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Thermal Management and Layout Optimization of LED Downlights Using CFD Simulation and Experimental Analysis

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ABSTRACT:
The increasing global demand for energy efficiency and environmental sustainability has positioned Light Emitting Diodes (LEDs) as a leading solid-state lighting (SSL) technology. LEDs offer numerous advantages, including high luminous efficacy, energy savings of up to 75% compared to traditional lighting, long service life and environmental friendliness. However, nearly 80–85% of LED input power is dissipated as heat, which significantly impacts their performance, reliability and lifetime if not managed effectively. This research focuses on the thermal management of LED downlights through Computational Fluid Dynamics (CFD) simulations and laboratory experiments. An 8-inch, 25W LED downlight is modeled using ANSYS APDL to analyze heat conduction, convection and radiation. Temperature distribution results from simulations are validated against experimental data, with less than 2% error in most cases, demonstrating the model's reliability. Further, optimization studies are performed to determine the ideal LED quantity and ring distance for improved heat dissipation. Results reveal that a 48-LED configuration with optimized spacing provides superior thermal performance, lowering maximum operating temperature by ~10% and extending the downlight's service life. The findings provide valuable insights for manufacturers to enhance LED product reliability through efficient thermal design and layout optimization, balancing energy efficiency, performance and longevity.

KEYWORDS: LED Downlights, Thermal Management, Heat Dissipation, Computational Fluid Dynamics (CFD), Finite Element Analysis, Layout Optimization, Energy Efficiency, Solid-State Lighting

1. INTRODUCTION

The world's most major problems currently incorporate the energy emergency, environmental change, energy productivity and the need to lessen discharges. High radiant productivity, energy investment funds, a long lifetime and being harmless to the ecosystem are only a couple of the interesting advantages that have made LED, another age of green strong state light source, so exceptionally esteemed. A solid-state lighting (SSL) system that can reduce electric power usage by up to 75% compared to traditional lighting systems is currently in development for use in commercial and residential settings. A number of nations' "solid-state lighting programmes," "rainbow schemes," "21st century lighting plans," and "GaN semiconductor lighting plans" have already implemented LED semiconductor lighting research, production and application.

Meanwhile, the "semiconductor lighting major project" has been initiated by China. Hundreds of academic institutions, businesses and other organizations specializing in semiconductor illumination have started developing, manufacturing and applying their findings.

Nevertheless, 80% to 85% of the power dissipates heat, whereas only 5% to 20% is converted to illumination by LEDs. Plus, light-emitting diode technology is chilly. The majority of the heat is dispersed to ambient by convection after being transported to the heat sink by conduction from the chip. A lot of heat will be generated when an LED operates continually. A high power LED's operating lifetime and reliability can be drastically diminished if heat is not quickly removed and dispersed. Thus, it is crucial to have efficient thermal management and optimization design.

When designing an LED lighting system to better regulate the temperature of the chip junction, the two main factors of efficient thermal design are the inside packaging and the exterior heat sink structure. Improvements in heat conduction from the chip to the heat sink are a result of this optimization of the internal packaging structure of LED devices. In the meanwhile, it can optimise the heat sink's structure to increase its heat dissipation capabilities to the ambient.

The luminous flux of an LED lighting system, at an affordable price and without sacrificing reliability, needs to surpass 1000 lumen levels to meet the daily lighting demand. An array of 33 high-power LEDs, with a combined output of 9 W, is designed in the article to meet the lighting needs of a daily basis. Nevertheless, comparing the thermal properties of individual LEDs to those of an array reveals significant differences.

The junction temperature of the LED array is very sensitive to environmental factors and the collateral damage caused by several chips. Accurately measuring the internal temperature distribution experimentally is challenging for LED devices due to their tiny size and complex internal structure. Nonetheless, using finite element analysis, it is able to forecast the distribution of internal temperatures.

1.1. Parametric modeling

An ANSYS parametric design language (APDL) is used to model LED lighting systems. The key parts of this system are a heat sink, solder, thermal interface material (TIM), a high-power LED array and a printed circuit board with a metal core. Table 1 lists all of the material specifications for the lighting system. The LED array's nine high power LEDs are supported by a 38.38 mm MCPCB with a 12.5 mm pitch. TIM improves the heat dissipation capabilities of the MCPCB by mounting a heat sink underneath it. The main parts of a high power LED bulb include the substrate, chip, bond wire, slug, silicone encapsulate, epoxy lens and so on.

The utilization of limited component computational liquid elements (CFD) programming considers a careful assessment of the heat conduction, convection and radiation in LED lights. The product produces discoveries, for example, a temperature field, a stream field and other comparable variables. Since this is the situation, the CFD program functions admirably for

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reproducing the heat from current LED lights. In view of the temperature and heat stream estimations from the detailed limited volume model, Chen and partners fostered a reduced warm model for LED bundles that can be utilized with an assortment of limit conditions. The LED bundle is modeled utilizing the limited component strategy to reenact different heat slugs, printed circuit sheets, cooling conditions and chip sizes.The discoveries furnish the business with the warm plan rules and relationships vital for the making of new LED light products.In request to streamline the plan of heat dissipation for LED downlights, Bai et al. used computational liquid elements (CFD) programming to run warm simulations of three-center white LEDs. They then concentrated on the warm opposition of different materials utilized in warm cross over channels, including substrates, patch, copper foil, aluminum substrates and that's just the beginning. At long last, they proposed a crossover quick warm channel strategy that utilizations copper to interface PN intersections and outer radiators. An examination was led utilizing the limited component strategy to decide the temperature field of a 15W LED downlight. The examination additionally considered the heat dissipation impact, warm elastic heat conductivity and the place of the chips comparative with the sort of radiator balance.

An advancement on the conventional lamp design, an LED downlight uses light-emitting diodes (LEDs) as its source of illumination. In short, LED downlights share all the best features of both old and modern downlights, including minimal carbon emissions, a long lifespan, a high Colour Rendering Index (CRI), a quick response time and cost savings [6]. The installation of LED downlights, which are aesthetically pleasing and little in weight, will not disrupt the building's overall harmony since they blend in with the interior design. The most common types of light sources utilised in LED downlights are Chip on Board (COB) arrays, high power LED (≥1W) arrays and small-medium power LED (≤0.5W) arrays.To achieve the most flattering and consistent lighting effect, the majority of modern LED downlights use small-to medium-power LED array light sources.

2. RESEARCH OBJECTIVES

1. To create a comprehensive mathematical model in three dimensions for simulating and visualizing heat dissipation in LED downlights, considering material characteristics, heat load and thermal resistance.
2. To compare Computational Fluid Dynamics (CFD) models with physical lab measurements, ensuring accuracy and reliability of the simulation approach and validating its outcomes.
3. To explore how different design elements, particularly the number of LEDs and distances between their rings, affect the efficiency of heat dissipation in LED downlights.
4. To evaluate the impact of these factors on the thermal properties of the lighting system.

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3. LITERATURE REVIEW

Yang, G., Liu, C., & Liu, H. (2023) Surface powerful geographical peculiarities like slant breakdown, avalanches, garbage streams and ice torrential slides are normal in cool, high-elevation places because of the escalated outer cycles, for example, icy mass liquefying. Understanding the water-heat cycle and how the ice hurling compel it prompts inside the cracks develops is essential for high and steep slants in high-height areas with controlled breaks. After this, it's feasible to research the debacle component inside the breaks brought about by continued freezing and defrosting, as well as the multi-field and multi-stage harm engendering. It is feasible to see the improvement of ice hurling force and give a hypothetical establishment to the component by outwardly following the water-heat relocation process inside the divided stone mass. The initial step was to demonstrate the way that molecule following and warm imaging procedures can follow the freezing front in rock breaks and the development of fluid water inside the stone utilizing research on molecule following and picture handling.

Rongier, et. al. (2023) Progressions in superior quality pillars have been made in auto front light. It takes many light sources per square millimeter to get this impact. The ongoing prevailing fashion is to utilize a solitary, extremely splendid LED instead of various, less powerful ones. Warm administration is fundamental because of the great energy thickness brought about by the 10W optical power produced by this optoelectronic source. At the point when this LED is important for its optical framework, the high convergence of radiation can make the framework overheat, which can make harm or disappointment happen as soon as possible. Making a solid multi-material science model to predict heat move in a LED lighting framework is the strategy used to hinder part disappointment in this article. By contrasting mathematical simulations and functional outcomes, this paper approves a thermo-optical coupling model for high splendor LEDs. To build its opto-warm model, the total optical portrayal of the LED has been completed. Then, a set-up for the trial has been arranged. It includes putting a dark plate before the LED so infrared thermography can record oneself heating that happens because of the light energy retention. With an incorrectness of fewer than 10%, the model is upheld by the fair arrangement between thermo-optical simulation and infrared thermography.

Rongier, et. al. (2022) the utilization of computerized and versatile superior quality pillars has advanced in car front brightening. The production of such capabilities requires the supplanting of many LED plans with novel LED ideas that use a solitary high-luminance LED. Warm administration is fundamental because of the great thickness of energy instigated by the glowing energy transmitted by such a semiconductor light source, which can arrive at 3000 lm (for example 10 W). The optical exhibitions and part trustworthiness are to be sure connected with the temperature of the LED. In this way, it is important to make mathematical models that are both precise and productive. By contrasting mathematical simulations and reasonable information, this

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work approves the high brilliance LED warm model. Complete part characterization is handled to develop the matching warm model.

Liu, et. al. (2021) Our current focus is on studying how the distributions of interfacial heat flux and interfacial temperature change during the evaporation of sessile droplets. The use of infrared imaging and temperature-sensitive paint (TSP) were two nonintrusive measurement techniques that were employed in tandem. After the interfacial temperature distribution was captured using TSP, the heat flux distribution was obtained by establishing a one-dimensional unstable transient model. The thermal patterns occurring during the evaporation of droplets were seen from above using an infrared camera. Our experiments were conducted using pentane, HFE-7100 and hexane as liquids. The results demonstrate that the contact line profile recorded by TSP agrees with the one recorded by an infrared camera. There were three distinct phases to the evaporation of droplets: the first was heating the droplets, the second was evaporation in convection cells and the third was evaporation in thin films. During the second step, infrared photos revealed convection cells, while TSP images clearly showed a temperature differential at the contact surface.

Su, et. al. (2022) Pulsating heat pipe (PHP) finds extensive application across various heat management domains due to its straightforward construction and exceptional heat transfer performance. It uses the vapour-liquid plug oscillation mode for heat transfer, which includes many processes such as bubble nucleation, growth, coalescence, collapse, evaporation and condensation of the liquid film, among others. It is so challenging to forecast PHP heat transfer performance because to the complexity of the heat transfer system and the multitude of affecting elements. A great deal of study on visualisation has been conducted in order to enhance the heat transfer theory and mechanism of PHP. With the goal of serving as a resource for researchers interested in PHP visualisation, this paper compiles and summarises the most recent advancements in the field. It then goes on to discuss the various visualisation techniques used in PHP studies, as well as the operating conditions, structural parameters and working fluids that have been investigated.

4. RESEARCH METHODOLOGY

4.1. Modelling the Dissipation of Heat from LED Downlights

The 8-inch 25W power LED downlight modelled in Figures 1 and 2 is the primary topic of this paper's research.

4.2. Laboratory Experiment and Computational Fluid Dynamics Modelling

- **Lab Measuring**

The 25W LED downlight was chosen for the laboratory measuring experiment and the temperature measuring instrument used was the 8-channel TP700.The laboratory temperature measurement platform was constructed using LED lighting, as depicted in figure 6. The measuring environment

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is a closed test room with constant temperature and no human movement. The ambient temperature was 26.7 degrees Celsius, as shown in Figure 4.

4.3. CFD Simulation

Presented in table 2 are the light source, materials, heat conductivity value and 60 pits medium power specifications for a 25W 8-inch 5630 LED array downlight.

5. DATA ANALYSIS

Table 3 data indicates that there was very little difference (≤2% inaccuracy) between the simulated and measured temperatures at positions 2 through 6. We will use the identical settings and boundary conditions in the upcoming optimization simulation experiment since this simulation approach is accurate and dependable. Additionally, it was discovered that the temperature at position 1 was only slightly higher than the simulated temperature (by 5°C). This suggests that manufacturing, assembly, measurement, or other processes may be the primary causes. Hence, it can be concluded that both the simulation and the measurement are accurate. The high temperature at position 1 indicates that the majority of inner ring LEDs had temperatures that were noticeably higher than those of the outer ring LEDs. Consequently, the light source plate's LEDs' operating temperatures range from one another, this will result in the inner ring LEDs having the lowest lifetime in the end. Furthermore, it will have an effect on the total lifetime of the light source plate. It is necessary to optimize the light source's layout design based on the findings of experiments and simulations.

5.1. Layout Optimization of Light Source

Many factors, including heat dissipation, electrical and mechanical construction, optical quality and manufacturing technique, need to be taken into account when arranging a light source optimally. There isn't enough space for an optimum configuration of the light source in 25W LED downlights with four-ring LED architecture due to the size constraint of the light aluminium substrate. As a result, the three-ring LED layout design method is suggested. The next thermal simulation will take into account the number of LEDs and their ring distance.

- **LED Quantity**

Keeping the total power at 25W, three rings of LEDs are considered, with schemes including sixty, forty-eight and thirty-six LEDs. Figure 6 shows the simulation results, Table 4 compares the data and all boundary conditions, materials and mechanical structure are same.

When it comes to configuring the power supply for LED downlights, the results from Table 4 that indicate less power and more number of LEDs should be the most effective. The uniform distribution of heat from the light-emitting diode (LED) source is a result of the reduced heat coupling effect. The production technique for welding LEDs onto aluminium substrates will grow more intricate, but more LEDs will be able to dissipate heat more effectively. There will be localized heat buildup due to the higher power of each LED, even though fewer LEDs can be integrated and welded more simply. A 25W LED downlight is best suited with 48 light sources, according to the research.

- **LED Ring Distance**

Three separate simulation studies are conducted with respect to the light source plate size. 10 mm, 12 mm and 14 mm will be the ring distances. Compare outcomes as displayed in Table 5.

- **Optimized Layout**

The light source optimization configuration of the 25W LED downlight was determined to have 48 LEDs in quantity created using layout optimization and temperatures are recorded in the same lab setting. The resulting temperatures are then compared to the outcomes obtained without optimization. Table 6 presents the comparison results. It is evident from the table that the optimized light source configuration LED lights have a lower working temperature, particularly the LED maximum temperature decrease of around 10%, which indicates an improved heat dissipation impact. Through optimization, the entire service life of LED downlights can be increased.

5. CONCLUSION:

This study demonstrates that efficient thermal design is vital for improving the operational stability, reliability and service life of LED downlights. By combining CFD simulations and laboratory validation, it was established that the inner-ring LEDs in multi-ring arrays experience significantly higher temperatures, reducing their lifetime compared to outer-ring LEDs. The research further highlights that: The simulation results matched experimental findings with minimal error ($\leq$2%), validating the approach. A 48-LED configuration achieved the best balance between heat dissipation and manufacturability compared to 36-LED and 60-LED configurations. Optimizing ring distances (10 mm–14 mm) showed measurable improvements, with larger spacing reducing localized heating. An optimized layout reduced maximum junction temperatures by ~10%, leading to an increase in the service life of LED downlights. Recommendations Manufacturers should adopt optimized LED quantity and spacing for uniform thermal distribution. Hybrid cooling techniques (such as phase-change materials or pulsating heat pipes) may be integrated for high-power LED systems. Future work should expand to real-time thermal monitoring and integration of AI-based predictive models for advanced LED thermal management. Thus, optimized thermal design not only ensures better luminous efficiency but also significantly contributes to the sustainability of LED technology in residential and industrial lighting applications

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