Design Principle Study of High Efficiency Compact Fluorescent Lamps

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Abstract—Design rules for small power T2 and T3 compact fluorescent lamps (CFLs) with power ranging from 5 to 23 W were investigated to develop high efficiency lamps. The relationships between light performance, electrical characteristics and tube design were studied. Phenomenological formulas of light efficacy were deduced from the experimental data. Calculations based on the design formulas are compared with the measured data for several brands and powers of lamps to verify the validity of the design formulas. The calculations fit well with the measured data. Maps relating light efficacy, lamp power and lamp geometry were created from the phenomenological formulas. The maximum light efficacy curves produced provide guidance for the development of high efficacy CFL lamps.

Keywords—CFL, phenomenological formula, design principle, efficacy, lamp design.

1 INTRODUCTION

Self-ballasted compact fluorescent lamps (CFLs) are widely used for replacing incandescent lamps as energy saving alternative light sources [Topalis and others 2002]. Much research work has been reported on the UV radiation in the positive column [Han and others 2008, Lister and others 2002] and optimized ballast design [Lester 19997]. But systematic research on lamp performance including light output and lamp electrical characteristics along with lamp geometry parameters has seldom been reported. Thus it is difficult to optimize lamp design and lamp parameters for lamp manufacturing. The purpose of this study was to develop design rules for CFLs lamps with T2 and T3 tubes based on benchmarking data to aid in the development of higher efficacy CFLs.

Three brands of spiral compact fluorescent lamps, respectively Osram, GE, and Philips were studied. Osram lamps with T2 and T3 tubes with power of 23 W were used as benchmarking samples and were measured to study the electrical parameters and the photometry performances to get the relationship

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TABLE 1.
Geometry Parameters of Lamp Tubes

Brands	Rated Power (W)	Tube Type	Inner Diameter (mm)	Arc Length (cm)
Osram	23	T3	8.5	67
	23	T2	6.8	68.3
	11	T2	6.5	38.8
	8	T2	6.5	30.6
	5	T2	6.5	16.8
GE	24	T3	8.5	70.1
Philips	24	T3	8.3	67.7
	12	T2	6.5	38.8
	5	T2	6.5	21.6

between light output, efficacy, and electrical characteristics, along with lamp geometry parameters. Phenomenological formulas are deduced based on the measured data. The measurement data of other brands of lamp tubes are compared with the calculated data based on the phenomenological formulas to verify the validity of the design formulas. The comparison shows that the calculation results are consistent with the measured data for GE and Philips lamps and other lamps with different powers. Light efficacy maps were created based on the phenomenological formulas. The maximum light efficacy curves obtained provide guidance for the development of high efficacy CFLs.

2 EXPERIMENTS

Three brands of lamps, OSRAM, GE, and Philips with rated lamp powers ranging from 5 to 24 W were studied. The lamps are purchased from local Chinese market. All tubes had spiral shapes with T2 or T3 tube diameters. The geometry parameters of these tubes are listed in Table 1 and the tube shapes are shown in Fig. 1. For the Osram T2 tube, the top end spiral of the tube is directly inserted into the plastic base (Fig. 1a). For all other tubes, the top end spiral is bent to a 90° angle to form a linear tube and the linear part is inserted into the plastic base (Fig. 1b). With the change of lamp power, the numbers of spiral are correspondingly added or reduced. In order to reduce the cold spot temperature, the bottoms of all these tubes are blown up to form a small conic-like shape. The dimension differences for the extruded parts of the tubes are small. All lamps were aged for 100 hours with its integrated ballast in the base-up position in an

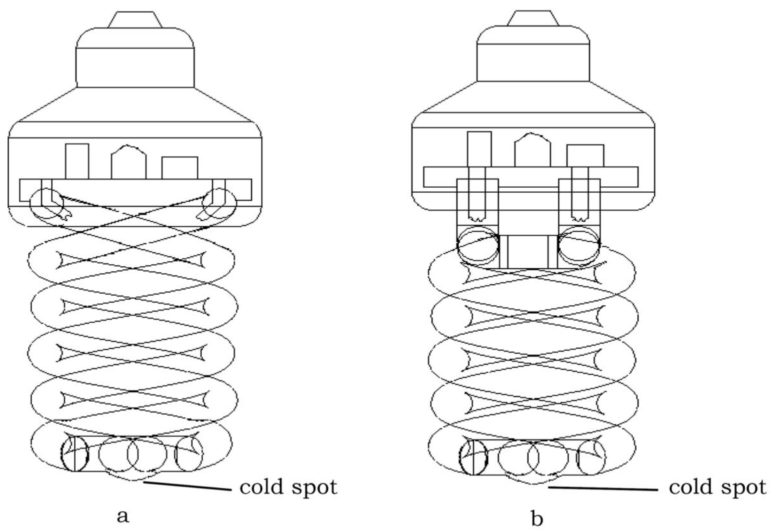

Fig. 1.
Tube shape of spiral compact fluorescent lamps.

open-air rack. Then the integrated ballast was removed from the lamp system to study only the characteristics of the discharge tube. The measured data reported herein are averages of five of the same types of tubes. The lamp with ballasts removed was driven by an ECG power supply (Yokagawa, HCS-102A) at a frequency of 25 kHz. The discharge current was varied from 40 to 260 mA and the voltage correspondingly changed as a result of the inherent characteristics of the tube itself. The tube current, the tube voltage and the tube power were recorded by a power meter. Since the voltage and the current are sinusoidal characteristics, here the power is assumed to be equal to the product of the RMS voltage, the RMS current and the power factor.

When these lamps are operated in base-up position, the coldest spot of the lamp is the special shape at the end of the tube. The cold spot temperature was measured by a Fluke thermometer (51 ⊓). In studying the relationship between light output and the cold spot temperature at a fixed current, temperature was controlled by a thermoelectric cooler (TEC) which is direct contact with the cold spot of the lamp. Thus, the cold spot temperature was correspondingly changed, through thermal conduction, with the temperature of the copper of the TEC.

The photometric parameters of the tubes, which were controlled by electronic control gear (ECG), were measured using photometry equipment made by Everfine (China). The lamp was placed in an 1 m diameter integrating sphere to be measured for its spectrum and lumen output by a high accuracy array spectrometer (HAAS-2000) which scaned over a wavelength range from 380 to 780 nm. Efficacy was calculated without including the ballast. All above measured data were recorded when the lamp had reached its steady output.

3 RESULTS AND ANALYSIS

3.1 ELECTRICAL PERFORMANCE

The performance of Osram 23 W T3 and T2 spiral tubes were measured first to study the relationship between photometric, electrical, and design parameters. The input current was varied by the ECG. Increasing the discharge current will elevate the cold spot temperature. It was found that the cold spot temperature was only a function of current density $\left(\frac{4I}{\pi d^2}\right)$ independent of the arc length, as shown in Fig. 2. More electrons will be produced with increasing current density and thus the elastic collision with gas atoms will increase, resulting in an elevated gas temperature. The tube temperature increase correspondingly increases with the gas temperature inside the tube [Waymouth 1978]. The relationship between the cold spot temperature (T) and the current density $\left(\frac{4I}{\pi d^2}\right)$ can be expressed by the following phenomenological equation, which is based on a fit to the measured data in Fig. 2:

$$T = -46\left(\frac{4I}{\pi d^2}\right)^2 + 76\left(\frac{4I}{\pi d^2}\right) + 35. \tag{1}$$

With the input current changing, the discharge voltage will correspondingly change due to inherent discharge characteristics. The discharge voltage is inversely proportional to the square root of the current, as shown in Fig. 3, which is ascribed to the negative current-voltage characteristics for low pressure gas discharge. When the current increases the electron temperature will drop due to

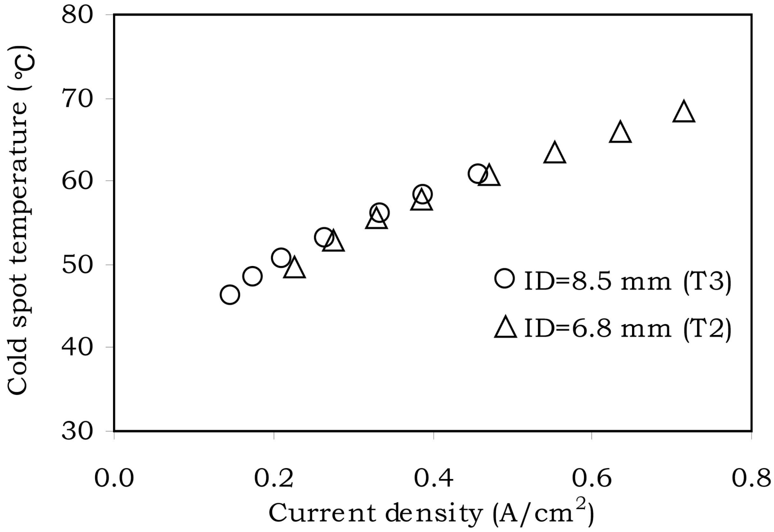

Fig. 2.
Influence of current density on cold spot temperature.

step-wise ionization at higher current density. A lower electron temperature corresponds to a lower electric field. Therefore the discharge voltage will fall when the current increases.

When the cold spot temperature varies by the thermoelectric cooler with a fixed current of 140 mA, the discharge voltage has a maximum value at a temperature of about 48 °C for the T2 tube and about 46 °C for the T3 tube, as shown in Fig. 4, which is close to the optimal temperature of 50 °C for a T2 tube found by Han and his colleagues [Han and others 2008]. The mercury pressure inside the discharge tube is determined by the cold spot temperature. When the cold spot temperature increases, there is more mercury atoms produced, so the voltage necessary to sustain the discharge becomes higher. But, further increasing the cold spot temperature provide more mercury atoms to be ionized, and the ionization rate at a given electron temperature is also increased, which requires lower electron temperature at a steady state. So, the voltage to sustain the discharge decreases with higher mercury pressure.

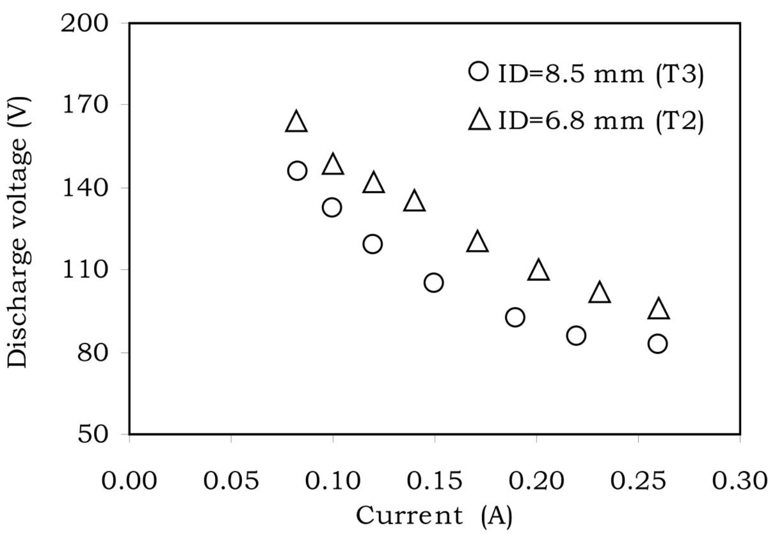

Fig. 3.
Relationship between discharge voltage and current.

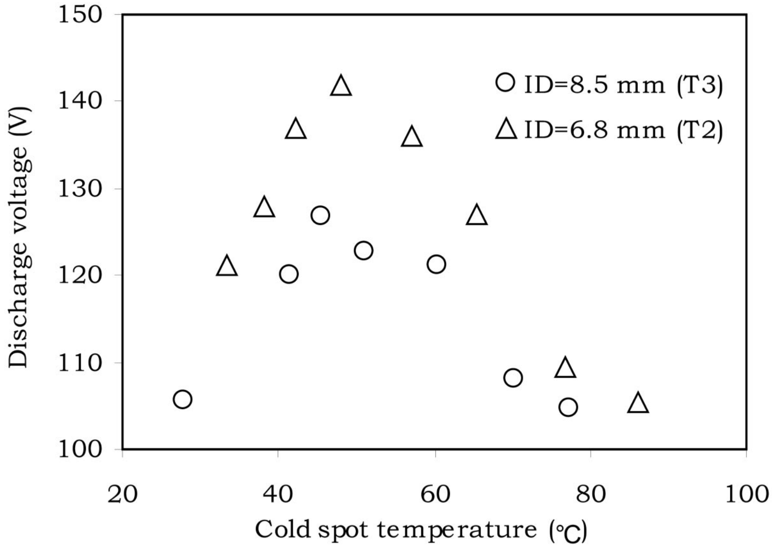

Fig. 4.
Relationship between discharge voltage and cold spot temperature at fixed current of 140 mA.

Therefore, the voltage is a function of both the current and the cold spot temperature, which can be expressed by the phenomenological formula through fitting the measured data in Figs. 3 and 4. Here the electrode fall voltage is supposed not to change too much with AC supply and the data is set to be about 13 V to simplify the equation. The relationship between the cold spot temperature and the discharge voltage below and above the optimal value of 48 °C have different power index trends.

$$V = \frac{0.7l}{I^{0.5} \times f(T)_1} + 13 \tag{2}$$

$$f(T)_1 = \left(\frac{T}{48}\right)^{0.01} \qquad (T < 48\ ^\circ\mathrm{C})$$

$$f(T)_1 = \left(\frac{48}{T}\right)^{0.2} \qquad (T > 48\ ^\circ\mathrm{C})$$

where, l is the arc length of the tube. The discharge voltage is linearly proportional to the arc length.

The phenomenological formula of the lamp power thus can be obtained according to (2).

$$P = \left[\frac{0.7l}{I^{0.5} \times f(T)_1} + 13\right] \times I. \tag{3}$$

3.2 PHOTOMETRY PERFORMANCE

Light output increases with current density until it reaches a saturation level, as shown in Fig. 5. The relationship between luminous flux and current density is a polynomial. As the current density increases, so does the rate of ionization and the production of mercury atoms in excited states, causing UV radiation to increase, thus visible light transferred from UV radiation will be improved. At the same time, however, the electron temperature falls, increasing the rate of de-excitation with slow electrons. As a result, the useful radiation intensity

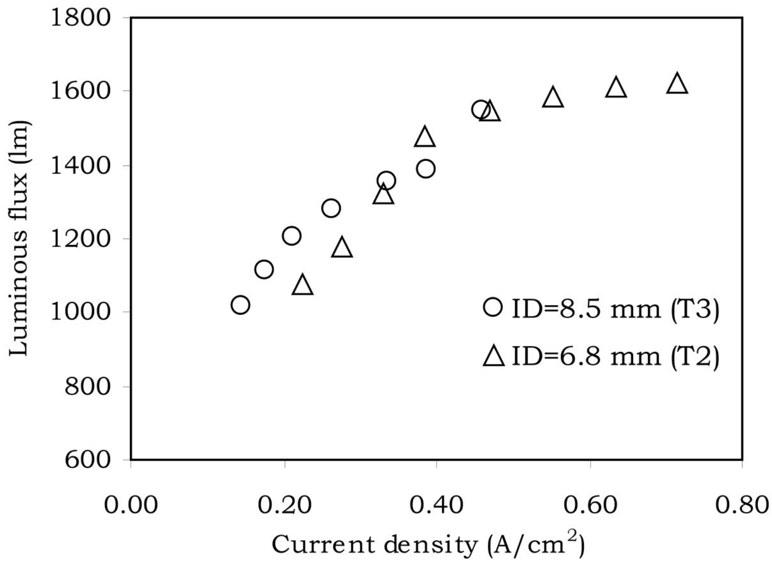

Fig. 5.
Relationship between light output and current density.

cannot increase as quickly as the current density does and it will gradually approaches a constant and will not increase further.

As the cold spot temperature varies at a fixed current of 140 mA, the light output reaches a maximum at a temperature of about 48 °C, as shown in Fig. 6. Here, the light output is a relative value and it was not measured in the integrating sphere. The optimal cold spot temperature of 48 °C for the maximum light output obtained here is close to the temperature of 50 °C for the maximum intensity of 254 nm radiation of T2 tube found by Han and his colleagues [Han and others 2008], and is a little higher than that of the tube with an inner diameter of 9.5 mm [Anderer 1991]. The relationship between the luminous flux and the cold spot temperature is a polynomial. At low cold spot temperatures, there is insufficient mercury to produce significant UV radiation. As the cold spot temperature increases, the UV radiation is gradually trapped. The maxi-

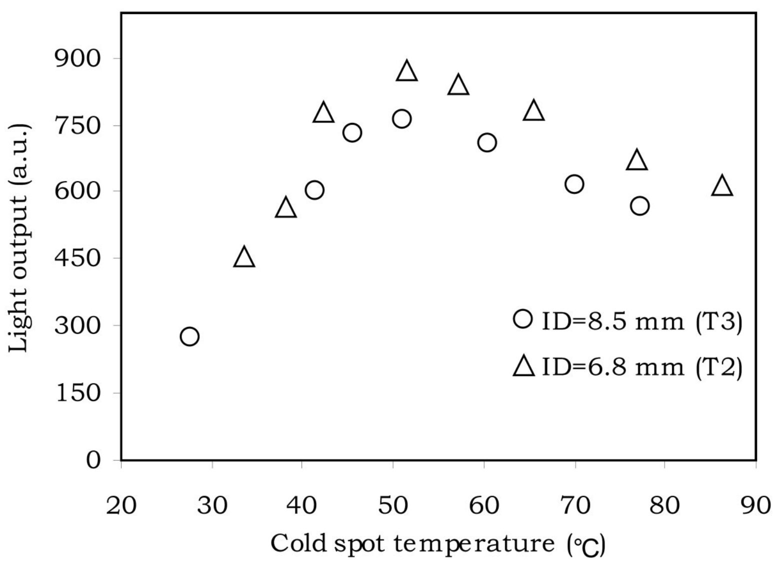

Fig. 6.
Relationship between light output and cold spot temperature at a fixed current of 140 mA.

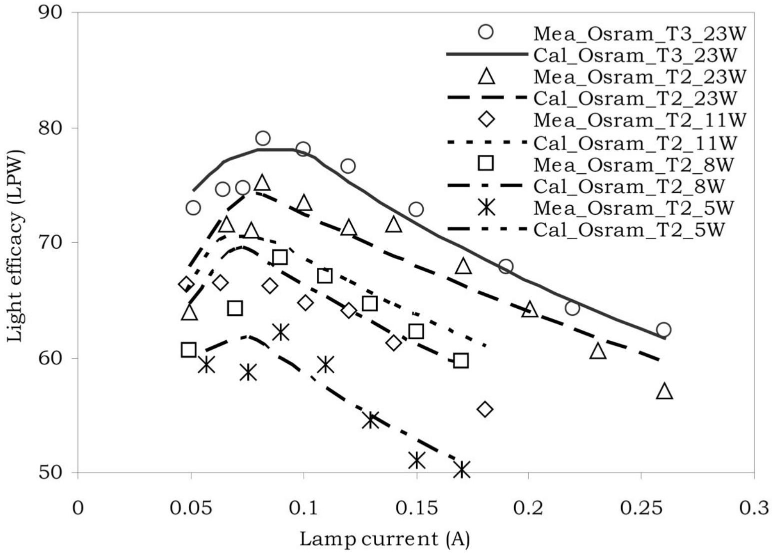

Fig. 7.
Comparison of calculated light efficacy with measured data for Osram tubes.

mum occurs when the effect of radiation trapping starts to dominate the rate of radiation production.

The phenomenological formula of the luminous flux (ϕ) thus can be obtained by fitting the measured data in Figs. 5 and 6. The influence of the cold spot temperature and the light output below and above the optimal value of 48 °C have different power index trends.

$$\Phi = \left\{-43\left[\left(\frac{4I}{\pi d^2}\right)^{0.4} f(T)_2\right]^2 + 91\left(\frac{4I}{\pi d^2}\right)^{0.4} f(T)_2 - 20\right\} \times l \tag{4}$$

$$f(T)_2 = \left(\frac{T}{48}\right)^{0.01} \qquad (T < 48°\text{C})$$

$$f(T)_2 = \left(\frac{48}{T}\right)^{0.5} \qquad (T > 48°\text{C})$$

where, l is the arc length of the lamp. The light output is linearly proportional to the arc length.

According to the above phenomenological formula of the lamp power (3) and the luminous flux (4), the light efficacy (η) can be obtained by the following equation:

$$\eta = \frac{\Phi}{P} = \frac{\left\{-43\left[\left(\frac{4I}{\pi d^2}\right)^{0.4} f(T)_2\right]^2 + 91\left(\frac{4I}{\pi d^2}\right)^{0.4} f(T)_2 - 20\right\} \times f(T)_1 \times l}{0.7I^{0.5}l + 13If(T)_1} \tag{5}$$

$$f(T)_1 = \left(\frac{T}{48}\right)^{0.01} \qquad (T < 48°\text{C}) \qquad f(T)_2 = \left(\frac{T}{48}\right)^{0.01} \qquad (T < 48°\text{C})$$

$$f(T)_1 = \left(\frac{48}{T}\right)^{0.2} \qquad (T > 48°\text{C}) \qquad f(T)_2 = \left(\frac{48}{T}\right)^{0.5} \qquad (T > 48°\text{C}).$$

In order to support the validity of (3), the calculated light output according to (1) and (3) were compared with the measured data for Osram, Philips and GE T3 and T2 tubes with power ranging from 5 W to 24 W, as shown in Figs. 7 and 8.

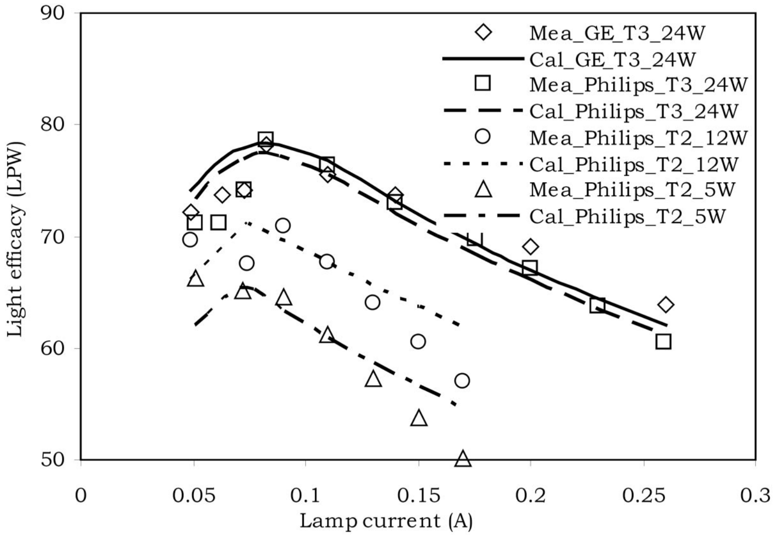

Fig. 8.
Comparison of calculated light efficacy with measured data for GE and Philips tubes.

It can be seen from the figures that, in general, the calculation is in good agreement with the measured data. The light efficacy has a maximum at relatively small current. There are two possible reasons for this phenomenon [Waymouth 1978]. One is that at a very low current density which corresponds to a very low electron density direct ionization occurs. The ionization frequency is only determined by the electron energy distribution, that is, by the electron temperature. With higher electron and current densities there is a chance of step-wise ionization. Consequently, the electron temperature drops as the current increases, so the slow electron will collide with an excited atom and take away the excitation energy as kinetic energy, leaving the atom in a lower energy state. Therefore, the maximum occurs when the effect of step-wise ionization starts to dominate the direct ionization. Another is that the cold spot temperature is lower than its optimized value at low current density, thus its light efficacy is low in the small current. When the cold spot temperature gets to its optimal temperature with increasing current, light efficacy reaches its maximum.

The light efficacy of T3 tubes are higher than that of T2 tubes at the same current. T2 tubes have larger current density which causes the cold spot temperature to increase even if the total current is the same, as shown in Fig. 2. Light efficacy will decrease with increasing mercury pressure because of the higher cold spot temperature.

The tube with a longer arc length has higher efficacy. As lamp length increases, the fraction of total input power consumed by the positive column will be greater. The efficiency approaches that of an infinitely long lamp since there is a relatively decreases in electrode losses, so that the total efficiency increases. But here it is found from the measured data that the tube with a rated power of 8 W had higher light efficacy that that of the tube with a rated 11 W power. Maybe this was caused by the wider distance in the spiral spacing for the tube with a rated power of 8 W, which can be observed from the shape difference of these two tubes. This need to be further confirmed by optical simulation to see whether the tube spacing distance has such a big influence. The actual cold spot temperatures at which the maximum efficiency was obtained are shown in Fig. 9. For all T3 tubes, the temperature is a little lower than the optimized

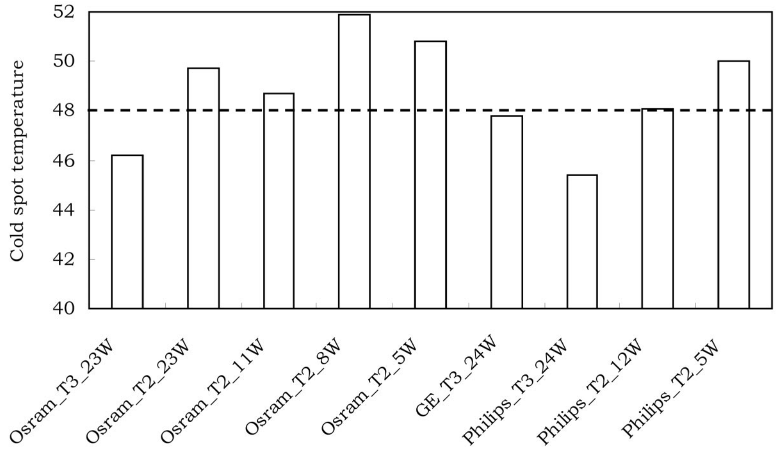

Fig. 9.
Actual cold spot temperature at which the maximum efficiency was obtained.

temperature of 48 °C, while for all T2 tubes, the temperature is a little higher. This is because the current density of the T3 tubes is lower than that of the T2 tubes. The larger tube diameter of the T3 tubes results in lower cold spot temperatures at the same input current, as shown in Fig. 2.

Light efficacy maps scale the three-dimensional relationship between light efficacy, lamp power, and lamp geometry parameters, and can be created according to (5), as shown in Figs. 10 and 11 respectively for T2 tubes and T3 tubes. Therefore, the lamp designs can be optimized based on these charts to get maximum light efficacy. When the tube length is fixed, the light efficacy has a maximum point with the change of input power. The maximum light efficacy curve thus can be obtained by connecting the maximum point in every curve with different tube lengths. The desired efficiency and lamp parameters for a lamp with assumed power thus can be found from the curve.

In order to get higher efficiency, the maximum efficacy curve should be pushed up. In the case of high current density, the cold spot temperature is always beyond its optimal value. So if the cold spot temperature of the tube can be fixed in its optimum of about 48 °C by possible shape changes so corresponding with

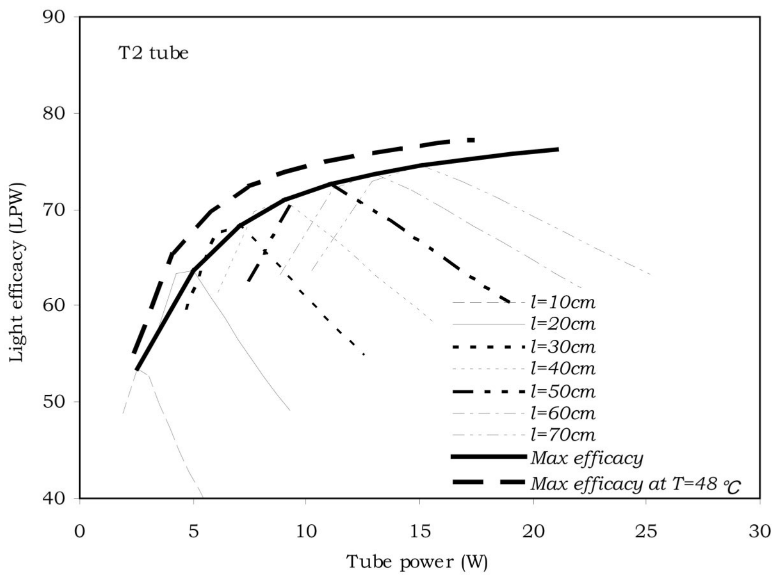

Fig. 10.
Relationship between light efficacy, tube power, and tube length for T2 tube.

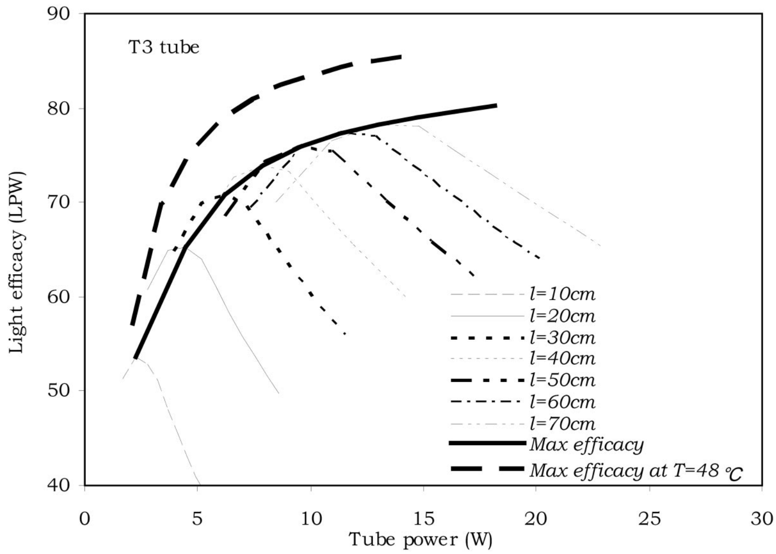

Fig. 11.
Relationship between light efficacy, tube power, and tube length for T3 tube.

current density change, the maximum efficacy curve can be pushed up, which is shown as the virtual curve in Figs. 8 and 9. Some other possible ways to control the cold spot temperature at its optimized value are reported in patents [Yasuda and Ikada 2007, Erdokertes and others 2003, Bruce and Richard 1998] and in the literature [Crawford and others 1989]. Special shapes are made on the lamp tube or the thermally control mechanism to maintain the cold spot at its optimal temperature in order to obtain optimized light output.

4 CONCLUSIONS

(1) The phenomenological formula of light efficacy as a function of the current density, cold spot temperature, tube diameter and length was deduced from the experimental data. The calculated results from the design equation fit well with the measured data for several brands and powers of T2 and T3 lamps.

(2) Light efficacy maps were created based on the light efficacy formula, which scale the three-dimensional relationship between light efficacy, lamp power, and lamp geometry parameters. The desired light efficiency and lamp parameters for a lamp with assumed power can be determined with reference to the light efficacy maps.

(3) The maximum light efficacy curve was obtained by connecting all maximum points in the light efficacy maps. Possible ways to improve efficacy were proposed and need to be further confirmed experimentally.

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