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Impact of Active Cooling On High Power Density Fixtures

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Abstract - Lighting fixtures are finding a wide range of applications in Roadways, Sports lighting, Architectural lighting, Industries, etc. Lumen requirement for these applications is constantly increasing thereby augmenting the power needed and consequently the heat generation. To suffice these needs, high power density luminaries with lumens output in several thousand are used. Hitherto, thermal management of these luminaires was achieved through passive cooling with the help of heatsinks attached at the back of LEDs. Heatsinks utilized for this high-power density fixtures are relatively large to provide a higher surface area for heat transfer. With the larger heatsinks in the lighting system, the cost associated with packaging, mounting, manufacturing increases significantly. In addition, weight and EPA of these fixtures increases as well which has a negative impact on retrofit applications where existing infrastructure is designed for lighter weight products and replacing with higher weight and EPA product is not an optimal solution. To address these concerns, the present study focuses on utilizing an active cooling method with multiple fans placed in parallel to reduce the system size and weight. Several parameters such as fan speed, number of fins, fin height, input power, are varied to evaluate LED temperatures. Comparison is made with various design configurations and optimized design obtained through analysis is used for the final product development. Overall reduction in the weight and cost associated is then discussed in details in the summary.
***Keywords*:** Fan, CFD, LEDs, Lighting fixtures, Weight

1. Introduction

Signify is a world leader in the lighting business which provides lighting solutions to professionals, consumers, industries. Various lighting applications include architectural lighting, sports lighting, outdoor lighting, Indoor lighting, etc [1]. Lumen requirement of the fixture depends upon the particular application, space coverage, desired light intensity, visual comfort needed, etc. Indoor applications with enclosed spaces and finite area for coverage have lesser lumen requirements compared to outdoor applications. With a larger area to cover and multiple functionality requirements, outdoor fixtures have higher input power requirements. With elevated input power, heat generation through the fixture also augments thereby needing larger heatsinks for heat dissipation. Due to manufacturing cost and size constraints, heatsink act as the bottleneck for providing higher input power and greater LED life expectancy for the given set of applications.

A considerable amount of research has been done to quantify and predict LED temperatures through CFD methodology. CFD techniques are generally used to optimize the heatsink based on the given input condition or to remove excess of the material in the heatsink which does not contribute towards the thermal performance. Iaronka et al. [2] studied the effect of natural as well as forced convection on the LED temperatures. CFD analysis was used to analyze the system performance and thereby improvement in the airflow. Arik et al. [3] studied the importance of thermal management at the package and system level. CFD analysis was used to study the availability and limitations of passive cooling techniques on the thermal management of luminaires. Janakova et al. [4] used CFD analysis and actual testing to quantify and reduce the thermal resistance of PCB and LED systems. Atci et al. [5] analyzed the airflow and particle distribution inside the duct using CFD with discrete phase modeling. They concluded that the placement of UV-C lamps significantly affects the UV-C dose distribution. Fan et al. [6] studied the effect of a passive cooling method such as heat pipes and thermosyphon on a single LED assembly. The analytical model developed showed a 50% reduction in the thermal resistance when compared with metal core PCBs. Boyan et al. [7] presented the topology optimized heat sink that exhibits superior thermal performance to the traditional design. The resultant design performed 21% better than the common lattice geometries. Feng et al. [8] studied thermally activated lampshade with 1.5 times the cooling capacity than that of the conventional design. He designed the system with two parallel conduction paths that assist the heat dissipation to the surrounding.

Luo et al. [9] performed experimental and numerical simulation on a micro-jet-based cooling system. It was demonstrated that this cooling system has better thermal performance compared to passive cooling technique. Yan et al. [10] investigated the effect of active cooling on LEDs in automotive headlights. Several configurations of active liquid cooling were studied, and optimal thermal performance was determined. Jang et al. [11] studied the effect of various design parameters such as temperature and air velocity on the LED performances. Zhang et al. [12] investigated the effect of high-performance TIM and piezoelectric fan on LED temperatures. Deng et al. [13] used the active cooling solution using liquid metal as the coolant for enhancing the thermal performance of LEDs. Badalam et al. [14] studied various active cooling methods for COB thermal management. He concluded that synthetic air jets devices are the most efficient ways to cool LEDs.

Though there are significant number of studies pertaining to thermal management of luminaries, most of the studies are focused on passive cooling techniques. They are focused on optimizing heat sink design for the given heat load conditions. The present study describes the effect of active cooling through multiple fans on the high power density luminaries. Effect of various parameters such as fan speed, fin height, number of fins, and input power on the LED temperatures have been studied. Based on the analysis, optimized design and reduction in the weight of the fixture are determined. Finally, overall cost saving due to weight reduction is determined and discussed briefly in the work presented.

2. Computational Methodology

Figure 1 shows the schematic of the luminaire assembly with fans mounted. Unwanted parts, small fillets, or champers are removed from the components of the geometry under consideration to reduce the computational time. Material properties such as thermal conductivity, density, specific heat, are constant over a given range of temperatures. The computational domain is comprised of an enclosure with walls kept at a certain distance from the object of interest to minimize the entry effects. Non-conformal assemblies are created with Hex-dominant mesh type to optimize the mesh count. Pressure inlet boundary condition is imposed on all sides of the wall. Drivers and LEDs are assumed to be lumped bodies and heat load are assigned volumetrically on them. SST k-w model is used to capture the turbulence formation. SIMPLE (Semi-Implicit Method for Pressure Linked Equations) algorithm with pressure velocity coupling is used to simulate the flow. The second-order upwind scheme is used for momentum discretization. For flow analysis, ANSYS Fluent solves conservation equations for mass and momentum as stated below [15]:

$$\frac{\partial \rho}{\partial x} + \nabla \cdot (\rho\, \mathbf{u}) = S\mathrm{m} \tag{1}$$

Equation (1) is the general form of the mass conservation equation and is valid for incompressible as well as compressible flows. Where the source S_m is the mass added to the continuous phase. Conservation of momentum in an inertial (non-accelerating) reference frame is described by Equation (2):

$$\rho\left(\frac{\partial}{\partial t} + \mathbf{u}\cdot\nabla\right)\mathbf{u} = -\nabla P + \rho\mathbf{g} + \mathbf{F} + \boldsymbol{\nabla}.(\bar{\bar{\boldsymbol{\tau}}}) \tag{2}$$

where, $\bar{\bar{\boldsymbol{\tau}}}$ is the stress tensor, $\rho\mathbf{g}$ and $\mathbf{F}$ are the gravitational body force and external body forces, respectively. ANSYS FLUENT solves the energy equation in the following form:

$$\rho\left(\frac{\partial}{\partial t} + \mathbf{u}\cdot\nabla\right)e = \nabla.\left(k_{eff} + \nabla T + \overline{\overline{\tau_{eff}}}.\vec{v}\right) + S_h \tag{3}$$

where k_{eff} is the effective conductivity, the first three terms on the right-hand side of Equation (3) represents energy transfer due to conduction, species diffusion, and viscous dissipation, respectively. S_h depicts the volumetric heat generation.

Fan selection is done based on the product size and cooling requirement needed for the present sport lighting fixture. AC Infinity axial 8025 fans are selected with a maximum flow rate of 22 CFM at 3200 RPM (Revolutions per Minute). It is a heavy-duty Aluminium fan with two fan guards, mounting screws, and a power plug with an overall life span of 67000 hours. In the case of computational analysis, Fan with a similar specification is chosen from the Icepak libraries. The fan curve of the selected fan is available in the solver directory. Four such fans are arranged in parallel to suffice the cooling need of the present system as shown in Figure 1.

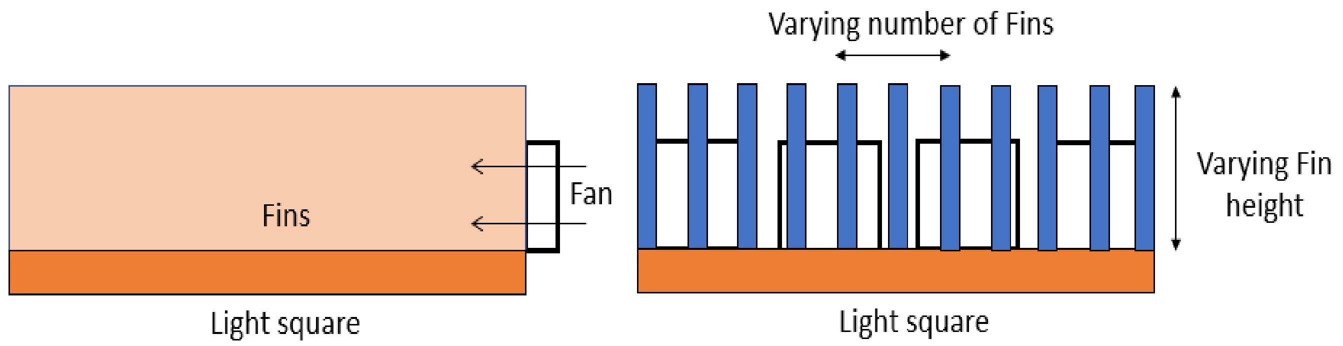

Figure 1: Schematic of Fan with Lighting Fixture assembly

3. Test setup and Validation

As specified in UL 19.10.3/19.11.3 clause, the thermal test was conducted in a draft-free room. Luminaire was rated for the highest wattage rating marked for the temperature rise test. The temperature test was performed for 7.5 hours which is the time it takes to achieve the steady-state and then three successive readings were taken at 15 min intervals. The test was conducted at the ambient temperature of 40^0C. K-type thermocouples were attached at multiple locations to measure the temperatures at the critical points.

For the initial set of validation with the experimental results, two sets of cases were considered. The first one is the case with passive cooling for the current design and the other with the active cooling with the help of four fans as mentioned above. The comparison of the simulation with the test is shown in Figure 2. It can be seen from Figure 2 that for both the cases simulations are within the error of $\pm 1^0$C when compared to the test results. Thus, we can conclude that the methodology presented is in good agreement with experimental values.

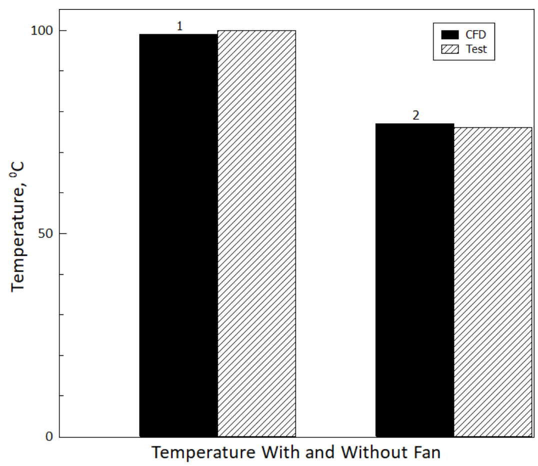

Figure 2: Temperature variation with and without Fan

4. Observations

It can be seen from Figure 2 that there is about 23^0C drop in the temperature with fan case when compared with no fan. The maximum temperature observed on the LEDs is around 77^0C for the 720W power input with fans attached. There is thus enough margin to increase the input power on the LEDs before it reaches the threshold. The first parameter therefore studied is varying input power on the LEDs until it reaches the upper limit. It can also be seen from Figure 3 that temperature varies linearly with an increase in power. The maximum power that can be reached with the current design is around 1200W with the maximum temperature below the critical limit.

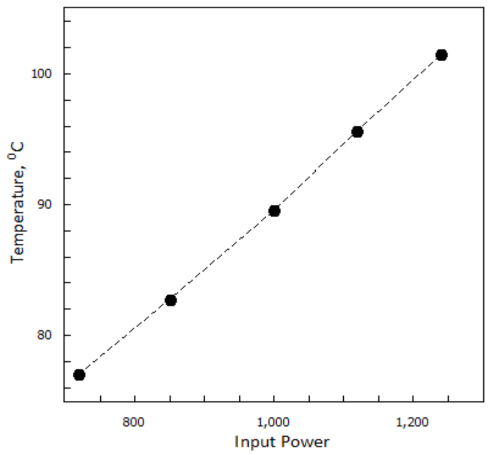

Figure 3: Temperature vs Power

Later keeping input power constant, RPM of the fans and thereby flowrates on the fan is varied as seen in Figure 4. Fan speed is varied from 1000 RPM to 3400 RPM, which accounts for the change in the air velocity from 1.3m/s to 5.1m/s. The temperature on LEDs reaches the critical point of 100^0C when air velocity approaches buoyancy-induced convection. It is observed from Figure 4 that temperature on the LEDs reduces exponentially with an increase in the fan RPM. It reaches the minimum temperature of about 75^0C at 3400 RPM. However, it is observed that changes in temperatures are insignificant after a certain increase in the fan speed value.

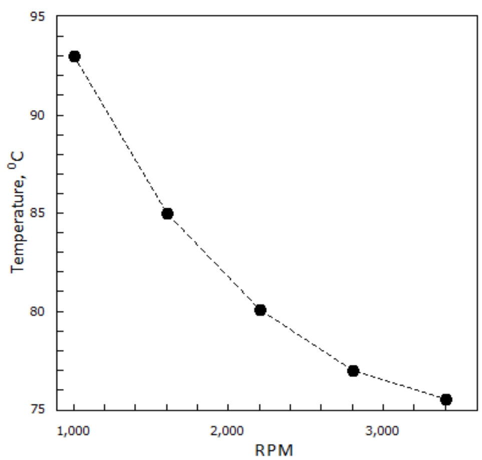

Figure 4: Temperature vs RPM

The most important aspect of the present study is to find out how much material we can reduce by installing fans for cooling the LED temperatures. In order to determine the material reduction two fin parameters, namely, fin number and height are varied over a certain range. Initially, Fan RPM, power on LEDs, and a number of fins (twenty in the present case) are kept constant. The height of the fins is varied from 120mm (which is the upper limit based on the effective projected area) until it reaches zero value. The weight of the heatsink for a present fixture is around 10kg. It can be seen from the Figure 5 that the temperature obtained on LEDs increases exponentially with a decrease in the fin height. The temperature on the LEDs reaches 118^0C with no fin case which accounts for a minimum weight of 4.8kg of the heatsink. The fin configuration with the height of 30mm and twenty fins satisfies the LED critical temperature condition, the corresponding weight of the heatsink is 6.2kg which corresponds to around 38% reduction in the weight of heatsink.

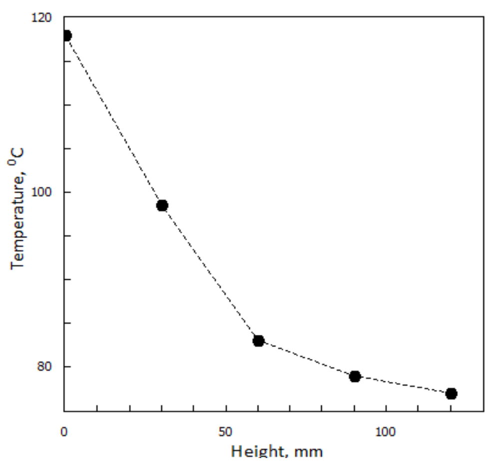

Figure 5: Temperature vs Height

For the second scenario, the height of the fins is kept constant whereas the number of fins is varied from twenty to zero. As seen previously, for no fin's case temperature reaches 118^0C which is above the critical limit specified by UL (Underwriters' Laboratories) standard. For the configuration with a minimum of six fins and height of 120mm, temperatures on LEDs are below the critical limit. The weight of the heatsink corresponding to the six fins configuration is 6.1kg accounting for 39% weight reduction. It can also be seen from Figure 6 that temperature on the LEDs increases exponentially with a decrease in the number of fins.

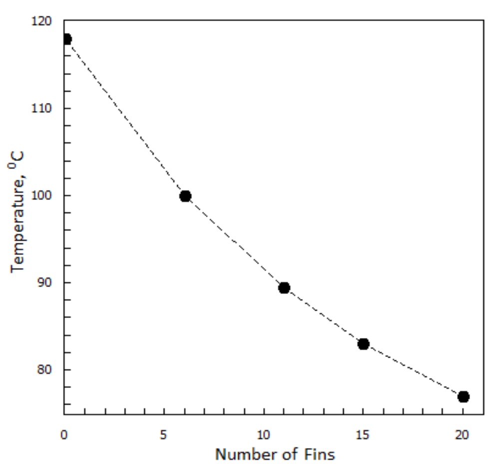

Figure 6: Temperature vs Number of Fins

Finally, the combined effect of varying both fin height and number of fins are also considered for the analysis. Based on the same, three different configurations with fin height 90mm, 60mm, 30mm, and the corresponding number of fins fifteen, ten, six respectively are studied. Figure 7 shows the variation of temperature on LEDs with varying weight based on the above-mentioned configurations. It is observed from Figure 7 that temperature variation is different for each of the variables considered during the analysis. Variation of fin height has a more pronounced effect on temperature than the varying number of fins keeping other input conditions the same. It can also be noted that the variation of temperature with mass is non-linear, signifying the effect of mass distribution due to fins design on the temperatures. As per standards critical limit for the temperature rise test is set to 105^0C, however, as per best practice in the industries, 5^0C margin is provided as the factor of safety. From Figure 7, configuration with 60mm fin height and ten number of fins have the least mass satisfying the temperature limit mentioned, i.e, 100^0C. Consequently, same configuration is selected for the decisive temperature rise test to validate the analysis for the product development. From the actual thermal test on this configuration, the temperature observed is within $\pm 1^0$C of the predicted simulation results. The mentioned configuration has 5.88kg of weight of the heatsink, 41% less compared to the present design with passive cooling having weight around 10kg. This decrease in the Fin height, number of fins, and thereby weight significantly reduces the EPA, packing, and installation cost of the lighting fixture.

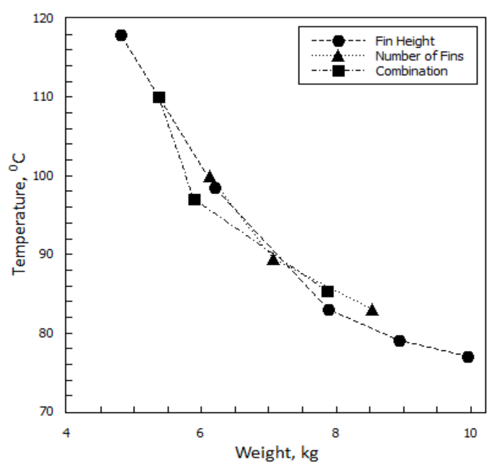

Figure 7: Temperature variation with Weight

5. Summary and Conclusions

The major conclusions drawn from the present numerical investigation for active cooling with multiple fans are as follows:

- Temperature increases linearly with an increase in input power. For our present case, keeping the heatsink the same as that of passive cooling, the power input of the fixture can be increased from 720W to 1240W with active cooling.
- Temperature decreases exponentially with Fan RPM. The temperature on the LEDs starts approaching the critical limits specified when fan speed approached buoyancy-induced convection.
- Temperature on the LEDs decreases exponentially with both increases in fin height as well as the number of fins. There is about 38% and 39% decrease in weight reduction respectively of the heatsink with active cooling compared to that with passive cooling.
- It is also observed that an increase in weight of the heatsink has a non-linear effect on the LED temperature signifying the effect of mass distribution due to fins.
- The configuration with 60mm fin height and ten fins is selected as the ultimate design for product development. The selected design is 41% lighter than the one with the original design of a passively cooled heatsink.

To give the perspective, in the typical sports arena there are about twelve fixtures on a pole and there are about six such poles installed. As seen before with active cooling, power input of the fixture can be increased from 720W to 1240W. Thus keeping the requirement of total input power same in a field, number of fixtures can be decreased from twelve to seven on each pole. The weight of the considered sports fixture along with the mounting is about 22.7kg. Thus, there is about 114kg of material removal from each pole which is quite significant considering the manufacturing cost associated.

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