Comparison of finite volume and one dimensional network methodologies for thermal management of lighting applications

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Abstract. Signify is focused on building a state-of-the-art, innovative and sustainable solutions for industries, homes, buildings, and communities. In the last decade or so there has been a considerable shift from using traditional incandescent luminaires to highly efficient, cheaper, and robust LED (Light Emitting Diode) based lighting fixtures. LEDs are semiconductor devices and thus their life depends largely on operating temperatures. Thermal management of the lighting fixture, therefore, becomes crucial for the overall performance. Heat sinks are designed for given operating conditions for better thermal management. With the improved LED efficiencies there are two alternatives that the product designer can opt for namely, to increase the lumen output for the present fixture or to reduce the overall heat sink size. To assist the product designer in this aspect, the present paper reports the thermal management of lighting luminaries using two different modelling techniques such as Finite Volume Method (FVM) and One Dimensional (1D) resistive network analysis. These two modelling techniques are employed to predict the temperature profiles on the luminaire and then compared them with the actual test results. The processing time, accuracy, and method of implementation for both these techniques are then discussed.

1. Introduction
The lighting fixture is an electrical device which includes a laminating circuit that provides illumination as mentioned in Quin et al. [1]. It has various electronic components such as driver, transformer, surge module, the illuminating circuit to perform different functions. The type and specification of these components depend on the environmental conditions, applications, and user experiences in which it is to be installed. There has been a major shift in technology in the last decades from the traditional incandescent light source to LED source as described in white paper [2]. It is mainly because LEDs offer higher energy saving and lesser maintenance over their life span. The life span of LEDs largely depends on their operating temperature. Higher the operating temperature lower will be the life span for LEDs. With the advent of new technologies, efficiency of LEDs has significantly increased which has eventually brought down the total heat generation from the source. Heat sink configurations must be constantly modified to meet challenging market requirements and cadre with customer needs. Thus, thermal management of lighting fixtures is of extreme importance for product development.

Presently, there are three modeling methods used for predicting temperature distribution across the fixture, namely, FVM, FEM (Finite Element Method), and 1D resistive network,
as mentioned by Perara et al. [3]. FVM and FEM are deployed using modeling software such as Ansys-Fluent, FloTherm, etc., as described in Petroski et al. [4]. For these methods, simplified geometry with external as well as internal air volume is used as a computational domain. Multiple meshing techniques are used to capture the temperature gradient across the walls and critical parts. Meshed parts are then imported into the solver for assigning material properties, boundary conditions, and heat loads. Once the baseline design is evaluated, the fixture is either redesigned using these modelling tools for improved conditions, or Lumen output capacity is increased for the same configuration as explained by Todorov et al. [5].

1D resistive network methodology on the other hand is developed using various governing and empirical equations for the given heat load conditions. The boundary layer concept of heat transfer and fluid mechanics is used for obtaining these correlations. Based on the product requirement and input conditions heat transfer coefficient (HTC) is calculated for given surfaces. For meeting the thermal requirement, luminaires are designed in such a way that the maximum temperature observed on each of the components should be less than the specified limit. To satisfy these requirements heat sinks are designed to remove the excess heat that is generated across various sources. The driver is selected as per specific lumen requirements prescribed by the customer. Heat generation across the fixture is calculated as mentioned in equations (1)-(7).

$$H_{Driver} = (1 - \eta_{Driver}) \times Q_{Input}$$  \hspace{1cm} (1)

$$Q_{LED} = Q_{Input} - H_{Driver}$$  \hspace{1cm} (2)

$$Q_{SingleLED} = Q_{LED}/N$$  \hspace{1cm} (3)

$$H_{SingleLED} = (1 - \eta_{LED}) \times Q_{SingleLED}$$  \hspace{1cm} (4)

$$H_{LED} = H_{SingleLED} \times N$$  \hspace{1cm} (5)

$$H_{Reflector} = 0.1 \times H_{LED}$$  \hspace{1cm} (6)

$$H_{Total} = H_{LED} + H_{Driver} + H_{Reflector}$$  \hspace{1cm} (7)

Where ‘Q’ is Power, ‘H’ is heat generation and ‘N’ is the number of LEDs. In the present study two modelling techniques, namely FVM and 1D resistive network theory are used to obtain the maximum temperature observed on the LEDs for given heat load conditions. Temperatures obtained for various heat sink configurations from these techniques are then compared with the actual test results. This comparison serves as the foundation for determining the accuracy of each of the methodologies. Finally, the merits and drawbacks of each of the methodologies are noted which can be used as initial thumb by engineers for future product design.

2. Finite volume method analysis

Figure 1 shows a schematic of the luminaire with light square and driver locations. Small fillets, chamfers, unwanted parts are removed or simplified for reducing computational complexities. Material properties are assumed to be constant over the given range of temperatures. The computational domain is formulated by creating an enclosure surrounding the luminaire as shown in figure 2. Boundaries of the computational domain are kept at a certain distance considering that there are no entry effects. Hex dominant cut-cell mesh is used along with creating non-conformal meshing assemblies. Pressure inlet boundary condition is imposed from all the sides except the mounting side. The mounting side is assigned as a wall boundary condition similar to that stated by Arik et al. [6]. Drivers and LEDs are modeled as lumped bodies with effective thermal conductivity and heat loads assigned volumetrically as mentioned by Iaronka et al. [7]. The zero equation model is used for capturing turbulence. A Semi-Implicit Method for Pressure Linked Equations (SIMPLE) algorithm is used for pressure-velocity coupling to simulate the flow field. Conjugate heat transfer analysis is carried out using coupled Navier stokes, and energy equations stated in Ansys Manual [8].

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3. 1D resistive network

The 1D resistive network uses various governing and empirical correlations for the given heat load conditions. Boundary layer approximation is used to obtain these empirical correlations. For the given input conditions, a corresponding correlation is used to calculate the heat transfer coefficient explained in the book [9]. HTC values calculated are then used to calculate the LED surface temperatures. Applying heat balance equation by assuming light square to be horizontal flat plate we get the following set of equations (8)-(12).

\begin{align*}
q_{\text{generation}} & \leq q_{\text{dissipation}} \\
q_{\text{dissipation}} & = (q_{\text{front}} + q_{\text{back}})_{\text{convection}} + (q_{\text{front}} + q_{\text{back}})_{\text{radiation}} \\
q_{\text{convection}} & = h_{\text{convection}} A (T_{\text{surface}} - T_{\text{ambient}}) \\
q_{\text{radiation}} & = h_{\text{radiation}} A (T_{\text{surface}} - T_{\text{ambient}}) \\
h_{\text{radiation}} & = \varepsilon \sigma (T_{\text{surface}}^2 + T_{\text{ambient}}^2) (T_{\text{surface}} + T_{\text{ambient}})
\end{align*}

For the initial condition, \( T_{\text{surf}} \) is assumed to be \( T_{\text{amb}} \), and total heat dissipation is calculated. The heat balance criterion mentioned in equation (8) is evaluated for this condition. If the criterion is not satisfied, \( T_{\text{surf}} \) is incremented till heat balance is satisfied. \( T_{\text{surf}} \) which satisfies the heat balance is the calculated surface temperature of the LEDs through 1D network analysis.

4. Test setup and procedure

The test is conducted in a draft-free room as specified by UL 1598 standard used for luminaires which includes safety testing for temperature, etc. The rated wattage of any lamp used for the temperature test is the highest wattage rating marked on the luminaire. The test is run for a minimum of 7.5 hrs and then three successive readings are taken at 15 mins intervals. The test is conducted at an elevated ambient temperature of 40°C with a source of heated air providing the elevated temperature for which the luminaire is marked. The maximum airflow past the luminaire is less than 9.1m/min. Power source case temperatures are measured by thermocouples attached directly upon the surface of the power source case at various locations.

5. Comparison of modeling methods with actual tests

The original design (baseline) of the product is with twenty fins and given height for the specified lumen output. As per UL standard maximum temperature obtained on the LEDs should not exceed 105°C. The present experimental study suggested that the maximum temperature obtained on the LEDs is 88°C for the baseline case. For baseline configuration results obtained
from FVM and 1D network analysis, error is within ±1°C when compared to experimental results as shown in figure 3. From a marketing and aesthetic perspective, four designs have been selected to achieve the required cost saving for the product. For the first design, fin height is reduced by 0.8 inches. For the second design, it is reduced by 1.8 inches. For the third design, five of the fins are removed thereby having fifteen fins equally spaced. For the fourth design, fifteen fins are used but with unequal fin spacing, that is, without altering the original fin structure. Maximum temperature obtained on the LEDs for various designs with FVM is shown in figure 4.

![Figure 3. Baseline Comparison](image)

![Figure 4. FVM analysis for various design](image)

It is seen from table 1 that temperature differences for 0.8 inch and 1.8-inch fin height reduction are much more predominant in the 1D network tool when compared with FVM. For 0.8 inch and 1.8-inch reduced fin height cases, 1D network tool is overpredicting temperature by 7°C and 15°C respectively. This is because, 1D network tool assumes HTC values constant throughout the fins, unlike FVM where it is calculated locally based on the temperature at the surface of the fins. Thus being conduction dominant analysis, changes in the surface area along the direction of heat transfer largely affects the temperature prediction in 1D analysis. For symmetric and unsymmetric fifteen fin cases, the temperature difference with 1D analysis when compared with FVM is much smaller than the initial two cases. For both fifteen fin cases, 1D network analysis overpredicts temperature by 4°C. Fifteen fins with asymmetry gives maximum cost saving with minimum tool changes and thus are experimentally tested for validation with the simulation results (figure 5). It can be seen from the results that FVM is within ±1°C error margin, however 1D analysis overpredicts by 4°C (figure 6). For FVM, sixteen physical cores are used for solving the present case. The time required for FVM analysis is around 21k sec for a single simulation. 1D network tool is based only on plugging various input values into excel based tool, it takes around 600 sec to get the temperature values. The accuracy of the FVM model is the highest however it is computationally expensive. 1D network tool is a simpler and faster tool than FVM but falls short to predict temperature for varying fin dimensions and spatial variation due to the assumption of constant heat transfer coefficient across the fins. Thus, the selection of the method depends on the computational power available, the accuracy required, and the timelines specified for the given project.

6. Summary and conclusion
A comparison of two methodologies for predicting temperature on LEDs is performed for various fin designs. It can be seen from the comparison that FVM is the most accurate method for predicting temperature with an error of less than 1%. However, it is computationally expensive and should be used where accuracy is of prime importance. This is when the product design is
Table 1. Comparison of temperature ($^\circ$C) obtained for various fin design with different modeling techniques

| Design          | FVM | 1D network |
|-----------------|-----|------------|
| Baseline        | 88  | 88         |
| 0.8 inch less   | 92  | 99         |
| 1.8 inch less   | 93  | 108        |
| Symmetry        | 89  | 93         |
| Asymmetry       | 89  | 93         |

Figure 5. Asymmetric fin design

Figure 6. Different fin designs

finalized and is ready for prototyping. The 1D network analysis methodology is faster, however, the computational error is around 15% compared to FVM analysis. It can be used as a direction tool at the beginning of the project to converge on the various concepts for the fin design.

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