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Light source thermal analysis I – Sodium high-pressure discharge Lamp

Fric Róbert · Elektrotechnika

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This is the first chapter from the series of papers focused on complex diagnostics and analysis of the temperature field in the light source that is caused by the light source generated heat. In this paper the specification of the high pressure sodium lamp as a heat source has been made. The analytical heating evaluation has been made and also the temperatures of the lamp have been measured. The finite element analysis of this thermal problem also helps to compare the results of used methods of thermal analysis.

1. Background

In general, the thermal phenomena is closely related with the functionality, safety and durability of the lighting device. During the design process of the lighting devices we have to allow for temperature limitations which can occur during operation. In many cases the choice of materials depends on expected thermal stress. Uncontrolled heat loss of the light source can cause damages or unwanted changes of light parameters.

The goal of the complex analysis is the application of this methods early during design process of the device. It is appropriate to analyze the temperature field together with ideas of the lighting device, especially the lamps. Hereby we can avoid unwanted effects or directly choose the placement of the components for perfect setting of the heat fluxes and temperatures inside the device. Then the device not only meet the standards, but also the heat transfer and cooling work properly.

2. Heat source specification

To make the analysis using any method, we need to know the heat sources inside the lamp as exactly as possible. The colour temperature of the high-pressure sodium discharge lamp range about 2000K. But, because of discharge nature of the light, the colour temperature says nothing about real heating. The heat source of the high-pressure sodium lamp is the gas discharge at the saturated sodium vapour conditions inside the discharge tube (plasma). The special discharge tube has reasonable resistance to thermal shock.

The spectrum of the discarge is line-structured. Thereat the specification of the quantity of generated heat cannot go out of radiation theory of the black body or the luminous efficacy. We need to use the energy ballance of the lamp, as specified e.g. in [6].

Based on these characteristics (Fig. 1) it is possible to evaluate that the heat generated by plasma and discharge tube wiring is about 70% of input power. The heat is taken out in form of IR radiation (about 55%) and also by conduction and convection out of the bulb (about 15%).

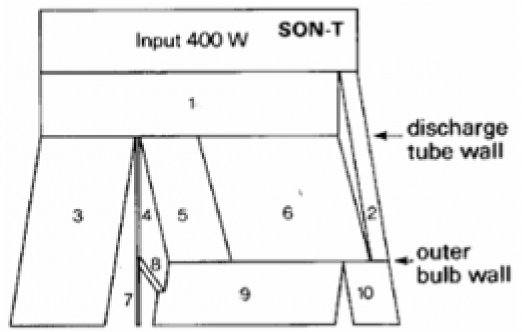

Fig. 1 Energy ballance of the 400W high-pressure sodium lamp [6]

1. Power in discharge column: 376W, 2. Thermal losses at electrodes – 24W, 3. Visible radiation – 118W, 4. UV radiation from discharge – 2W, 5. IR radiation from discharge – 80W, 6. Thermal losses in discharge column – 176W, 7. UV radiation – 1W, 8. IR radiation – 1W, 9. Total IR radiation – 221W, 10.Convection and conduction–60W.

3. Analytical heating calculation

We can simply express the basic temperatures analytically. To be able to arrange the equivalent thermal scheme, we have to take a look at the architecture of the lamp and eventually apply some simplifications. We need to build an alytical model, which may not to be too complex.

It is appropriate to use the system of coaxial cylinders as a model. The cylinders have an infinite length and a cross-section of them represents the cutting of the lamp locally in place of the discharge tube. In this model the inner cylinder represents the discharge tube, the outer cylinder represents the glass bulb of the lamp. Between the faces there is a vacuum. According to this model it is possible to arrange equivalent thermal diagram (Fig. 2). The values t_1, t_2 and t_0 [°C] represent temperatures of the discharge tube, outer bulb and ambient space. The heat generated by discharge tube is represented as heat flux P [W].

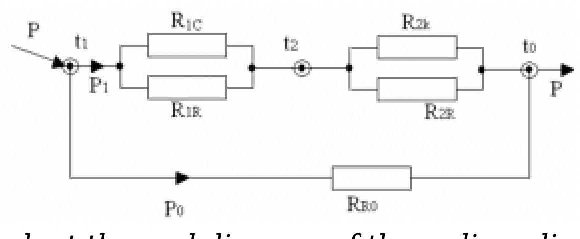

Fig. 2 Equivalent thermal diagram of the sodium discharge lamp

The heat is transferred through several paths:

- Radiation between the discharge tube and the bulb, in equivalent thermal diagram

represented by resistance R_{1R}.
- Radiation of the bulb to ambient, represented by resistance R_{2R}.
- Convection around the bulb, represented by resistance R_{2K}.
- Radiation from the discharge tube (and related wiring) to ambient, which passes through the glass bulb, represented by resistance R_{0R}.
- Conduction from the discharge tube throught the wiring and supports, represented by resistance R_{1C} .

We assume that there is no heat transfer following the axial direction. In general, we can evaluate particular resistances according to [1],[4]:

- Convection resistance between body and ambient:

$$R_K = \frac{L}{Nu.\lambda.A} \tag{1}$$

where: L – characteristic dimension, Nu – Nusselt´s number, &latex \lambda& – ambient heat convection coefficient, A – surface of the body

- Radiation resistance between two bodies or between body and space:

$$R_R = \frac{t_s - t_\infty}{\epsilon.Co.A\left[\left(\frac{T_s}{100}\right)^4 - \left(\frac{T_\infty}{100}\right)^4\right]} \tag{2}$$

where: R_R – radiation resistance, ϵ – surface emissivity or equivalent emissivity, C_O – emissivity of the black body surface, t_s – surface temperature, t_∞ – ambient temperature or second body temperature.

The equivalent thermal diagram is solvable as an electrical circuit, considering the equivalency of the temperature and electric fields [4],[5]. The solution consist of solving the non-linear system of equations where the unknown quantities are the temperatures. Mostly it is necessary to use the computer system to evaluate the results. Temperatures of this solution were evaluated by using software Mathematica [7]. The load conditions, initial values and equations were entered in the way the system required and the iterative non-linear solution using the *Newton iteration method* was ran. Ambient temperature was set to 20 °C. The results are shown in Tab. 1.

Tab. 1: Results of the analytical calculation of the lamp heating

input power	70W
discharge tube temperature	t_1 = 967 [°C]
outer bulb temperature	t_2 = 214 [°C]
convection film coefficient	α = 10.2 [W/m^{2}K]
heat flux P_0	P_0 = 947.5 [W/m]
heat flux P_1	P_1 = 652.5 [W/m]
ratio of heat flux P_0 to overall heat flux P	P_0/P = 34.7 %

4. Numerical analysis

Following the specification of the heat source and analytical calculations it is possible to evaluate the temperature rise by the finite element method (FEM, ref. [3]). The convection film coefficiet as the input of numerical analysis has been obtained as a result of analytical calculation of thermomechanical model in previous chapter.

The 70W sodium discharge lamp has been modelled as 3D object (Fig. 3) with a couple of simplifications using computer system *SolidEdge*. The geometry has been transferred to FEM system ANSYS [8].

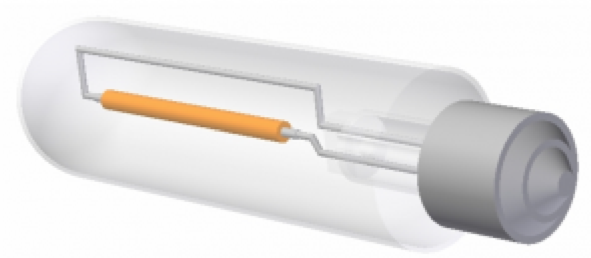

Fig.3 simplified 3D model of the lamp

The material proberties have been assigned to each of the parts. Next, the model has been divided into number of finite elements (mesh). Then boundary conditions and loads have been applied, reflecting the conditions of the analytical model. The model includes all types of heat transfer – convection, conduction and radiation.

The final temperatures of the 70W sodium discharge lamp (Fig. 4, 5) were obtained by non-linear iterative solution.

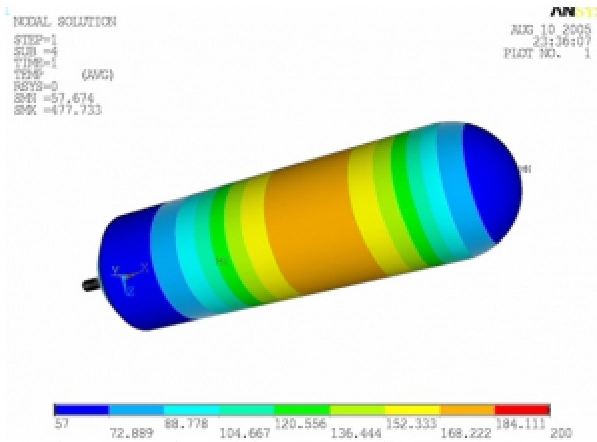

Fig. 4 Heating of the outer bulb, 70W lamp

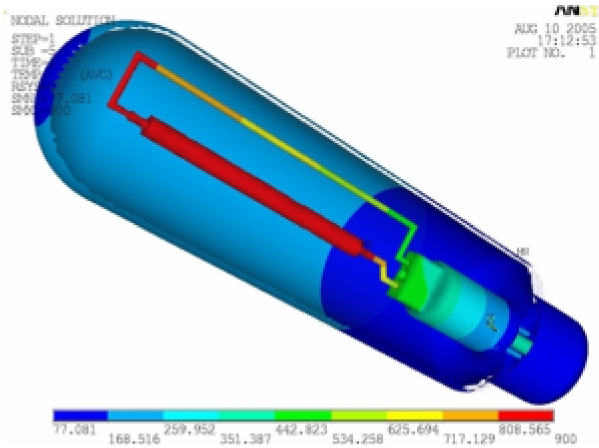

Fig. 5 Heating of the interior of the lamp, 70W lamp

The average temperature of the outer bulb range about 120°C. The temperatures of the sides of the bulb stand between 50 and 90 °C and the maximum temperature of the bulb near the discharge tube is about 180°C. Temperature field of interior of the lamp (Fig. 5) shows the thermal stress of the consequent parts.

5. Experiment – measurement of the temperatures

The heating of the 70W sodium discharge lamp was measured by linear series of thermocouples attached to outer surface. The results were evaluated as heating profiles (Fig. 6). The profiles are shown for each radial placement of the measurement points by step of 30 degrees from the top.

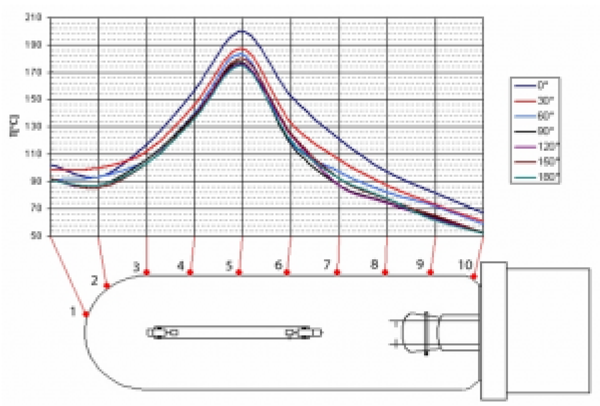

Fig. 6 Outer heating profiles of the sodium discharge lamp 70W, radial from the top

Measurement was performed by the same conditions, as numerical analysis assumed, at steady-state. The lamps were hanged in the air, the ambient temperature was 19 – 20°C. Temperatures at the signed points of the bulb surface are shown in the figure 5.

In collaboration with (and thanks to) company OSRAM Nové Zámky also the temperature field of the 70W high-pressure sodium discharge lamp was measured using thermovision camera. The temperature of the center of outer bulb reached on average 207°C. Maximal heating was at the top of the bulb – 214°C. The heating of the discharge tube inside the lamp was evaluated to 800 – 1000°C. The temperatures were obtained at ambient temperature around 35°C. More detailed measurement description, complex results and discussion will be provided in future articles and papers.

6. Conclusion

It can be seen, that our results of numerical and analytical analysis of the surface temperature approximately correspond to the measured values. The differences of numerical solution appear most by the temperatures of the outer glass bulb. This can be caused by the fact, that we assumed some simplifications not only in geometry but also by modelling of the radiation. The simplified radiating system had to be used because of complexity and size of the view-factor matrix and also regarding the duration of the solution. The differences in analytical model appeared as well, according to character of the model. In the real lamp the thermal flux flows also in direction of axis, which our model didn’t provided.

In general we can state, that measuring of surface temperature have confirmed our results of analytical and numerical analysis, especially regarding the heat distribution. The models can be improved in the future. The FEM models can be used in the lamp design process or also in the thermal analysis of the whole luminaire.

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Department of Mechanics, Faculty of Electrical Engineering and Information Technology, Ilkovičova 3, 812 19 Bratislava 1, Slovak University of Technology in Bratislava