Paper

Development of High-power LED Lighting Luminaires Using Loop Heat Pipe

Bin-Juine HUANG*, Huan-Hsiang HUANG**, Chun-Wei CHEN* and Min-Sheng WU*

*Department of Mechanical Engineering, National Taiwan University
**Advanced Thermal Devices, Inc.

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ABSTRACT

High-power LED should reject about 6 times of heat of the conventional lighting device and keep the LED junction temperature below 80°C to assure reliability and low light decay. In addition, no fan is allowed and the heat dissipation design should not interfere with the industrial design of lighting fixture and have a light weight. This thus creates an extreme thermal management problem. The present study has shown that, using a special heat dissipation technology (loop heat pipe), the high-power LED lighting luminaire with input power from 36 to 150W for outdoor and indoor applications can be achieved with light weight, among 0.96 to 1.57 kg per 1,000 lumen of net luminous flux output from the luminaire. The loop heat pipe uses a flexible connecting pipe as the condenser which can be wounded around the reflector of the luminaire to dissipate the heat to the ambient air by natural convection. For roadway or street lighting application, the present study shows that a better optical design of LED lamps can further result in power consumption reduction, based on the same illumination on road surface. The high-power LED luminaries developed in the present study have shown that the energy saving is > 50% in road lighting applications as compared to sodium light or >70% compared to mercury light.

KEYWORDS: LED lighting, roadway lighting, loop heat pipe application, energy saving, optical design

1. Introduction

Solid state lighting or light emitting diode (LED) at low-power level has been widely used in many electronic products. For high-power LED for lighting purpose, though the LED cost per lumen is decreasing rapidly, however, it is thought that the wide-spread LED lighting application will likely take several years before the LED light can provide the same performance as metal halide, high pressure sodium, and fluorescent lighting[1)2)]. Besides this, the reliability of LED light including durability and lighting decay is also an important factor affecting the wide-spread application of LED lighting.

In recent years, the LED efficacy value has exceeded 60 lumen per watt, which is comparable to or even better than that of mercury lamps. This means that the LED lighting applications such like roadway lighting may become feasible shortly. Though the present LED efficacy is still lower than high-pressure sodium HID lamp, the better lighting directness, longer life, good light loss factor of LED may result in a better performance for roadway lighting.

The present study intends to develop the high-power LED lighting technology including four topics: (1)design of high-power LED lighting fixture with good heat dissipation and light weight; (2)long-term roadway lighting test for collecting field performance and durability data; (3)optical design and feasibility analysis of LED roadway lighting; (4)energy saving analysis of LED lighting.

2. Design of high-power led lighting fixture

A high-power LED lighting system needs to dissipate heat to the ambient in quantity which is several times of the conventional lighting device and keep the LED junction temperature below 80°C to assure reliability and low optical decay. Heat dissipation is thus an important issue in high-power LED lighting technology. National Taiwan University has been devoted to the development of high-power LED lighting fixture using a special low-cost heat dissipation device (loop heat pipe, LHP)[3)] to develop

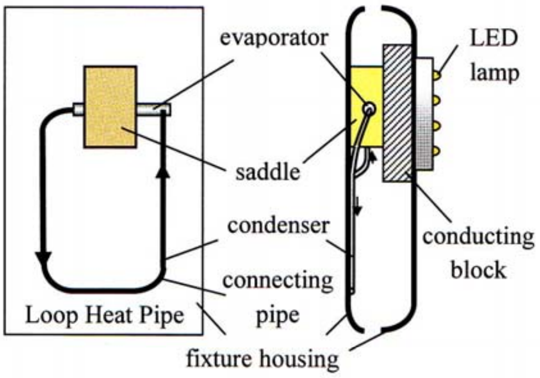


Figure 1 Design of LED lighting fixture using loop heat pipe (LHP)

Figure 2 100W LED lighting fixture using LHP

Figure 3 150W LED lighting fixture using LHP

the fan-less lighting fixture of high-power LED.

LHP is a remote heat transfer device originally developed for aerospace application[4]. The structure of LHP used in LED lighting fixture is shown in Figure 1. The evaporator of the LHP is attached on the backside of the LED module through a heat conduction block to absorb the heat generated in the LED lighting module. The absorbed heat evaporates the working fluid inside the LHP to flow through a flexible connecting pipe to the condenser plate which is the housing of the lighting fixture. The vapor is condensed in the condenser from which the heat is dissipated to the ambient. The condensed liquid then returns to the evaporator through the connecting pipe by capillary effect of the wick inside the evaporator. Since the wick structure inside the evaporator can be made at micro pores to induce large capillary force, LHP can transport large amount of heat to a long distance with flexible connecting pipes. For LED lighting fixture, LHP can transport heat to the housing that acts as the heat dissipation surface to the ambient without altering the outlook and with light-weight structure.

The only problem left in using LHP is its high manufacturing cost. National Taiwan University and ATD (Advanced Thermal Devices, Inc.) have developed a patented design and manufacturing process that can make cheap LHP at mass production cost of about 10USD for 100W LHP. Using the low-cost LHP as the heat dissipation device, we have designed two types of high-power LED lighting fixtures: Model SL-614 with rated input power 100W shown in Figure 2 and Model SL-914 with rated input 150W shown in Figure 3. The weight of the fixture is 5.5 kg for SL-614 and 8.5 kg for SL-914. The SL-914 LED lighting fixture uses 1W LED lamps with efficacy 72 lumen/W. The total luminous flux of SL-914 fixture reaches 8,836 lumen at 149W input (DC45.2V), which is probably the brightest LED

Table 1 Characteristics of LED lighting fixture

LED Lighting Fixture Model	SL-614	SL-914
Dimension, mm	580×250×120	630×315×120
Weight, kg	5.5	8.5
No. of LED lamps	84 (6×14)	126 (9×14)
LED lamp efficacy, lm/W	45	72
Total DC Power input, W	97	149
Total output luminous flux, lm	3,510	8,836
Specific weight, kg/1000 lm	1.57	0.96
Thermal resistance from LED base to ambient, K/W	0.25 (stagnant air)	0.20 (stagnant air)

lighting fixture. The 1W LED lamps of SL-914 are connected with 14 lamps in series and 9 rows in parallel. The measured thermal resistances of the lighting fixture from the base of LED lamp to the stagnant ambient air are 0.20 and 0.25 K/W for SL-914 and SL-614 respectively. Table 1 summarizes the design specification of SL-614 and SL-914.

3. Road test of high-power led lighting

We have done many road tests for the high-power LED lighting luminaires we designed. The SL-614 LED lighting fixture was developed in August, 2005, using a LHP with heat transfer rate 100W and LED lamps with efficacy 45 lumen/W. The total luminous flux of the luminaire is 3,600 lm. We immediately performed an outdoor test to observe the long-term performance of the high-power LED lighting fixture in real situation. This luminaire was installed in a city alley (7m wide) with lamp tilted angle 30 degrees and lamp height 5.5m. The demonstration and monitoring of the LED light in the city alley started right after the installation on September 18, 2005.

The illuminance S_o of SL-614 at 4m right beneath the LED luminaire was measured monthly as the performance index. S_o decreases with time in 20 months operation with total running time 6,000 hours. But it is seen that S_o actually varies with the total DC power input P_{in} which was not kept constant due to the ambient temperature variation and adjustment at the beginning of the test. To evaluate the LED lighting performance more correctly, we use the specific illuminance per unit power input (including wire loss) I_s as the indicator:

$$I_s = \frac{S_o}{P_{in}} \quad \cdots\cdots\cdots (1)$$

where S_o is the illuminance at a fixed position relative to the LED lighting fixture.

Figure 4 show that the specific illuminance I_s is between 0.63 and 0.73 lux/W in 20 months operation with total running time 6,000 hours. I_s increases at the beginning then start to decrease and finally return back to the initial value. This is mainly due to the LED junction temperature variation which varies with the ambient temperature. From the monitored data shown in Figure 4, in summer when ambient temperature > 20°C, I_s decreases slightly. But, I_s returns to the starting value (0.7 lux/W) when the ambient temperature drops to 15°C in February 2, 2007.

The use of constant-voltage power supply will cause the LED light output to vary more sensitively with ambient temperature variation. The present demonstration uses constant-voltage power supply for LED since the field test is carried out in Taiwan where the annual ambient temperature variation is not large (<20°C). The constant-current power supply is better for LED since the total power input to LED as well as the LED light output varies less sensitively (around 10%) at large ambient temperature variation (~40°C). For the application in some other areas, we will use constant-current power supply.

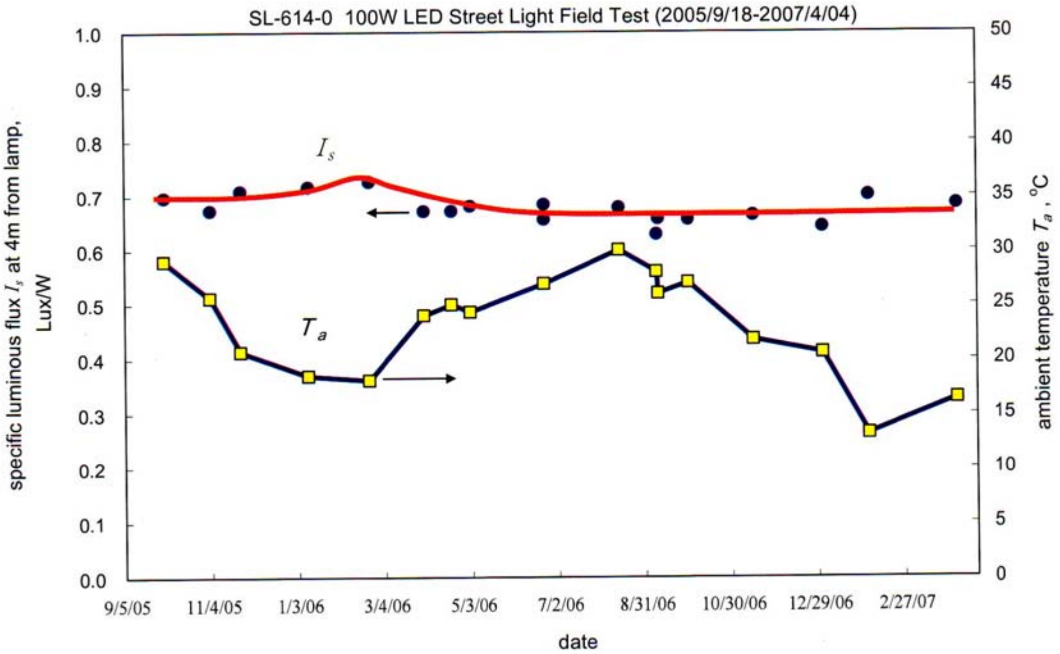


Figure 4 The specific illuminance I_s of SL-614 100W street light

Figure 5 200m roadway LED lighting field test in NTU

The net luminous flux of SL-614 was measured at 3,516 lm with DC power input 101W (21.4V) without line loss. The corresponding electrical resistance of LED is 4.53 ohm. In real installation, the current is 5.01A for 24.9V input voltage at 125W input power. The total resistance including wire is 5.0 ohm. The line resistance is estimated to be 0.47 ohm and the line loss is 13W, about 13/(125-13)=11.6%. This line loss can be reduced or eliminated in the future by replacing the wire or placing the power supply inside the lighting fixture. Nevertheless, the present long-term performance test data shows that SL-614 has very little light decay in 20 months field operation. This is resulted from the good heat dissipation control using LHP that keeps a lower LED junction temperature (<70°C at T_a<30°C). Besides, SL-614 has never experienced any malfunction and service so far.

As the LED lamp is rated to have 30% light decay in 50,000 running hours, from the present road test results for about 6,000 hrs running time, it shows that this target is achievable.

In June, 2006, we also built a 200m LED lighting roadway in the campus of National Taiwan University for experiment and demonstration, as shown in Figure 5. The 100W LED luminaries were installed on the road with 5.2m height.

4. Optical design and feasibility of led roadway lighting

Since the property of emitting surface of LED lighting, optical design is necessary and important for roadway lighting. Previously the lighting fixture optics was designed in symmetry type in light intensity distribution and caused poor performance on road. To be more suited with the roadway lighting, we have made an asymmetry optical design on the lighting fixture for gaining the better illumine efficiency and illumination uniformity on road at the same power input. Some aluminum reflectors in the specific angle reflecting the light emitted from LED lamps and optical lens arrays with different shapes covering on the LED lamps and reflectors are compacted in the lighting fixture. Figure 6 shows the asymmetry in lighting intensity distribution of the lighting fixture.

It has been questioned that the present LED lighting technology can meet the roadway lighting standard such as IESNA[5] or CIE. In order to answer that, we use the best LED fixtures with luminous flux 60 lumen/W to study the roadway lighting performance. Following the IESNA standard, we perform a roadway lighting performance simulation.

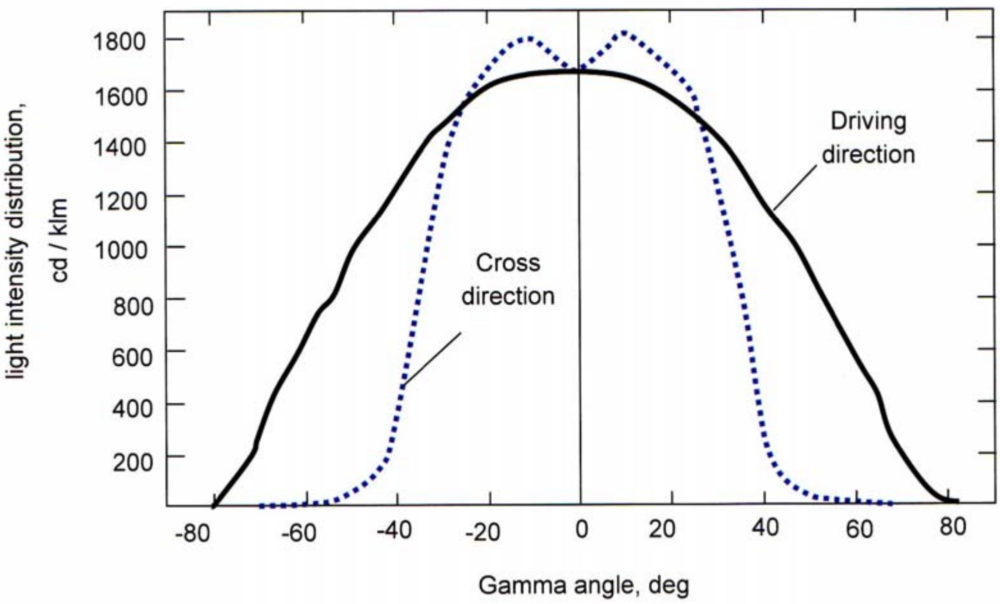


Figure 6 Light intensity distribution of SL-614 with asymmetry optical design

Two cases are studied: (1)100W LED/6,000 lumen for 6m-wide lane with pole height 9.8m and pole spacing 30m, single side installation; (2)135W LED/8,000 lumen for 15m-wide roadway with pole height 10m, two sides staggered installation with pole spacing 35m, 100m in total distance.

Case (1):

This LED (6,000 lumen) lighting intends to replace the 250W mercury lamp in a city. Figure 7 shows the illumination distribution on the road surface. The results listed in Table 2 show that LED lighting can meet the IESNA standard requirement.

Case (2):

This LED (8,000 lumen) lighting intends to replace the 400W mercury lamp in a city. The LED is installed two sides of the road in staggered rows with pole spacing 35m, and lamp height 10m. The results listed in Table 3 show that LED can meet the IESNA standard. Figure 8 shows the illuminance distribution of the road surface. It is noticeable that the light loss of LED on highway lighting is 14.5% which is smaller than conventional lighting device.

The above analysis for the two cases shows that the present LED lighting technology can meet roadway lighting standard.

However, there might be several variables for roadway lighting design, such as limited height and pole spacing of lighting fixtures. For the low height luminaires with long spacing on road, we can modify the structures of optical designs described before to improve the optical characteristics of luminaires. Figure 9 shows the comparison of illumination distribution for one 5.2m height lighting fixture with 6,000 lumen on a 9.1m-wide and 35m-long road which obviously indicates the optical designs of the luminaires provide almost 1.5 times lighting field.

Table 2 6,000 lm LED lighting performance for a 6m wide lane

		IESNA Standard
Maximum illuminance (Lux)	30.5	-
Minimum illuminance (Lux)	4	-
Average (Lux)	13.4	> 3~10
Uniformity (avg/min)	3.3	<4
Uniformity (max/min)	7.6	-

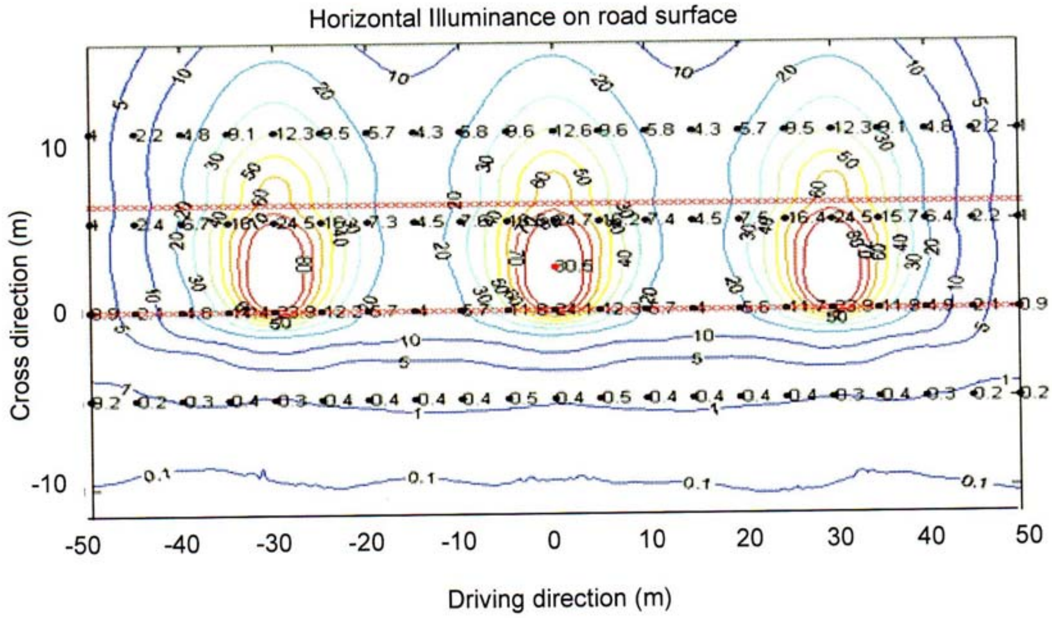


Figure 7 Illuminance distribution on the road surface using 6000 lm LED

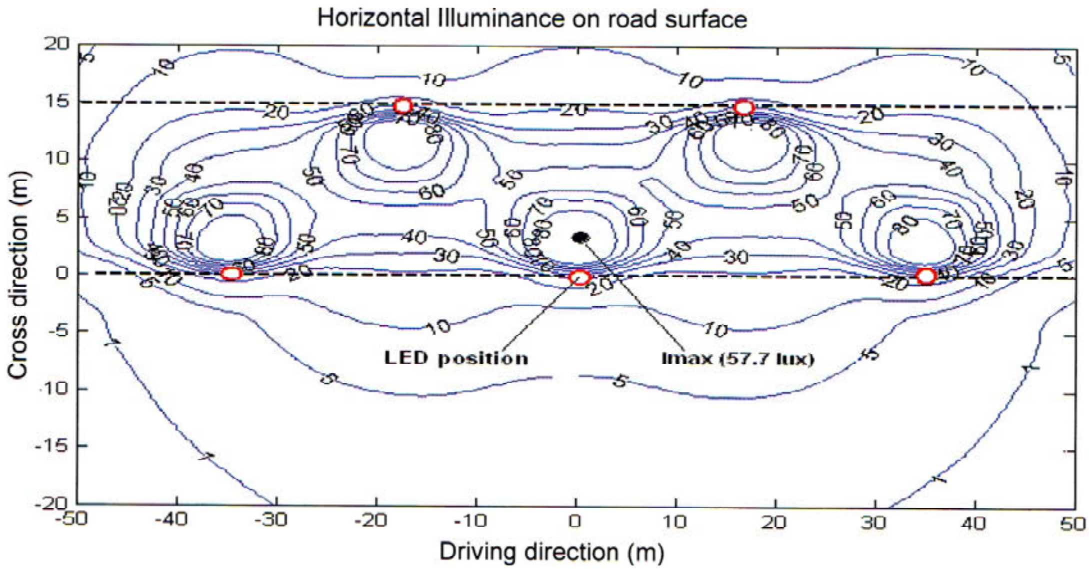
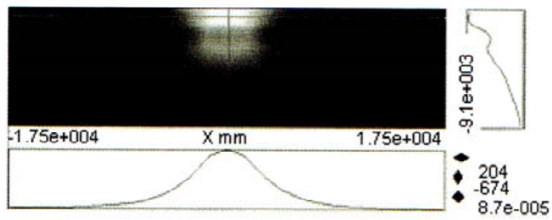


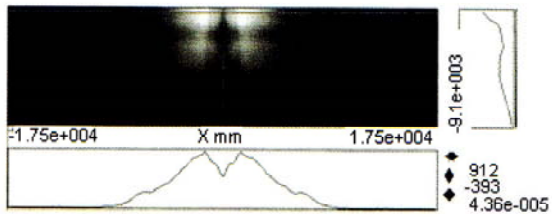
Figure 8 Illuminance distribution on the road surface using 8,000 lm LED

Table 3 8000 lm LED lighting performance for a 15m wide highway

		IESNA Standard
Maximum illuminance (Lux)	57.7	-
Minimum illuminance (Lux)	7.9	-
Average (Lux)	24.8	>12
Uniformity (avg/min)	3	<3
Uniformity (max/min)	7.3	-
Light loss (%)	14.5	-



(a) illumination distribution of one original luminaires



(b) illumination distribution of one designed luminaires

Figure 9 comparison of illumination distribution

5. Energy saving analysis of led lighting

The present LED efficacy is still lower than high-pressure sodium HID lamp. However, the better lighting directness, longer life (low light decay), better coefficient of light utilization may result in a better overall performance in roadway lighting. Six factors will affect the energy saving of LED roadway lighting: (1)lamp efficacy η_L; (2)luminaire efficiency η_m; (3) Power supply efficiency η_p; (4) Lighting-to-target effectiveness η_R; (5)luminaire maintenance factor C_m; (6) life cycle-average illumination ratio η_{Da}.

The LED lamp efficacy reaches 72 lm/W in 2006 and is expected to be 110 lm/W in 2010. The luminaire efficiency η_m depends on the design of the lighting fixture. For conventional lighting fixture, it ranges from 0.4 to 0.7. For the design using LHP in the present study, we can obtain 0.85. The power supply efficiency η_p that converts AC to DC power for LED is > 0.87 in the present study. The LED have about 110° light emission angle, while the conventional lamps usually have 360° and needs reflector to direct the light beam to the target.

Therefore, the lighting-to-target effectiveness η_R or coefficient of utilization is between 0.2 and 0.4 for conventional lighting fixture. For LED designed for roadway lighting in the present study, we can reach 0.85. The luminaire maintenance factor C_m depends on the environmental condition at service. For LED in the present study, it is estimated at 0.8 since the optical window for light output is much smaller than conventional lighting fixture (0.7).

The life-cycle final illumination ratio η_D is defined as the ratio of the final illuminance at the life time to the initial illuminance:

$$\eta_D = \frac{L_N}{L_i} \quad (2)$$

where L_i is the initial illuminance (for brand new product); L_N is the illuminance at the life time N (year). The life cycle-average illumination ratio η_{Da} is defined as the ratio of the average illuminance for the life time to the initial illuminance:

$$\eta_{Da} = \frac{(L_i + L_N)/2}{L_i} \quad (3)$$

The life-cycle final illumination ratio η_D depends on the maintenance budget and management system. For conventional lighting fixture, η_D is around 0.4 in .general. For LED, we use a strict criterion for η_D to be 0.7 which follows the definition of the lifetime of LED.

Table 4 shows the energy saving analysis of LED lighting compare to sodium lamp and mercury lamp. Based on the power consumption per net illuminance to target, $p_o=1/e_o$(W/lm), LED can save 35.4% and 65.0% energy consumption compared to sodium lamp and mercury lamp respectively in brand new performance. The LED also have longer lifetime with 30% light decay in 50,000 hours, if the heat dissipation is resolved properly. Hence, the lifetime performance can save about 53.5% energy and 74.8% compared to sodium and mercury lamps, respectively.

Table 4 Energy saving, LED vs. Sodium and Mercury lamp

Brand new performance	Sodium	LED	Mercury	LED
1. Lamp efficacy, η_L (lm/W)	120	72	65	72
2. Luminaire efficiency, $\eta_m = \eta_2 \times \eta_p$	0.595	0.72	0.595	0.72
-secondary optics efficiency, η_2	0.7	0.85	0.7	0.85
-power supply efficiency, η_p	0.85	0.85	0.85	0.85
3. Lighting-to-target effectiveness, η_R	0.4	0.85	0.4	0.85
4. overall lighting efficiency for brand new luminaire, $e_o = \eta_L \times \eta_m \times \eta_R$ (lm/W)	28.6	44.2	15.5	44.2
-power consumption per net illuminance to target, $p_o = 1 / e_o$ (W/lm)	0.035	0.023	0.065	0.023
Energy saving=[p_o(HID) - p_o(LED)] / p_o(HID)	-	**35.4%**	-	**65.0%**
Lifetime performance				
5. luminaire maintenance factor, C_m	0.7	0.8	0.7	0.8
6. Lifetime decayed illuminance, η_D	0.4	0.7	0.4	0.7
-life time, yr	3	10	3	10
-lifetime-average light decay, $\eta_{Da} = \eta_D + (1-\eta_D)/2$	0.7	0.85	0.7	0.85
7. Lifetime-average overall lighting efficiency, $e_{LCYC} = e_o \times C_m \times \eta_{Da}$ (lm/W)	14.0	30.1	7.6	30.1
-lifetime-average power consumption per net illuminance to target, $p_e = 1 / e_{LCYC}$ (W/lm)	0.071	0.033	0.132	0.033
Lifetime energy saving=[p_e(HID) - p_e(LED)] / p_e(HID)	-	**53.5%**	-	**74.8%**

4. Conclusions

The present study has shown that, using a special heat dissipation device (loop heat pipe), the high-power LED lighting fixture with input power 100W and 150W can be easily achieved with light weight, between 0.96 and 1.57 kg per 1,000 lumen illuminance. A long-term roadway lighting field test using 100W LED lighting fixture (SL-614) in a city lane was carried out. The city lane test has been continued over 20 months (until April, 2007) without light decay and any failure so far.

A 200m road test was also carried in the University campus. Six 100W LED of Model SL-614 was installed in the existing pole with 5.2m high.to replace the original 400W mercury lamps. The installation has been completed in June 12, 2006. The average illuminance on road surface is 10 lux with max 63 lux. The roadway average luminance is 4.1 cd/m^2. A large amount of energy saving is achieved.

Using the unique heat dissipation technique (loop heat pipe) and the most-advanced LED lamps with efficacy >72 lumen/W, we developed a 150W LED with 8,836 lumen luminous flux (fixture efficacy larger than 60 lumen/W).

The 200m road test in campus is still underway but using the 150W super-brightness LED since Dec. 11, 2006. The roadway lighting analysis shows that this super-high power LED can meet the CIE or IESNA roadway lighting standard. The life-cycle energy saving of the LED roadway lighting compared to sodium lamp is 53.5% based on 2006 technology of LED and is expected to be 75% in 2010. This is mainly due to the high coefficient of utilization and low light decay of LED. The results obtained in the present study will probably open up the widespread application of LED roadway lighting.

Acknowledgements

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References

(1) John W. Curran, Shawn P. Keeney: Replacement of fluorescent lamps with high-brightness LEDs in a bridge lighting application, Sixth International Conference on Solid State Lighting, Vol. 6337, 2006. T. Taguchi, J. Light & Vis. Env. 30 (2006) 177.

(2) John P, Peck, C. Vishnu Shastry: LED light fixture for parking garages, Sixth International Conference on Solid State Lighting, Vol. 6337, (2006).

(3) B. J. Huang, C. H. Wang, T. T. Lin, H. H. Huang and Y. Y. Yeh: Development of a low-cost LHP for commercial application. 13^{th} International Heat Pipe Conference, Shanghai, China. Sept.21-25, (2004).

(4) N. Narendran, L. Deng, R. M. Pysar, Y. Gu and H. Yu: Performance Characteristics of High-Power Light-Emitting Diodes. Proceedings of SPIE - The International Society for Optical Engineering, Vol.5187, Third International Conference on Solid State Lighting, p 267-275 (2004).

(5) American National Standard Practice for Roadway Lighting, Illumination Engineering Society of North America Report #RP-8-00, August (1999).

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