Advanced Natural Convection Cooling Designs for LED Bulb Systems

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The movement to LED lighting systems worldwide is accelerating as energy savings and the reduction in hazardous materials increase in importance. Government regulations and rapidly lowering prices help to further this trend. Today's strong drive is to replace light bulbs of common outputs (60W, 75W and 100W) without resorting to Compact Fluorescent (CFL) bulbs containing mercury while maintaining the standard industry bulb size and shape referred to as A19.

For many bulb designs in the USA, this A19 size and shape restriction forces a small heatsink which is barely capable of dissipating heat for 60W equivalent LED bulbs with natural convection for today's LED efficacies. 75W and 100W equivalent bulbs require larger sizes, some method of forced cooling, or some unusual liquid cooling system. Generally none of these approaches are desirable for light bulbs from a consumer point of view. Thus, there is interest in developing natural convection cooled A19 light bulb designs for LEDs that cool far more effectively than today's current designs.

Current A19 size heatsink designs typically have thermal resistances of 5-7°C/W. This article presents designs utilizing the effects of chimney cooling, well developed for other fields that reduce heatsink resistances by significant amounts while meeting all other requirements for bulb system design.

Current LED light bulb designs are essentially composed of three regions: a base at the bottom for installing into a luminaire, a central region which is a heatsink and contains space for the electrical driver (power supply), and the upper region which is the optical portion of the bulb where the LEDs reside and some type of optical beam spreading system (Figure 1).

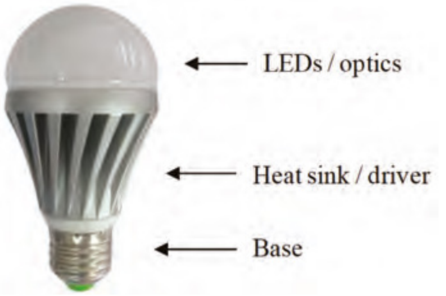

Figure 1. LED Light Bulb Construction

To determine the effectiveness of a typical LED bulb, several commercially available bulbs were bought and tested to determine heatsink and system performance. There were two criteria chosen to evaluate them. First, the heatsink itself was evaluated for its convective thermal resistance. This is a straightforward calculation using the average surface temperature, power dissipated and ambient temperature.

The heatsinks showed nearly isothermal conditions under test when examined with an infrared imaging camera (a commercial FLIR SC620 was used in this investigation). Second, a modified dimensionless parameter was chosen to evaluate the bulb system level performance.

Potential Solutions for Performance Shortfall

One potential solution for this performance shortfall is to consider chimney type designs. Chimneys have existed long before the modern era and been adopted for use in electronics cooling in various applications. Perhaps the earliest example of modern research in this area is that of Ellenbaas with his work examining free convection of parallel plates and vertical tubes with parallel walls in the 1940's [2]-[3]. In subsequent decades the research has continued including up to the present time. For example, in the 1970's and 1980's much work was conducted around shrouded heatsink concepts, though the work has continued to the present time.

However, a typical LED bulb design lacks one primary element for a chimney design - there is no central core opening. Since many chimneys are of cylindrical shape, this suggests that a design with a cylindrical light guide for the LEDs could be created and allow for a central thermal chimney.

Annular Chimney Design (V3)

One proposal for such a solution is shown in Figures 2 and 3. This bulb assembly still has the same base in the same location, but the LEDs, optical elements and the heatsink all occupy the same general region of the bulb. There is a solid central core about 26mm in diameter, then an open annular region which comprises the through chimney, and an outer area with the LEDs, light guide and

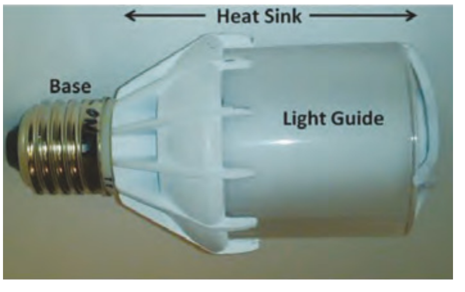

Figure 2. Prototype V3 Assembly

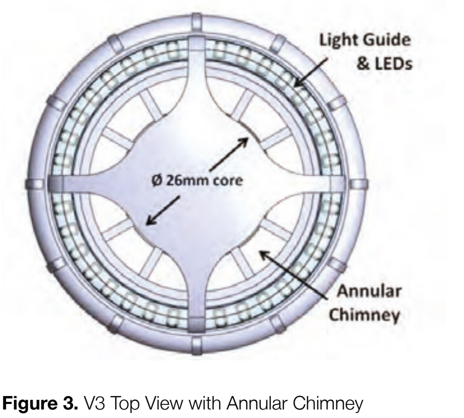

Figure 3. V3 Top View with Annular Chimney

other support structure. The entire assembly fits within the A19 envelope defined by the ANSI standard. This particular design was designated prototype V3 (version 3).

As seen in Figure 2, a prototype bulb was constructed. The main heatsink was made by the lost wax casting process with a standard aluminum casting alloy. Other parts except the base were machined, and different printed circuit boards (PCBs) were created for different testing conditions. Two types of PCBs were created: one with actual LEDs, and a second with surface mount resistors. The latter design allowed for more accurate measurement of thermal input energy. LEDs can be used but accurately knowing the thermal input energy is difficult; one must accurately measure the radiometric light output energy for an input electrical energy to measure the difference, and light energy can be reabsorbed into the system and become an input load.

The V3 design was tested to understand overall system performance and compared to computational fluid dynamics (CFD) numerical solutions using FloEFD™.

CFD simulations were conducted to correlate to the various tests. In the vertical orientations, about 150,000 cells were used and horizontally about 100,000 cells were used. Sufficient room above and below

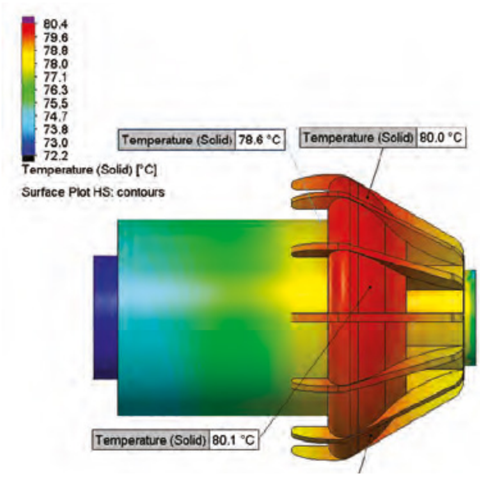

Figure 4. CFD Image of V3 Horizontal Position

Test Case	Location	T/C	IR Image	CFD
Vert Up	Outer HS Chimney	*see text 71.6	73.7 n/a	73.6 72.5
Vert Down	Outer HS Chimney	74.4 71.3	75.2 n/a	74.4 73.0
Horizontal	Outer HS Chimney	78.1 75.9	80.7 n/a	80.1 78.6

Table 1. CFD Image of V3 Horizontal Position

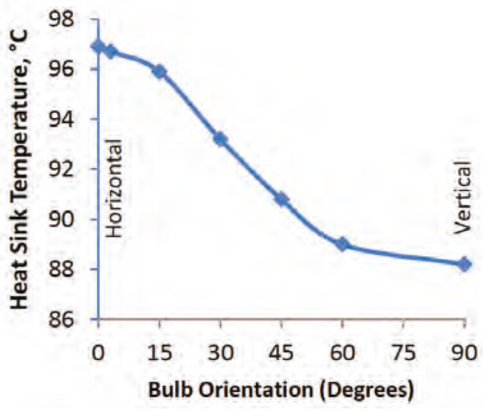

Figure 5. V3 Design Orientation Sensitivity

the lamp (as defined by the gravity vector) is used for proper flow development, and one bulb diameter around the sides was adequate for spacing around the bulb without influencing results unduly. Mesh sensitivity studies were conducted primarily by increasing the number of partial cells FloEFD uses, which refines the mesh around the fluid to solid boundaries (partial cells are part solid, part fluid and a unique cell used by FloEFD). Maximum cell counts of five to six hundred thousand cells were solved and compared to coarser meshes; results were found to be 0.1 to 0.2°C different from the coarser meshes so the coarser meshes were deemed acceptable. In all CFD simulations, radiation was selected as part of the solution routine. The heatsinks were painted with a special white paint and the emissivity was measured to be 0.975 on both the heatsinks and a special flat panel painted sample.

A few pertinent observations should be made from these results. First, the thermocouple used to measure the outside heatsink temperature in the Vertical Up orientation was not attached properly and is quite sensitive in this orientation (the "*" entry in Table 1). Although this was found later, the test was not repeated though in other orientations the thermocouples gave reliable results. Other temperature differences are within instrument errors. Second, there is a noticeable improvement in the heatsink thermal resistance (nearly 20% better than any of the commercial bulbs tested). Third, horizontal performance is worse – not surprizing, since chimneys are meant for vertical operation. As seen in Figure 5, angles from 45° to 0° showed significant increases in temperature for the heatsink (0° indicates horizontal, and 90° is vertical up). This graph is based on the verified CFD model dissipating higher power levels at these angles. Variations between vertical (90°) and tipped to 45° showed only modest increases in overall thermal resistance.

Other variations of this V3 design were modeled to see how much improvement could be made over this design. They included varying the number of internal fins in the annular chimney and varying the fin height.

Chambered Design with Annular Chimney (V6)

Given the limitations of the V3 design, another solution was sought. The vertical solutions needed to be better, and some method to improve the horizontal system performance would be needed for bulbs with higher power levels than used for tests in V3.

An advanced chimney system was devised and prototyped, still remaining within the design outline of an A19 bulb. This system involves a unique chamber internal to the chimney yet is open to the lamp bottom, sides and top. The annular chimney is thus split into separate chimneys – in this case, the "Y" shaped chamber creates the three of them – to allow the chamber access to the various sides of the bulb. This heatsink geometry is shown in Figures 6 and 7. Test results at 11.9W of thermal power showed that the V6 heatsink thermal resistance is 4.0°C/W. This is an improvement of 13% over the V3 performance at a similar power input. It is

Figure 6. Prototype V6 Assembly

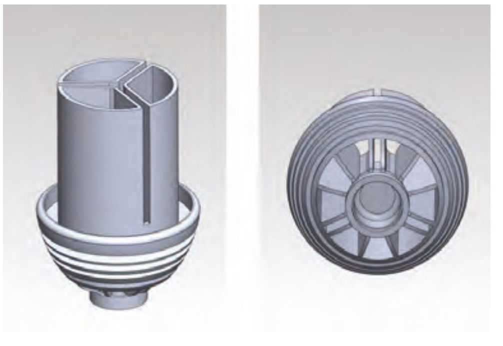

Figure 7. V6 Heatsink Detail

a fair assessment to state the efficacy of a chamber and chimney type system is a large improvement over the typical LED bulb design (a one third reduction over the typical LED lamp tested).

The significant improvement is the improvement in system thermal resistance though there is still room to improve the convective path, and the conductive path is relatively similar to before.
The performance improvements were created by better airflow patterns in the design. Vertically there are strong drafts created in the chimney and chamber sections. Velocities 200mm above the bulb reached nearly 0.6 m/s in the CFD simulation, indicating a strong draft created by the bulb design, and over 10% higher than the V3 design. Reducing the LED driver core size opens the annular region in V6 to permit greater airflow, along with optimizing the flow paths.

Furthermore, the chamber design has an advantage over the pure chimney design in the horizontal orientations. As noted earlier, one drawback of a pure chimney design is poor horizontal performance. The V3 design horizontal R_θ gains 0.74°C/W to 5.34°C/W. In the V6 design, there is a slightly larger difference but the overall system performance is significantly better than V3. The V6 temperature gain is 10.2°C and the thermal resistance gain is 0.86°C/W. Table 2 shows a summary of the performance differences in the orientations.
For horizontal use, the chamber construction is designed for external air to pass through the "Y" shape. From a CFD analysis in one horizontal orientation, one can see the airflow through the chamber as shown in Figure 8.
As expected, the chamber provides cooling in horizontal orientations that standard chimney designs such as V3 cannot.

Parameter	Vert Up Rθ, °C/W	Horiz Rθ, °C/W
V3 Chimney	4.6	5.34
V6 Chamber	4.0	4.86

Table 2. V3 and V6 Heatsink Differences by Orientation

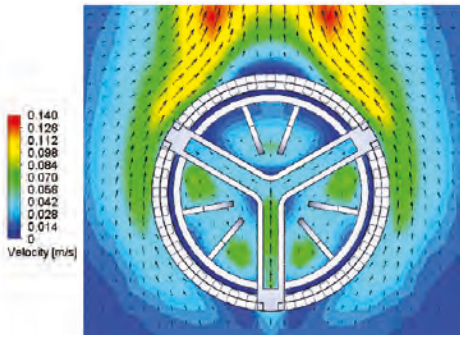

Figure 8. Airflow in Chamber, Horizontal Orientation

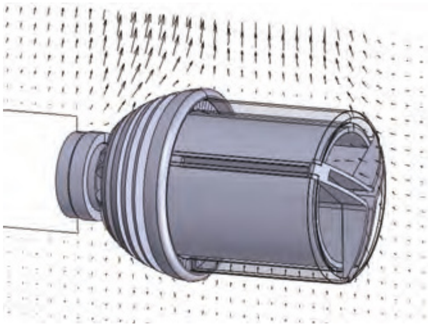

Figure 9. Air Flow into Chimney Core

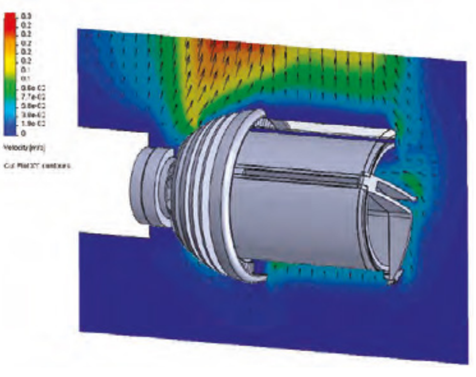

Figure 10. Velocity Vector & Contour Plot

However, one surprising finding from simulation was that the chamber created the movement of air into the chimney regions when horizontal which provided more cooling. The velocity vector plot of Figure 9 shows this air flow (seen near the top cap in the right of the figure). Figure 10 shows a similar view with color contours.

This airflow inducing effect of the chamber will be studied in a later paper. It is primarily due to the chamber creating a particular draft that imparts momentum to surrounding air and pushes this external air into the surrounding chimneys.

Chambered Design with External Fins (V8)

While V6 is better than V3, it was clear the thermal performance is not enough for a 100W equivalent bulb dissipating 18W. At 4°C/W and a 55°C ambient, the boundary condition temperature for the LED printed circuit board (PCB) would be 127°C, and the resulting junction temperature would likely be 135°C or higher (exact temperature would depend on the LED model and drive current applied). To keep the junction temperature below 120°C (a common maximum), the heatsink should not exceed 110°C. This 55°C rise over ambient for 18W applied means the heatsink resistance should not exceed 3°C/W as a design goal. To achieve this, a similar heatsink to V6 was created with a 2mm larger outer diameter for the annulus outer core, and external fins added outside the light guide section. The lower heat sink section was redesigned for better inlets. Other dimensions were kept the same as V6 and the overall outline was kept within the A19 envelope. Even with the addition of the fins and larger chimney annulus, the heatsink areas are nearly identical between V6 and V8 (39,035 vs 38,705 mm²). Figures 9 to 11 show the V8 bulb and heatsink.
The V8 prototype was tested and simulated at a number of power levels and orientations. A resistor PCB was used with input powers of approximately 6, 9, 13, 17 and 21W, and simulations were conducted

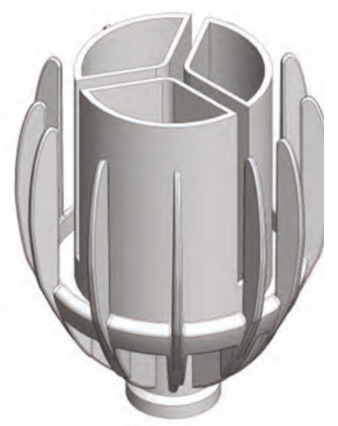

Figure 11. V8 Heatsink detail

Figure 12. Prototype V8 Assembly

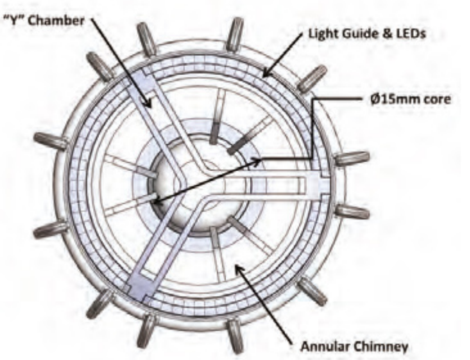

Figure 13. V8 Assembly Top View

with 9, 13 and 21W of input power. IR and thermocouple data were within 1.5°C for all tests. Simulation mesh dependency studies were conducted similar to the process described for V3 to ensure adequate mesh density for the simulations. Figures 14 and 15 show some of the test and simulation results.

The V8 prototype performed significantly

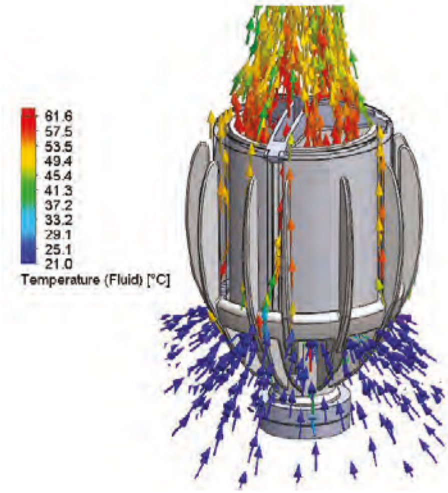

Figure 14. CFD Simulation of V8 Vertical Up Test

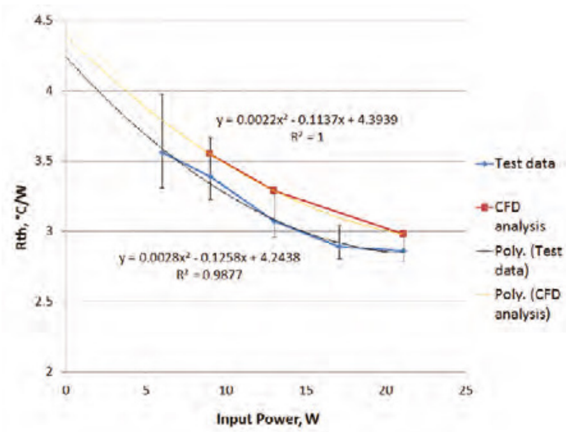

Figure 15. Performance of V8 in Vertical Up Orientation

better than the V6 design. As seen in Figure 15, the results show reasonable agreement for the tests and the simulations. By performing an examination across a wider range of thermal input powers, a general performance diagram of the heatsink can be generated. Table 3 shows results for the vertical up orientation. The test data is the average of the thermocouple and the IR image data, and the error estimates based on the possible worst errors for the type of measurement. For each data set, a second order polynomial curve fit was applied and the equations shown.

A few important observations are found from this performance chart. The simulation solutions are conservative compared to the actual tests though close to the upper end of the experimental error band. Small air currents in the lab may account for this as the simulation assumes perfectly still air. The outer fins are very effective at removing heat in the presence of low air currents. Second, the V8 design performance is a large improvement over the V6 design. At 11.9W of input power, the heatsink resistance is about 3.1°C/W, almost a 25% improvement in the vertical orientation. At the higher power levels for 100W equivalent bulbs (18W input), the heatsink tests just below 3°C/W, meeting the design target. Third, the two key changes in the V8 design account for the improved performance – the larger annular region (2mm larger outer diameter) and the fins. Simulations show the outer fins account for about 2/3 of the improvements, and the larger annular region the other 1/3.

The values for Table 3 use approximately 12W of input power for V3, V6 and V8 designs. The commercial LED lamps ranged from approximately 7W (40W equivalent bulb) to 13W (60W equivalent). Even as the convective resistances of the new designs are an improvement over the commercial units tested, it is still a significantly higher resistance than the conductive resistance in the system. Finally, the horizontal performance of the V8 prototype is also significantly improved over the V6 design. The external fins provide significant new cooling paths in the horizontal orientation.

Parameter	Vert Up Rθ, °C/W	Horiz Rθ, °C/W
V3 Chimney	4.6	5.34
V6 Chamber	4.0	4.86
V8 Chamber	3.1	3.83

Table 3. Heatsink Differences by Orientation (12W power)

Conclusions

Several interesting results have been found during this study. First, the current design of LED bulbs performs adequately for the current power dissipations but will not be enough for future 75 and 100W equivalent bulbs. Second, rather than a standard central LED engine design, a cylindrical LED layout and light guide with a chimney enhances thermal performance and can still fit within the desired A19 design envelope. Last, a novel chimney and chamber design was developed for enhanced performance. Unusual air flows were noted as well in horizontal positions and will be evaluated in future work.

Though the V8 prototype design is far better than current designs, it is a bit marginal of a system that will adequately cool the 100W equivalent light bulb at 2.9°C/W. Future work will look at designs beyond the types shown in this paper (and beyond this paper's scope) that again reduce the overall system thermal resistance – allowing a 100W natural convection cooled LED bulb to fit within the A19 envelope.

References:

[1] Proceedings of the ASME 2013 International Technical Conference and Exhibition on Packaging and Integration of Electronic and Photonic Microsystems InterPACK2013 July 16-18, 2013, Burlingame, CA, USA

[2] W. Ellenbaas, "The Dissipation of Heat by Free Convection from the Inner Surface of Vertical Tubes of Different Shapes of Cross Section," Physica, 9, pp 865-874, Sept 1942.

[3] W. Ellenbaas, "Heat Dissipation of Parallel Plates by Free Convection," Physica, IX, No. 1, Jan 1942