total photometric efficiency, E_L(25C) is 107%, then the optical efficiency, E_O, is about 1.07 / 1.13 = 94-95%, quite a reasonable number for an optical system with a single exposed lamp and with high reflectivity paint.

Customer-oriented Data

In an application, our customers don't care what temperatures we measure near the lamp. At most, they care about room ambient. We may have an idea of ambient room temperature, though it is rarely known accurately, and rarely is it constant over the seasons. And so, it is desirable to know performance of the luminaire in various room temperatures. For commercial fixtures, the temperatures of importance are typically 25-30°C. For industrial fixtures, it is, of course, a wider range.

Figure 10 shows relative lumens for this commercial fixture in varying room temperatures. As expected, the lumens fall as temperature increases past 28°C. That is, the design of this commercial luminaire is optimized for 25-30° ambient temperatures. In this case, the optimum is 27-28°C, with a typical deviation of 2% over 25-30°C. However, even at 35°C ambient temperatures, the lumen output is 95% of optimum.

Figure 11 shows LPW for varying room temperatures. For customers who are sufficiently sophisticated to realize that lumen output decreases with increasing room ambient, then a key question becomes the cost of light vs. temperature. Does the cost of power for lighting increase when the room ambient is too high?

For this luminaire and ballast, although the light output at, say, 40°C is only 90% of optimum, the LPW at 40°C is 98% of optimum. That is, the light output falls10% at 40°C, but so does the input power. Only the power for the light actually delivered (within 2%) is billed by the power company. The ballast delivers essentially constant lamp current. It is the decreasing lamp voltage (as temperature increases) that is the major cause of the lower lumen output. The lumen efficacy of the lamp over this temperature range is not decreasing substantially, permitting LPW to remain approximately constant.

Conclusions

The thermal factor of a luminaire can be measured quite simply, by noting the air temperature near the lamp cold spot. This permits a luminaire designer to separately consider thermal factor and optical efficiency. A somewhat more stable temperature measurement point is on the lamp glass at the intersection of the glass tube and the metal end cap, but manufacturers' data is not published for this point. The lamp manufacturers should consider adding such data to their technical publications to facilitate T5 luminaire design.

Even when a luminaire is in an ambient above the normal optimum, the efficacy (LPW) of the system may remain approximately constant, thereby dropping input wattage as ambient temperature increases and lumen output decreases.

The thermal factor, FT(T), should be applied as a light loss factor to lighting designs where the application conditions imply an ambient different than 25°C. (Recall that luminaire photometry occurs at 25°C.) Since this thermal factor is unique for each luminaire design, it is incumbent upon luminaire manufacturers to publish thermal factors at various temperatures for their products.

Footnotes

[1] Photometry for T5 High-Output Lamps and Luminaires, John Zhang and Peter Ngai, Journal of the illuminating Engineering Society, Winter 2002, pp136ff.

[2] Philips MASTER TL5 lamps, Oct 2002, p 5 *(Provisional publication)*.

[3] Silhouette T5, T5HO, and T5 Circular Fluorescent Lamp Technology Guide, Sep, 2001, p12.

[4] Philips Lighting Company Lamp Specification & Application Guide, 2001.2002, p 63.

[5] Sylvania Lamp & Ballast Product Catalog 2002, p112.

[6] Day-Brite Lighting (Genlyte Thomas Group) NVLAP accredited photometric laboratory 200016-0.

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Form No. WP-8050-R02 07/09

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