Thermal Performance of an Indoor Oblong LED Lighting Prototype Incorporating Heat Pipes

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Abstract
An innovative indoor LED lighting prototype that uses pressed-flat grooved heat pipes as heat transfer channels to conduct LED-released heat to heat-sink-fins is proposed. Natural convection inside the flow channels within the heat-sink fins serves as the main heat dissipation mechanism. In order to accommodate different illumination directions, the thermal performance of the LED lighting prototype at different inclination and rotation angles (different heat pipe performances) were experimentally investigated. The results show that the temperature distribution of the prototypes is dependent on inclination angles, however, independent of rotation angles. FFT analysis reveals that dominant fluctuation frequencies of the temperature around the central area of the prototype with different inclination angles are about 4.7 minutes.

Keywords: LED; illumination; heat pipe

1. Introduction
1.1 LED (Light Emitting Diode)
A light emitting diode (LED) consists of a p-n interface that emits light, ranging in wavelength from the infrared to the ultraviolet. The mechanism through which an LED emits light is as follows: when forward biased, electron and electron hole carriers travel through a depletion region into p-type and n-type areas, respectively, to recombine with another carrier. This recombination process releases energy in the form of light and heat.

LEDs are capable of emitting light of both the visible and non-visible spectrum. Visible light-emitting LEDs can be further divided into traditional brightness and high brightness LEDs. The traditional brightness LED industry is mature, with applications as indicator lights in home electric appliances, information and electronic products. In contrast, high brightness LED is a more recent technological development, and currently the focus of intense research. These types of LEDs can be used for large illustration boards, traffic signs, and backlight sources, as well as being found in automotive applications. (Steranka et al., 2002) (Craford, 2005)

1.2 The application of white light LEDs on indoor lighting
White light LEDs have several advantages over traditional incandescent tungsten lamps or fluorescent lamps, including:

1. Low power consumption, low voltage, at around 1/8 of incandescent lamps or 1/2 of fluorescent lamps.
2. Lifetimes of over 10,000 hours, approximately 10 times that of fluorescent lamps.
3. Quick response at high frequency. LEDs require only 100 ns to respond, which is much quicker than regular incandescent lamps (100 to 300 ms).
4. Environmentally friendly, quake proof, crash proof and recyclable without pollution.
5. Flat packaging allows it to be developed into light, thin, short, and small products.

1.3 Heat dissipation requirement of LEDs
As previously mentioned, energy is released in the form of light and heat during the recombination of electrons and electron holes inside an LED. Traditional LED lights produce lower lighting intensities, and, subsequently, less heat, making heat emission inconsequential in these applications. Using LEDs as regular indoor illumination sources will require lighting emission intensities equal to those of incandescent or fluorescent bulbs. With the improvement of white light LED efficiency, this is a real possibility. The driving voltage of a single white light LED is low, and correspondingly, it is unlikely that a single LED will ever be capable of meeting emission intensity
requirements with current packaging. There are two solutions to this problem: (1) combining LED light sources and (2) using a large crystalline grain process to make LEDs larger (0.6 to 1 mm$^2$) than typical regular crystalline grains (0.3 mm$^2$). Either solution requires large quantities of heat to be released from the tiny LED packaging. Without an effective dissipation of heat, the light emitting efficiency of LED will be reduced, and if sufficiently hot, the LED component may even be destroyed. Removing heat from LED components is the most significant challenge in LED lighting technology (Park et al., 2004) (Hwang et al., 2004).

1.4 A heat pipe as a heat transfer channel

The heat pipe concept was first suggested by Gauger (1944), although it was not immediately implemented. In 1963, Grover (1966) filed for a patent on an "Evaporation-Condensation Heat Transfer Device," and as a result, heat pipes were put into practice. Based on different wick structures, heat pipes can be divided into wicks and thermal siphons. Both types are efficient at transmitting a great amount of heat by using the latent heat of different working fluids as they undergo phase changes.

Wick structure heat pipes are composed of the following materials: (1) an airtight container, (2) a capillary structure (wick structure), and (3) working fluid parts. Wick structures offer channels for working fluids to flow back on capillary power, which frees heat pipes from requiring extra power. When the evaporation end of the pipe is heated, the heat will vaporize the working fluids close to the pipe wall. The vapor pressure in the heated end is increased, generating a vapor flow to the condensation end. At the condensation end, the vapor releases its latent heat and condenses into a liquid. The liquid inside the wick structure returns to the evaporation end through capillary force to complete the cycle. In this vapor-liquid cycling process, outside power is not needed. Latent heat from phase changes will complete the transfer of heat, making a great amount of heat transmission possible.

Currently, little or no information is available in the literature concerning the thermal performance of rectangular heat pipes with discrete point sources. Only Lai et al. (2008) investigated a similar LED lighting configuration that used heat pipes as heat transfer channels to conduct heat from an LED to heat-sink fins. Natural convection inside the flow channels within the heat-sink fins or the forced convection made by the returned flow of an HVAC system serve as the overall heat elimination mechanism. It has been shown that with natural convection, the highest temperature of the mid-section heat pipe can reach 60°C with an even temperature distribution without distinctive highs. With a slight breeze (with 1 m/s airflow) induced by an air return, the highest heat source temperature is reduced to 42°C, later, there is hardly any difference in temperature compared to the increase of air flow.

The goal of this study was to effectively remove heat from the developed indoor LED lighting prototype using appropriate heat transfer channels (rectangular grooved heat pipes) combined with the integrated operation of building environment control. The thermal performance of the so-developed LED lighting prototype at different inclination and rotation angles (different heat pipe performances) were experimentally investigated to accommodate different illumination angles.

2. Research Method

2.1 Development and design of the experiment model

This study replaced traditional fluorescent lamps with white light LEDs. This innovative modular design can replace the T-bar room lighting equipment (Fig.1.) used in offices, libraries, classrooms, and hospitals. If heat cannot be directly removed from the LED, the junction temperature of the LED chips will become too high, negatively affecting light output and LED life. Thus, white light LEDs and heat dissipation requirements were integrated into room lighting equipment and placed in common rigid frame ceilings. The following details the experimental model development.

![Fig.1. The Proposed Prototype Installed in a Common Rigid Frame Ceiling](image_url)

Heat pipes can be used as heat transfer channels to transfer the released heat to the heat-sink fins. Natural
convection around the heat-sink fins, or the forced convection induced by the return airflow of an HVAC system, can serve as the overall heat elimination mechanism. The released heat of the LED light can be successfully transferred to the ceiling space or the HVAC evaporator to ensure normal operation of the LED light and maintain long LED lifetime. (Fig.2.)

In this application, LED lighting must achieve a lumen output (about 1200 lm), typical to indoor lighting. This experiment used 36 x 3W white light LEDs to satisfy the aforementioned illumination requirements. Four heat pipes were installed into the lighting equipment to facilitate heat transfer. Each rectangular heat pipe was attached to nine 3W white light LEDs. These LEDs can be regarded as discrete point-heat-sources. Six fins were placed on each side of the heat pipes to enhance heat dissipation. The pitch between fins was adjustable, and was fixed to 9 x 10^{-3} m.

This structure can be installed in a common rigid frame ceiling (as in Fig.1.). In accordance with repetition principles and reasonable boundary conditions, this study uses 1/4 of the prototype as the investigation target. It is referred to as the experiment model, as in Fig.3.

The LED grains used in this investigation were white light 3W LEDs (Lumileds, 2007). Nine 3W LEDs were evenly attached to the bottom of the 5 x 10^{-3} m high rectangular grooved heat pipe. The two sides of the heat pipe and fins were combined to form the condensation end. The heat pipe wall is copper, while the wick structure is a copper groove. The original pipe diameter was 8 x 10^{-3} m. A small amount of cold rolling was applied to the cylinder heat pipe to facilitate an appropriate paste surface of LED grains. The pressed-flat heat pipe measured 5 x 10^{-3} m in height and 0.6m in length, as depicted in Fig.4. The internal working fluid was water. The evaporation section and condensation length were 0.468 m and 0.102m, respectively.

Heat emission paste was applied to the surface between the LED grain bottom and heat pipe. The purpose of the heat emission paste was to fill the gaps between surfaces and between each component in the heat emission module, reduce the contact thermal resistance and enhance heat emission performance. The heat conduction coefficient of the heat emission paste was 4.18W/m·K for temperatures between 0 and 170°C.

2.2 Experimental apparatus
The entire system was controlled in a 25°C air environment. The nominal water mass inside the heat pipe was 2.52x10^{-3} kg. In order to accommodate different illumination angles, inclination angles (θ) of 0°, 30°, 60°, and 90° of the experimental model were used, as shown in Fig.5.(a). Rotation angles, α, were set at 0°, 30°, 60°, and 90° as in Fig.5.(b). Ten thermocouple points were evenly distributed in the heat source area under the codes CH7 through CH16. Three thermocouples were distributed on the two sides of the condensation ends, respectively, under codes CH2, CH3, and CH5 (left end), and CH18, CH20, and CH21 (right end). Temperature changes from the initial to steady state condition were recorded. Omega T-type (PR-T-24) thermal couples were used to measure the temperature in this experiment.

3. Results and Discussion
3.1 Influence of rotation angle on heat dissipation
In this section, the inclination angle, θ, was fixed to 0° at different rotation angles, α (α=0°, 30°, 60°, and 90°) to measure the thermal performance of the prototypes.
The small figure on the top left of Fig.6. shows the time variations of different pipe wall temperatures when the heat pipe rotation angle was 0°. The temperature quickly changed from a transient state to a steady state in approximately 200 seconds. Similar behaviors were observed for rotation angles of α=30°, 60°, and 90°. Fig.6. depicts the heat pipe wall average temperature at steady-state for rotation angles of 0°, 30°, 60°, and 90°. When the inclination angle, θ, was 0°, the influence of rotation angle was not significant. After the heat pipe with the nominal water amount reached steady state, the LED bottom (i.e. heat pipe wall) average temperature was around 46°C.

In horizontal rotation, under the proposed heat dissipation model, the steady state temperature of the heat pipe with a nominal water amount was quite good. The heat source area was not observed to change as a function of rotation angle, and is due to the smooth vapor flow inside the pipe, which allows the vapor to be effectively spread to the condensation end. There is also sufficient condensation fluid, flowing back to the heat source area and allowing the heat source to remain at a stable temperature.

3.2 Influence of inclination angles on heat dissipation

Using the same experimental method, the rotation angle α was fixed to 0° (LEDs emit downward vertically) while the inclination angle θ was varied. Thermal performance of the rectangular grooved heat pipes was measured for θ=30°, 60°, and 90°.

3.3 At an inclination angle of 30°

From Fig.7., the steady state temperature of the heat pipe can be grouped into 2 categories. The average temperatures of CH9, CH10, and CH11 were 65°C, 75°C, and 70°C, respectively. The temperatures at these points (bottom left part of the heat pipe) were higher than those at other points and unstable. In Section "Observation of unstable phenomena", the temperature spectrum of the point CH11 will be discussed to explore this instability. In the transient states of CH10, CH11, CH12, and CH13, after initiation of the LED light source, there is a period of sudden temperature overshooting. The peak temperature of the overshoot is quite high, with a duration as long as 10 min. This is detrimental to LED life, that is, if the LEDs are used in situations of frequent switching on and off, these temperature overshoots will adversely affect device lifetime. The temperatures in CH12 and CH13 in the initial stage are also quite high. At steady state, they drop to around 55°C. This is likely related to the detailed flow field inside the pipe and is worth future investigation.

3.4 At an inclination angle of 60°

From Fig.8., the steady state temperature of the heat pipe wall is between 50 and 85°C. The average temperature of CH9 and CH10 was 85°C, while CH11 was 75°C. At these points (i.e. bottom left part of the heat pipe), the temperature was higher than in other measurement points. The overall temperatures were around 5 to 10°C higher than those observed at 30° inclination angles. In their steady state, the
temperatures at all locations are unstable. The temperature in CH12 (on the top right part of the heat pipe) was also quite high in the initial stage. At steady state, it decreased to around 55°C.

3.5 At an inclination angle of 90°
From Fig.9., the steady state temperature of the heat pipe with a nominal amount of water was between 50 and 95°C. The highest heat average temperatures in CH9, CH10, and CH11 were between 85 and 95°C, while in CH12 it was around 75°C, and in CH8 around 65°C. The overall temperatures at an inclination angle of 90° were higher than those at the previous two
inclination angles. Steady state temperatures in these places were also unstable.

4. Findings
At any inclination angle $\theta > 0^\circ$, gravity causes fluid inside the pipe to flow downwards, which in turn, causes the vapor to flow upwards. At high inclination angles, insufficient water quantity results in very high temperatures occurring in a stratified distribution. This is possibly due to the fact that the fluid in the pipe is concentrated at the bottom condensation end, and so the heat source is unable to conduct heat via phase
changes. Heat transfer then only occurs through the heat pipe wall, thus causing the stratified temperature distribution.

4.1 Observation of unstable phenomena

From the time-temperature figures (Figs.7.-9.), the temperature fluctuation in the heat pipe with the nominal amount of water was most distinctive in CH10 and CH11. The frequency profile of the inclined heat pipes is of considerable interest since it relates to local high-temperature fluctuations. Using MATLAB’s FFT (Fast Fourier Transform) command on the CH11 data, the frequency spectrum was obtained, as shown in Fig.10. Temperature variation frequencies $f_N$ in this experiment were lower than 0.01 (Hz). The sampling frequency of the data logger $f_s$ was 1 (Hz), and thus, satisfies the Nyquist criterion ($f_s$ must be at least twice $f_N$). The measured temperature will help distinguish temperature variation periods.

The top right small figure in Fig.10. corresponds to the spectrum created by air conditioning, which was used to stabilize the thermal environment outside the experiment models. Those frequencies (from the air conditioning) were excluded from the frequencies in the CH11 spectrum. From Fig.10.(a), at an inclination angle of 30°, the temperature fluctuation was around 0.003437 Hz (4.8 min) with a dominant frequency. At an inclination angle of 60°, the dominant frequency in CH11 was 0.003806Hz (4.5 min) (data and figure not shown). From Fig.10.(b), at inclination angle 90°, the dominant frequency of the temperature was 0.003348Hz.

Fig.10. Spectrum of Temperature Fluctuation of Point CH11 at Inclination Angle 30 and 90

(X: Frequencies Made by Air Conditioning)
Thus, under different inclination angles, dominant frequencies of temperature fluctuation around the central area of the heat pipe were consistently around 4.7 minutes.

5. Conclusion

In a horizontal rotation, under the proposed heat dissipation model, the steady state temperature of the heat pipe with a nominal amount of water is quite good. The temperature of the heat source area was observed to be independent of horizontal rotation angles. At high inclination angles, insufficient water quantity leads to very high temperatures in a stratified distribution.

At an inclination angle of 30°, the temperature in the bottom left of the heat pipe center was higher than in other places, and steady state temperatures were observed to be unstable. From the four transient temperature curves, after the initiation of the LED, there was a sudden rise in temperature with a very high peak. The transient time can be as long as 10 min. At an inclination angle of 60°, the temperature in the bottom left of heat pipe center was higher than that in other places. The overall temperature was around 5 to 10°C higher than that at a 30° inclination angle. At steady state, the temperatures at all locations were unstable. At an inclination angle of 90°, the overall temperature was higher than those at the previous two inclination angles, and steady state temperatures were also unstable. FFT analysis of data from the different investigated inclination angles revealed dominant fluctuation frequencies of the temperature around the central area of the heat pipe at about 4.7 minutes.

Acknowledgements

Support from the National Science Council of ROC in this study is gratefully acknowledged. The author's sincere gratitude goes to Assistant Professor Ming-Tzer Lin and Mr. Zhao-Qi Zheng at the Institute of Precision Engineering, National Chung-Hsing University, Taiwan for their assistance throughout the measurements.

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