Great Lab Challenge 2014

Heat Pipe Cooling Design System for Osram LED Luminaires

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Introduction and Motivation

LEDs are currently the pioneering innovation in an industry that is moving towards long-lasting, energy efficient, and high output solutions. However, the issue of heat generation is a significant hurdle towards realising the full potential of LEDs because the sensitivity of LEDs results in a greater vulnerability to the detrimental effects of heat. The detriment is twofold; both the lifetimeand light outputhave shown appreciable reductions with higher heat.

Our goal for this project is to propose alternative forms of passive cooling that are both efficient and cost-effective. We aim to improve the efficiency specifically in two areas:

i) The transfer of heat out of the LEDs.

ii) The design of the LED casings and housings themselves.

We are not entirely eliminating the heatsink approach, but we aim to modify current designs and utilise different technologies in conjunction with heatsinks. We hope to do so in a way that will increase the commercial viability of LEDs significantly, with methods and design elements that serve to enhance the LED package holistically.

In this proposal, we have provided two designs, each specialising in its own application; Design 1, a bulb-shaped design, and Design 2, a flat planar design. The bulb design is more geared to small scale applications such as decorative lighting and indoor applications, although it is still viable on a larger scale. In contrast, the flat planar design is designed to be compatible with SSL-based modules currently in use, and is able to provide reliable lighting across large areas such as in commercial and industrial use.Each sub-topic in the Technical Details section will be labelled to indicate its relevance to either Design 1, Design 2, or both.

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A. Technical Details – Cooling Solutions

1. Heat Pipe – Design 1 & 2.

Our motivation behind choosing the heat pipe as an enhancement to current LED cooling solutions stems from their high reliability and widespread use in similarly high-powered sensitive applications such as computer technology. We believe that it is able to provide a more effective cooling solution than a simple heatsink for three reasons;

Firstly, the circulation of the working fluid inside the heat pipe is able to transfer heat with minimal difference in temperature as opposed to current heatsinks which need to operate at a higher temperature before the heat removal rate becomes appreciable. This results in a higher operating temperature which is a significant cause of lifespan reduction. Our design is able to initiate cooling from the outset, allowing a lower operating temperature to be maintained, hence increasing lifespan and enhancing a major selling point of LED systems.

Secondly, heat pipes are a form of passive cooling; that is, they are able to function without any additional power input. This is in contrast to active cooling solutions such as fans and Peltier cooling which draw power as they are used. These need to increase the efficiency of the LEDs by a large proportion in order to justify their implementation, since they consume power themselves. However, our passive cooling methods are able to act as a direct upgrade over current systems without increasing the running costs, which can be significant in large-scale commercial applications.

Thirdly, its high reliability and low maintenance even under high stress conditions make it ideal for the high-power LED's anticipated use especially in the commercial and industrial sectors. These require low-maintenance lighting because both the structure and volume of these sectors make frequent maintenance and replacement extremely expensive and labour intensive. We believe heat pipes are the ideal solution because, barring leakages, they have little to no points of failure, especially due to the lack of moving parts.

We have two different designs incorporating heat pipes, each with a specific intended application. Our bulb type design uses a loop shaped heat pipe, while the planar design includes linear heat pipes. Although the working principle of both pipes is roughly the same, the choice of shape for each design is intended to match the shape of the casing and the airflow created by each design. As such, each section has its own explanation.

1.1 Working Principle – Design 1 & 2.

A heat pipe consists of a working fluid inside a sealed conductive container. By choosing a working fluid whose boiling point is close to our intended operating temperature of the LED, we are able to ensure that the heat produced during the operation of the light causes the fluid to vaporise. As the latent heat of vaporisation for most liquids is very high, the working fluid is able to absorb large amounts of heat from the LEDs easily as it turns into vapour.

The vapour travels along the pipe to the cooler end at which point it gives up its heat and condenses back into a liquid form. The liquid form then flows back to its original point and repeats the cycle. The pipe is lined with a wick, which serves to absorb the liquid, as well as provide a means for it to flow back to the heated end by capillary action. This is due to the fluid pressure continually replenishing the working fluid as it evaporates.

Heat is removed from the cooler end by convection and through interaction with the surrounding airflow. We have designed the pipes in such a way as to allow air to flow opposite to the movement of the fluid by capillary action, so as to maintain the temperature gradient and heat removal all the way along the heat pipe.

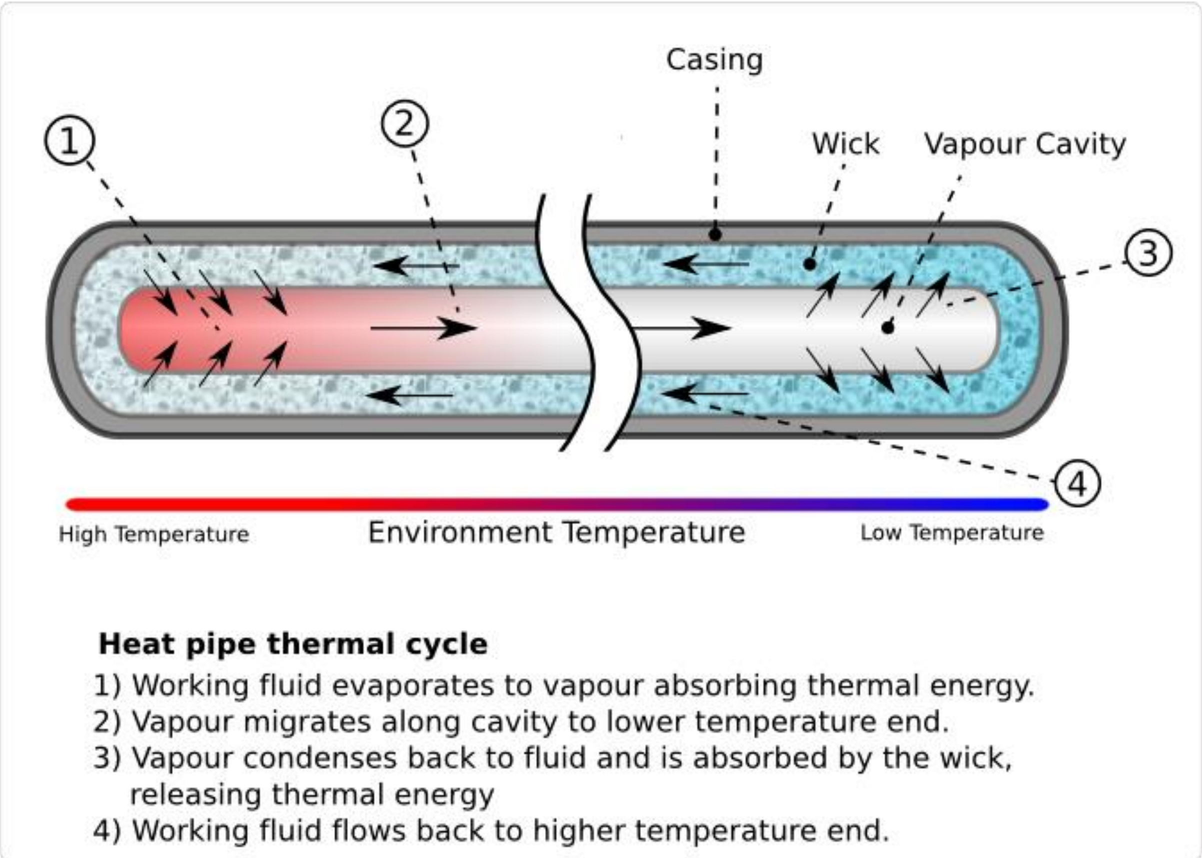

Fig. 1 – Heat Pipe Cycle, Source: Wikipedia

We have several choices of working fluid suited to our temperature range which are:

i) water

ii) ammonia

iii) ethanol

iv) acetone

All of these are viable in the temperature range of 25 degrees Celsius up to over 100 degrees Celsius. By varying the internal pressure and amount of fluid we are able to optimise the heat pipe our specific LED operating temperature.

We plan on making the heat pipe out of either copper or aluminium as both are excellent thermal conductors and are relatively easy to obtain. The final choice of material will be dependent on the working fluid eventually chosen as each fluid interacts chemically in a different way.

At the condenser end, fins are attached to the heat pipe to provide maximum surface area in contact with the surrounding air. This greatly increases the heat transfer rate out of the package, and increases the efficacy of the heat pipe as well, as it relies on both evaporation and condensation of the working fluid to work. A small amount of regular maintenance to remove dust or a dust filter is therefore necessitated by the nature of the cooling solution.

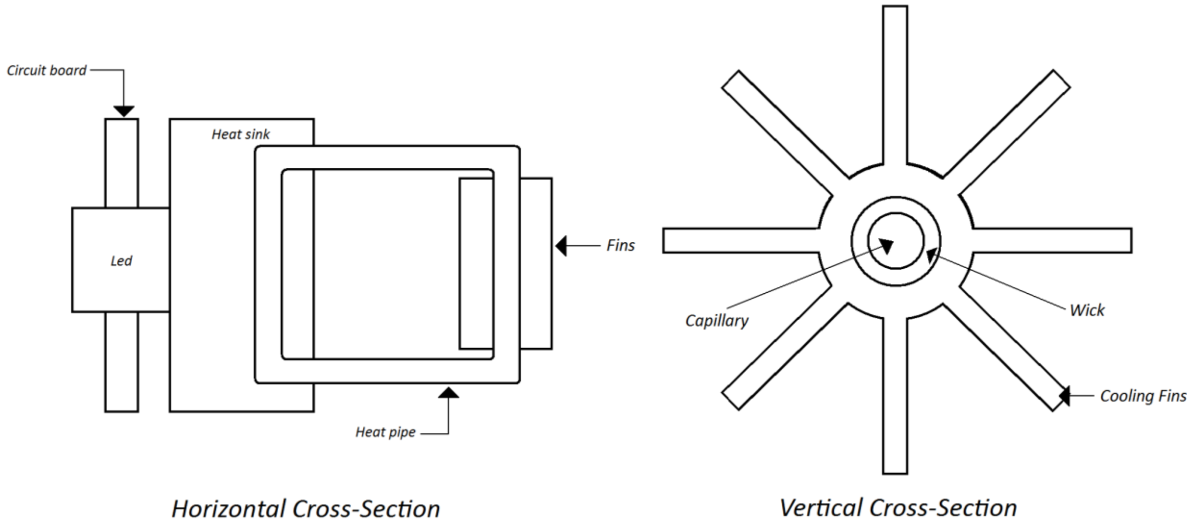

Fig. 2 - Vertical and Horizontal Cross Section of Heat Pipe

1.2 Capillary Pumped Loop Heat Pipes – Design 1.

We opted to use loop heat pipes in our bulb shaped design (Design 1), as shown in the diagram. One end of the loop is connected to the evaporator, where it receives heat from the components, and the other end of the loop is in contact with the air, at the condenser side. There are fins attached to the condenser side of the loops that serve to dissipate heat, and hence cool the working fluid.

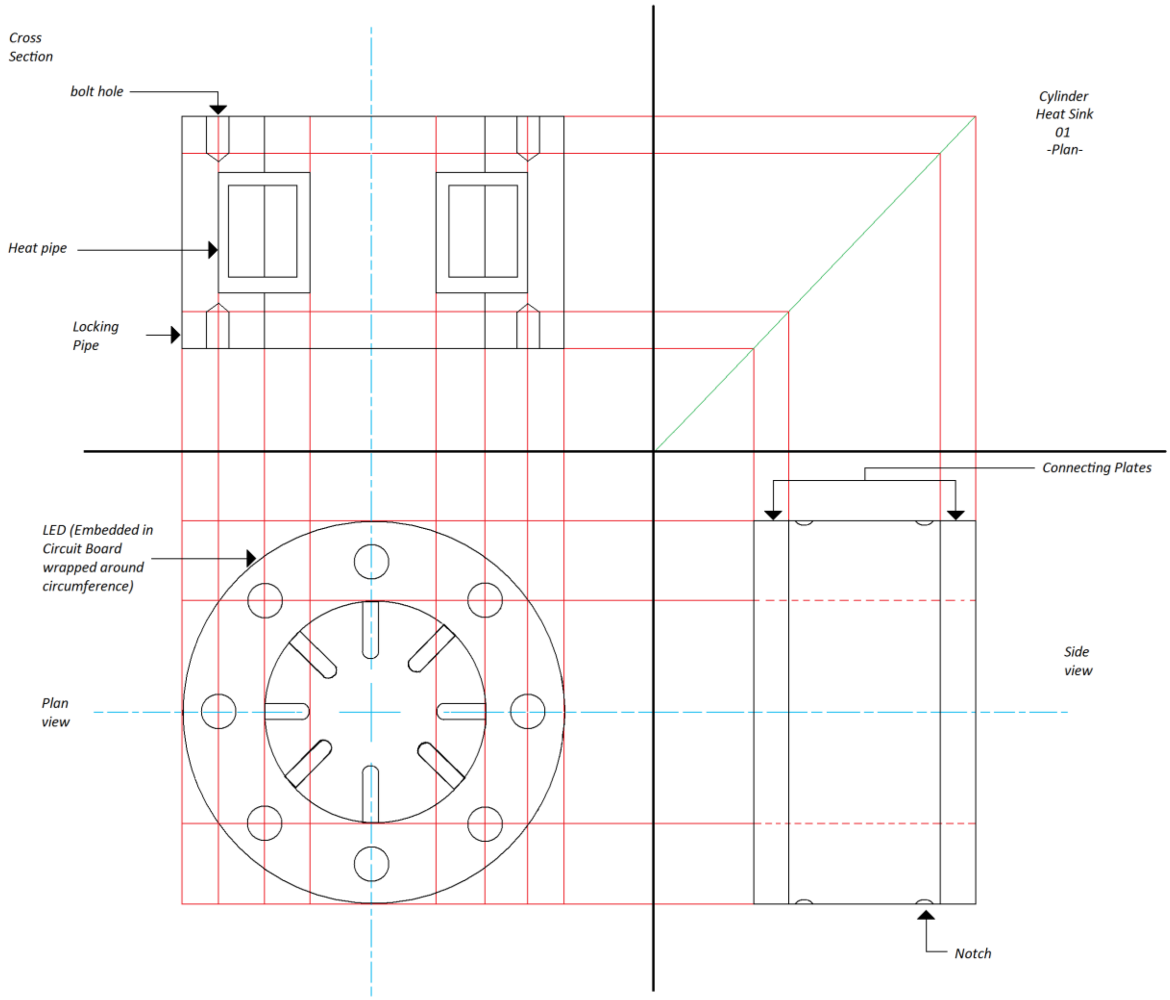

Fig. 3 - Schematic of the bulb shaped design.

The core of the bulb consists of heat pipes arranged in a ring, and embedded in either copper or aluminium blocks which serve as the evaporator. For ease of reference, the picture has been simplified with the exclusion of fins on the evaporator and condenser ends. The LEDs will be attached to the exterior of the cylinder while two plates at the ends hold the whole package together.

Inside the heat pipe, working fluid will circulate from the hot end of the loop (the evaporator) to the cold end in air. At the hot end, working fluid absorbs heat from the components and vaporises. Hot working fluid vapour flows around the loop and travels to the condenser side. Outside the condenser, air heated by the hot working fluid rises, while inside the condenser, the working fluid travels downwards.In the condenser,working fluid condenses as it travels downwards, and continues to release heat to progressively cooler air so by the time it leaves the condenser, the temperature of the working fluid is close to that of the air.

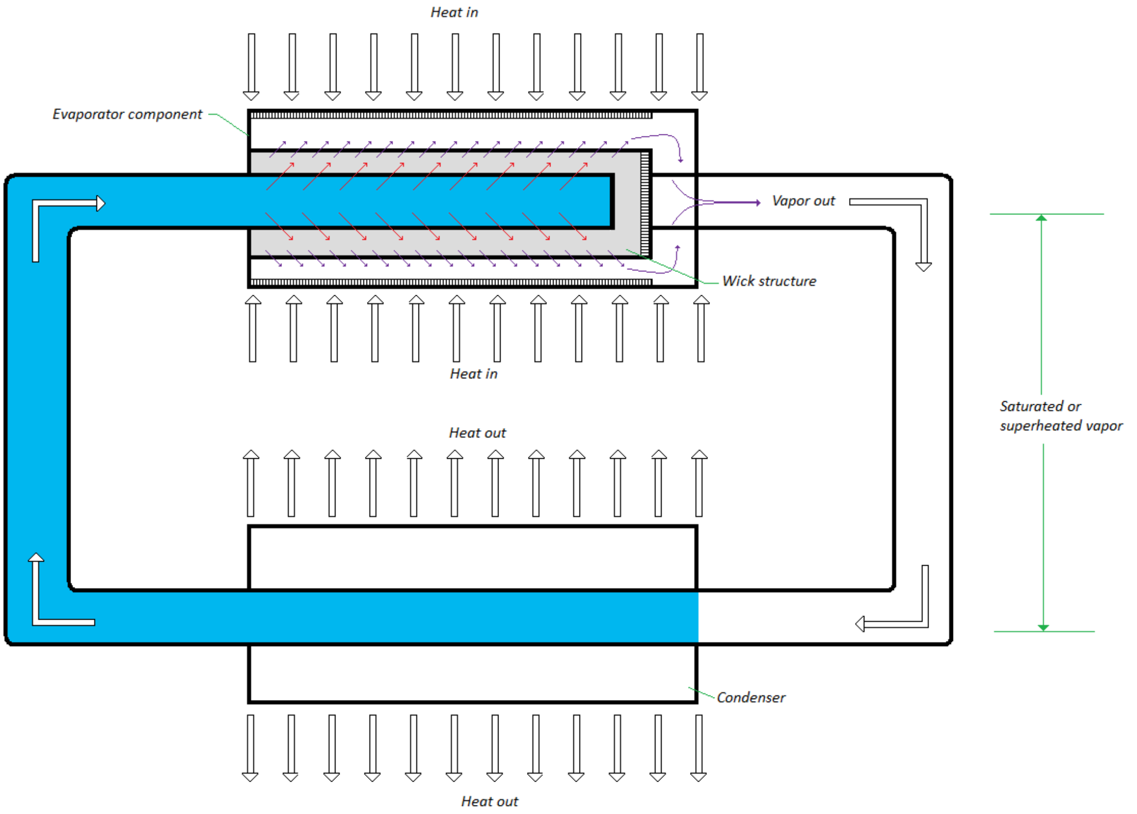

Fig. 4 - Mechanism of the loop heat pipe.

The working fluid then continues to travel around this loop in repeating cycles. This causes cool working fluid to continuously come into contact with the evaporator, thus maintaining a temperature gradient and facilitating constant heat transfer out of the lighting system.

1.3 Cylindrical Heat Pipes – Design 2.

Our use of cylindrical heat pipes for the planar light (Design 2) represents another innovation. We have drawn inspiration from pin type heat sinks, which show good heat removing capability in any direction but most optimally when air flows parallel to the pins.Using cylinders instead of the more traditional planar heatsink allows for better heat removal regardless of orientation. In contrast to this, standard heatsinks will not function effectively if the plates are oriented perpendicular to airflow.

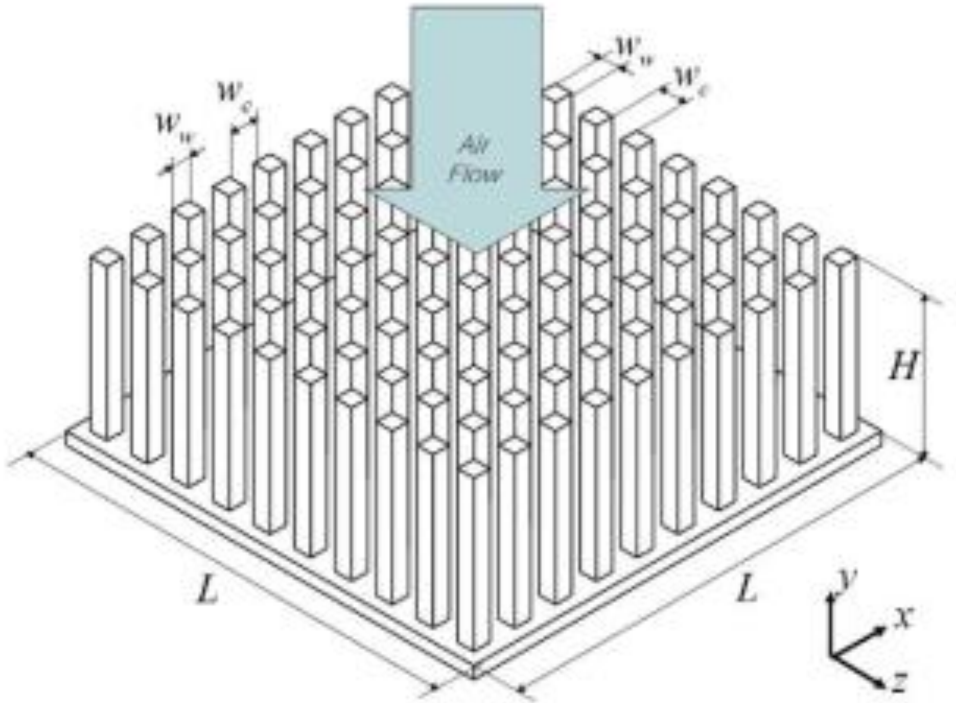

Fig. 5 - Macro view of the planar design: each 'column' represents a single heat pipe. Source: International Journal of Heat and Mass Transfer 52 (2009) 3510–3517.

We have modified the conventional design by replacing the pins in the pin type heatsink with miniature heat pipes. Hence, the heat pipes will be arranged in a configuration similar to that of pins in conventional pin type heat sinks.

Each individual heat pipe will work in the same way as a conventional cylindrical heat pipe. Working fluid in the centre of the heat pipe vaporises as it absorbs heat from the components. This vapour then rises in the centre of the cylinder. It cools as it comes into contact with the walls of the cylinder and condenses back into a liquid. This liquid then travels downward back to the bottom of the reservoir via capillary action and completes the cycle.

2. Elimination of Internal Thermal Resistances– Design 1 & 2.

Over the course of studying the design of current LED cooling systems, we came to the conclusion that a major inefficiency exists due to the placement of the circuitboard between the heat plug and the heatsink. Therefore we decided to find a way to eliminate the thermal resistance of the circuit board entirely. We decided that the key is to have the base of the LED in direct thermal contact with the heat sink. In order to facilitate this, we opted to use flexible circuitboards with LEDs embedded inside, which will then be mounted onto the heatsink. The LEDs are embedded in such a way that the light emitting end is on one side while the heatplug that exists in standard designs is on the other side of the circuit board.

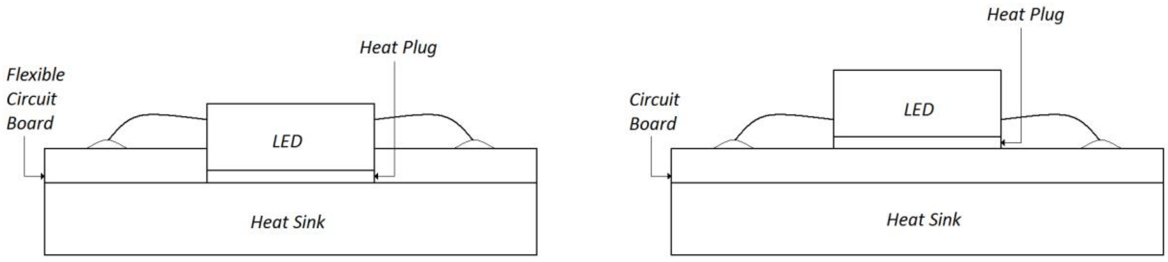

Fig. 6 - Comparison between our configuration of flexible circuit board (left) and standard rigid circuit board arrangements (right)

The use of flexible circuitboards in this manner as opposed to a rigid circuitboard allows for compensation for any possible manufacturing errors in ensuring that the base of the LED is in thermal contact with the heatsink at all times. This is because the flexible circuit board is able to be adjusted, so as to ensure that the base of the heat plug is always in contact with the evaporator package. In contrast, if a rigid circuit board is used, any errors in the shape of the board will lead to air gaps between the heat plug and the heat sink, and hence greater thermal resistance. This problem is exacerbated due to the fact that we are implementing a cylindrical design, which is more difficult to machine exactly. This problem can be circumvented by our use of flexible circuit boards, which i) do not need to be machined in a cylindrical shape, but simply wrapped around a cylinder and ii) are easy to fit snugly, hence eliminating air gaps.

The significance of the circuit board as a thermal resistor is not to be underestimated, as the thermal conductivity of the materials, although able to be improved with recent innovations, cannot currently match up to that of metals.

Material	Coverage [%]	Conductivity [W/m·K]	Thickness [μm]
Copper	50	385	70
Dielectric	100	3	150
Aluminium	100	180	1600

Table 1 - PCB Material Properties - Source: Qpedia Magazine, September 2009

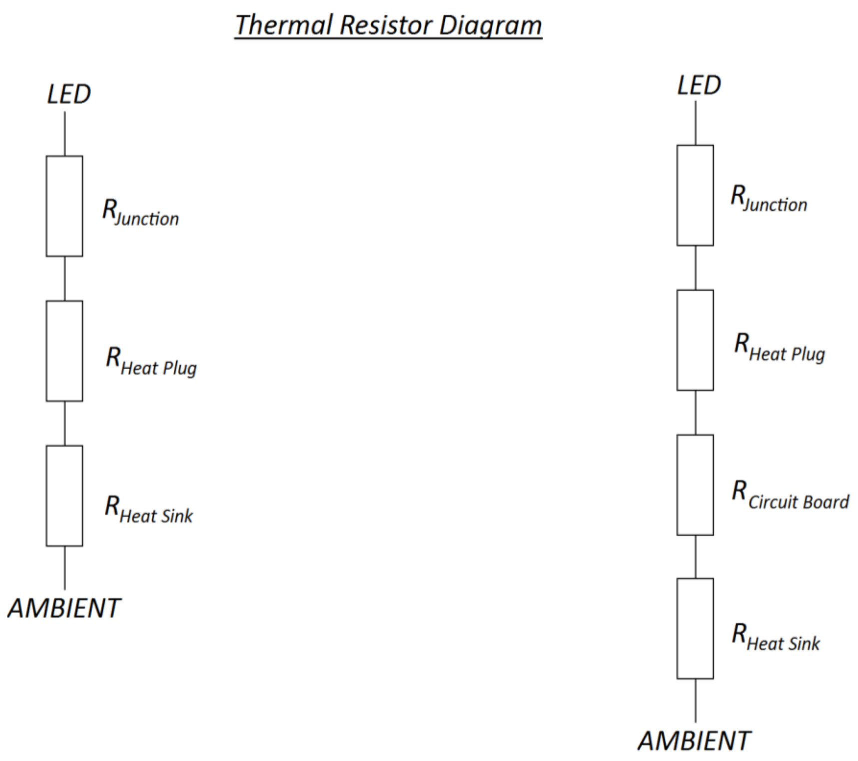

Fig. 7 - Thermal resistor diagram showing our design that eliminates the circuit board as a thermal resistor (left) versus conventional designs where heat flows through the circuit board (right)

The above model combined with the data from Table 1 supports our conclusion that the heat transfer rate will be drastically improved with the use of this circuit design, as the dielectric is by far the most significant thermal resistor in the model, having almost 60 times more thermal resistance than the copper portion,

3. Convection Facilitation

3.1 Cylindrical Shape – Design 1

When choosing the design of our bulb, we wanted to bear in mind two key objectives:

i) To provide maximum illumination in all directions with the LEDs.

ii) To allow sufficient airflow for heat exchange.

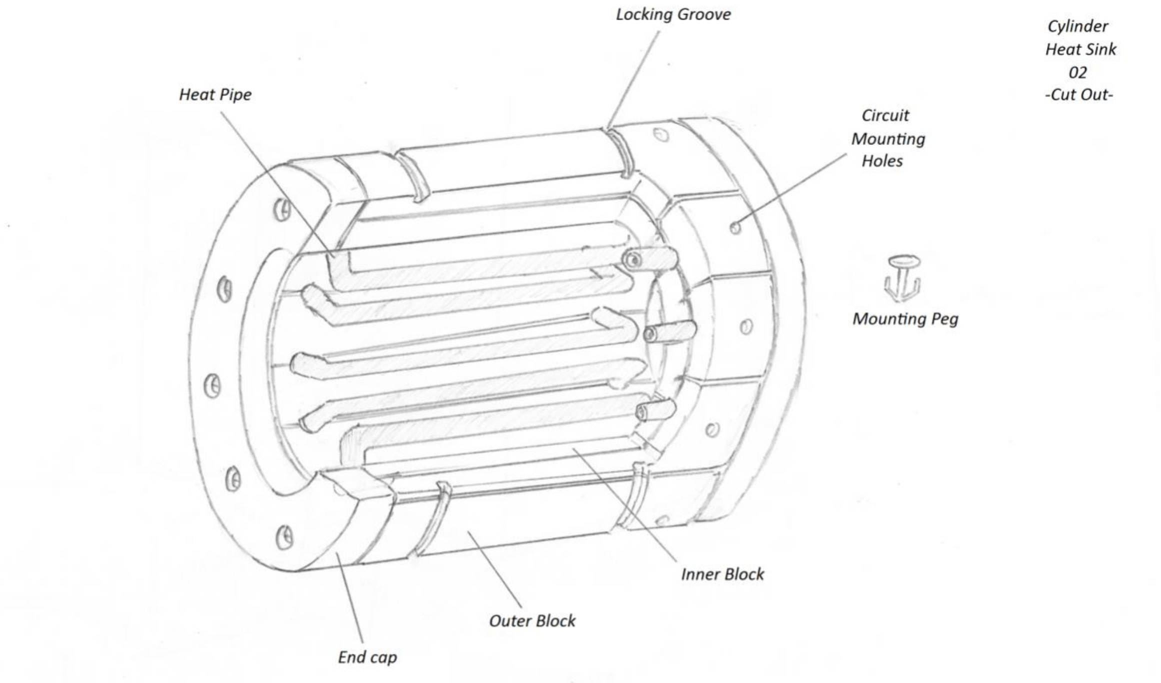

Fig. 8 -Cutout sketch of the bulb design (Design 1). Note that the cylinder is oriented horizontally in this sketch, whereas in the actual configuration it will be oriented vertically to facilitate upward airflow.

We decided on placing the LEDs on the outside of a cylinder and creating a channel in the centre for air to flow freely. The heat exchange between the heat pipes and the air naturally creates a convection current rising through the centre of the cylinder. This convection current is caused by the hot air in the centre of the cylinder rising and exiting the cylinder at the top, which is open. As this hot air rises, it sucks in cool air from the bottom of the cylinder (also open). Hence, the heat pipes on the inside of the cylinder will receive a constant flow of cool air, thus increasing the temperature gradient and leading to more effective cooling.

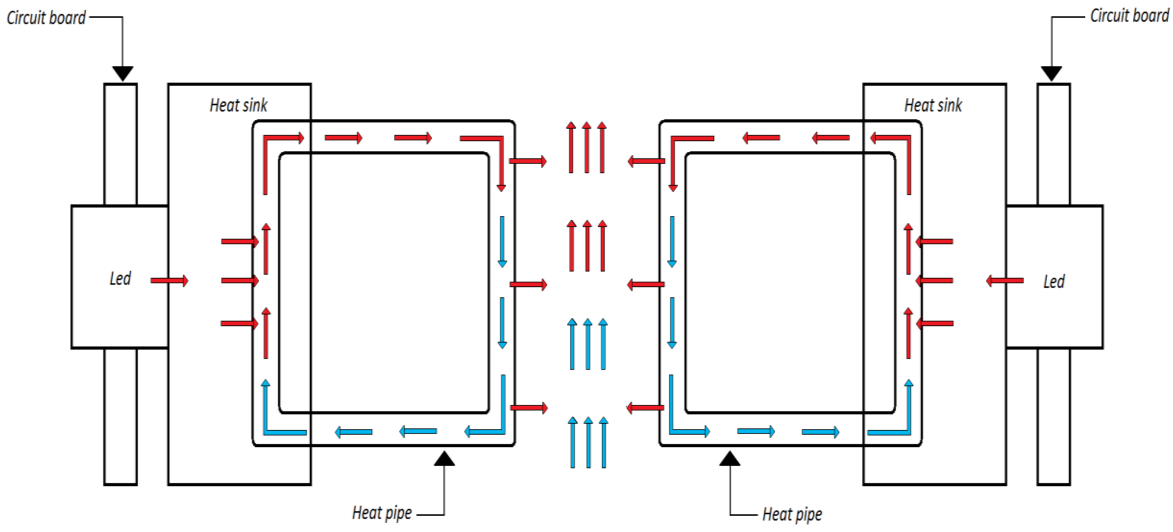

Fig. 9 -Circulation of heat and air flow in a cross section of the cylindrical design. Cool air enters the cylinder from beneath, warms up, and leaves the cylinder from above.

This can be contrasted with current heatsink designs that do not sufficiently take advantage of the rising of hot air from the heatsink to create a convection current. Consequently, hot air around the heatsink stagnates and lingers for longer than necessary, hence reducing the temperature gradient and the overall effectiveness of the cooling. Furthermore, in a large number of applications, the cylindrical bulb will be attached to a cavity in an office ceiling, over a room that is often air conditioned or is otherwise climate-controlled to be suitable for human occupants. Hence, the air being sucked in from the bottom of the cylinder will be much cooler than air in the ceiling cavity above the luminaire.

3.2 Planar Shape – Design 2.

This design consists of multiple segments of square aluminium pieces with the flexible circuit board mounted on one side and cylindrical heat pipes embedded on the other, in similar fashion to a pin type heatsink. The aluminium piece will also have multiple perforations all the way through of a similar diameter to that of the heat pipe (3mm-5mm).

The perforations exist to allow air to flow evenly throughout the whole circuit board as opposed to a solid board. This prevents overheating of the central regions of the planar light. In status quo, as the area of the board becomes increasingly large, less cool air is able to reach the centre area. This simultaneously decreases the lifetime of those LEDs that are exposed to more intense heat and sets a limiting factor on the size of an LED lamp. This is a cause for concern especially in large scale commercial applications where large quantities of light need to be supplied.

Our design allows efficient airflow in any direction especially along the heat pipes to remove heat in an efficient manner. These perforations enable the board to be placed in any orientation and at any angle without significantly compromising its cooling ability, although maximum efficiency is achieved when the pins are vertically oriented, as the air is able to flow parallel to the pins.

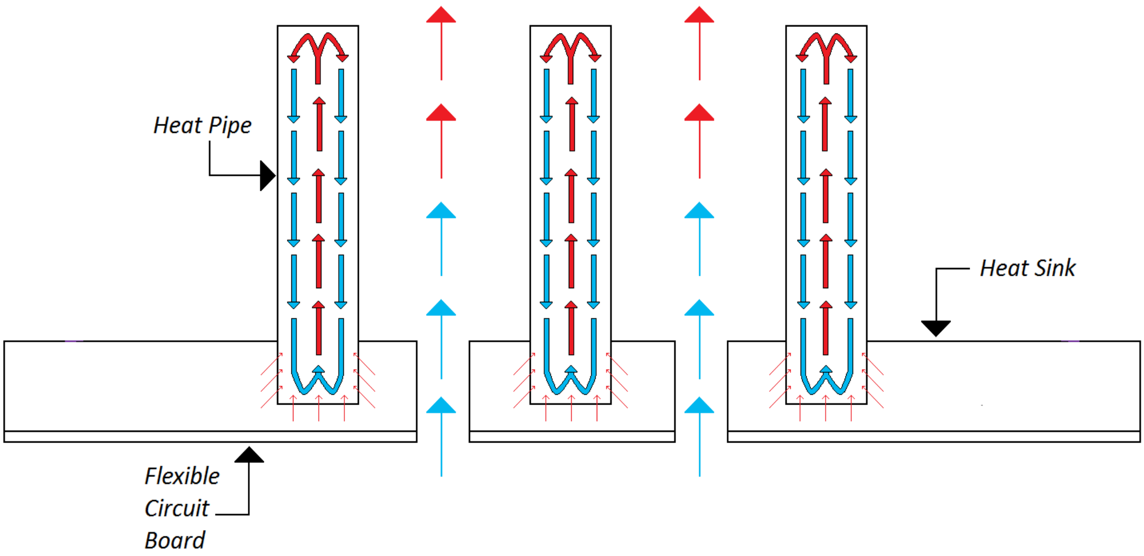

Fig. 10 - Airflow diagram showing a cross-section of a close-up of Design 2

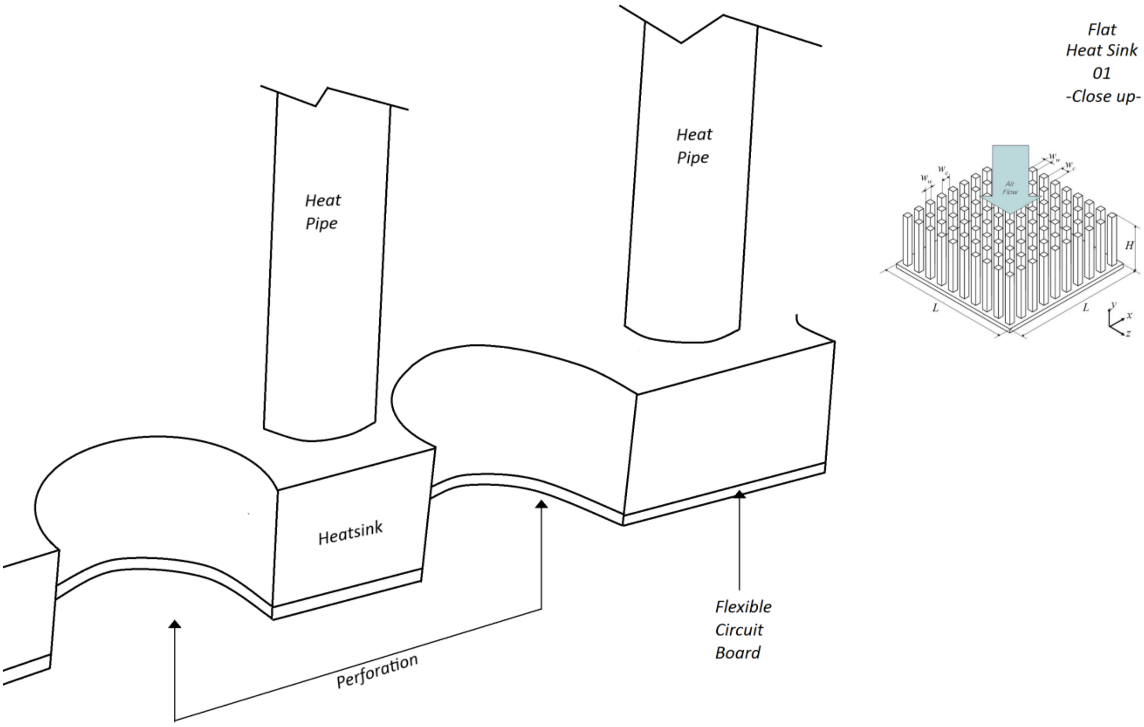

Fig. 11 - Micro and Macro view of the heatsink in Design 2

In the diagram, a close-up cross section of the heatsink mechanism is shown. The heat pipes are embedded directly in the circuitboard with the perforations as close as possible to the heat pipe so that cool air is able to come into direct contact as quickly as possible.

The top right hand corner is an overview of what the finished section will look like, showing all the heat pipes and the entire heatsink. The entire design will consist of multiple sections connected together (see 2.2). The heat pipes are vertically oriented instead of a flared design so as to achieve maximum benefit while maintaining a compact design.

4. Additional Cooling Options

4.1.Fan – Design 1.

In situations where sufficient ventilation is unachievable due to environmental characteristics a fan may be necessary to ensure optimal performance of the heatsink. We propose the use of an ordinary DC fan to provide the necessary air flow. Aside from the inclusion of a dust filter, Design 1 accommodates a fan reasonably well due to the ease of air flow through the design. The fan might be necessary in the following situations:

i) When there is too limited a space around the unit for efficient airflow by natural convection.
ii) In warmer environments where the ambient temperature is especially high.

For Design 1, we propose mounting a fan at the bottom-end ‘mouth’ of the cylinder, to suck in cool air from beneath the cylinder and propel it over the heat tubes and upwards out of the top of the cylinder. This will essentially speed up the intended natural upward flow of air through the cylinder.

B. Technical Details - Secondary Design Elements

1. Flexible Circuit Board – Design 1 & 2

Flexible circuit boards consist of a polymer laminate that is printed with metal foil to create circuits. They have widespread use in electronics, especially when compactness is desired e.g. in cameras and other similar devices. They have several desirable characteristics including heat resistance and durability. They arenormally used to accommodate compact electronics packages such as cameras and other handheld electronic devices.

For our designs, the flexible circuit board serves first of all as an interface to deliver electricity to the LEDs. They are especially useful because they easily accommodate cylindrical (see 2.0), planar, and any other designs for any possible luminaire shape. Added benefits include the flexible circuit board's resistance to shock and heat damage.

2. Segmented Design

2.1. Segmented Design - Design 1

The design of this cylinder consists of multiple blocks of aluminium surrounding heat pipe loops with a central channel for airflow (refer to Figure 8). The segments and pipes are designed to interconnect easily to form a snug fit. This design allows for easy assembly at the manufacturing stage and easy maintenance and replacement in the event a single part is damaged. We also propose the use of small quantities of thermal paste or some similar material to ensure that thermal contact between all the segments is maintained.

Surrounding the cylinder, the flexible circuit board with embedded LEDs will be wrapped and attached with metal clips. Also, the design is reinforced by metal caps at both ends to hold it in place.

2.2. Segmented Design - Design 2.

We propose that our LED boards be manufactured in segments of between 5cm-10cm in width and length. The use of flexible circuit boards (see Secondary Design Elements) can accommodate these designs well and allows interconnection of multiple plates easily. This has several benefits:

i) It allows for easy maintenance and replacement of damaged parts, since any failure is naturally contained to a single segment. The compartmentalisation of LEDs in such a manner allows the wholes system to maintain a reasonable operating level even in the case of one or two segment failures.

ii) The segmented design allows for some slight movement which, coupled with the flexibility of the circuit board, lends itself to application with moving parts as well as preserving the integrity of the system in the event of shock or impact. This is in direct contrast to current designs consisting of a rigid structure that cannot withstand much physical stress.

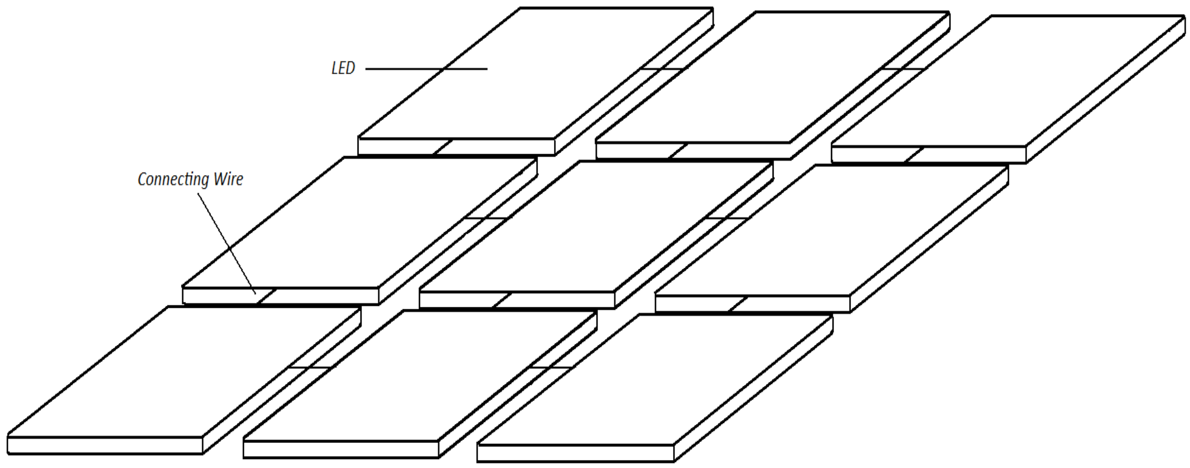

Fig 12.Macro view of Design 2, showing the segmented design. Each LED 'pane' can function independently of the others, and can be removed and replaced easily. Vertically arranged heat pipes not shown.

Marketability.

Considering the target market is mainly commercial, our design helps address several concerns relevant to the potential market. Firstly, we anticipate that our cooling solution will effectively increase the lifetime of the LEDs used by removing heat more efficiently and at a higher volume rate especially for commercial LEDs that have high running times. This allows LEDs to be run at full efficiency without compromising light output. We also project that our solution can maintain the operating temperature at a lower rate than the status quo, also increasing the light output.

Studies have shown that the lifetime of LEDs is heavily dependent on temperature, with the majority of failures of LEDs being attributed to heat related causes. Considering the large scale of commercial applications, the predicted increase in lifetime over many bulbs can save a significant amount of the cost of replacing the bulbs, aside from the energy savings due to the higher efficiency. Our belief is that this heavily outweighs the slight increase in cost, if any, due to the additional cooling solutions we propose.

Our use of the flexible circuit boards and segmented design of the housings allows for easy and quick maintenance, as opposed to the possibility of replacing the entire unit in the event of minor failure. The use of such versatile materials lends itself to an even wider range of applications especially from a design standpoint, with customised lighting solutions becoming a reality at a much cheaper cost. These design elements allow customisation even at the production stage, with components lending themselves easily to innovative and interesting designs.

Besides, the greatest concern for marketability will be the cost of the new design. As the LEDs being used will be essentially identical to that already in use for LED luminaires, the main issue will lie with the less common components of our design, namely the heat pipes and flexible circuit boards.

Flexible circuit boards have slightly higher material costs than rigid circuit boards. However, there is the possibility of cost reduction due to benefits such as reduction of assembly costs due to the elimination of connectors and solder joints. Thus, we believe that the final cost impact will be negligible compared to the savings in energy and maintenance costs with our design.

Compared to the heatsink only approach, heatpipes can be expensive, especially in small quantities. In more demanding applications, however, the cost of heat pipes is competitive with other alternatives. The cost of heatpipes also drops significantly in high quantity applications, especially for large sized applications. Furthermore, we believe that mass production of these heat pipes can drive down the manufacturing costs significantly.

In conclusion, we believe with sufficient fine-tuning of the design and materials, the increased heat dissipation effectiveness and versatility of the designs will offset any increase in cost due to the materials. The focus of marketability lies primarily on the increased efficiency of the lighting system, with the flexibility and versatility of the system as a value added bonus.

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