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Abstract - This paper describes some of the current research in the area of lamp wall temperature control for the purpose of enhancing light output under elevated temperatures. More specifically a thermally conductive heat pipe has been employed to maintain optimum lamp wall temperature under varied ambient temperatures. Advantages of a heat pipe over previous methods of enhancing light output include no external power necessary and flexibility in orientation within the fixture. The experiments described include the calibration of a heat pipe against a known thermal load, the application of a heat pipe to a lamp in a test chamber and the placement of a heat pipe within a fixture. Theory and experimental data indicate that optimum lamp operating conditions can be maintained throughout an ambient temperature range which typically reduces light output by 20%.

I. INTRODUCTION

This paper describes the use of a heat pipe for the purposes of reducing the lamp wall temperature of a fluorescent lamp in an enclosed fixture. Previous studies [1,2] have shown that both light output and lamp/ballast efficacy are greatly reduced as the minimum lamp wall temperature (MLWT) exceeds 40°C. The typical enclosed fixture produces an ambient temperature of 40-50°C. At this elevated ambient temperature the MLWT can reach 50-60°C and light output is reduced by as much as 25% with a decrease in efficacy of 12%. The use of a heat pipe to reduce the lamp wall temperature of a fluorescent lamp will improve its performance with respect to light output and efficacy.

Previous heat pipe applications [3] have concentrated on the use of fluorescent lamps operated outdoors. The device used in that work was cumbersome and complex for the application considered. Recent advances in heat pipe technology may enable the heat pipe to become a cost effective means for improving the light output and efficacy of fluorescent lamp systems.

The objective of this research is to investigate the feasibility of maintaining near optimum light output and efficacy of a fluorescent lamp system through the use of a heat pipe. The first step taken was to calibrate the heat pipe against a known power load. The heat pipe was then applied to the surface of a lamp in a test chamber, simulating ambient conditions inside a fixture. Finally, the heat pipe was placed in a fixture to demonstrate the performance that would result in a realistic application. A brief description of the principles of operation of the heat pipe is included. Following the presentation of experimental results is a discussion of these results and a summary considering further efforts in this area.

II. PRINCIPLES OF OPERATION

The heat pipe is a device of high thermal conductivity characterized by a near isothermal surface of low thermal impedance [4]. The device's heat transport is based upon the latent heat of vaporization. Figure 1 is a schematic of a heat pipe and describes its main components. The heat pipe consists of a sealed metal tube with an internal wick material and filled with a working fluid. The wick permits the heat pipe to be used in any orientation. Selection of working fluid material is determined by the range of control temperatures desired. As heat is applied to the evaporator region, or source the vapor pressure of the working fluid increases. The increase in vapor pressure is the driving force for the movement of the vapor through the adiabatic region towards the condenser region where heat is dissipated and the vapor condenses. The condensed vapor is then returned to the evaporator by capillary action through the wick completing the cycle.

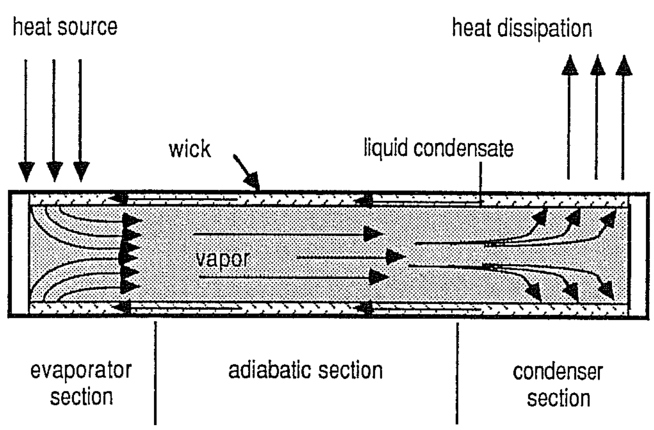

Fig. 1. Cross section schematic of the heat pipe illustrating the transfer of heat.

At start-up when heat is applied to the evaporator there is a temperature gradient between the evaporator and condenser. A pressure gradient is then produced along the length of the pipe initiating the flow of the vapor. When the heat pipe action commences vapor moves to the condenser region and is eventually returned to the evaporator region. The entire process of thermal transport is via phase transformations, with the liquid-vapor material being nearly the same temperature throughout the heat pipe. By selecting a working fluid with a high value of latent heat of evaporation for the temperature range of interest large quantities of heat can be transported making for a high thermal conductivity.

An important aspect of the heat pipe design is the dissipation of the heat at the condensing region. This determines the rate at which heat will be removed for a particular working fluid to operate over its effective temperature range.

III. EXPERIMENTAL APPARATUS AND METHODOLOGY

Two experimental setups were required to carry out a series of tests that would both characterize the heat pipe against a known power source and measure the heat pipe's performance as applied to a fluorescent lamp.

A. Calibration Apparatus

A calibration experiment was conducted which monitored the control spot temperature of the heat pipe as a function of input power. A schematic of the calibration apparatus is shown in Figure 2. A variac delivered ac power to a measured length of nichrome wire wrapped around the evaporator region of the heat pipe. The power was measured using an in-line watt meter. Insulation surrounded the region in which power was delivered to assure that all the electrical power was absorbed by the heat pipe and not by the surrounding atmosphere. Enclosing the heat pipe was a 2 ft length of 8 in diameter acrylic tubing used to dampen any air movements to maintain constant heat dissipation. The tube was open ended and had vent holes at the fin region to allow adequate ventilation in order to maintain a constant ambient temperature. The temperature was measured at various positions along the heat pipe with thermistors. The heat pipe was tested in both the horizontal and vertical orientations for an input power range of 0-3.5 W in 0.5 W increments. The comparison of orientations was made to weigh the advantages of the effects of gravity aiding condensate return to the evaporator over the heat dissipation efficiency of the fin.

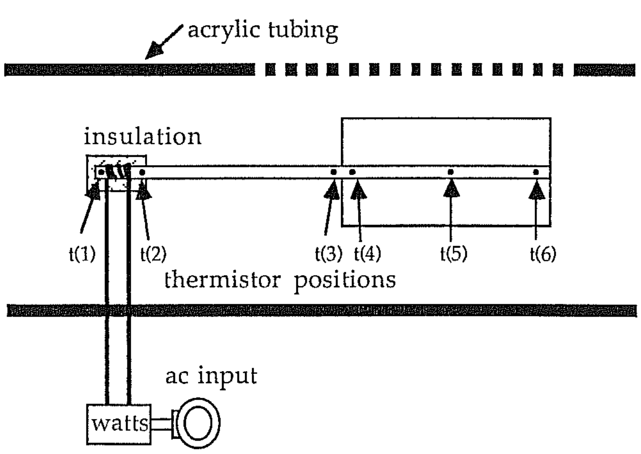

Fig. 2. Experimental setup used to calibrate the heat pipe with a known power source.

B. Lamp Chamber Apparatus

A lamp chamber was constructed to simulate the ambient conditions that a fluorescent lamp would see in a variety of enclosed fixtures. The lamp chamber experiments consisted of two thermally isolated and controlled regions as shown in Figure 3. Region I contains two 40 W F40-T12 lamps each operated with separate single lamp core ballasts. The power into each lamp/ballast system is measured along with the temperature of a control spot located on the bottom surface of the lamp at its midpoint. The control spot temperature for each lamp is monitored with a thermocouple imbedded in a copper junction which makes thermal contact with the lamp wall. Two sizes of copper junctions were used to determine the effect of cooling spot size on lamp efficacy. The small junction measures 0.5 in from the curved surface which contacts the lamp to the surface that contacts the heat pipe, with a width of 3/8 in and a length of 0.5 in. The large junction has the same dimensions except the length is 5.0 in giving it a contact area ten times that of the small junction. The lamp shown on the right in the lamp chamber schematic is designated as the control lamp to which the heat pipe is to be applied. Relative light measurements were made on the control lamp via a double slit collimator located approximately 8 in from one end of the lamp. Region I is thermally isolated and its temperature is controlled to provide a range of ambient conditions similar to those that a fluorescent lamp would experience in an enclosed fixture Region II is the heat dissipation chamber and as in Region I its temperature is independently controlled by a proportional controller. For all tests Region II was kept at 25°C. Between the two chambers is a small opening through which the heat pipe can be positioned onto the control spot junction which is coupled to the surface of the control lamp, while allowing the dissipation fin of the heat pipe to remain at 25°C.

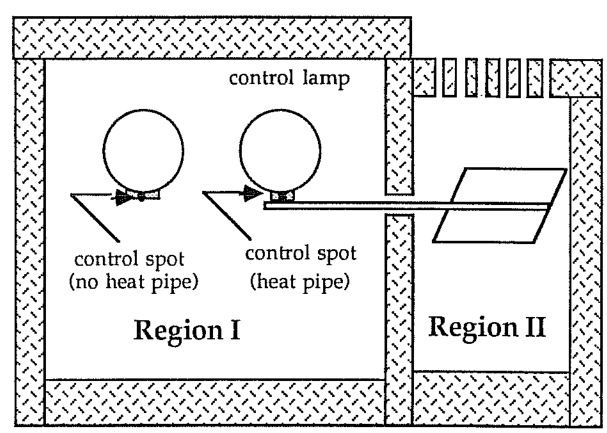

Fig. 3. The thermally isolated system used to measure the performance of the heat pipe. The temperatures in Region I and II are independently controlled to simulate a fixture environment.

With the dissipation fin in an ambient of 25°C the heat pipe was tested using both the large and small junctions in turn. Two tests were conducted with each of the two sized junctions in place in order to determine the lamp wall temperature that the lamp would attain without the heat pipe at the different chamber temperatures. The lamp chamber ambient temperature was varied from 30-60°C in 5°C increments. Each ambient temperature level was held constant for a minimum of two hours to ensure equilibrium.

C. Fixture Application

To demonstrate a practical situation the heat pipe was employed to lower the temperature of a 40 watt F40-T12 U-tube lamp in 2 x 2 ft lens fixture. The fixture was surface mounted on a ceiling test plane and a small hole was made in the fixture wall near the midpoint of the lamp's curvature to facilitate attachment of the heat pipe to the lamp. The heat pipe was placed in thermal contact with one of the lamps using the small junction to monitor control spot temperature. When equilibrium was reached the junction was held in place and the heat pipe was removed to determine the change in control spot temperature. The ambient temperature surrounding the heat dissipation fin was approximately 21°C and was between 40°C and 45°C inside the fixture.

IV. EXPERIMENTAL RESULTS

A. Heat Pipe Calibration

The calibration of the heat pipe against the known input power is shown in Figure 4. Horizontal orientation of the heat pipe had a range of control spot temperatures from 21°C at zero power conditions to just over 40°C at 3.5 W. Under the same power loading the control spot temperatures associated with the vertical positioning of the heat pipe ranged from 21°C up to 52°C at the 3.5 W power load. In both orientations the dissipating fin was in an ambient temperature of 25°C. This data enabled the estimation of the thermal power extracted from the lamp with the two junction sizes used in the lamp chamber experiments.

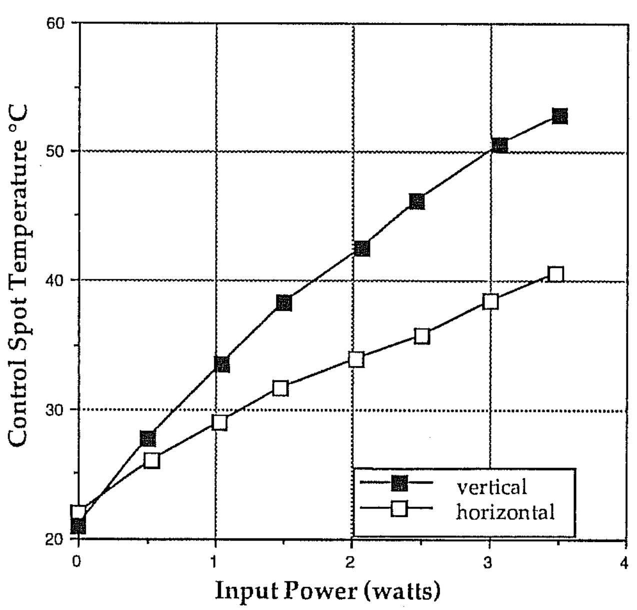

Fig. 4. The measured cold spot temperature for a heat pipe oriented in vertical and horizontal positions for an input power range of 0-3.5 W.

B. Lamp Chamber Tests

Control spot temperatures for two of the configurations tested in the lamp chamber are plotted in Figure 5 as a function of lamp chamber ambient temperature. The heat pipe used with the large junction produced cold spot temperatures 5°-10°C higher than those obtained using the small junction with the heat pipe. The control spot temperatures with the heat pipe show that the larger junction is higher in temperature by virtue of absorbing more heat. The control spot temperatures of the two junction sizes without the heat pipe remained similar to each other across the range of ambient temperatures. The control spot temperatures obtained with heat pipe cooling were approximately 10-28°C lower than the uncooled control spot temperatures over the range of ambient temperatures.

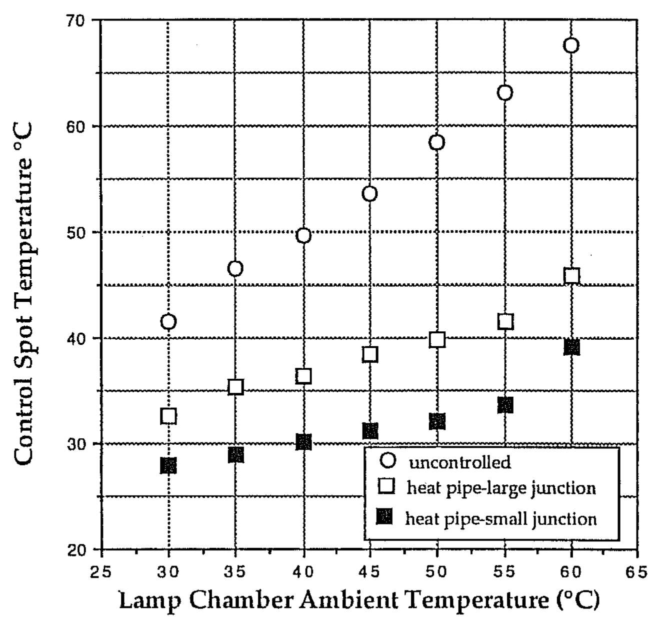

Fig. 5. Measured cold spot temperatures for the lamp controlled by the heat pipe coupled with both small and large junctions, as well as, the uncontrolled lamp.

Relative light measurements for the configurations tested are shown in Figure 6. The relative light outputs for the configuration of the uncontrolled lamp, the heat pipe with large junction, and the heat pipe with small junction as a function of lamp chamber ambient temperature show that the use of the heat pipe maintains the most constant light output over all of the ambient temperatures for the smaller junction. Note that the light output begins to decrease for the larger junction at ambients above 50°C. The decrease in light output at the increased ambient temperature depends upon both the amount of heat the cooling fin can dissipate and the junction size used to couple the heat pipe to the lamp wall.

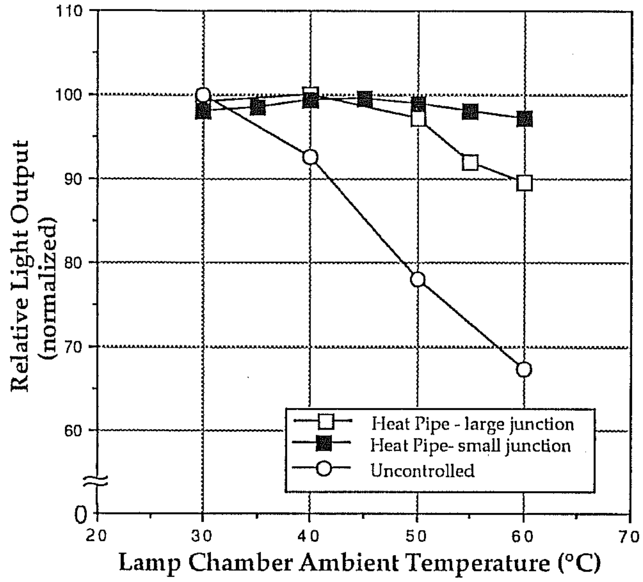

Fig. 6. The relative light output for the lamp controlled by the heat pipe coupled with both the small and large junctions, and uncontrolled over a 40-60°C ambient temperature range.

Normalized lamp efficacy versus lamp chamber ambient temperature for the same three configurations is shown in Figure 7. The curves follow the same trend as the relative light output. The lamp controlled with the heat pipe with the small junction maintains its high efficacy at high ambient temperatures while the large junction its efficacy decreases above the 50°C ambient temperature.There is some evidence of both curves having a slight maximum at 40°C ambient temperature.

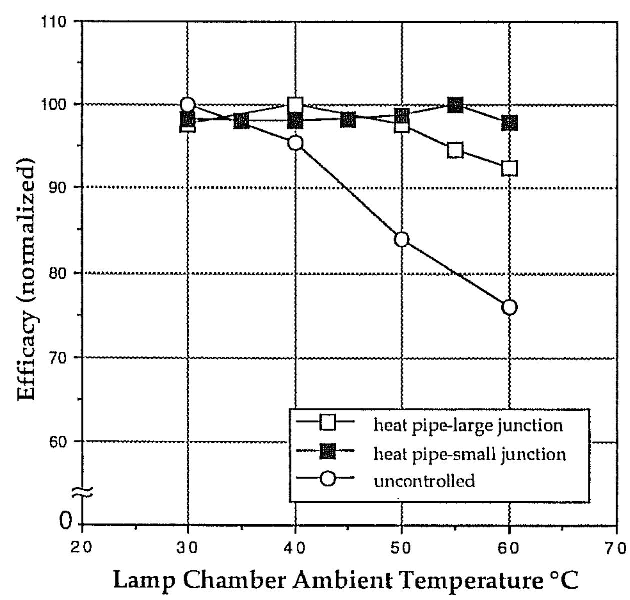

Fig. 7. The change in efficacy of a fluorescent lamp system with and without lamp wall temperature control over an ambient temperature range of 30-60°C.

C. Fixture Test

The heat pipe controlling one lamp of a 2 x 2 ft U-tube lens fixture demonstrated a reduction in control spot temperature of approximately 20°C. The heat pipe cooled lamp was visibly brighter than the uncontrolled lamp, as viewed through the lens. For this particular fixture the ambient temperature inside the fixture ranged between 40°C and 45°C. The control spot temperature for the uncontrolled configuration reached approximately 49°C on two separate runs. In utilizing the heat pipe the measured junction temperature was reduced to 29°C.

V. DISCUSSION

A. Actual Lamp Wall Temperature

The actual lamp wall temperature was not directly measured in these experiments. Doing so would have affected the intimate contact between the lamp and the copper junction necessary for efficient heat transfer. The cold spot measured in the copper junction was less than the lamp wall temperature . Considering that the lamp is the heat source and the heat pipe is the heat sink it follows that a thermal gradient exists across the copper junction in which the control spot temperature is measured. Therefore the control spot measured is lower than the actual minimum lamp wall temperature. The difference between MLWT and control spot temperature can be estimated by referring to Figures 5 and 6. Figure 5 shows the control spot temperatures for the small junction to range from 28-31°C for ambient temperatures of 30-50°C. Figure 6 shows that for the same ambient temperature range the corresponding light output varies by less than 2% from its maximum. Previous work on the temperature dependance of fluorescent lamps [1,2] show that the temperature dependance is relatively flat between 37°C and 40°C MLWT. On this basis we estimate that the actual MLWT's are approximately 9°C greater than the cold spot measurements.

For the uncontrolled lamp measurements (Figure 5) the control spot measurements are still taken with a copper junction but without the heat pipe. In this case the control spot temperatures are closer to the actual MLWT due to a smaller thermal gradient. Figure 6 shows that the light output for the uncontrolled lamp is near maximum for a control spot temperature of 42°C indicating that the actual lamp wall temperature is slightly above the 37-40°C MLWT where maximum light occurs.

Based upon the above estimates of actual MLWT the results from the fixture test indicate an actual MLWT of 37°C for the 29°C cold spot temperature measured. At this temperature the lamp/ballast system is operating close to maximum efficacy, well above the efficacy obtained from the uncontrolled mode with a control spot temperature of 49°C.

B. Cooling Spot Size

Several factors need to be examined to determine optimum cooling spot size. Advantages of a small cold spot include minimal shadowing, low heat removal requirements (therefore simplified heat dissipation requirements) and maintenance of near optimal efficacy at high ambient temperatures. However too small a cooling spot size has limitations. Upon initial operation of the lamp the migration and condensing of excess mercury to a small spot will take a long time. Additionally a small cold spot limits its location to the lower surface of the lamp wall. With a small cold spot the mercury will condense into droplets large enough to fall from the control area resulting in loss of control and thus reduced light output.

C. Heat Dissipation Design

In this study a cooling fin was attached to the condensing region of the heat pipe. Although near optimum light levels and efficacy were maintained over a wide range of lamp chamber ambient temperatures only one dissipation ambient temperature was accounted for. In the controlled experiments the cooling fin was in an ambient temperature of 25°C. The surface temperature of the fixture shell is generally higher than the surrounding ambient. A pragmatic design would employ the fixture shell as the heat dissipating fin, utilizing the large surface area to offset the increased thermal environment. Future studies will consider practical heat dissipation techniques for a range of thermal environments and a variety of fixture designs.

VI. SUMMARY

This study has examined the use of the heat pipe to reduce the lamp wall temperature of fluorescent lamps. The advances on heat pipe technology enable the device to be used in any orientation and their widespread use has reduced their manufacturing cost to a level which would allow them to be used in lighting applications.

Experimental tests have shown that the use of a heat pipe to reduce lamp wall temperature results in near optimum lamp/ballast system performance over a wide range of lamp chamber temperatures. At ambient temperatures that typically reduce efficacy by 20% the use of the heat pipe reduced this loss to less than 2% from maximum efficacy.

While we have demonstrated the effectiveness of the heat pipe in one fixture type further experimentation is required in order to ensure an equal level of performance for a variety of fixture types. With the advent of compact fluorescent systems and considering their inherently high operating temperatures the implementation of the heat pipe as a cooling device could find substantial utility.

VII. ACKNOWLEDGEMENT

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