THERMAL ANALYSIS AND OPTIMIZATION OF HIGH POWER LED ARMATURE

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It is an effective way of energy conservation to use high power LED armature in street lighting. However, there exists some restrictions in front of the usage of that, like overheating of LED chips and high weight of armature case. Generally, aluminum heat sinks are attached to housing of the armature to get effective working of LED armature. In this study, a street type high power LED armature has been modeled numerically, transient thermal system has been analyzed and the results have been compared with experimental results in order to decrease the armature weigh and increase efficiency. Also, in experimental studies thermal camera and thermocouples have been used for thermal measurements. Finally, multi-objective optimization has been performed to decrease the armature weight, while keeping maximum temperature on armature between in safely working interval.

Key words*: Thermal analysis, CFD, LED armature, Optimization.*

1. Introduction

Energy conservation and green energy topics gradually gains importance for government policies in order to protect the environment and reduce hazardous wastes. People also become conscious about this subject and prefer renewable energy and recyclable product. One of the most energy consumption area is outdoor and indoor illumination around the entire world. There are many research and development studies in order to decrease consumed energy in this area [1-4]. By improvements in solid-state lighting (SSL) systems, the development of high power LEDs is no doubt one of the best inventions at the scientific researches in two decades on lighting systems. Because of advantages of usage, such as: energy saving, high light quality, long product life and environmental friendly properties, high power LEDs are being widely used at various areas. For instance road and building lighting, household lighting, automotive lighting, traffic signal lights, and billboards are commonly usage areas of this technology. Considering the advantages and areas of usage high power LED or SSL systems which are more efficient and beneficial in many aspects compared to conventional lighting systems. Also it has been seen that high power LED luminaires for outdoor lighting are more efficient with respect to power input and light output (lumen/watt) compared with incandescent and florescent lamps. As an example in 110W LED armature, product life with 60000 hours is nearly five times longer others and energy efficiency approach to 75% with 115 lumens per watt (ln/W)[5]. Together with improved LED lighting technology and becoming prevalent of LED application save most of energy in illumination area.

Several European countries are converting their conventional road lighting systems by high power LED lighting technologies. The history of LED reaches back to the discovery of semiconductors, in the recent century many studies have been done to improve LED technology and to expand its application area. Light-emitting diode was invented in 1907 by Henry J. Round and improvements on LED continued to todays. Henry J. Round applied 10 volts electricity to silicon carbide (carborundum) and observed the emitting of yellowish light [6].Oleg Losev made studies on LED, for his new inventions he took out patents, and published articles in 1920s [7]. On the other hand, the production and wide usage of LEDs has been seen after 1960s in the USA [8-10]. However, LED has not been used as lighting device until 1990s due to its low emitting light. The first high bright LED was discovered in 1994 in blue light as based on indium gallium nitride (InGaN) [11]. The first high bright LED having high power input was introduced in the beginning of 21th century [12-14]but it was faced with a problem which is overheating due to high power input which is a necessity for continuity in high brightness. Because of this reason, working efficiently of a high power LED luminaire depends on dissipation of generated overheat. Higher junction temperature while operating luminaire causes critical problems like reduction in lifetime, in light quality, in energy efficiency, etc. The most common method is dissipating overheat by using aluminum heat sink to decrease the chip temperature. However, this solution leads to generate armature in high weight with respect to its power ratio due to heavy heat sink. For instance the sample armature which is used in experiments of this study has nearly 10 kg weight, and its heat sink composes the 90 percent of total weight. There exist many studies in literature in order to decrease the weight of armature and to minimize junction temperature of LED. Some of these studies to decrease the total armature weight have been done by subtracting some parts like bottom board from PCB or changing it with lighter material [15, 16]. Besides this, changing geometrical structure of fin or armature is a common used method to accomplish this purpose [17-19]. Adding a proper fan to heat sink also another effective solution to cool armature [20]. Another method to regulate the heat distribution on heat sink is the multi-LED packaging method in which higher voltage LEDs take places at edges and lower voltage ones at middle of armature [21]. In order to predict the behavior of heat dissipation or make thermal management for a LED armature, the most acceptable way is generating numerical model and performing thermal analysis. Thus, the effects of parameters on junction temperature can be predicted previously. In recent studies it is possible to reach many studies have been done by using different software in numerical modelling and CFD analysis. Main aim of these studies is to determine how much heat is dissipated by heat sink and where maximum heated regions are placed on armature and what is its effect on junction temperature [19-25]. Besides this, a few studies on the street type LED armature have been observed in literature and they do not include all aspects of thermal management. This study aims to obtain the optimum shape design for a street type high power LED armature. Thus, experimental and numerical studies have been performed on armature and by comparison of results the numerical model has been validated. In the thermal measurements thermal camera and thermocouples have been used on original sample armature. Then numerical modelling and CFD analysis have been carried out by using ANSYS and Fluent software. In order to reduce the armature weight while sustaining operating temperature in desired level, multi-objective optimization of armature geometry has been done where plate fin dimensions have been defined as variables.

2. **Methodology**

In this study, a street type high power LED armature has been used as the sample and all experiments have been done on it. The sample LED armature is produced in M2 lighting class by the properties 110 Watt, and 90 pieces LED chips shown in Fig.1. First of all, experimental measurement has been performed with thermal camera and thermocouples on armature while it is operating in real environmental conditions. By this way, the maximum temperature and most heated region can be determined on the surface of plate fins. Then, numerical model of armature has been generated for computational fluid dynamics (CFD) analysis by using Fluent software. This provides to observe temperature distribution on armature in design stage. After the both of experimental and numerical studies the closeness at results of these studies verified the accuracy of numerical model.

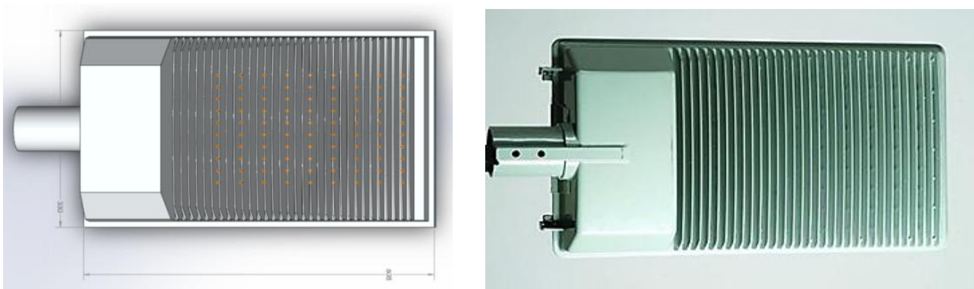

Fig.1. CAD model of armature and its photo.

2.1 Experimental Setup

The experimental studies have been done in two stages, in order to measure temperature of armature while operating and determine the most heated region on it. The first thermal measurement has been done by using thermal camera which has given an opportunity to see thermal distribution in all surfaces of armature. As a second method, thermocouples and data logger have been used to measure the temperature distribution on armature. By using both of these methods the experimental side of study has been reinforced and each of these measurements has been verified by each other.

2.2 Thermal Camera Measurement

In the thermal camera measurements Testo-875 handy and robust thermal imager has been used. In order to take good thermal image necessary environmental conditions have been supplied in CFD laboratory, also operating conditions of armature in outdoor have been generated to obtain realistic results. The environmental temperature has been kept constant in 25 °C while operating armature for thermal measurements. The armature has been turned on, and heating has been observed on armature which has continued to reach thermal equilibrium. After the equilibrium time the temperature increase has stopped and the temperature distribution has remained constant on armature. Then, several thermal photos taken from different aspects, by this way the most heated zones of armature has been determined.

2.3 Thermocouple Measurement

The second experimental method is thermocouple measurement that has been applied to measure maximum temperature on various region of armature. These measurements also have been done in operating conditions of armature by using 6-channel data logger and with J and K type thermocouples shown in Fig.2.

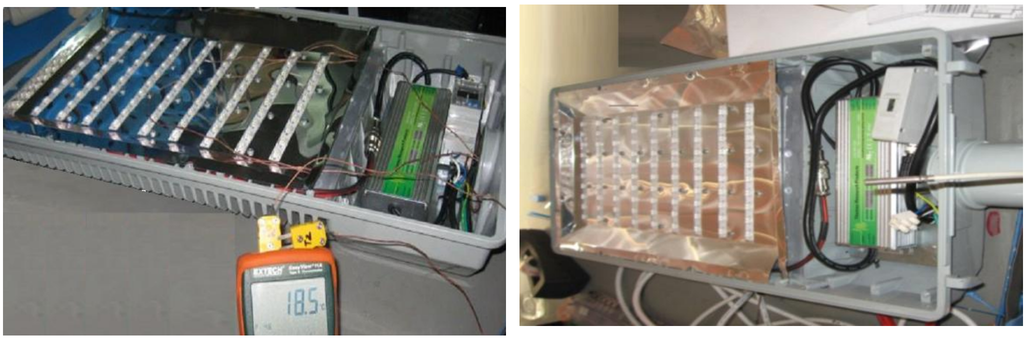

Fig.2. Temperature measurement with thermocouples on armature (Fluke-971 and Extech EA11A)

In experimental study, first, thermal characteristic of armature has been tested for a long time to get realistic performance of it by using thermocouples. Thermocuple and thermal camera results were compared on the same fin suface as 37,7°C, 37,2°C and LED surface as 41,3°C, 40,6°C, respectively. This experiment has used for a verification of thermal camera measurements because the results shows that the maximum heated regions are same and the temperature values are very near at the both of the experiments. The advantage of thermocouple experiment is the opportunity of measurement at inner volume of armature. Therefore the junction temperature of LED chip could be calculated with solder point temperature, thermal resistance of LED, the forward current and voltage calculations from measured value that are very nearest place of LED pieces. Some measurements also have been done on heat sink or on fins of armature.

2.4 Numerical Analysis

Computer Aided Design (CAD) model generation from original armature in exact dimensions is a necessity for numerical analysis. Because of this reason, the original armature has been disassembled to main components which are heat sink, electricity driver unit, and tempered glass. Then, dimensions of the components have been taken sensitively by conventional methods and the CAD model of armature is generated by using a CAD modeling software. Precision in sizing of model is important to reach real dimension in armature model so, by numerical analysis that can be possible the verification of model and the accession to realistic results. According to real geometrical measurement the armature was drawn in 3D CAD software. The material properties were loaded to CAD model and the physical properties were compared each other. After generation of CAD model the verification is made between sample armature and model in physical properties like weight, volume, etc. At the next step, the CFD model has been produced from the CAD model; it includes two flows which are inner flow and outer flow. Heat flux from LED surfaces was defined by 679W/m^2 as heat sources. The inner flow is among the armature between LEDs and glass, the outer flow also is between the boundaries of control volume and surfaces of armature. After that, the meshing operation is applied on model, the distant areas from critical areas has been meshed relatively coarse sizes while the critical areas which near to LEDs has been meshed in fine sizes. Before analysis, mesh sensitivity was measured between 500.000 elements as a coarse mesh and 4.000.000 elements for fine case. Proper mesh number was found about 3.500.000 elements. In fine case study, the armature mesh number has 3.6 million elements. In simulation, transient condition and RNG k-e turbulence model were selected. In thermal analysis, conduction, convection and radiation models were enabled. At the CFD model the LEDs have been used as heat sources and total power quantity shared to LED quantity which is 90 pieces. Gasket opening and vent outlet were specified as pressure boundary conditions. Inlet air temperature at gasket opening was considered to be at ambient temperature 298 K. Wall boundary conditions were taken adiabatic conditions. At the base and roof atmospheric pressure conditions were applied. Velocity distribution at the environment was taken stagnant. Then, heat flow from LED surfaces to armature is 679W/m2. In model the armature was located at 15 degree angle to surface because in practice the armatures are hanged out at this position. No-slip and no-penetration condition was assigned on the interfaces between solid and fluid regions. Zero velocity boundary conditions were applied on the boundaries of the ambient air.

2.5 Optimization

The most important part of this study is optimization, so first of all the objective of optimization is determined. The major aim of the optimization is to decrease the weight of armature while keeping the operating temperature of armature between its safely working temperature boundaries. Therefore it is a necessity to make multi-objective optimization on this problem. After the some investigation on armature geometry that has been seen some refinements can be done on fin geometries so the fin height, fin top and bottom width have been selected as parameters of optimization. These three parameters are shown in Fig.3 with cross section of heat sink which had been simplified to two fins by utilizing the symmetrical geometry of armature in order to minimize solution time of numerical analysis. The decrease on these parameters means decrease of armature volume in other words minimizing the weight of armature that is the main aim of the optimization study.

The thermal analysis has been done by using ANSYS-Fluent software and for optimization study same software's optimization module has been used, it is response surface methodology (RSM). RSM is a superior alternative to Taguchi technique, and it works successfully to solve robust design problems. Two important approaches that contribute most to robust design are combined array designs for design construction and dual response surface approach for modelling and optimization formulation [26]. Input and output parameters of optimization with their initial values, constraints, and objectives are shown in Table 1. Here, the initial values are exact values which measured from sample armature and the constraints determined as 50 percent upper and lower values of initial values. As objective that is commanded the minimization of input parameters while keeping output parameter in desired interval. In optimization study, also maximum temperature constraint was selected as a 40°C all over the armature with respect to other design constarints. Thermal management and optimization cases of armature were evaluated eccording to literature [27].

Table1. The optimization parameters and constraints

Parameters	Initial value	Constraints Lower Upper Bounds	Objective
Fin Height (mm)	50	25 - 75	Minimize
Fin Bottom Width (mm)	5.6	2.8 - 8.4	Minimize
Fin Top Width (mm)	2	1-3	Minimize
Maximum Temp. all over the armature (°C)	25	20 - 40	Keep interval

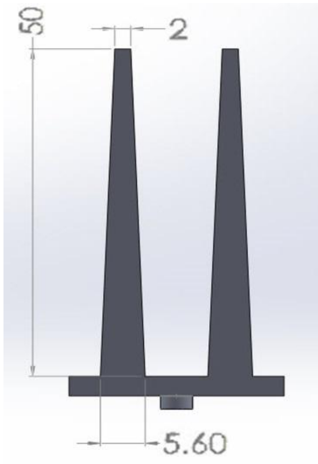

Fig.3. Optimization parameters and cross-section of simplified geometry

3. Results and Comparison

In this part, all results of this study have been presented that are experimental, numerical, and optimization studies and the results have been compared with each other. Closeness between experimental and numerical results has validated this study. Firstly, the results of experimental studies which are thermal camera and thermocouple measurements have been presented and they have been compared numerical analysis results of high power LED armature. Then, the optimization results have been presented and the decrease of weight by optimization has been shown in this section.

3.1. Thermal Camera Measurement Results

Thermal camera measurements and experimental setup were given in Fig. 4. Temperature legend has been scaled from blue to red colors, which represent the temperature range between 20 °C and 40 °C. The maximum temperature of fins can be seen in Fig.4a as 37.2 °C while the maximum temperature was measured as 40.6 °C in Fig.4c. Moreover, it can be seen, the aluminum heat sink of armature has high temperature while the LEDs have lower temperature value due to reflecting materials. Also because of tempered glass properties, left sides of armature has higher temperature compared to center of armature. In Fig.4b and Fig.4d temperature changes along P line along fins and LEDs were shown as diagrams. These thermal camera experiment results and the temperature dissipations in figures have similar results for numerical analysis. Experimental studies were performed for a long time to get reality results and compared numerical simulations.

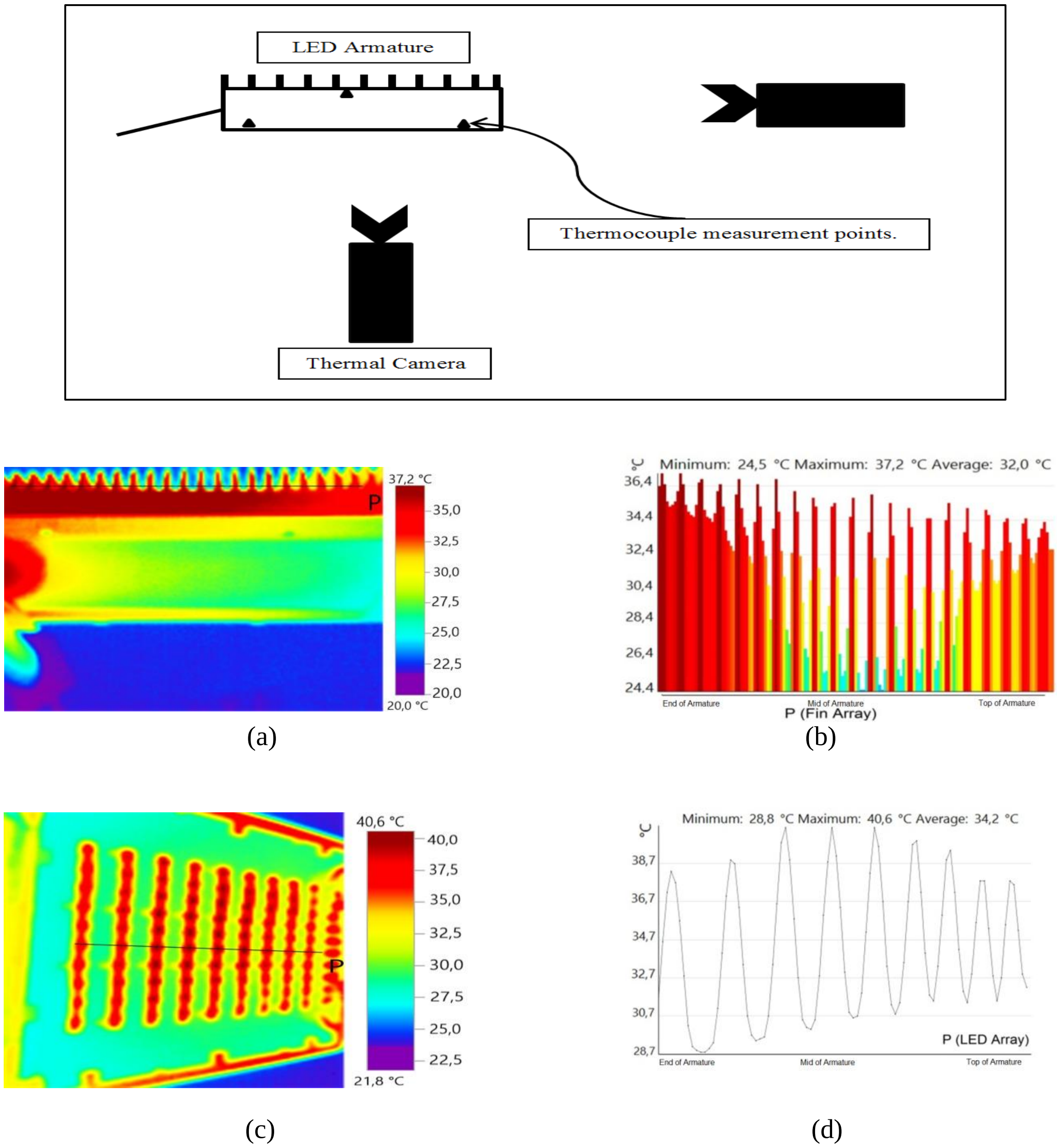

Fig.4. Experimental setup. Thermal camera image of armature (a) right view, and (b) temperature distribution on fin array, and (c) bottom view, and (d) temperature distribution on LED array.

Table 2 has been generated according to report of thermal camera software which is Testo IRsoft software. The values in the next table show the P-lines values along fins and LEDs. Here, the most critical ones are maximum temperature which shown at tip end of fins while at the middle region of LEDs. As compared fig. 4c and fig. 5, it can be seen that there is coincidence between experimental measurement and numerical simulation.

Table2. Temperature values by thermal camera on fins and LEDs

	Temperature (°C) on Fin	Temperature (°C) on LED
Maximum Temperature	37,2	40,6
Minimum Temperature	24,5	28,8
Average Temperature	32,0	34,2

3.1 Thermocouple Measurement Results

In this experimental study a 6-channel data-logger and J and K type thermocouples have been used. In the thermocouple experiment the maximum temperature on fins of heat sink is measured 35.6 °C from tip side of armature while the position of armature is placed with 15^0 angles to ground. Similar result of numerical study is also observed at this experiment; when the armature is thermally steady state the maximum temperature is 33.7 °C measured while its position is parallel to ground. The measurement of fin temperature in these experimental studies is significant to determine the LED junction temperature because the junction temperature cannot be measured directly so, it can be calculated with solder point temperature, thermal resistance of LED, the forward current and voltage values.

3.2 Numerical Simulation Results

The thermal analysis has been performed by Fluent software in which heat dissipation occurs by natural convection from surface of heat sink and by conduction from chips to outer surface. In the numerical calculation of this heat transfer problem energy equations are used. Then, k-e turbulence model is used in the solution of analysis and SIMPEC method is applied as a solution method, so the analysis results converged after 1400 iteration. After the iterative solution very near results to experimental results are obtained with highest temperature is 35.0 °C (308 K) at the tip of armature. The following figure shows the temperature distribution on armature and it is seen the air temperature changes by heat dissipation. This state illustrates the interaction between solid and fluid as a result of CFD analysis. In the Fig.5 that is shown the heated air increases due to angled position of armature and the warm air in inner section causes overheating at tip of armature. The importance of the CFD analysis is thermal interaction of solid and fluid, here the contact temperature changes with each iteration step till approach equilibrium point and it affects the final result. The variation of temperature in fluid due to change of solid temperature helps to numerical analysis in calculation in order to reach the experimental results of physical model.

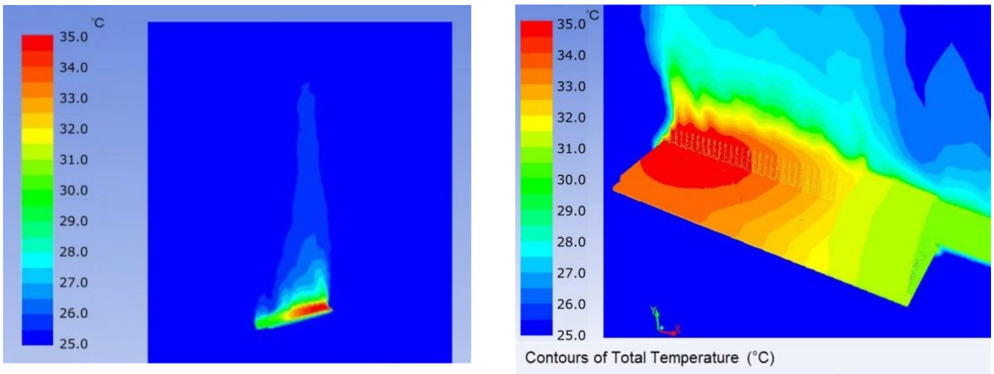

Fig.5. Heat distributions on armature and control volume in numerical simulation.

3.3 Optimization Results and Comparison

Optimization study has been performed on simplified geometry by using response surface optimization module of ANSYS software. In thermal analysis stages of optimization process transient thermal module of same software has been used to investigate the flow motion and heat dissipation from starting point. In this part, the effectiveness of optimization for decrease the weight of heat sink is indicated by decreasing of geometry dimensions. In the Table 3 that is presented the effects of optimization on simplified geometry weight and consequently on total weight. After the optimization process the weight of simplified geometry which represents heat sink with two fins has decreased from 0.191 kg to 0.130 kg. When applied the optimized geometry values to total armature the total weight decreases to 7.73 kg which is 1.59 kg lighter than original armature weight.

Table3. Comparison of weights before and after optimization

	Before Optimization	After Optimization	Decrease in Weight (%)
Simplified geometry weight (kg)	0.191	0.130	31.94
Total armature weight (kg)	9.32	7.73	17.06
Average Temperature (^{o}C)	32<40	34.2<40	-

Table 4 and Fig.6 also shows input and output parameters and the variations of them after optimization study. Here, the input parameters are dimensions of geometry and the output parameter is value of maximum temperature in armature. Decreasing in input parameters reduces armature weight and the output parameter almost remain same at 37.7 °C which is under the bound of reliable working temperature 50 °C for this armature[5].

Table 4. Optimization parameters, constraints and optimized values

Parameters	Initial Values	Optimized Values	Constraints Lower –Upper Bounds	Decrease in Dimension (%)
Fin Height (mm)	50	38.87	25 - 75	22.26
Fin Bottom Width (mm)	5.6	4.84	2.8 - 8.4	13.57
Fin Top Width (mm)	2	1.22	1 – 3	39.00
Max. Temperature(°C)	25	37.7	20 – 40	Reliable interval

The effect of the optimization on fin geometry is clearly shown in Fig.6 the decreasing of the parameter made the armature in lighter weight. The weight decrease is 31.94% at the simplified geometry while the ratio is 17.06% on total armature weight. Residuals for conservation of continuity, momentum and energy equations were given in Fig. 7.

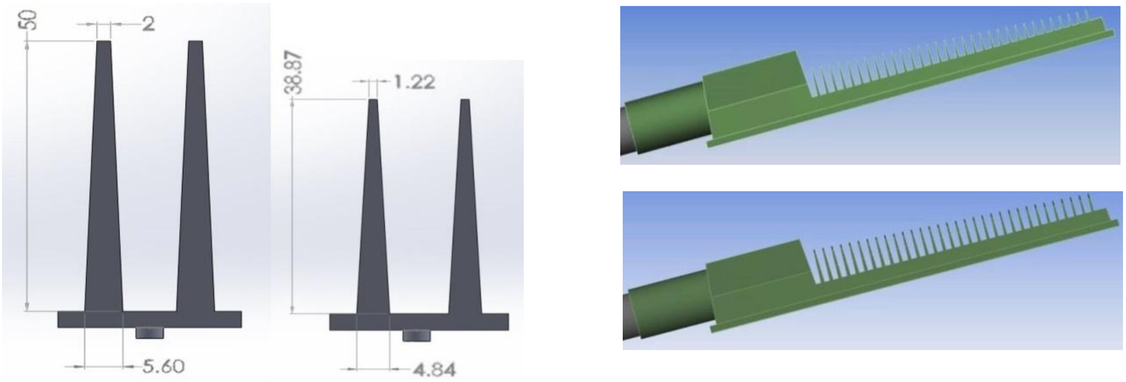

Fig.6. Geometrical parameter before and after optimization in simplified model (left), in whole armature model (right).

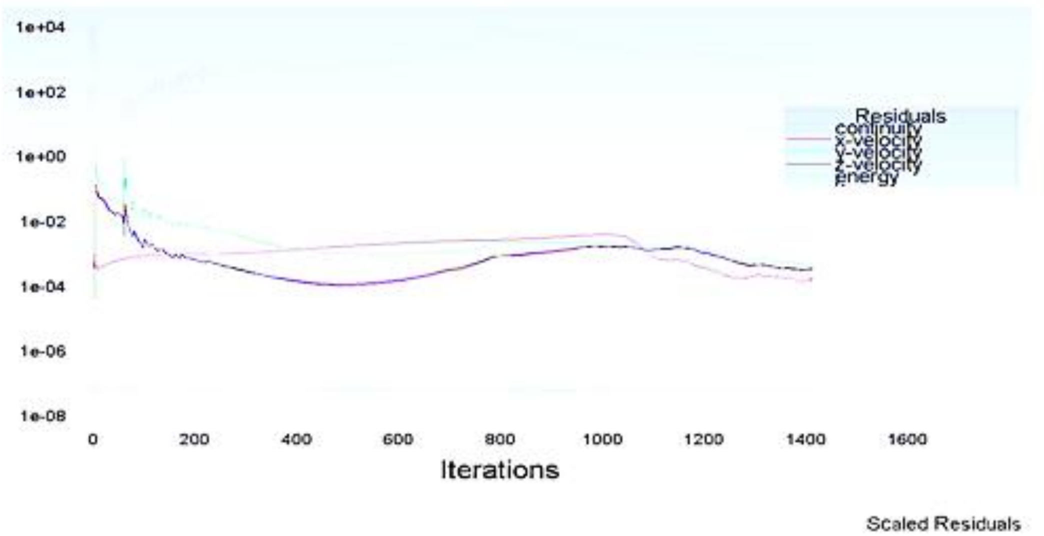

Fig.7 Iteration number for convergence criteria.

4. Conclusion

As a conclusion, in this study a street type high power LED armature has been modeled and analyzed thermally by numerical simulation. Also working temperature of real armature has been measured by thermal camera and thermocouples. Both of experimental and numerical studies results have been compared each other and the numerical simulation has been validated. Finally, by optimization study on fin geometry the armature weight has been decreased by keeping temperature in reliable working interval. By the optimization operation already energy efficient system has become also cost efficient with lower weight. Experimental studies were performed for a long time to get reality results and compared numerical simulations. Critical areas on system have been detected by numerical analysis and thermal camera images that will be beneficial for efficiently dissipation of heat in new design of armatures. Energy conservation also can be done on high power LED armature by applying optimization operation on array of LED chip, electricity driver, and arrangement of lamppost.

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