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Mathematical Model of Electrical Cabinet Cooling

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Abstract : The article focuses on cooling systems in electrical engineering, which are an interesting area of exploration and discovery. Specifically, it focuses on the mathematical calculation of cooling in electrical engineering. Cooling was provided by a heat pipe, which represents an interesting way of heat removal. The first part describes the origin and effect of elevated temperature in electrical equipment. The second part deals with the proposed procedure of calculating the mathematical model in cooling This calculation relates to cooling by heat pipe at different volumes of working substance and at different temperature loads. The aim was to design a mathematical model by means of which the amount of heat removed from the heat pipe is calculated. The results of this model give theoretical information on the amount of heat removed.

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1 Introduction

The current development in the field of electrical engineering offers increasingly higher operational performance. The new, modern product design also wants to save space. Therefore, when it comes to electrical equipment that needs to be cooled, the question arises: how to ensure the cooling process of these equipment in the most efficient and energy saving way? There is a space for exploring and experimenting on this issue.

2 Heat loss

The heat generated by electrical conductors and electronic circuits is defined as the lossy Joule heat. It is also known as resistive or ohmic heat. It is one of the energy losses that cause overheating of electrical equipments. As a result of losses on the conductor and electrical components, heat is generated and that is dissipated from the surface to the environment. The amount of heat dissipation depends in particular on the conductor core material, the type and size of the electrical equipment and the magnitude of the electric current. Joule's heat is proportional to the performance of the electrical equipment [1].

Maintaining the required operating temperatures in electrical equipment is an important condition for the correct operation of these equipment. Optimum operating conditions can be maintained with different types of cooling equipment. When designing these cooling systems in electrical engineering, great emphasis is placed on interior temperature and relative humidity. The reason is to create a safe environment for all electrical equipment. Electrical cabinets are designed to prevent dirt, dust and water from entering. The basic design criterion is the permissible operating temperature inside the core of the driver. The cross-sectional dimension of the conductor directly affects

the resistance of the line and thus the amount of heat generated. Excess heat is undesirable [2].
Manufacturers determine the maximum operating temperature of electrical components installed inside the equipment, typically at 50°C. When designing the cooling of electrical enclosures, a temperature of approximately 10°C below the maximum allowable temperature is considered. This extends the life of the device and minimizes the risk of overheating. The most common air temperature inside the electrical enclosure is 35°C. It is a compromise between the life of the components used and the way of cooling [2,3].
An example of a temperature-dependent lifetime for electrical equipment may be a capacitor. It has become one of the most commonly used components in electrical engineering. Its lifetime depends mainly on the temperature. The table 1 shows values that confirm the significant effect of temperature on the length of the proper functioning of the capacitor [4].

Table 1 Capacitor life dependence on ambient temperature [4]

Ambient temperature [°C]	Number of years of service life
45	32
55	16
80	4

Various types of cooling are used to create optimal operating conditions. The primary goal of any cooling system is to increase the performance and reliability of the chilled modules. There are various air or liquid cooling devices for heat dissipation in electrical engineering. Air cooling is one of the simplest cooling methods most commonly used for various electrical systems. The advantage of air cooling is its ease of use and ease of use, but the thermophysical properties of air make these systems less attractive. For high-performance electrical engineering, liquid cooling is generally much more efficient than air cooling. This is due to better thermo-physical properties and also to provide a higher heat transfer coefficient than for gases. However, liquid cooling brings risks and potential problems such as leakage, corrosion, increased weight and condensation. Water is most often used for indirect cooling, but direct cooling must use a dielectric liquid due to the requirement for electrical insulation [5].
The cooling system based on the phase change of the working medium is one of the less used cooling technologies. Thermal energy is absorbed or released as the working medium changes its phase. The phase change is usually between gaseous and liquid states. Devices that work on this principle are called heat tubes. The main disadvantage of this technology is the limited thermal capacity of the liquid phase [5].

3 Principle of heat pipe

The heat pipe is a closed two-phase system in which the heat transfer is mediated by circulating the vapor and liquid phases of the working medium between the heated and cooled areas. A schematic representation of the heat pipe is shown in Figure 1. By supplying the heat flux to the evaporating part of the system, the liquid on the inner wall begins to evaporate, then the steam continues to the condensation part, where it starts to condense upon contact with the colder internal environment. The intensity of the heat transfer between the condensation and evaporation part is due to the high value of the heat transfer coefficient in the inner space of the tube during the phase transformations of the working substance. As a rule, the heat pipe comprises a certain inactive adiabatic portion located between the condensation and evaporation portions. The heat pipes can be divided into graviation, rotary and capillary tubes [6] [7].

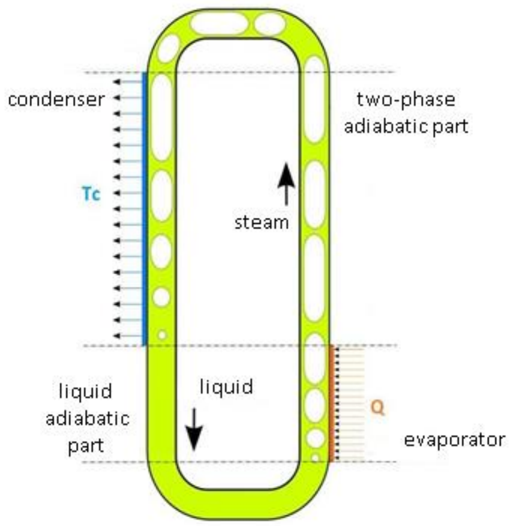

Figure 1 Schematic diagram of a two-phase heat pipe [5]

3.1 Mathematical model

The whole mathematical model is designed to remove heat from the electrical enclosure. Based on the simple measurements performed on the model of the heat pipe, temperatures and pressure were recorded at events that took place in the heat pipe. From these input data, the potential performance of the heat pipe was calculated, which is able to take of the interior cabinet and transfer it to the outside. This calculation of the mathematical model of the heat pipe was performed on the basis of the theoretical relationships determined for this issue under ideal conditions. The values of physical quantities were determined from the tables based on the measured values of outside temperature and pressure inside the tube. The thermal equilibrium theory between the evaporator and condensation part of the heat pipe was used in the power calculation.

$$\dot{Q}_k = \dot{Q}_v \quad (1)$$

This equilibrium implies that the power drawn at one end of the heat pipe must be equal to the power drawn at the other end. Therefore, the power calculation was chosen for only one part of the heat pipe.

3.1.1 Calculation of power on condenser and evaporator

The basic dimensions of the condenser and evaporator of the heat pipe are given in Table 2 and in Table 3.

Table 2 Capacity dimensions

Name	Symbol	Unit	Value
capacitor length	l_k	(m)	0,78
capacitor width	$š_k$	(m)	0,3
condenser height	h_k	(m)	0,3
pipe length	l_r	(m)	0,3
number of pipes vertically	$n_č$	(-)	10
number of tubes in the whole capacitor	n_c	(-)	260
inner pipe diameter	d_1	(m)	0,013
pipe external diameter	d_2	(m)	0,015
slat spacing	s_l	(m)	250.10^{-5}
lamella height	h_l	(m)	0,3
lamella thickness	δ_l	(m)	25.10^{-5}

Table 3 Evaporator dimensions

Name	Symbol	Unit	Value
outside diameter of pipe	d_o	(m)	0,015
inner pipe diameter	d_i		0,013
length of the computational element of the lamella	h_f		0,050
height of the computational element of the lamella	b_f		0,050
lamella thickness	δ		25.10^{-5}
clearance between the lamellas	a		235.10^{-5}

Table 3 Evaporator dimensions(continue)

Name	Symbol	Unit	Value
entry area of the cross section	A_o	(m^2)	$11,75.10^{-5}$
smallest cross area	A_s		$8,23.10^{-5}$
inner surface of the pipe	A_i		1,078
total evaporator surface	A_c		39,248
bare tube surface without lamellas	A_{to}		1,2438
lamella surface	A_f		38,334

The properties of the working medium that need to be changed when changing the heat load or evaporator volume are listed in Table 4 at 25 ° C.

Table 4 Working medium parameters at 25 ° C

Name	Symbol	Unit	Value
supply air temperature	t1	(°C)	21
exhaust air temperature	t2	(°C)	29
mean temperature	t	(K)	298,15
kinematic viscosity	ν_v	$(m^2.s^{-1})$	$1{,}57.10^{-5}$
dynamic viscosity	μ	(Pa.s)	$1{,}87.10^{-5}$
thermal conductivity	λ_v	$(W.m^{-1}.K^{-1})$	0,026
density	ρ_v	$(kg.m^{-3})$	997
the latent heat of evaporation	$l_{2,3}$	$(kJ.kg^{-1})$	2 441,66

Various heat transfer coefficients on the inside and outside of the condenser tubes were considered in the calculation. Both coefficients had to be recalculated through the relationships in the given case with different filling of the evaporator volume.
In the inner space of the horizontal tubes of condenser, condensation of saturated water vapor took place into liquid. The heat transfer coefficient in this space was calculated from the relation [7]:

$$\alpha_{ki} = 0{,}56\sqrt[4]{(g l_{3.2}\varrho^2\lambda^3)/(\nu\vartheta d_i)} \qquad (2)$$

The outside side of the tube was cooled by forced convection of air from an external fan. The heat transfer coefficient on the outside of the pipe was expressed from a number of interrelated relationships. First, the areas of the slats and tubes. [8]
Minimum external flow cross-section:

$$S_0 = h_k š_k - n_č\, d_2 l_r - \frac{l_r}{s_l} h_l \delta_l \qquad (3)$$

Slat area without tubes:

$$S_r = 2 l_k h_k - \frac{2 n_c \pi d^2}{4} + 2\delta_l h_k + 2 l_k \delta_l \qquad (4)$$

Surface of the lamella and the free pipe section:

$$S_2 = S_r + \pi d_2 (s_l - \delta_l)\frac{l_r}{s_l} \qquad (5)$$

Inner surface of the pipe at the span of the lamella:

$$S_1' = \pi d_1 s_l \qquad (6)$$

Inner surface of the whole pipe:

$$S_1 = \frac{l_r}{s_l} S_1' \qquad (7)$$

Heat transfer coefficient to rib:

$$\alpha_v = 0{,}223\frac{\lambda_r}{d_2}\left(\frac{d_2 m_v}{S_0 \mu_v}\right)^{0{,}65}\left(\frac{S_r}{d_2}\right)^{0{,}19}\left(\frac{s_l}{h_l}\right)^{0{,}14} \qquad (8)$$

Rib efficiency:

$$\eta_r = \frac{\tanh(m\, h_l)}{m\, h_l} \qquad (9)$$

$$m = \sqrt{\frac{2\alpha_r}{\lambda_l \delta_l}} \qquad (10)$$

Heat transfer coefficient on the outside of the pipe:

$$\alpha_2 = \alpha_r \psi \left(1 + \left((\eta_r - 1)\frac{S_r}{S_2}\right)\right) \qquad (11)$$

To calculate the heat pipe power, the mean logarithmic temperature and the heat transfer coefficient must be calculated.
Mean logarithmic temperature difference:

$$\Delta t_{str} = \frac{\Delta t_1 - \Delta t_2}{\ln\frac{\Delta t_1}{\Delta t_2}} \qquad (12)$$

Heat transfer coefficient:

$$k = \frac{1}{\frac{1}{\alpha_1} + \frac{S_1'}{S_2}\frac{1}{\alpha_2}} \qquad (13)$$

Total heat output dissipated by heat pipe:

$$\dot{Q} = k \Delta t_{str} S_1 \qquad (14)$$

The resulting values of the heat pipe performance, which were calculated on the basis of mathematical relations, are listed in Table 5. Calculation was performed at different heat loads and evaporator volume fillings with water.

Table 5 Theoretically calculated heat pipe power

Simulated power [W]	Calculated potential performance				
	20 %	40 %	60 %	80 %	100 %
500	638	640	643	644	648
750	891	895	897	911	913
1,000	1,123	1,134	1,149	1,152	1,154
1,500	1,235	1,237	1,240	1,242	1,246
2,000	1,407	1,416	1,422	1,425	1,441

4 Conlusions

The study points to the theoretical results of cooling efficiency using a heat pipe at various thermal loads and system fill volumes. The results were obtained on the basis of a mathematical model with initial measured parameters.

The results show that theoretically calculated values of heat output have approximately the same values with the amount of simulated heat supplied. At lower thermal loads of 500 W, 750 W and 1,000 W, higher heat dissipation values were calculated using the model. At 1,500 W and 2,000 W simulated power, the heat transfer power was lower. In the mathematical model, the actual capacitor dimensions were assumed and were fixed. Based on these values, the calculation in which the temperature and the pressure in the heat pipe were variable was also developed. All other physical quantities were derived from the temperature-based tables.

The mathematical model gives only theoretical information, which is based on the table values for given temperatures. The results from this model can be compared with the actual amount of heat dissipated from the heat pipe.

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