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Experimental Investigations of a Passive Cooling System Based on the Gravity Loop Heat Pipe Principle for an Electrical Cabinet

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Abstract: This paper deals with the experimental research and verification of a passive cooling system operating on the principle of a loop gravity heat pipe designed for cooling electrical cabinets. This type of cooling works automatically by changing the state of the working substance and thus saves energy consumption. Since the designed cooling system ensures heat transfer from the interior cabinet to the outdoor space, where the heat can naturally dissipate to the surroundings, it is dustproof. The heat pipe consists of an innovative evaporator concept designed to minimize liquid and vapour phase interference in the refrigeration circuit. The aim of the research was to experimentally determine the limit performance parameters of the refrigeration system for different volumes of working medium in the evaporator and decrease heat loss in the cabinet interior. The designed device was verified experimentally and by mathematical calculations as well. The greatest benefit of the work is that the cooling device was able to ensure temperature conditions inside the electrical enclosure at a heat load of 2000 W under 60 °C, 1500 W under 55 °C, 1000 W under 50 °C, 750 W under 45 °C and 500 W under 40 °C.

Keywords: loop thermosiphon; passive cooling; electronics; heat dissipation; phase changes

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1. Introduction

The current design of electrical equipment focuses on higher performance parameters that improve and accelerate human work. Any activity of electrical elements causes energy losses. When an electric current passes through a solid of certain conductivity, the energy of the electric current is transformed into thermal energy by means of resistive losses in the material. Energy in the form of heat is generated at the atomic level. Through the collisions of the molecules, the conductive electrons transfer kinetic energy to particles that are not involved in the transfer of electric current. In this way, the kinetic energy of the stationary particles increases, and the conductors overheat. The heat generated by electrical conductors and electronic circuits is defined as Joule's heat loss. As a result of losses on the conductor and electrical components, heat is generated and is dissipated from the surface to the environment.

Heat dissipation from the space with a power element is important for the safe operation of components found in electrical systems, especially for their reliability. As a result of their degradation, durability or even melting, the amount of heat dissipated depends on the way the heat is transferred, the temperature difference between the conductor and the environment, and the thermal conductivity of the conductor's environment [1–3].

The maximum operating temperature in electrical equipment depends on the electrical components. The optimum temperature of the individual electrical components is given by the technical specification of the installed components. The most common working temperature in electrical equipment is between 40–50 °C [4–7]. As the internal temperature rises, the reliability and durability of electrical components decrease. This has a great impact on precision measuring instruments, controllers and power supplies.

In electrical equipment, heat is usually transmitted by conduction and convection. Convection is used to release and mix air in an open electrical box. If a closed dust-free box is needed, heat is dissipated through the wall by conduction. These two methods of heat removal can be referred to as active and passive cooling.

The active cooling system includes external devices in its operation that support the cooling operation. This technology helps to increase the airflow rate and improves heat transfer and heat dissipation. Active cooling systems use forced convection to cool electrical enclosures through various types of fans, heat exchangers and cooling units. Cooling systems with such air intake cannot prevent contamination of the interior of the box. Air coming from external space brings dirt and dust with them. It is this contamination of the interior of the enclosure that has a negative impact on the electronic components, which reduces their service life. When clogging the system with external dirt, the overall maintenance of these devices increases. These negative effects give rise to the innovation of electrical enclosures to prevent dirt and dust from penetrating their interior [8].

Another method of heat removal can be performed by passive cooling. Passive heat dissipation transfers heat mainly from the housing of the electrical equipment. The heat transfer takes place through the flow of heat from a warmer environment to a colder one. Electrical enclosures can be open or closed. With open devices, heat is simply dissipated by natural air circulation. Closed construction is advantageous in terms of airtightness and dust-freeness. A great advantage of passive cooling is the lower cost of manufacturing and operating electrical enclosures. Passive cooling is one of the most commonly used, least expensive and easiest to implement cooling methods. Passive cooling methods include free cooling and cooling with heat pipe technology [9].

The gravity loop heat pipe (loop thermosiphon) belongs to passive cooling methods using heat pipe technology. In this way, it is possible to remove a large amount of heat with low working substance content in the heat pipe. The whole system operates automatically, with low operating noise and minimum electric power consumption. From a constructional view, a loop thermosiphon is one of the simple heat exchangers for heat transfer. Figure 1 shows the parts of the gravity loop heat pipe. It can be oriented in a vertical or slightly inclined position. The name of the gravity heat pipe implies that it uses gravity to circulate the working medium when it operates [10].

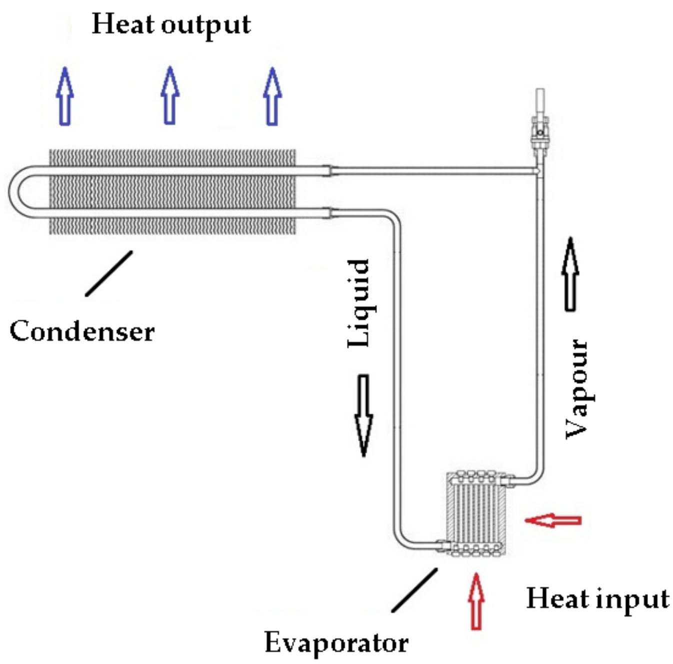


Figure 1. Gravity loop heat pipe.

The heat pipe consists of a hermetically sealed circuit with a working medium at a precisely defined pressure. The heat transfer is based on a two-phase self-circulation of the heat transfer working medium. There is a condenser at the top and an evaporator at the bottom of the heat pipe. The distance between the evaporator and the condenser must be chosen with an adequate height difference. Inside the heat pipe, the working medium circulates from the evaporation to the condensation section in one direction in a closed loop. The liquid boils in the evaporator depending on the amount of supplied heat from the environment in which the heat pipe is located. The gaseous state of the working substance flows to the condenser, where it condenses to a liquid and releases the heat of evaporation. The working substance is cooled and, under the action of gravitational force, flows down into the evaporator again [11]. The entire heat transfer process in a heat pipe is constantly repeated.

Gravity loop heat pipes have better thermal properties than active cooling systems because they use phase changes to transfer heat. The advantage is that the phase changes also occur at low mass flow rates, which increases the heat transfer coefficient. The selection of the working medium is flexible because there is no direct contact of the medium with the cooled component. The working medium is able to flow over relatively long distances without needing an external power supply, e.g., pump. Heat transfer over longer distances depends mainly on the thermodynamic properties of the working substance. The service life of the heat pipe is almost unlimited. This is due to the hermetically sealed design of the heat pipe without moving elements and the phase changes that are constantly repeating.

The simplicity and uniqueness of loop thermosiphons in relation to phase-change heat transfer encourage many kinds of research of new prototypes and applications of these exceptional devices. Scientists Palm and Khodabandeh were among the first to focus on the choice of working substance and its effect on performance and design in closed heat pipes. The research results were demonstrated by simulating heat transfer [12]. Further research on two-phase heat transfer equipment has focused on various working substances used in the heat pipe system. Jouhara and his scientific team used the azeotropic working substance water-ethanol in a thermosiphon closed heat tube. The experiments were focused on the thermal properties of this mixture, the heat transfer performance, and the total thermal resistance. The results of the research proved the functionality and practical use of the proposed device in various applications even with an evaporator inclination from 0° to 90° [13]. Zimmermann and Melo presented work focused on an experimental investigation of a carbon dioxide thermosiphon loop designed to fulfill the geometric and temperature requirements of a specific FPSC (free-piston Stirling cooler). Experiments were carried out varying the temperature difference between the heat source, i.e. air at the entrance of the evaporator and heat sink and the internal surface of the condenser, refrigerant charge, and evaporator airflow rate. The experimental results were explored using the thermal conductance concept applied to each heat exchanger and also to the whole loop. It was found that the loop was able to carry a maximum heat transfer rate of 514 W with a heat source-sink temperature difference of 11 °C [14].

Specific applications of the use of heat pipes can be seen, e.g., in the industrial power industry for the cooling of nuclear reactors, gas turbine blades, rotors, and transformers, in the electronics for the cooling of power components of electronic equipment, and in the avionics, medicine and automotive industries [15–19]. Heat pipes can also be used to reduce flue gas temperature in the flue gas tract of the heat source described by Čajová Kantová et al. [20].

Heat pipes play an important role in increasing the cooling efficiency of data centers. Zhang et al. proposed an integrated system of mechanical refrigeration and thermosiphon (ISMT) by combining two independent loops, a mechanical refrigeration loop and a thermosiphon loop, with a three-fluid heat exchanger. The experimental results show that it has sufficient cooling capacity. The EER of the thermosiphon mode reaches 10.7 and 20.8, when the indoor and outdoor temperature difference is 10 °C and 20 °C, respectively, and the AEER of the ISMT is 12.6, which is much higher than traditional air conditioners (TAC) [21]. In his publication, Jouhara analyzes the need for data center cooling, which is constantly increasing in energy and involves high costs. A simple cooling system based on heat pipes is designed which has the potential to save energy up to 75% [22]. Another proposed system in this area is from Singh and his colleagues. This system is designed for cold areas below 0 °C because it is based on storing ice or cold water on a heat pipe. The proposed system can be used as a pre-cooler in data centers [23]. Wang, Zhang, Li, and Luo used a combination of heat pipe processes and a cooling cycle to compress the vapor in their research to cool the data center. This resolved certain issues that arose during data center cooling processes, such as valve life and heat exchange areas [24].

During further investigation of the cooling system based on the thermosiphon loop in the telecommunication box, an analytical model was developed by Chehade et al., which was subsequently tested experimentally. The designed device was tested at a maximum thermal load of 500 W and with various working fluids suitable for the space with electronic components. The cabinet space cooling system provided good results between the model and the experiment. Based on the results of the model, it was concluded that increasing the thermal efficiency of the system is possible by increasing the diameters of the pipes in the evaporating and condensing part of the heat pipe [25]. Kim et al. developed a two-phase loop thermosiphon system for the B-ISDN telecommunications system and evaluated its performance both experimentally and by visualization techniques. The design of the proposed thermosiphon system was aimed to cool multichip modules (MCM) up to a heat flux of 8 W/cm^2. The results indicated that in the loop thermosiphon system, cooling heat flux is capable of 12 W/cm^2 with two condensers under the forced convection cooling of the condenser section with acetone or FC-87 as the working fluid [26].

Lamaison and his research team introduced a cooling system using microchannel evaporators to cool processors. Increasing the diameter of the pipe in the heat pipe by 30% increased the heat flow by 10–60%. The results of the research served to improve the geometry of the designed device [27]. Zhu and Yu proposed an ejector-assisted copper–water loop heat pipe with a flat evaporator (ELHP) for applications in electronic cooling and performed a simulation of its steady-state operation. The simulation results indicated that the ELHP can achieve a better performance than BLHP (basic loop heat pipe), which could be beneficial to the applications in electronic cooling [28]. Khodabandeh investigated an advanced thermosiphon loop with an extended evaporator for the cooling of three parallel high-heat flux electronic components. The tested evaporators were made from small blocks of copper in which five vertical channels with a diameter of 1.5 mm and length of 14.6 mm were drilled. Tests were done with isobutane (R600a) at heat loads in the range of 10–90 W/cm^2 for each of the components with forced convection condenser cooling and with natural convection with heat loads of 10–70 W [29].

Recent years of scientific experiments in research centers have proven the versatile use of heat pipes. Scientists have used heat pipes for cooling in various areas of electronics. The Sarno research team investigated the cooling of electronic components onboard aircraft using a gravitational heat pipe. The heat pipe cooling has two times more heat dissipation capacity than conventional cooling systems [18]. Sun's team designed a new cooling technology that combines the principle of phase change with natural cooling. This heat removal method was used to cool the telecommunications base stations. The measurement results show a 50% energy saving [30]. Samba and colleagues performed an experimental measurement of the cooling of a small telecom cabinet. Cooling was provided by means of a gravitational heat pipe, to which air was supplied via fans. The working medium was n-pentane. Measurements have shown that by this method of cooling it is possible to transfer heat three times more than with fans [6]. Tsoi and colleagues dealt with the cooling of telecommunication systems. They designed a new plate-type loop thermosiphon and examined its thermal performance under free and forced convective cooling conditions with both vertical and horizontal orientations [31]. Sundaram and colleagues investigated a loop thermosiphon for cooling air inside a telecommunication cabinet. They proposed a model based on the combination of thermal and hydraulic management of a two-phase flow in the loop and experimentally tested a closed thermosiphon loop with different working fluids that could be used for electronic cooling [32].

Miniature periodic two-phase thermosiphons with different evaporator sizes were also investigated for cooling electronic devices. A device with a larger volume transmitted higher heat loads of 110 W. Start-up phenomena were also observed, which proved to be smooth [33]. Further research with miniaturized two-phase devices that are being developed for electronic device applications has been investigated with various working substances [29,34]. Chang and his team conducted a deeper study of the boiling phenomena and thermal properties of TPLT in electronics cooling. They investigated interfacial structures, boiling instability, heat transfer rates, as well as the effect of pressure on the phase change associated with heater performance and condenser thermal resistance. They concluded that at lower heat loads, the phenomena in the heat pipe are cyclic, unstable, and are characterized by longer onset times [35]. Chehade and his research team investigated optimal TPLT loading in the range of 3% to 12%. Experimental studies revealed that of several working substance loading ratios, the optimal ratio was between 7% and 10%. The optimal cooling capacity, which was achieved by regulating the temperature and flow in TPLT to 5 °C and 0.7 L/min, was also studied [15].

The introduction of the article pointed out the current research works on heat dissipation by the cooling systems based on the loop thermosiphon principle. Every study is exceptional with new proposals and applications, which brings new knowledge in this area. The subject of our research is the design of a dustproof passive cooling device for electrical cabinets operating on the principle of phase change of the working substance capable of transmitting high heat output of 500 to 2000 W. This is an unconventional method of cooling electrical enclosures and can bring many benefits. A novelty of the refrigeration equipment is a new evaporator which can enable more intensive heat transfer and high heating power up to 2000 W. In the following sections, the paper deals with the design and construction of the cooling device, experimental research of its cooling effect under different operating conditions, mathematical calculation equipment, and analysis of the results obtained.

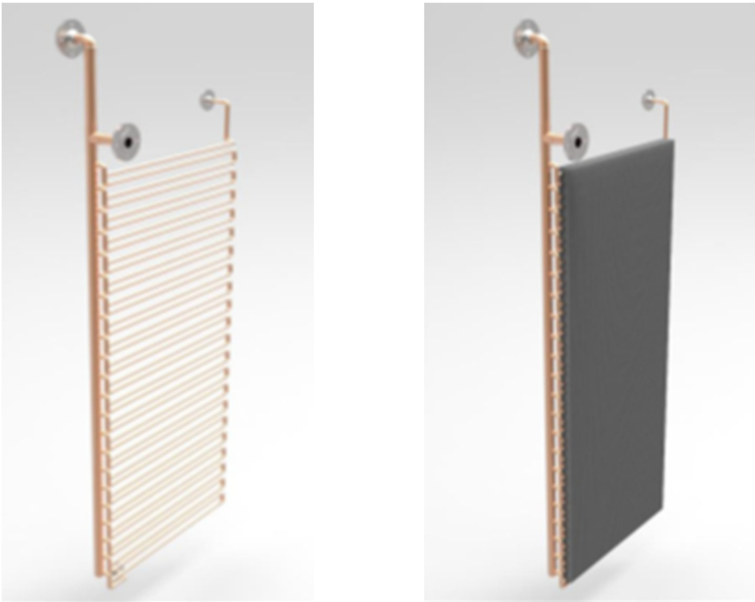
2. Cooling System Design

Current research in the field of electronics cooling is constantly looking for new ways to reduce the heat load of electrical components and thus improve their functionality and extend their lifetime. In view of all these criteria and requirements, the present article deals with the cooling of the interior of electrical enclosures by a gravity loop thermosiphon. The cooling system consists of two main parts, namely the evaporator and the condenser. The cooling process works on the principle of evaporation of the working substance in the evaporator so that only heat is dissipated from the internal space of the electrical equipment. In the condenser, the steam condenses, so that the heat is transferred to the outside. In our experimental measuring device, the evaporator is placed inside the cabinet at the back and the condenser is located above the cabinet construction. The heat dissipation to the ambient is carried out by forced convection on the steam-to-air heat exchanger.

The cooling system was designed for the real type of electric enclosure of energy converters. The main idea of the cooling system design was a dustproof electric enclosure. Therefore, a gravity loop heat pipe was used to dissipate heat from the electrical enclosure. The construction of the enclosure was supplemented with seals so that dust particles from the external environment could not leak into the indoor environment. The cooling system consisted of three basic parts: an evaporator, condenser, and working medium. The evaporator of the cooling system is located on the rear wall inside the cabinet, and the condenser is located above the cabinet. The evaporator and the condenser are connected by a pipeline through the working substance flows. The distance between evaporator and condenser is 30 cm. There is a heat transport working medium inside the cooling device. Heat transfer from the evaporator to the condenser occurs due to phase changes of the working fluid.

3. Evaporator Design

The task of the evaporator is to remove heat from the interior of the electric enclosure and to deliver it into the condenser by means of the vapors of the working medium flowing in the evaporator distributor. It is a finned tube heat exchanger, as shown in Figure 2. It consists of a pipeline, distributor, and fins. The pipeline and distributor are made from copper, and the fins are made from aluminum. The pipeline consists of 32 pipes with a diameter of 15 mm placed horizontally on top of each other in the shape of a meander. The distributor consists of one vertical pipe with a diameter of 35 mm with connections on each horizontal pipe. The heat exchange surface of the heat exchanger is enlarged by 265 aluminum fins with dimensions of 1650 × 50 × 0.25 mm and a spacing of 2.5 mm. The total dimensions of the evaporator are 1750 × 730 × 50 mm. The total volume of the evaporator is 4.9 L. The external heat exchange area of the evaporating part of the heat pipe is 42 m^2. The inner surface of the evaporator is 0.94 m^2.



(**a**) (**b**)

Figure 2. Evaporator design (**a**) without fins and (**b**) with fins.

The evaporator design also includes technical elements for separating vapor flow from the condensate flow to increase its ability to dissipate heat from the cabinet environment in places where it connects pipes to the distributor. Figure 3 shows the vapour and liquid phase distribution inside the evaporator.

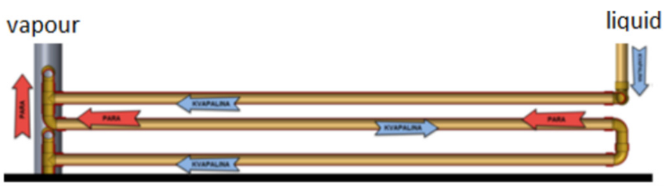
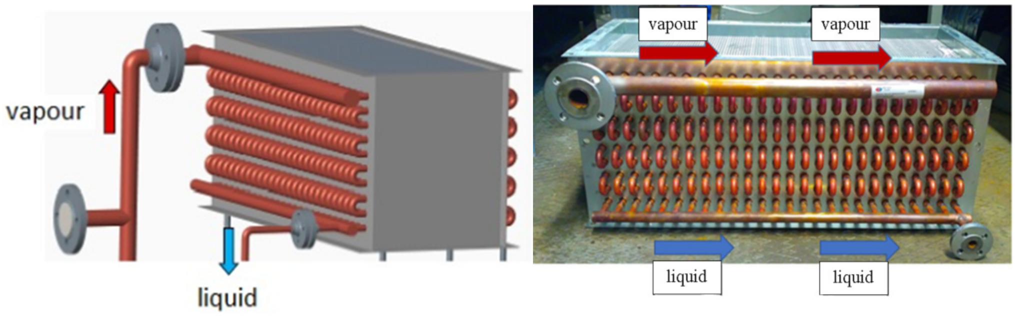


Figure 3. Vapour and liquid phase distribution inside the evaporator.

4. Condenser Design

The task of the condenser is to receive the heat flux transferred from the evaporator and dissipate heat to the surroundings. It is a finned tube heat exchanger consisting of a distributor, collector, pipelines, and fins. The distributor, collector, and pipeline are made from copper, and the fins are made from aluminum. The distributor consists of one horizontal pipe with a diameter of 35 mm placed at the backside on the top of the condenser. The collector consists of one horizontal pipe with a diameter of 15 mm placed at the backside on the bottom of the condenser. The distributor and condenser are connected in 26 places by pipelines consisting of 10 pipes with diameters of 15 mm placed horizontally on top of each other in the shape of a meander. The goal of the condenser design was to ensure uniform distribution of the working fluid along the condenser with minimal pressure losses. Figure 4 shows the working fluid distribution in the condenser. The heat exchange surface of the heat exchanger is enlarged by 88 aluminum fins with dimensions of 650 × 300 × 0.25 mm and a spacing of 2.5 mm. The total condenser dimensions are 730 × 300 × 250 mm. The total volume of the condenser is 13.5 L. The outer heat exchange area of the condensing part of the heat pipe is 29.95 m^2. The inner surface of the condenser is 3.2 m^2.



(a) (b)

Figure 4. Condenser design (**a**) in the model and (**b**) in reality.

5. Working Fluid

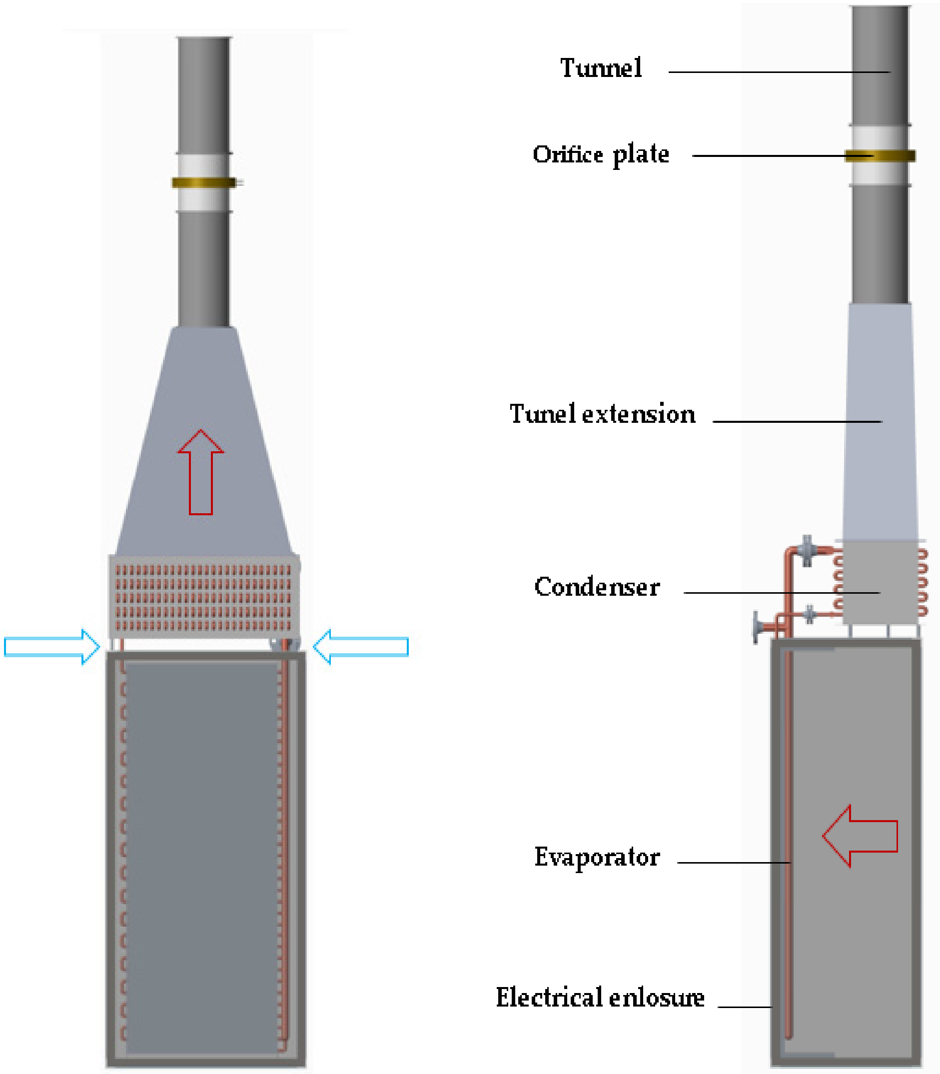
The first consideration when choosing the right working medium is the operating temperature range at boiling. The working medium affects the heat transport, and it is one of the most important aspects of heat pipe production. As a result of an improper working medium, the efficiency of the loop thermosiphon is reduced, and thus, the service time of the device is shortened. Within the approximate temperature range, there may be several possible working media, and to determine the most suitable of these fluids for the intended use, it is necessary to examine the various characteristics. The main requirements are good thermal stability, high thermal conductivity, vapour pressure which is not too high or low in the operating temperature range, high latent heat, low viscosity of liquids and vapours, satisfactory freezing point, specific heat capacity, and dynamic viscosity [36]. Table 1 mentions several working substances that are used in heat pipes. The advantages of methanol, acetone, and ethanol are their lower boiling point, good dielectric properties and ability not to freeze compared to water. Water has a significant value of latent heat, which has a favorable effect on evaporation. For the experiment, distilled water was chosen as a working fluid due to its very good thermophysical properties, wide temperature range, availability, price, high flash point, and auto-ignition temperature [37].

Table 1. Typical working fluids of loop thermosiphons [38].

Working Fluid	Melting Point at Atmospheric Pressure [°C]	Boiling Point at Atmospheric Pressure [°C]	Latent Heat of Vaporisation [kJ/kg]	Useful Range [°C]
Acetone	−95	57	518	0–120
Methanol	−98	64	1093	10–130
Ethanol	−112	78	850	0–130
Water	0	100	2260	30–200

6. Experimental Research

The task of the experimental research was to remove waste heat from the interior of the electrical enclosure and thus ensure suitable temperature conditions for electrical elements operation. The aim of the research was not to exceed a temperature of 60 °C inside the electric enclosure during the operation of the refrigeration equipment at a thermal load from 500 to 2000 W. Research works were performed on the experimental model of the electric enclosure at heat dissipations of 500 W, 750 W, 1000 W, 1500 W and 2000 W. Joule's heat was simulated by using electrical heating elements placed on three levels on the top, in the middle, and on the bottom of the electric enclosure. The whole model of the experimental measuring device consists of an electrical enclosure with electrical heating elements, a cooling system, and a measuring part for thermal performance evaluation shown in Figures 5 and 6.



(a) (b)

Figure 5. Model of experimental measuring device (**a**) from the front and (**b**) from the side.

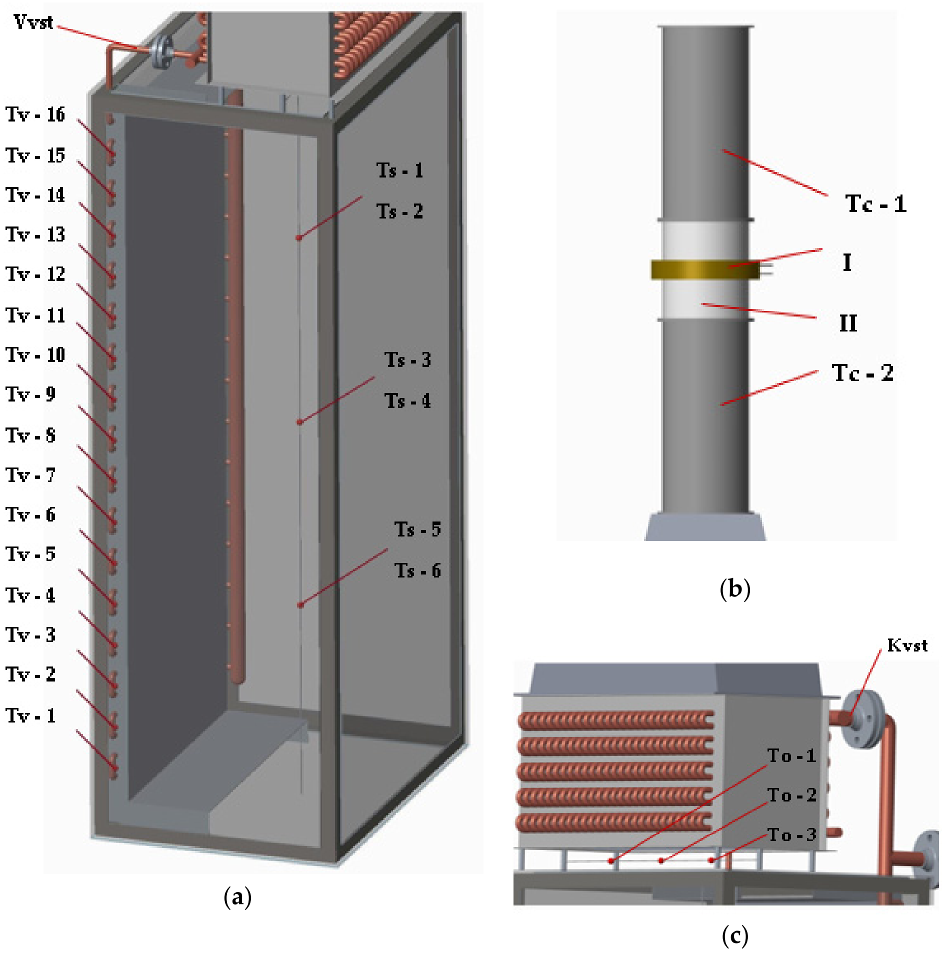


Figure 6. Placement of temperature and pressure sensors (**a**) on the evaporator, (**b**) on the orifice plate, (**c**) and on the condenser.

The enclosure dimensions are 2000 × 850 × 600 mm. The arrows in Figure 5 showed the airflow direction through the condenser and inside the electric enclosure. The evaporation part of the heat pipe was located in the interior of the electrical enclosure, where it receives heat, and the condensation part was placed above the electrical enclosure, where it dissipates heat to the ambient atmosphere. The distance between the evaporator and condenser is 30 mm. This configuration ensures the proper function of a gravitational loop heat pipe that uses the gravitational force for working substance circulation. Temperature sensors placed inside the electric enclosure give us data about interior temperature. The measuring part consists of a tunnel with temperature and pressure sensors, orifice plate and tunnel extension. The tunnel diameter is 160 mm, and the total length is 1000 mm. The orifice is placed in the middle of the tunnel. The diameter of the orifice throttle element is 60 mm. Mass airflow was measured in the tunnel. Temperature sensors placed under and above the condenser provided data to determine the heating power of the cooling device.

The layout of the temperature and pressure sensors is shown in Figure 6. Inside the cabinet were temperature sensors located on the individual bends of the evaporator tubes, marked Tv-1 to Tv-16. Their task was to record the temperature, which provided information about the flow of the working medium in the evaporator. To control the interior temperature, sensors Ts-1 to Ts-6 were placed in the lower, middle and upper part of the cabinet. Temperature sensors marked Tk-1 to Tk-9 were placed on the condenser. They were used to control the flow of the working medium in the condenser. Temperature sensors To-1 to To-3 were placed below the condenser to record the temperature of the air entering the condenser. Two temperature sensors were placed in the tunnels in front of and behind the orifice plate to record the outlet temperature of the air from the condenser. Two pressure sensors were placed in front and behind the orifice throttle element for the determination of air velocity from pressure differences.

Before measuring, the whole heat pipe system was vacuumed to create an environment suitable for the phase transformation of the working substance. More intensive heat removal by the cooling device was provided by the active members like fans situated in the interior and exterior of the experimental measuring device. The task of the interior axial fans was to ensure uniform airflow directly to the evaporator. The external axial fan placed above the measuring part had the task of intaking air from the surroundings. Thus, heat flux was dissipated from the condenser, and it could be quantified. The cabinet was insulated from the outside by mineral wool thickness of 100 mm. The measurement was carried out at different volumes of water, the working medium. At each heat load, the evaporator was charged with a working medium of 20%, 40%, 60%, 80%, and 100%.

The experimental measurements were performed continuously every day for two weeks under the same conditions. Therefore, the results were not affected. The process of each measurement consisted of creating a vacuum, filling it with a working substance, heating the environment in the cabinet, stabilizing the temperature, and cooling the space and equipment. Figure 12 shows part of one measurement during temperature stabilization.

7. Mathematical Calculations

In this study, the calculation of the maximum heating power transferred by the cooling device from the interior of the electric enclosure to the surroundings was performed. The purpose of the mathematical calculation was to find a simple method to theoretically determine the heating power transferred through the phase change of the working substance which occurs inside the loop thermosiphon at loaded heat. The calculation was performed on the basis of the theoretical relationships of convective heat transfer inside the tube and on the outside of the finned tube. The calculation was based on the theory of thermal equilibrium of a heat pipe, where it is assumed that the amount of heat received in the evaporating part of the device is equal to the amount of heat dissipated by the condensing part to the surroundings. The computational relations were applied in ideal conditions. The values of the physical quantities used in the relationships were determined from the tables on the basis of the measured temperatures and pressures of the electrical enclosure interior, the outside environment, and the cooling device obtained during the measurement [39,40].

$$\dot{Q}_c = \dot{Q}_e \tag{1}$$

Due to the thermal balance, it was sufficient to create a model for calculating the total heating power removed by the cooling device for only one part of the device. The calculation was performed for the condenser part according to the equation:

$$\dot{Q} = k \Delta t_{avg} A_1 \tag{2}$$

Equation (2) depends on the inner surface of condenser tubes A_1 (m^2), average logarithmic temperature difference Δt_{avg} (K) and overall heat transfer coefficient k (W/m^2·K).

The overall heat transfer coefficient depends mainly on α_1 (W/m^2·K), the condensation heat transfer coefficient inside the tube, and α_2 (W/m^2·K), the convective heat transfer coefficient on the outside tube of the condenser, and is defined by the equation:

$$k = \frac{1}{\frac{1}{\alpha_1} + \frac{A_1'}{A_2}\frac{1}{\alpha_2}} \tag{3}$$

The calculation of heat transfer coefficients inside the pipe and on the surface depends on the density, thermal conductivity, dynamic and kinematic viscosity, surface tension, thermal conductivity, and latent heat. The efficiency of the fins and the size of the heat exchange surface are also important factors in heat exchange. The values of these physical quantities depend on temperature and change over time. It follows that the heat transfer coefficient is within a certain interval. The calculation of the condensation heat transfer coefficient inside the horizontal tubes of the condenser, in which the condensation of water vapour to the liquid took place, was performed according to the following equation [41]:

$$\alpha_1 = 0.56\sqrt[4]{(gl_v\varrho^2\lambda^3)/(v\Delta\theta d_i)} \tag{4}$$

where g (m/s^2) is the gravitational acceleration, l_v (J/kg) is the latent heat of vaporization, ϱ (kg/m^3) is the air density, λ (W/m·K) is the thermal conductivity, ν (m^2/s) is the kinematic viscosity, $\Delta\theta$ (K) is the temperature difference of the tube wall and media, and d_i (m) is the inner tube diameter. In the range of our investigated temperatures, the values of the heat transfer coefficient during condensation in the range of 330–520 W/m^2·K were calculated.

On the outside of the condenser tubes, heat was transferred to the surroundings by forced air convection due to the forced air flow from the external fan. The convection heat transfer coefficient on the outside of the tube was defined by the equation:

$$\alpha_2 = \alpha_f\psi\left(1 + \left(\left(\eta_f - 1\right)\frac{A_f}{A_2}\right)\right) \tag{5}$$

The heat transfer coefficient outside the tube mainly depend on α_f (W/m^2·K), the heat transfer coefficient, at the fin, where η_f (-) represents the fin effectiveness, A_f (m^2) indicates the fin area without the tube area, A_2 (m^2) represents the fin area and the corresponding section of the free tube, and ψ (-) is the correction factor. The convection heat transfer coefficient on the outside of the tube was in the range of 35–70 W/m^2·K.

The heat transfer coefficient at the fin was calculated according to the equation

$$\alpha_f = 0.223\frac{\lambda_f}{d_e}\left(\frac{d_e m_a}{A_a\mu_a}\right)^{0.65}\left(\frac{s_f}{d_e}\right)^{0.19}\left(\frac{s_f}{h_f}\right)^{0.14} \tag{6}$$

where d_e (m) is the outside tube diameter, λ_f (W/m·K) is the fin thermal conductivity, m_a (kg/s) is air mass flow, A_a (m^2) is the air mass flow area, μ_a (Pa·s) is the dynamic viscosity of air, s_f (m) is the distance between fins, and h_f (m) is the fin height.

The air mass flow area was calculated according to the equation

$$A_0 = h_c w_c - n_c\, d_e l_p - \frac{l_p}{s_f}h_f\delta_f \tag{7}$$

where h_c (m) is the condenser height, w_c (m) is the condenser width, n_c (-) is the number of the fin column in the condenser, d_e (m) is the outside tube diameter, l_p (m) is the tube length, h_f (m) is the fin height, s_f (m) is the distance between fins, and δ_f (m) is the fin width.

The inside tube area was calculated according to the equation

$$A_1 = \frac{l_p}{s_f}A_1' \tag{8}$$

where l_p (m) is the tube length, s_f (m) is the distance between fins, and A'_1 (m^2) is the internal tube area in the section between fins.

The internal tube area in the section between fins was calculated according to the equation

$$A_1' = \pi d_i s_f \tag{9}$$

where π (-) is the Ludolf number, d_i (m) is the internal tube diameter, and s_f (m) is the distance between fins.

The fin area and the corresponding section of the free tube were calculated according to the equation

$$A_2 = A_f + \pi d_e \left(s_f - \delta_f\right) \frac{l_p}{s_f} \tag{10}$$

where A_f (m^2) is the fin area without the tube area, π (-) is the Ludolf number, d_e (m) is the outside tube diameter, s_f (m) is the distance between fins, δ_f (m) is the fin width, and l_p (m) is the tube length.

The fin area without the tube area was calculated according to the equation

$$A_f = 2l_c h_c - \frac{2n_t \pi d_e^2}{4} + 2\delta_f h_c + 2l_c \delta_f \tag{11}$$

where l_c (m) is the condenser length, h_c (m) is the condenser height, n_t (-) is the total number of tubes, π (-) is the Ludolf number, d_e (m) is the outside tube diameter, and δ_f (m) is the fin width.

The fin effectiveness was calculated according to the equation

$$\eta_f = \frac{\tanh\left(m h_f\right)}{m h_f} \tag{12}$$

where m (-) is a constant and h_f (m) is the fin height.

$$m = \sqrt{\frac{2\alpha_f}{\lambda_f \delta_f}} \tag{13}$$

where α_f (W/m^2·K) is the heat transfer coefficient on the fin, λ_f (W/m·K) is the thermal conductance of the fin, and δ_f (m) is the fin width.

8. Results and Discussion

The optimal state of cooling electrical enclosures by a cooling device was investigated depending on the volume of the working medium and the heat load. The measurement results are shown in Figures 7–11. The individual columns show the amount of dissipated heat calculated from the measured values of temperature and pressure in the measuring part and average temperature inside the electrical enclosure calculated from temperatures measured at the top, middle, and bottom.

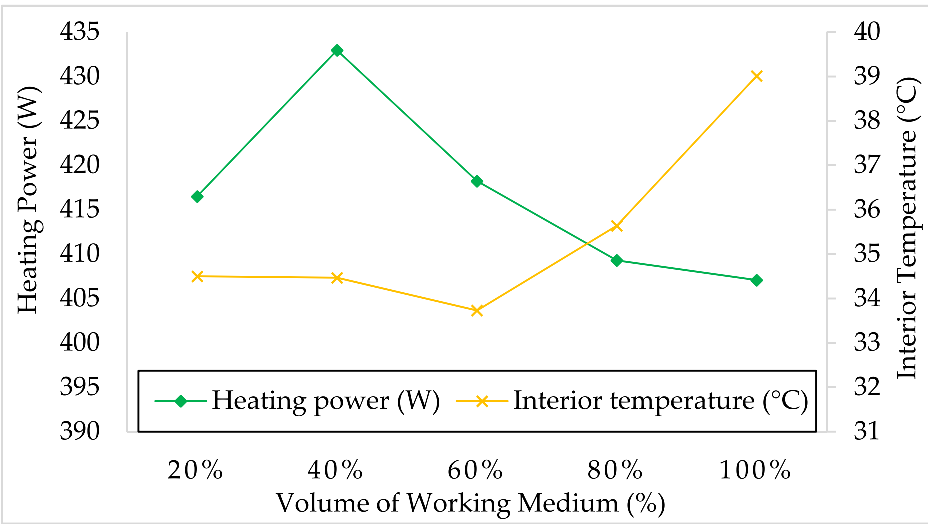


Figure 7. Measurement results at a heat load of 500 W.

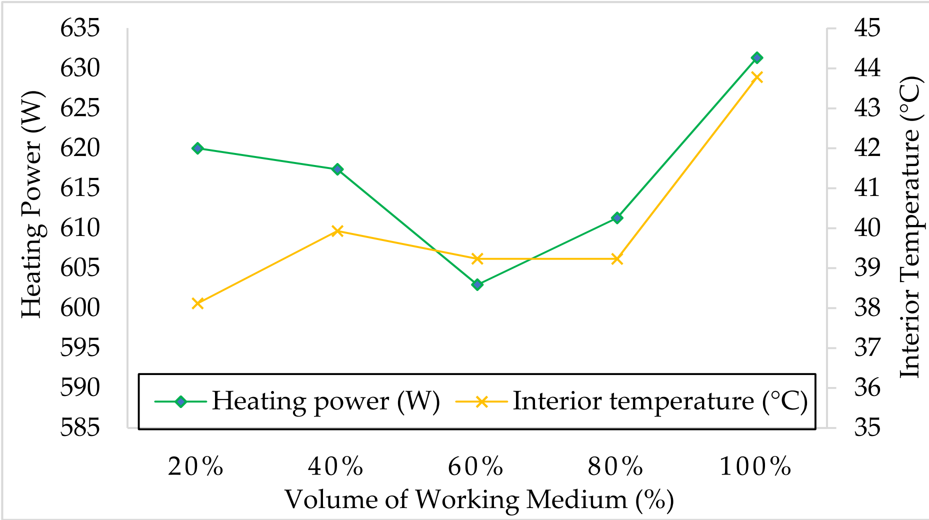


Figure 8. Measurement results at a heat load of 750 W.

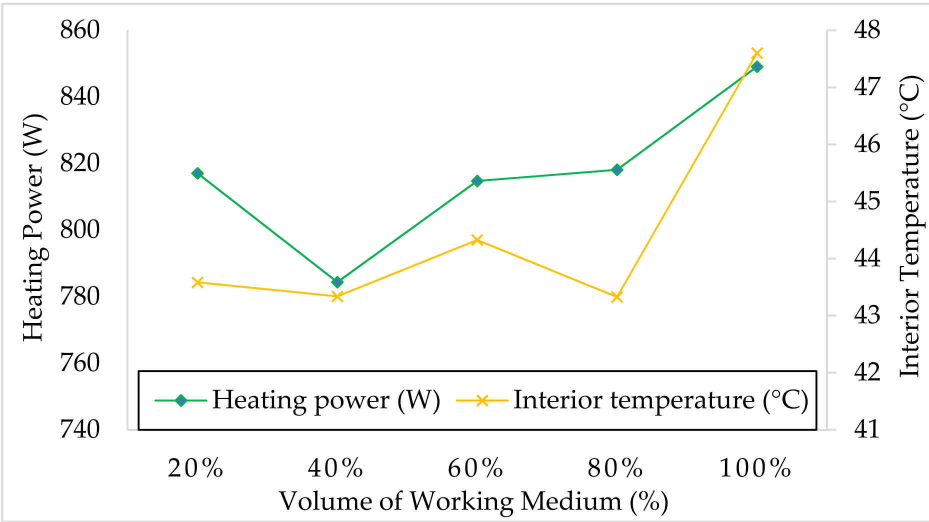


Figure 9. Measurement results at a heat load of 1000 W.

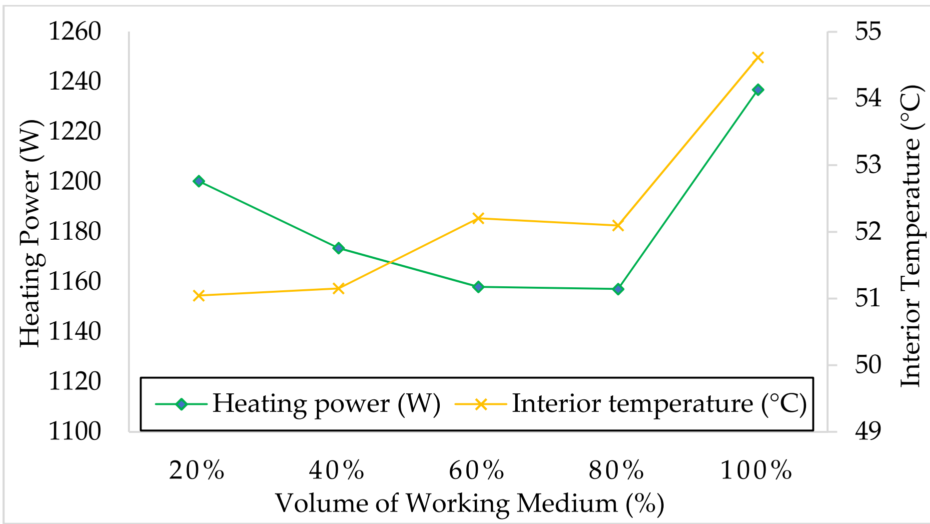


Figure 10. Measurement results at a heat load of 1500 W.

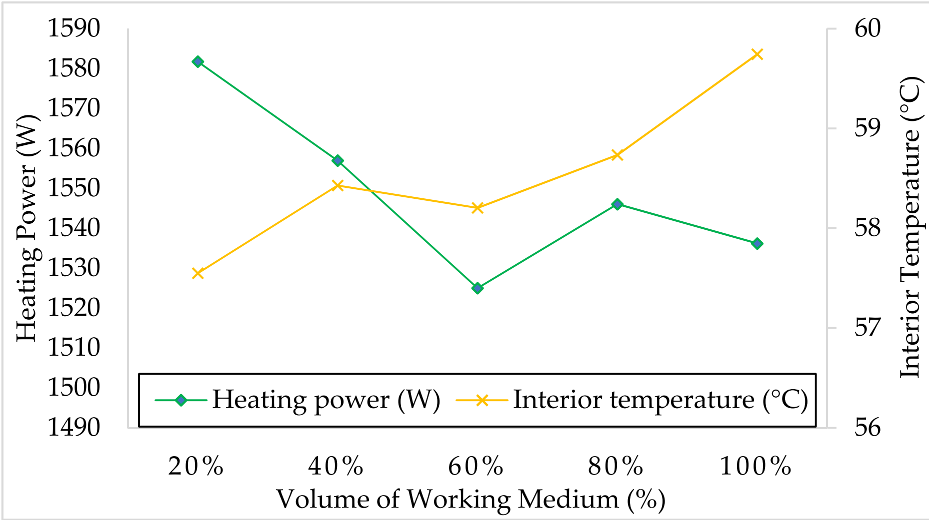


Figure 11. Measurement results at a heat load of 2000 W.

Figure 7 shows the results of heat transfer by means of a loop thermosiphon, the evaporating part of which was loaded with a simulated heat of 500 W from electrical resistance bodies. The analysis of the results showed that the cooling device removed heating power in the range of 433–407 W with an average value of 415 W and average operating temperature inside the electrical enclosure in the range of 33.5–39 °C at all investigated volumes of working medium. In terms of power dissipation to the environment, no dependence of the effect of the amount of working fluid in the evaporator was observed. From the point of view of the temperature in the interiors of the cabinet, it can be stated that at a volume of 100%, the temperature was significantly higher than at a volume of the working substance in the range of 20–80%. The best result was obtained with a working medium amount of 40% when the cooling system removed a heating power of 432 W from the electrical enclosure and the average operating temperature inside the electrical enclosure reached 34.5 °C.

Figure 8 shows the results of heat transfer by means of a loop thermosiphon, the evaporating part of which was loaded with a simulated heat of 750 W from electrical resistance bodies. The analysis of the results showed that the cooling device removed heating power in the range of 615–630 W with an average value of 620 W and average operating temperature inside the electrical enclosure in range of 43–48 °C at all investigated volumes of working medium. In terms of power dissipation to the environment, no dependence of the effect of the amount of working fluid in the evaporator was observed. From the point of view of the temperature in the interiors of the cabinet, it can be stated that at a volume of 100%, the temperature was significantly higher than at a volume of the working substance in the range of 20–80%. The best result was obtained with a working medium amount of 20%, when the cooling system removed a heating power of 620 W from the electrical enclosure and the average operating temperature inside the electrical enclosure reached 38 °C.

Figure 9 shows the results of heat transfer by means of a loop thermosiphon, the evaporating part of which was loaded with a simulated heat of 1000 W from electrical resistance bodies. The analysis of the results showed that the cooling device removed heating power in the range of 780–850 W with an average value of 817 W and an average operating temperature inside the electrical enclosure in the range of 43–48 °C at all investigated volumes of working medium. In terms of power dissipation to the environment, no dependence of the effect of the amount of working fluid in the evaporator was observed. From the point of view of the temperature in the interiors of the cabinet, it can be stated that at a volume of 100%, the temperature was significantly higher than at a volume of the working substance in the range of 20–80%. The best result was obtained with a working medium amount of 20%, when the cooling system removed a heating power of 818 W from the electrical enclosure and the average operating temperature inside the electrical enclosure reached 43 °C.

Figure 10 shows the results of heat transfer by means of a loop thermosiphon, the evaporating part of which was loaded with a simulated heat of 1500 W from electrical resistance bodies. The analysis of the results showed that the cooling device removed heating power in the range of 1157–1236 W with an average value of 1185 W and an average operating temperature inside the electrical enclosure in the range of 51–54.6 °C at all investigated volumes of working medium. In terms of power dissipation to the environment, no dependence of the effect of the amount of working fluid in the evaporator was observed. From the point of view of the temperature in the interiors of the cabinet, it can be stated that at a volume of 100%, the temperature was significantly higher than at a volume of the working substance in the range of 20–80%. The best result was obtained with a working medium amount of 20%, when the cooling system removed a heating power of 1200 W from the electrical enclosure and the average operating temperature inside the electrical enclosure reached 51 °C.

Figure 11 shows the results of heat transfer by means of a loop thermosiphon, the evaporating part of which was loaded with a simulated heat of 2000 W from electrical resistance bodies. The analysis of the results showed that the cooling device operates at all variants of working fluid volume very well when the cooling device was able to remove heating power in the range of 1525–1581 W with an average value of 1549 W and an average operating temperature inside the electrical enclosure in the range of 57.5–59.7 °C. In terms of power dissipation to the environment, the dependence of the effect of the amount of working fluid in the evaporator was observed. In this case, a lower heating power dissipation was observed at the working fluid volumes of 60–100% than at the volumes of 20–40%. From the point of view of the temperature in the interiors of the cabinet, there was a temperature increase that was observed at volumes of 60–100%. The best result was obtained with a working medium amount of 20%, when the cooling system removed 1582 W from the electrical enclosure heating power of and the average operating temperature inside the electrical enclosure reached 57.5 °C.

Overall, we can say that the proposed refrigeration equipment operated reliably under all tested conditions and achieved excellent results. Some dependence of the amount of working substance on the amount of heat removed was expected, but this was not clearly demonstrated. It is probable that the specially designed construction of the evaporator allows device uniform operation at different operating conditions. A slight decrease of the cooling effect was shown only in the case of a filling volume of 100%, when in all performed measurements, an increase in temperature was observed in the interiors of the cabinet, but not so much as to significantly affect the operation of electrical elements.

Figure 12 shows the temperatures and pressure courses inside the enclosure at the heat load of 1000 W, working fluid amount of 80%, and with fans turned on inside the enclosure. At the beginning of the measurement, the enclosure was heated to a temperature of about 80 °C by supplying the heat load of 2000 W. Then, the supplied heat was reduced to 1000 W, and the fans inside the cabinet, which are meant to the direct the flow towards the evaporator, were turned on. Then, it can be seen that the temperature inside the enclosure rapidly decreased in a few minutes to 50 °C and gradually decreased in time to approx. 45 °C. This indicates that the cooling device operates and cools the interior enclosure.

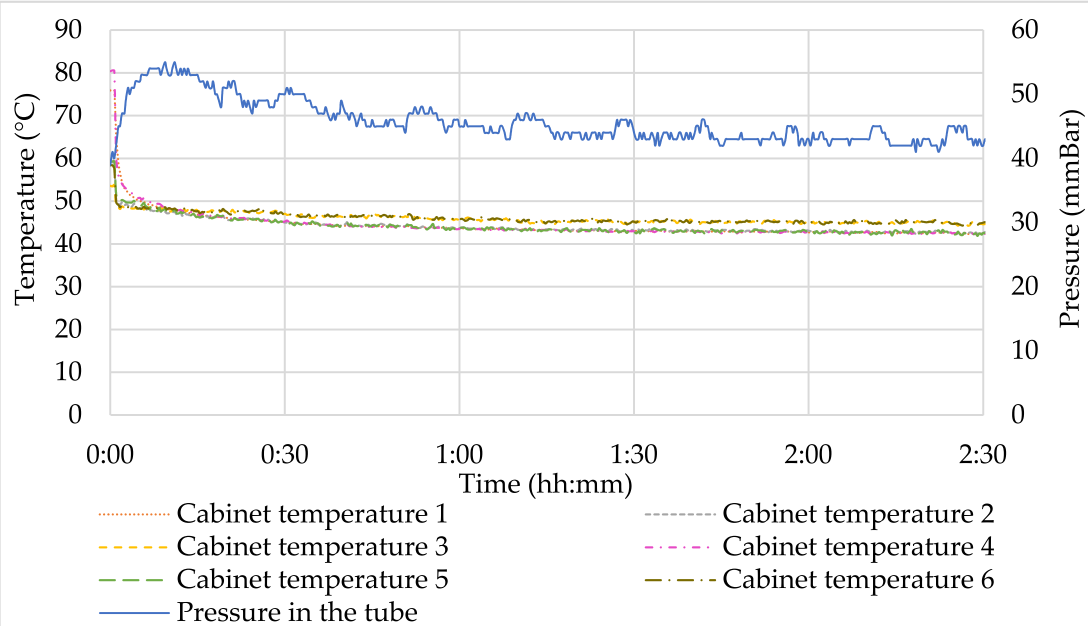


Figure 12. Temperature courses at a heat load 1000 W, working fluid amount of 80% and with fans turned on inside the enclosure.

Figure 13 shows temperatures and pressure courses inside the enclosure at the heat load of 1000 W, working fluid amount of 80%, and with fans turned off inside the enclosure. This figure shows the part of the measurement during which the temperature inside the cabinet stabilized. It is seen that temperatures in some parts of the enclosure rose above 60 °C, but most temperatures were under 60 °C. This is a good sign that the cooling device is able to operate without the help of fans directing the airflow inside the enclosure.

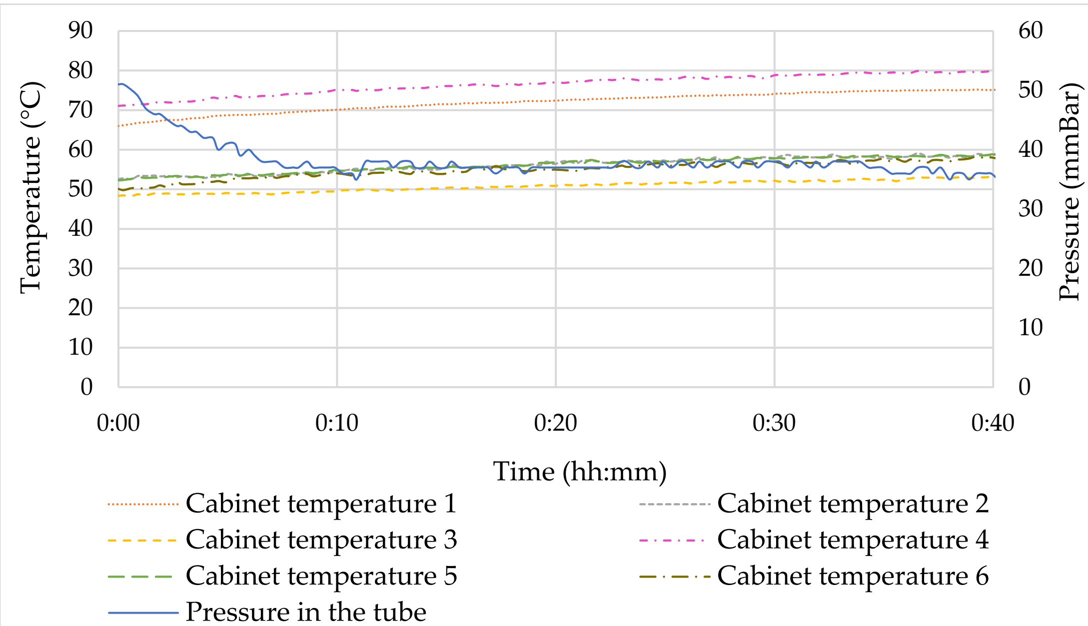


Figure 13. Temperature courses at a heat load of 1000 W, working fluid amount of 80%, and with fans turned off inside the enclosure.

The pressure profile inside the device throughout the experiments corresponds to the changing temperature conditions inside the cabinet. Before starting the measurement, the air was sucked out of the device, and subsequently, the device was filled with the working medium so as to guarantee the conditions of heat transfer by changing the phase of the working medium. The device worked independently without connection to an external vacuum pump. During the whole experiment, no air was sucked in from the exterior into the device, which can also be seen from the course of the pressures in Figures 12 and 13.

Figures 14 and 15 show a comparison of the results of the heating power transferred by cooling device obtained by measurement and by mathematical calculation at 1000 W and 500 W. Differences between the measured and calculated values of approximately about 25–30% can be seen. This demonstrates, therefore, that this simplified method considers idealized conditions. It often happens that the theoretical calculations differ from the real measured values, which are more decisive than the calculated ones. This calculation has shown the maximal theoretical heating power transferred by the cooling device at this setup and has additional indicative meaning for us.

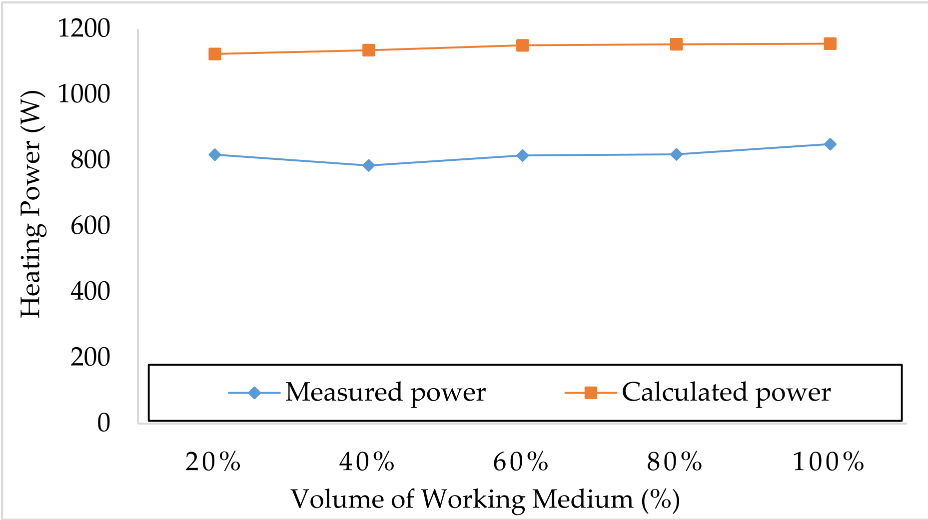


Figure 14. Comparison of measured and calculated results at a heat load of 1000 W.

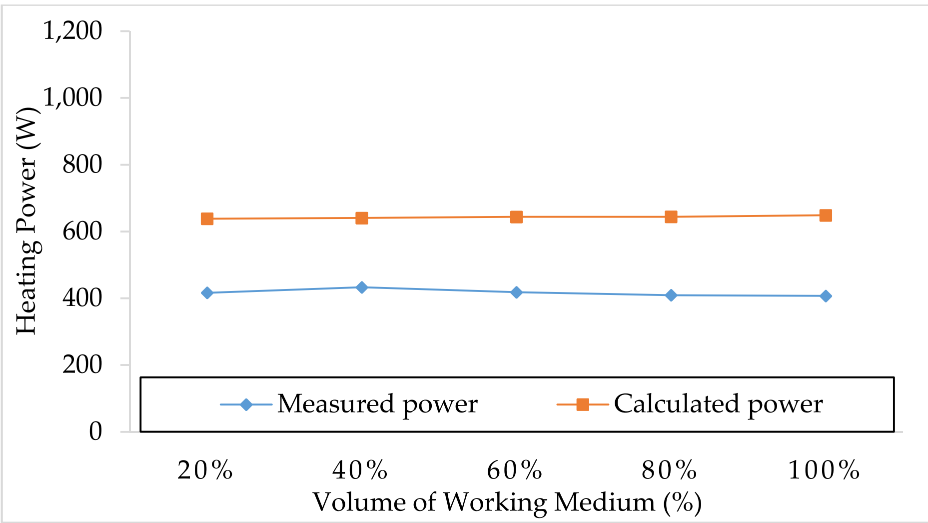


Figure 15. Comparison of measured and calculated results at a heat load of 500 W.

The entire loop thermosiphon system is controlled automatically, according to the heat flow with low operating noise and minimal electricity consumption. Another method of cooling is refrigeration units and air conditioners, which, unlike heat pipes, are directly dependent on an external energy source [42,43]. The designed cooling system with a heat pipe is a simple and highly efficient device that can be adapted to various operations in a wide range of parameters. The current market also offers several products to choose from in the field of active cooling [44]. The flow of the working substance in the heat pipe is ensured by gravity and the resulting buoyancy, which drives the flow of the two-phase refrigerant into the condenser. The height difference and density increase the potential of the driving force, which contributes to the increase in the flow and thus to the greater heat dissipation compared to the capillary heat pipe [27]. The big advantage is the unattended and simple operation of the entire system. From a functional point of view, it works without any problems while maintaining unchanged initial conditions during the entire period of operation inside the tube. In terms of heat transfer, the loop thermosiphon is a simple, commonly used heat exchanger. The difference is in the phase change that takes place in the heat pipe and does not take place in the water-air or air-air heat exchangers [7,45].

On the other hand, the design of a heat pipe is more complex in terms of production in terms of material, time and finances. An important condition for the effective operation of the proposed system is to ensure the vacuum tightness of the heat pipe. The joints on the welds are very sensitive parts necessary to maintain pressure and are recommended to be inspected in detail. The operation of a loop thermosiphon depends on the placement of the individual parts in a vertical or slightly inclined position [46].

The studies of cooling systems in an enclosed space with electrical elements mentioned in the introduction of this work are focused on passive heat dissipation using a heat pipe. This study is also focused on the passive cooling of the electrical cabinet with a new design of the heat exchangers of the cooling equipment, the operation of which is affected by the forced airflow from the fans. A similar problem of the loop thermosiphon was solved during the cooling of a telecommunication box. Various working substances and their physical properties on the effect of evaporation at 300 W, 400 W and 500 W have been investigated [25]. In our research, we mainly observed the operating parameters in the interior of the cabinet, and the maximum amount of heat transferred was 2000 W.

Another study of a closed telecommunication cabinet also examined the flow inside the cabinet without other technologies. The results of experiments and numerical methods confirmed that cooling depends directly on the airflow inside the cabinet. The turbulent flow regime was investigated at speeds of 0.827 m/s, 0.704 m/s, and 0.757 m/s. The maximum heat load was 180.5 W [17]. Axial fans with a speed of 2 m/s ensured the airflow in the electrical cabinet. Our experimental research included additional heat dissipation technology (a loop thermosiphon) compared to the telecommunication box. Forced convection has an effective effect on cooling in confined spaces, but in combination with a heat pipe device, the efficiency is much higher.

The experimental equipment of the cooling system is designed specifically for cooling a separately located closed electrical cabinet. This solution design ensures dust-free and trouble-free operation even with higher amounts of heat loss. In other research work with data centers [7], cooling has been designed for larger spaces. In this case, the cooling was solved by mixing the air with the surrounding environment, or the circulation of air with the exterior was ensured. This method of cooling works efficiently but causes high amounts of dustiness on electrical components.

9. Conclusions

Heat dissipation in electrical engineering is possible in various ways. When designing the cooling devices of electrical enclosures, the cooling power and a low economic cost have to be taken as the most important factors. The present paper describes the method of dustproof cooling of the internal space in an electrical enclosure by the cooling system with a gravity loop heat pipe which utilizes heat transfer through phase changes of the working substance based on the presented results. The cooling device has a unique designed evaporator for separating vapour flow from the condensate flow to increase the heat flux transfer limitation. Due to this evaporator design, it has been shown that the amount of working substance does not have a large effect on the transferred heating power, as in similar types of refrigeration equipment with an evaporator without the possibility of separating the vapor from the liquid phase. Slight deterioration of the cooling effect was demonstrated at 100% of the working substance volume in the evaporator. Another benefit of the cooling device is that it was able to ensure temperature conditions inside the electrical enclosure at a heat load of 2000 W of under 60 °C, 1500 W under 55 °C, 1000 W under 50 °C, 750 W under 45 °C and 500 W under 40 °C. The advantage of this cooling system is that it is a dustproof passive cooling capable of dissipating a large amount of heat and keeping the working temperature of the electrical elements inside the cabinet low, which guarantees suitable conditions for their operation. The other advantage is that it is a passive cooling system. The method of heat dissipation from the electrical enclosure to the external space through the gravity loop heat pipe has added value, especially at higher heat loads, when the dissipated heat can be reused in certain cases. This method of cooling system offers a lot of space to explore and improve, e. g., through combinations with another evaporator, condenser, and working media variants, which will be the subject of further research.

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Data Availability Statement: All the data analyzed in the article have been given.

Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

A_a	[m^2]	air mass flow area
A_1	[m^2]	inner surface of condenser tubes
A_1'	[m^2]	inner surface of the pipe of the section concerned
A_2	[m^2]	outer surface of the fin and the corresponding section of the tube
A_f	[m^2]	fin area without tube area
d_e	[m]	outside tube diameter
d_i	[m]	inner tube diameter
g	[m/s^2]	gravitational acceleration
h_c	[m]	condenser height
h_f	[m]	fin height
k	[W/m^2·K]	overall heat transfer coefficient
l_c	[m]	condenser length
l_p	[m]	pipe length
l_v	[J/kg]	latent heat of vaporization
m	[-]	constant
m_a	[kg/s]	air mass flow
n_c	[-]	number of fin column in the condenser
n_t	[-]	total number of tubes
$\dot{Q}$	[W]	total heating power
$\dot{Q}_c$	[W]	total heating power on the condenser
$\dot{Q}_e$	[W]	total heating power on the evaporator
s_f	[m]	distance between fins
w_c	[m]	condenser width

Greek Letters

α_1	[W/m^2·K]	condensation heat transfer coefficient inside the tube of the condenser
α_2	[W/m^2·K]	convective heat transfer coefficient outside the tube of the condenser
α_f	[W/m^2·K]	heat transfer coefficient at the fin
δ_f	[m]	fin width
$\Delta\theta$	[K]	temperature difference of tube wall and media
Δt_{avg}	[K]	average logarithmic temperature difference
λ	[W/m·K]	thermal conductivity
λ_f	[W/m·K]	fin thermal conductivity
μ_a	[Pa·s]	dynamic viscosity of air
η_f	[-]	fin effectiveness
π	[-]	Ludolf number
ρ	[kg/m^3]	air density
ν	[m^2/s]	kinematic viscosity
ψ	[-]	correction factor
Other		
AEER	[-]	annual energy efficiency ratio
B-ISDN	[-]	broadband integrated services digital network
BLHP	[-]	basic loop heat pipe
EER	[-]	energy efficiency ratio
ELHP	[-]	ejector-assisted copper–water loop heat pipe with a flat evaporator
FC-87	[-]	fluorinert liquid
FPSC	[-]	free-piston Stirling cooler
ISMT	[-]	integrated system of mechanical refrigeration and thermosiphon
MCM	[-]	multichip cool modules
TAC	[-]	traditional air conditioners
TPLT	[-]	two-phase loop thermosyphon

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