

THERMAL FIELD SIMULATION OF A TUNGSTEN FILAMENT LAMP REFERRING TO ITS LIFETIME

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This article deals with the calculation of the filament lifetime regarding the evaporation of tungsten mass from the filament surface. The filament of an incandescent lamp represents an electric resistor. Its resistance depends on the intensity of tungsten mass evaporation. If an electrical power is applied, it is converted to heat that causes the temperature rise in the filament. The intensity of tungsten mass evaporation depends strongly on the filament temperature. Therefore, the modelling of filament geometry and simulation of its temperature field is described as well. The finite element method (FEM) has been used for the temperature field solution. The steady temperature fields were derived in the five solution steps. Calculation of separate solutions differs with reference to the filament diameter reduction in the process of evaporation. Actually, the change of the diameter represents decreasing of the filament material (tungsten). Following this change, the assumed lamp life is evaluated subsequently. The result of the life calculation was compared with the life data listed in the work standard for 7528 car lamp produced by OSRAM that we have modelled. The temperature field obtained by FEM was compared with thermovision camera measurement.

Keywords: filament lifetime

1 INTRODUCTION

The lamp life indicates the total time of lighting the lamp till the moment when it is non-functional. There are a lot of reasons that affect the lamp life, *eg*, working temperature of the tungsten filament, the value of the voltage supply, equability of the wire intersection, working position, lamp environment, type of filling gas and its pressure, production technology *etc*.

The lamp efficiency units are given in lumens per watt of input power (lm/W), where the lumen is a measure of the visible light output. The efficiency of the designed lamp is determined by the initial temperature of the filament that has a critical effect on the lamp life.

As references [1], [2] and [4] describe, the filament life diminishes with decreasing the tungsten wire radius.

Operating a tungsten wire at a high temperature leads to evaporation of tungsten atoms from the surface. The result is a reduced diameter of filament in certain localized areas with higher temperature. If some critical temperature is reached in this area, the filament breaks down or melts due to overheating, and the lamp becomes no longer useful. This is also the most frequent reason how the tungsten filament lamps end their life.

It is known that the filament develops hot spots, *ie*, regions that are slightly higher in temperature than those nearby. The hotter regions evaporate more rapidly, causing more rapid thinning of the wire than on average. These thin areas will run even hotter because the resistance is higher there. Since the current must be continuous throughout the wire, the thin areas dissipate more power. Thus a positive feedback cycle develops which

causes the hot spot to increase in temperature more and more rapidly until it reaches the melting point or break down of tungsten and the filament fails.

References [1] and [2] provide information about numerical and analytical calculation of the tungsten filament life. The lifetime of an extended filament (the tungsten wire) is calculated by formula (1), which is derived from the principle of the conservation of mass

$$t - t_i = \Delta t = \frac{r_i}{\Omega} \int_x^1 \frac{dx}{R(T)} \quad (1)$$

where r_i is the initial wire radius at time t_i , x is defined as a normalized wire radius r/r_i , Ω is the atomic volume ($1.57 \times 10^{-23} \text{cm}^3/\text{atom}$), $R(T)$ is the rate of evaporation of tungsten atoms per unit surface area, per unit time ($\text{atoms}/\text{cm}^2 \cdot \text{sec}$) and t is the time.

The primary normalized radius step width (Δx) used here is 0.001. This step width produces a temperature step of approximately 3 K. Equation (1) is integrated numerically when successive iterations on the whole temperature array produce less than 0.2 K change of any computed temperature.

The lamps life is more often measured through their life tests in practice because analytical solving of filament temperature is too complicated. As this analytical method is not handled satisfactorily at the present time, we will use the modern computational means — FEM analysis in our procedure.

This article deals with a numerical calculation of the filament life using the temperature dependence of the evaporation rate M_w ($\text{g cm}^{-2} \text{sec}^{-1}$) of the tungsten mass.

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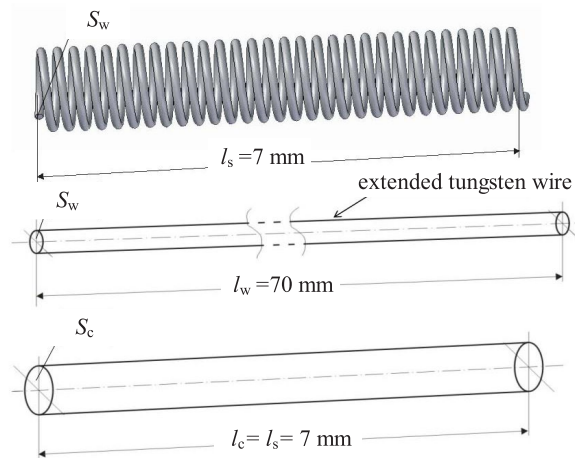


Fig. 1. The coil simplification by the cylinder. S_w is the cross-sectional area of the tungsten wire, d_w is the tungsten wire diameter, S_c is the cross-sectional area of the cylinder and d_c is the diameter of the cylinder.

The filament coil was simplified to the shape of a small cylinder (Fig. 1). Into its volume the Joule heat will be generated (heat generation rate HG).

If we eliminate technological and random errors in the process of coil production, we can expect that the location of the most probable breaking point will be in the middle of the coil. Maximum of the generated heat is concentrated here. We use the term gash at the modelling process regarding the loss of tungsten mass from the area located at the centre of the cylinder. Therefore, we reduce the diameter of the gash step-by-step in five ANSYS solutions of the steady-state thermal analysis. Physical meaning of the evaporation rate M_w ($\text{g} \cdot \text{cm}^{-2} \cdot \text{sec}^{-1}$) [3] is the weight of tungsten mass evaporated from area unit per time unit. It is a very strong function of temperature.

The 2nd part of our paper describes the replacement of the coil with the cylinder, the next assumptions and simplifications for heat source calculation and other parameters needed for model specification.

In the 3rd part there are calculated two factors that modify the heat source. The first one represents the difference in surface size between the coil and cylinder. The second one has a meaning of a “coiling factor for reabsorbed power”.

Simulation of the filament temperature field is described in section 4. Here, the working temperature of the coil is compared with the filament model number 1 (with minimal reduction of the cylinder diameter). Both of these results are verified by measurement with a thermovision camera.

In section 5 there is introduced the way of calculation of the assumed lamp life and this result is compared with the life data listed in the work standard of this lamp.

2 THERMO-MECHANICAL MODEL OF THE FILAMENT — ASSUMPTIONS AND SIMPLIFICATIONS

As an object of modelling and thermal simulations the automotive lamp (type 7528, OSRAM Slovakia) has been taken. The filament coil was simplified to the shape of a cylinder (Fig. 1). Into its volume the Joule heat will be generated. In accordance with the above-mentioned simplification the power condition in the circuit must remain unchanged because of equality of the generated heat. The next assumed simplifications are equalities of the length, volume and electric power between the cylinder (index c) and the coil (index s — like spiral), as described in terms (2), (3) and (4).

$$l_c = l_s \quad (2)$$

$$V_c = l_s \quad (3)$$

$$R_c I_c^2 = R_s I_s^2 \quad (4)$$

The electric current causes heating of the coil with a total length of the wire $l_w = 70$ mm. The length of coil (with convolutions) between lead-in wires is $l_s = 7$ mm = l_c . The work standard specifies the electric parameters of the coil, and with aspect to these coil parameters and the above-mentioned conditions we obtain the following electric parameters (resistance (5), current (6) and voltage (7)) of the cylinder:

$$R_c = R_s/100, \quad (5)$$

$$I_c = 10I_s, \quad (6)$$

$$U_c = U_s/10. \quad (7)$$

Before starting the thermal analysis it is necessary to define: the thermal conductivity coefficient of applied materials (λ), the thermal convection coefficient (α) from the outer bulb surface to the surrounding, and the heat generation rate (HG in W/m^3). These parameters depend on unknown temperature. So, λ , α , [5] and HG have to be evaluated by an iterative method. The surface of the cylinder is defined as the radiating surface with temperature dependence of the total tungsten emissivity coefficient ε_w [4]. It was also necessary to establish and modify the heat generation rate HG . For the marginal part (HGM) and the gash part (HGG) we could derive the following expressions:

$$\begin{aligned} HGM &= \frac{R_m I_c^2}{V_m} = \frac{\rho_w(T)(l_m/S_c)}{S_c l_m} I_c^2 = \frac{\rho_w(T)}{S_c^2} I_c^2 \\ &= \frac{\rho_w(T) I_c^2}{[\pi(d_c/2)^2]^2} = \frac{16 I_c^2}{\pi^2 d_c^4} \rho_w(T), \quad (8) \end{aligned}$$

$$\begin{aligned} HGG &= \frac{R_g I_c^2}{V_g} = \frac{\rho_w(T)(l_g/S_g)}{S_g l_g} I_c^2 = \frac{\rho_w(T)}{S_g^2} I_c^2 \\ &= \frac{\rho_w(T) I_c^2}{[\pi(d_g(T)/2)^2]^2} = \frac{16 I_c^2}{\pi^2 (ppd_c)^4} \rho_w(T). \quad (9) \end{aligned}$$

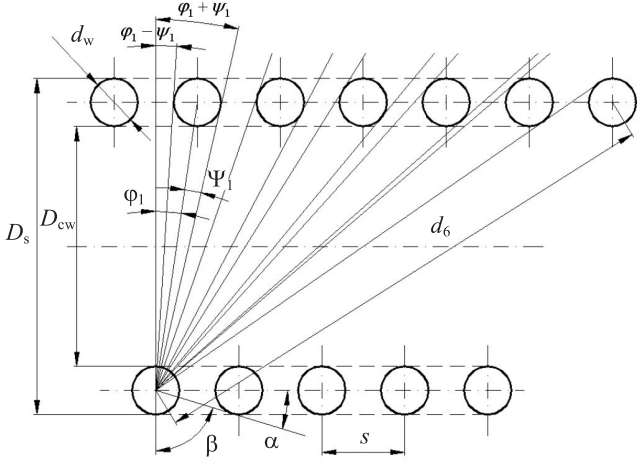


Fig. 2. The cross-section of the coil. D_s is the diameter of the coil, D_{cw} is the core wire diameter, s is separation, d_i are distances of circle centers, d_w is the tungsten wire diameter.

In (8) and (9), a constant value of current I_c has been assumed. Actually, the electric current through coil I_s holds its value unchanged. This fact was verified in practice by measurements on car lamps during their life tests. Symbols R_m and R_g represent the electric resistance of corresponding parts (marginal and gash, respectively). Tungsten resistivity $\rho_w(T)$ [6] is a temperature dependent parameter, and “pp” represents the percentage decrease of the cylinder diameter at the gash. Parameter d_c is the initial diameter of the cylinder derived from condition (3), eg

$$V_c = V_s; \quad \frac{\pi}{4} l_c d_c^2 = \frac{\pi}{4} l_w d_w^2; \quad d_c = \sqrt{10} d_w. \quad (10)$$

According to the design data of the coil the tungsten wire diameter is $d_w = 102.29 \times 10^{-6}$ m.

3 THE HEAT SOURCE (HG) MODIFICATION

The thermal power P_s of the lamp filament (coil) is dissipated by radiation losses P_r (which are dominating) as well as by heat loss to the gas P_g , and by conduction to the leads P_l . Thus

$$P_s = P_r + P_g + P_l = P_r + \Delta P \quad (11)$$

where the two non-radiation loss terms have been merged together into the ΔP .

The radiated power from the tungsten wire can be obtained by multiplying the blackbody emittance $M_e(T)$ with the total tungsten emissivity $\varepsilon_w(T)$ and the coil surface area A_s (σ is known as the Stefan-Boltzmann constant):

$$P_r = A_s \varepsilon_w(T) M_e(T) = A_s \varepsilon_w(T) \sigma T^4. \quad (12)$$

If we omit the two non-radiation losses (represented by ΔP), we can write the equality between P_s and P_r

$$R_s I_s^2 = A_s \varepsilon_w(T) \sigma T^4. \quad (13)$$

The second term in (13) is the heat radiated by electromagnetic waves to the ambient.

The modelled cylinder has the surface area A_c that is smaller than the surface area of the coil A_s . Therefore, the outlet heat from A_c is not equal to the outlet heat from A_s . So, the heat generation rate HG derived using (8) and (9) is too big now and must be reduced as follows: Joule heat into the ambient is smaller in the case of the cylinder than the Joule heat of the coil. But in condition (4) we defined that the electric power of the cylinder should remain equal to the electric power of the coil

$$R_c I_c^2 = R_s I_s^2,$$

$$A_c \varepsilon_w(T) \sigma T^4 \neq A_s \varepsilon_w(T) \sigma T^4.$$

It is obvious that if we want to get the working temperatures of the coil using ANSYS steady-state thermal analysis, it is necessary to reduce expressions (8) and (9) by A_c/A_s ratio:

$$\frac{A_c}{A_s} = \frac{\pi d_c l_c + 2\pi \left(\frac{d_c}{2}\right)^2}{\pi d_w l_w + 2\pi \left(\frac{d_w}{2}\right)^2} \approx \frac{1}{3} \implies A_c \approx \frac{A_s}{3}. \quad (14)$$

After that, the heat flow, due to radiation from modelled cylinder surface into the ambient air, is described by expression (15)

$$R_c I_c^2 = \frac{A_s}{3} \varepsilon_w(T) \sigma T^4. \quad (15)$$

The last expression (15) reflects two needed facts:

1. The surface size A_c is replaced by the surface size A_s . It could be possible to observe condition (4) in this way.
2. The heat generation rate $R_c I_c^2$ is reduced sequentially by A_c/A_s ratio which represents multiplying the original heat generation rate HG by one third. Therefore, equations (8) and (9) expressing HG will be multiplied by one third. The difference between the surface sizes of the cylinder and the coil is accounted for in this way.

Except for this reduction it is necessary to increase HG due to the following: as we mentioned earlier, the second term of (13) is the heat radiated by electromagnetic waves to the ambient. This statement should be better for the developed tungsten wire. Coiling the wire the power generated on the inside of the coil has a chance of being absorbed, thereby increasing the filament temperature. On the assumption that the radiating power leaves the coil surface vertically it is possible to interpret the fraction of reabsorbed power. This calculation assumes the fiction of an infinite coil. More precisely, from each convolution the surrounding convolutions absorb the same quantity of power. This is a simplification again because convolutions situated closer to the marginal part of the coil transfer more power (to the anti-absorbing surrounding) in comparison with centric convolutions.

Table 1. The power leaving the surface ξ_{out} in angle degrees (the mark * in Tab. 1 means that approximate data are used here).

wire diameter — d_w	0.0001*
core wire diameter — D_{cw}	0.0005*
coil diameter — D_s	0.0007*
separation — s	0.000175*

k	1	3	5	7	9	11
φ_i	8.297	23.629	36.098	45.591	52.696	58.062
d_i	0.000606	0.00065	0.00074	0.00086	0.00099	0.00113
ψ_i	4.730	4.379	3.861	3.343	2.895	2.527
	A	B	C	D	E	F
	3.567	6.224	4.229	2.288	0.867	-0.056
β	73.398					
ξ_{out}	90.574		ξ_{in}	89.426		

All expressions and derivations will be visible from Fig. 2 that represents the longitudinal section of the coil. The fraction of reabsorbed power ξ_{in} is expressed from the coil geometry in angle data. One circle is taken as a standard and other ones are identified by parameter $k = 1, 3, 5, 7, 9, 11$. Analysis of the radiating power leaving the coil surface is performed on the standard circle.

$$\varphi_i = \arctg \frac{\frac{s}{2}k}{D_{cw} + d_w}, \quad (16)$$

$$d_i = \sqrt{(D_{cw} + d_w)^2 + \left(\frac{s}{2}k\right)^2}, \quad (17)$$

$$\psi_i = \arcsin \frac{d_w}{2d_i}, \quad (18)$$

$$\beta = 90 - \alpha = 90 - \arcsin \frac{d_w}{2s}. \quad (19)$$

In order to produce the filament, the tungsten wire is uniformly spirally wound on a molybdenum core wire (cw).

In Fig. 2 we can see that the circle with distance d_6 (from standard circle) does not transmit power any more to the anti-absorbing surround. Now, we can express the power leaving the surface as ξ_{out} :

$$\begin{aligned} \xi_{out} &= \varphi_1 - \psi_1 \\ &+ [(\varphi_2 - \psi_2) - (\varphi_1 + \psi_1)] + [(\varphi_3 - \psi_3) - (\varphi_2 + \psi_2)] \\ &+ [(\varphi_4 - \psi_4) - (\varphi_3 + \psi_3)] + [(\varphi_5 - \psi_5) - (\varphi_4 + \psi_4)] + \beta \\ &= A + [B] + [C] + [D] + [E] + \beta = 90.57442^\circ. \end{aligned}$$

This calculation of the power leaving the surface performed on the standard circle is also documented in Tab. 1. It is a sum of leaving powers to the bottom half-space (β) and fractions of power that are leaving the coil surface throughout the upper half-space. Due to the geometrical symmetry of the standard circle it is sufficient to perform the total analysis only on the half-circle (180°). So, the fraction of reabsorbed power ξ_{in} can be expressed as:

$$\xi_{in} = 180^\circ - \xi_{out} = 89.42558^\circ. \quad (20)$$

As we can see, almost one half of the emitted power is re-absorbed, increasing the filament temperature. For these reasons, both equations (8) and (9) expressing HG will be multiplied by a factor of 1.5.

4 SIMULATION OF FILAMENT TEMPERATURE FIELD

As we already mentioned before, the ANSYS program is built on the FEM base. The matrix form of algebraic equations system which describe the unsteady temperature field of the analysed area has the form

$$\mathbf{K}_3 \dot{\mathbf{T}} + (\mathbf{K}_1 + \mathbf{K}_2 + \mathbf{K}_4) \mathbf{T} = \mathbf{P}_1 - \mathbf{P}_2 + \mathbf{P}_3 + \mathbf{P}_4 \quad (21)$$

where \mathbf{K}_1 is the thermal conductivity matrix, \mathbf{K}_2 is the convection matrix, \mathbf{K}_3 is the specific heat matrix, \mathbf{K}_4 is the radiation matrix, \mathbf{P}_1 is the vector of heat sources transformed into the nodal points, \mathbf{P}_2 is the vector of heat flow caused by conduction, \mathbf{P}_3 is the vector of convection heat flow, \mathbf{P}_4 is the radiation heat flow vector, \mathbf{T} is the vector of unknown nodal temperatures and $\dot{\mathbf{T}}$ is the time derivative of the vector \mathbf{T} . The system of equations (21) will be reduced by the time dependent terms in the case of steady state analysis.

Simulation of the filament temperature field follows the data related to the main filament of the car lamp with internal OSRAM type symbol 7528. The work standard specifies the electric parameters of the coil which have an informative nature for its design. Electric voltage $U_s = 13.5$ V and current $I_s = 1.88$ A are needed to obtain an electric resistivity $\rho_w(T_{init})$ of the coil at working initial temperature.

If $R_s = \rho_w \frac{l_w}{S_w}$, then $\rho_w = \frac{U_s S_w}{I_s l_w} = \frac{U_s}{I_s} \frac{\pi (d_w)^2}{4}$. By substituting corresponding terms we get the mentioned electric resistivity $\rho_w(T_{init}) = 84.3 \times 10^{-6} \Omega \text{cm}$. Symbol l_w is the total length of the coiled wire and S_w is the cross-sectional area of the tungsten wire.

The initial value of the coil operation temperature $\Rightarrow T_{init} = 2790$ K can be obtained from the known temperature dependence of electric resistivity $\rho_w = f(T)$ [6].

Analysing the evaporation of tungsten mass from the gash we count with actual gash temperature T_g in expressions (8) and (9). In the case of the initial temperature T_{init} (it is also starting temperature T_g) the electric resistivity $\rho_w(T_{init})$ is already known. For each next solution step we try to attain the simulation with gash temperature that is higher by 100 K than the temperature in the previous solution step. The gash temperature sub-intervals rise in this way and we fix the constant value of the evaporation rate M_w [3] for them. So, calculation of the electric resistivity $\rho_w(T)$ (included in (8) and (9)) is obtained through gash temperature T_g .

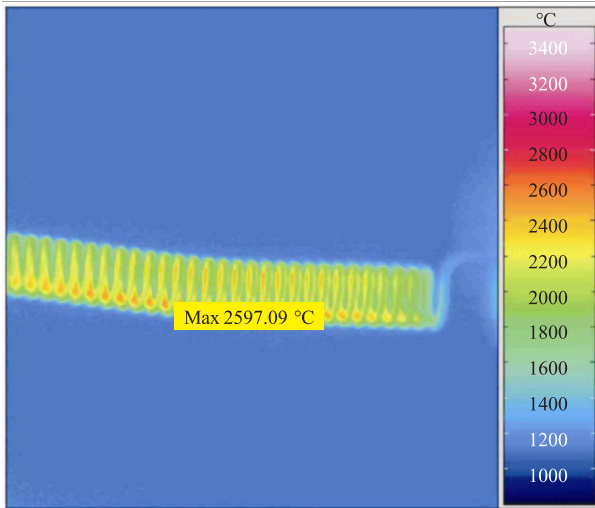


Fig. 3. Snapshot of the main filament with a thermovision camera.

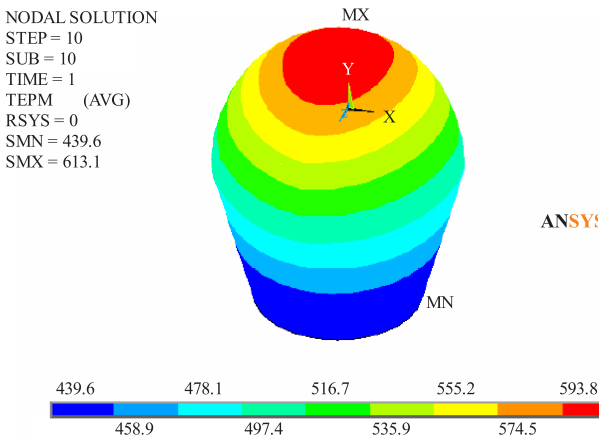


Fig. 5. Numerical results of absolute temperature on the bulb.

Parameter “ pp ” (the percentage decrease of cylinder diameter at the gash) has been set to 99% in the first solution step ($pp_1 = 0.99$).

As we use informative electric parameters U_s and I_s for the design of the coil, so minimal mechanical defects are expected on the coil surface. Thereby, the initial temperature T_{init} that is specified theoretically can be compared with:

- the results of measurements by thermovision camera $T_{max} = 2597.19^\circ\text{C} = 2870\text{ K}$ (with a new car lamp — Fig. 3),
- the results of simulation for the first solution step $T_{max} = 2822\text{ K}$ (gash diameter has been set to 99% of the cylinder diameter “ pp ” — Fig. 4 and Fig. 5 and position of the bulb is upright).

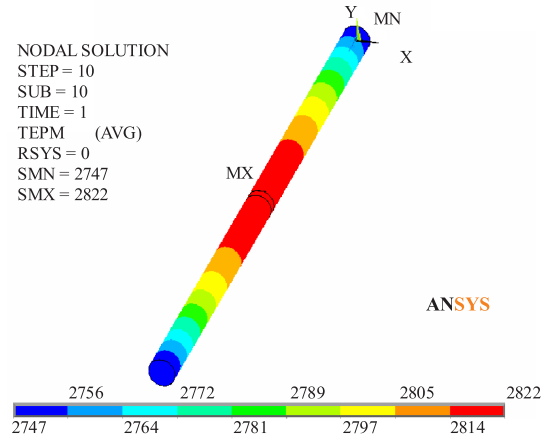


Fig. 4. Numerical results of absolute temperature on the cylinder obtained by FEM analysis.

5 THE CALCULATION OF ASSUMED LAMP LIFE

According to the physical meaning of the evaporation rate M_w ($\text{g} \cdot \text{cm}^{-2} \cdot \text{sec}^{-1}$) [3] it is possible to derive the formula for the time Δt that elapses until the tungsten mass (with weight Δm) evaporates:

$$\Delta t = \frac{\Delta m}{M_w A_{gc}} = \frac{\gamma_w \Delta V}{M_w \pi (pp_i d_c) l_{gc}} \quad (22)$$

where $\gamma_w = 19.5\text{ g} \cdot \text{cm}^{-3}$ is the tungsten density (its temperature dependence is not accounted), A_{gc} is the surface area of the gash (placed on the cylinder), pp_i is reduction (in percents) of the initial diameter of cylinder d_c for “ i ” solution step (reductions are performed only for gash diameter), l_{gc} is the length of the gash (placed on the cylinder).

Formula $\Delta V = V_i - V_{i+1}$ represents the volume of the evaporated mass. During this evaporation the gash diameter is reduced from $(d_g)_i$ to $(d_g)_{i+1}$, and

$$\begin{aligned} \Delta V &= \pi l_{gc} \left[\left(\frac{d_g}{2} \right)_i^2 - \left(\frac{d_g}{2} \right)_{i+1}^2 \right] = \frac{\pi}{4} l_{gc} \left[(d_g)_i^2 - (d_g)_{i+1}^2 \right] \\ &= \frac{\pi}{4} l_{gc} d_c^2 (pp_i^2 - pp_{i+1}^2). \end{aligned} \quad (23)$$

Then the time

$$\Delta t = \frac{\gamma_w d_c (pp_i^2 - pp_{i+1}^2)}{4 M_w pp_i}. \quad (24)$$

As shown below in Tab. 2, the solution was performed in five steps with sequential reduction of the “ pp ” — parameter regarding the tungsten mass loss.

We have analysed five models \Rightarrow four sub-intervals are available. For each of these sub-intervals we have taken the average temperature T_{av} and prescribed the appropriate evaporation rate.

Table 2. Evaluation of the filament (also lamp) life.

model- <i>i</i>	1	2	3	4	5
<i>pp</i>	0.99	0.6	0.4	0.33	0.29
T_g (K)	2800	2900	3000	3100	3200
sub-interval (K)	2800–2900	2900–3000	3000–3100	3100–3200	
T_{av} (K)	2850	2950	3050	3150	
M_w (g cm ⁻² sec ⁻¹)	1.958×10^{-7}	6.047×10^{-7}	1.799×10^{-6}	5.167×10^{-6}	
Δt (hours)	140.152	24.145	3.110	0.637	
$\sum \Delta t$ (hours)	168.045				

When the gash diameter is changed from $pp_1 = 0.99$ to $pp_2 = 0.6$, then the partial time is $\Delta t = 140.15$ hours. Summation of these partial times Δt leads to the assumed lamp life $\sum \Delta t = 168$ hours, specified theoretically. In comparison with the life data listed in the work standard for 7528 car lamp we can observe that our calculation differs only by a small difference: design life $L_d = 200$ hours, rated life $L = 150$ hours.

6 CONCLUSION

The main goal of this paper was the car lamp lifetime calculation regarding the evaporation of tungsten mass from its filament surface. The rate of evaporation depends very strongly on the appropriate average temperature of the filament. The filament coil was simplified to the shape of a small cylinder. Into its volume the Joule heat will be generated that causes a temperature rise of the filament and of the whole lamp. Tungsten evaporation has been placed in the middle of filament. Here is concentrated the maximum of generated heat. We have used the term gash while modelling the process regarding the loss of tungsten mass from the area located at the centre of the cylinder. Therefore, we have reduced the diameter of the gash step-by-step in five finite element solutions of the steady-state thermal analysis. For each of these sub-intervals we have taken the average temperature and the appropriate evaporation rate. From these evaporation rates the total lamp life has been calculated. In comparison with life data listed in the work standard for 7528 car lamp we can observe that our calculation differs only by a small difference. Our proposed procedure of the lamp lifetime calculation is very effective and accurate. Additional improvement of this calculation could be reached using the real filament shape in the FEM model, and by using more step-by-step reductions of the filament diameter. This will be the content of our further work.

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