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**Abstract:** This study mainly focuses on the influence of anodic aluminum oxide (AAO) nanostructure generated on condenser section inner surface on the heat transfer performance of gravity heat pipes. AAO nanotubes were first grown by anodizing the inner wall surface of the condenser section of aluminum alloy gravity heat pipes through different anodizing voltages and treatment times. The nanostructure effect on the temperature distribution and overall thermal resistance was then investigated by using a thermal performance test system under different input heat powers. The experimental results showed that the generation of AAO nanostructure on the inner surface significantly enhances heat transfer performance; that is, the temperature difference between the evaporator and condenser sections and overall thermal resistance are reduced. Such an effect can be more significant in the case of a lower heat source. The percentage decreases in temperature difference and overall thermal resistance can be reduced by up to 58.83% and 58.79%, respectively, compared to the unprocessed heat pipe.

**Keywords:** thermosyphon heat pipes; condensation heat transfer; anodic oxidation treatment; nanotube membrane

# 1. Introduction

With the rapid development of information technology and electronic industry, most electronic devices and components generate more and more waste heat when performing a large number of calculations. With the demand for thin and light electronic products, how to more effectively remove waste heat in a limited space has become one of today's important key technologies. Among the many heat transfer solutions used in the information technology and electronic industry, the use of heat pipes is one of the most effective heat transfer solutions known to people, which has the advantages of fast thermal response, simple structure, light weight, and high reliability. There are many types of heat pipes, which can be typically divided into three sections: evaporator section, adiabatic section, and condenser section, and is a passive two-phase heat transfer device that transfers heat through evaporation and condensation [1]. The gravity-aided heat pipe (or simply gravity heat pipe) is known as the simplest two-phase closed thermosyphon, which is characterized by only relying on gravity to guide the working fluid from the condenser section back to the evaporation section.

The studies on improving the overall heat transfer performance of gravity heat pipes mainly focused on changing heat pipe inclination angle and filling different working fluids. For example, Solomon et al. [2] conducted experiments to investigate the performance enhancement of a gravity heat pipe with a thin, porous copper coating under different inclination angles. The experimental results revealed that at any inclination angle, the heat transfer performance can be improved by the thin, porous copper coating. Compared with a heat pipe without such a coating, the heat transfer coefficient of the evaporator can be increased by 44% at a heat flux of  $10 \text{ W/m}^2$  for an inclination angle of  $45^\circ$ .



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Hassan et al. [3] considered filling water-based  $Al_2O_3$  nanofluids with different concentrations into a vacuum copper heat pipe to investigate its heat transfer performance. The experimental results showed that the heat transfer performance of the heat pipe with a nanofluid was significantly improved compared to that of the heat pipe with water at the beginning. However, after repeated use, this improvement was found to be getting worse and worse, because the phase change of water causes the stability of the suspended nanoparticles in water to deteriorate. It was also found from Scanning Electron Microscope (SEM) that some nanoparticles were attached to the tube wall during the phase change process, which made it more difficult for the working fluid to flow back and increased the overall thermal resistance. Recently, Ozbas et al. [4] studied the design of different internal structures and different inclination angles to improve the heat transfer performance of gravity heat pipes (Normal, Type-1, Type-2, and Type-3). The experimental results showed that Type-2 has the best heat transfer performance when the inclination angle is 26°. Kaya [5] experimentally investigated the heat transfer performance of a gravity heat pipe filled with water-based CuO nanofluids of different mass concentrations under different input heat powers. The experimental results showed that when the input heating power is 600 W, the best heat transfer performance can be obtained for the nanofluid with a concentration of 2%. Gallego et al. [6] conducted the heat transfer performance of a gravity heat pipe with different concentrations of water-based Al<sub>2</sub>O<sub>3</sub> nanofluids under different input heat powers and filling ratios through experiments. The experimental results showed that, compared to the case of using deionized (DI) water as the working fluid, when the input heat power is 60 W and the concentration is 0.1 wt%, the heat transfer performance can be improved by 14.8%. Kumar et al. [7] experimentally investigated the influence of the nanoparticle concentration of water-based Al<sub>2</sub>O<sub>3</sub> nanofluids on heat pipe heat transfer performance under different input heat powers and inclination angles. The experimental results showed that the thermal resistance decreases with the increase of the inclination angle and the concentration, and the best heat transfer performance can be achieved when the inclination angle is  $90^{\circ}$  and the concentration is 4%. Arun et al. [8] conducted the heat transfer performance of gravity heat pipes filled with DI water and Al<sub>2</sub>O<sub>3</sub> nanofluids. The experimental results showed that the heat pipe performance can be improved by 41% using alumina nanofluid as the working fluid, compared to water, and the effect is more obvious under the larger inclination angle and higher heat input.

In addition to changing heat pipe inclination angle and filling different working fluids, modifying the inner surface structure of heat pipes is currently another method that is considered to be expected to improve the heat transfer performance. For example, Solomon et al. [9] applied an anodizing technology to the heat transfer performance of a gravity heat pipe. It was found that the nanoporous film prepared on the inner wall of the heat pipe after anodic oxidation treatment can increase the nucleation density, thereby increasing the generation of bubbles during the boiling of the working fluid, and further improve the heat transfer performance (15%) and reducing the thermal resistance (15%). Singh et al. [10] investigated the effect of anodized surface on the heat transfer performance of flat gravity heat pipes with different filling rates, inclination angles, and heat pipe shapes. The experimental results showed that the pore density of the anodized heat pipe is increased up to 90% compared with that of the non-anodized heat pipe. Weng and Yang [11] investigated the effect of AAO nanotubes generated on the inner surface of gravity heat pipes on heat transfer performance, and found that increasing the length and diameter of AAO nanotubes could reduce the temperature variation between the evaporator section and the condenser section, thereby reducing the overall thermal resistance between them. Recently, Zhao et al. [12] investigated the effect of wettability on heat pipe heat transfer performance. The experimental results showed that within the heat power input range of this study, the performance gradually decreases with the increase of the contact angle. Bahmanabadi et al. [13] experimentally investigated the effect of evaporator section inner radially grooved surface on the heat transfer performance of gravity heat pipes. The results showed that the heat pipe with radially an inclined triangular-grooved surface has the

best heat transfer performance, and its thermal resistance can be reduced by about 36.13%, compared to that of the heat pipe with a smooth surface. Jiang et al. [14] combined the fluidized bed heat transfer technology with heat pipe to design a three-phase gravity heat pipe and investigated the effect of glass bead size on the heat transfer performance of the heat pipe under different input heat powers. The experimental results showed that when the input heat power is 300 W and the solid holdup is 5%, the overall thermal resistance can be reduced to 27.67% in the case of glass beads with a diameter of 200 mm. Ng et al. [15] studied the effect of graphene-nanoparticles (GNPs) coatings with different wettability on heat pipe heat transfer performance. The experimental results showed that the heat pipe with cured GNPs coating has 31% higher thermal conductivity and 37% lower thermal resistance. Recently, Anand et al. [16] gave a comprehensive review of the experimental studies on cylindrical gravity heat pipes for low-temperature applications, including the effects of heat pipe geometry, heat pipe inclination, input heat power, working fluid, and filling ratio on the performance of heat pipes. Sudhan et al. [17] summarized the various heat transfer mechanisms involved in depositing nanoparticles on the evaporator section or using nanofluids and porous coatings in the evaporator section.

Previous studies have only investigated how to use the anodized inner surface of the evaporator section of a gravity heat pipe to improve the heat transfer performance of the heat pipe; however, the anodic oxidation treatment on the inner surface of the condenser section has not been considered in the literature. Therefore, the main purpose of this study is to generate AAO nanostructure on the inner surface of the condenser section of a gravity heat pipe to improve its heat transfer performance. By varying the process parameters of an anodic oxidation treatment method, anodizing voltage and treatment time, and under different input heat powers, a thermal performance test system is then used to investigate the effect of the generated surface nanostructure on the temperature distribution and overall thermal resistance of the gravity heat pipe.

#### 2. Research Methods

## 2.1. Generation of AAO

The generation of AAO is also known as conversion coating, which is a technique in which the aluminum or aluminum alloy substrate to be anodized is immersed in an acidic electrolytic solution and a direct current is passed through it to generate an AAO structure. It can be divided into three stages. In the first stage, the conductivity of the aluminum surface is high, and the initial current will therefore be large. As a result, aluminum ions  $(Al^{3+})$  are easily dissolved on the wall surface of the substrate and react with oxygen ions from the electrolytic solution to form a dense alumina  $(Al_3O_2)$  barrier layer. In the second stage, the alumina on the surface of the barrier layer reacts with hydrogen ions and then causes partial dissolution of the surface (generation of aluminum ions), resulting in surface unevenness. Over time, the concentrated electric field accelerates the dissolution and then results in nanopores to appear on the surface. In the third stage, due to the concentration of the electric field, the aluminum ions at the bottom of the pores are continuously dissolved until the dissolution and formation of alumina reach a dynamic equilibrium, leading to the steady growth of AAO nanotubes. The tube diameter can be enlarged by increasing the anodizing voltage, and the tube length can be extended by increasing the treatment time [11,18–21].

#### 2.2. Anodic Oxidation Treatment

The material used for the gravity heat pipes in this study was 6063-T5 aluminum alloy. The tube has an outer diameter of 19 mm, an inner diameter of 17 mm, and a length of 300 mm, divided into three sections: a 100 mm condenser section, a 100 mm adiabatic section, and a 100 mm evaporator section, as shown in Figure 1. The following stages were performed to generate AAO nanostructure on the inner surface of the condenser section for a gravity heat pipe:

- 1. An aluminum alloy pipe was placed in an oven and annealed at 450 °C for 3 h to make aluminum atoms more compact and to decrease metal's internal stress concentration.
- 2. The aluminum alloy pipe was first mechanically polished with #600, #1200, and #2000 sandpaper sequentially to ensure a smooth surface. Then, it was soaked in acetone  $(CH_3COCH_3)$  and ethanol  $(C_2H_6O)$ , placed in an ultrasonic cleaner to be cleaned for 30 min, and rinsed with DI water to ensure that surface impurities and oil stains could be removed.
- 3. The aluminum alloy pipe was immersed in an electrolytic solution composed of phosphoric acid ( $H_3PO_4$ ), sulfuric acid ( $H_2SO_4$ ), and DI water in the ratio of 2:1:1, and placed on a magnet stirrer to maintain the homogeneity of the electrolytic solution [11]. The anode was connected to the aluminum alloy pipe, the cathode was connected to the copper rod, and the power source was supplied by a power supply. Electrolytic polishing was performed at a constant current of 15 A, and the pipe was cooled down to room temperature after 90 s of treatment. This stage was repeated three times. The polished aluminum alloy pipe was rinsed with DI water to ensure the removal of residual electrolyte.
- 4. The aluminum alloy pipe was immersed in an electrolytic solution containing 0.3 M oxalic acid ( $H_2C_2O_4$ ), and the ambient temperature was controlled at 5 °C. The copper rod was placed in the center of the pipe, the anode was connected to the aluminum alloy pipe, the cathode was connected to the copper rod, and the power was turned on. The first anodizing treatment was carried out at the anodizing voltage to be explored, and the treatment time was set to 2 h. After the first anodizing treatment, the pipe was washed with DI water to ensure that was no electrolyte residue, and soaked in undiluted phosphoric acid, and placed in an ultrasonic washing machine for 2 h to remove the uneven AAO nanostructure generated by the first anodizing treatment, so that the subsequent second anodizing treatment could generate more uniform AAO nanostructure. Then, the pipe was subjected to a washing process to ensure that the phosphoric acid solution and surface impurities were removed cleanly.
- 5. The pipe with AAO nanostructure was subjected to the second anodizing treatment in the above-mentioned manner to obtain longer AAO nanotubes generated on the condenser section inner surface of the pipe. According to experimental requirements, the treatment time can be controlled to reach the required length of AAO nanotubes.

The anodizing voltage range of this experiment was 20 V to 50 V, and the treatment time range was 3 h to 9 h. The anodized pipe was cleaned with DI water for subsequent heat pipe thermal performance testing.

## 2.3. Experimental System Setup

The pipe with AAO nanotubes was welded to an aluminum alloy cap, one end was sealed, and the other end was drilled and tapped for subsequent installation of an anti-leak valve. The pipe was washed again to make sure it as clean, the valve was installed, and the pipe was tested to check that it was completely sealed. Then, the pipe was evacuated by a vacuum pump, and the working fluid (acetone) was injected into the heat pipe through a trident valve.

Figure 2 shows the schematic diagram and photographic appearance of the thermal performance test system built for this study. The experimental system was divided into three zones: heating zone, transportation zone, and cooling zone. In the heating zone, a red copper block was heated by a resistive heating rod to provide a stable heat source. The cooling zone was connected to a circulating water bath through a cooling device to control the temperature at 25 °C. In order to avoid additional heat exchange, these zones were covered with thermal insulation foam. Three thermocouples were embedded in each zone to observe the temperature change of the entire gravity heat pipe. The obtained data could then be used to further analyze the thermal performance through specific mathematical relationships. The overall thermal resistance *R* of a gravity heat pipe is one



of the key parameters of the heat transfer performance of the heat pipe. It is the reciprocal of conductance; that is,



(b)

Figure 1. Aluminum alloy pipe: (a) schematic diagram, (b) photographic appearance.

$$R = \frac{1}{U} = \frac{\Delta x}{kA} \tag{1}$$

where *U* is the overall thermal conductance, *k* is the overall thermal conductivity, *A* is the cross-sectional area, and  $\Delta x$  is the distance between the two ends to be tested. Fourier's law of conduction relates heat power input ( $Q_{in}$ ) with its temperature gradient (about  $-(\overline{T}_e - \overline{T}_c)/\Delta x$ ), thermal conductivity (*k*), and cross-sectional area (*A*), written as

$$Q_{in} = kA \frac{\overline{T}_e - \overline{T}_c}{\Delta x}$$
(2)



(a)



Figure 2. Experimental system: (a) schematic diagram, (b) photographic appearance.

Substituting Equation (2) in Equation (1) gives

$$R = \frac{\overline{T}_e - \overline{T}_c}{Q_{in}} \tag{3}$$

Here  $\overline{T}_c$  is the average of the three temperatures obtained in the condenser section (T1, T2, and T3), and  $\overline{T}_e$  is the average of the three temperatures obtained in the evaporation

section (T7, T8, and T9). Note that the absolute relative uncertainty and standard deviation of temperature measurement were estimated to be less than 5.60% and 0.51 °C, respectively.

## 3. Results and Discussion

When electronic components are operated at high speed, they are prone to heat accumulation and high temperature due to the discharged waste heat, which may cause the electronic components to lose the expected operating speed or even suffer permanent damage. Therefore, how to effectively reduce the temperature of the heat source is an important key to the improvement of technology in the electronics industry. In this section, the focus is on the temperature distribution and overall thermal resistance under different anodizing voltages (20 V to 50 V) and treatment times (3 h to 9 h), which represent different AAO nanostructured condenser section inner surfaces. The input heat powers considered are 25 W, 50 W, 75 W, and 100 W. The highest power (100 W) is mainly used as a case to show the influence of AAO nanostructure generated on condenser section inner surface on the heat transfer performance of gravity heat pipes.

First, the validity of the experimental design is verified by comparing the experimental results with those of Weng and Yang [11]. Weng and Yang's work is a case of gravity heat pipes using AAO nanostructure generated on the inner surface of evaporator section. For comparison, nanotubes were generated on the evaporator section inner surface under the maximum anodizing conditions (50 V and 9 h). The results of the temperature distribution T(X) are checked against the corresponding data obtained by Weng and Yang. The comparison is in excellent agreement with maximum absolute percentage error to be only 1.73%, as shown in Figure 3.



Figure 3. Comparison of the results of present study with those of available work.

#### 3.1. Temperature Distribution

In Figure 4, the temperature distributions T(X) under an input heat power of 100 W are plotted for different anodizing voltages at a treatment time of 3 h. As shown in the figure, the temperatures of the evaporator section (at X = 210 mm, 240 mm and 270 mm) of the heat pipe after anodic oxidation treatment is lower than those of the heat pipe without anodic oxidation treatment ('normal' line), which shows that the generation of AAO nanostructure can effectively reduce the heat source temperature. In addition, it can be seen that for the same treatment time, the larger the anodizing voltage, the larger the temperature decreases in the evaporator section, but the temperatures in the condensation section do not change significantly. Therefore, when AAO nanotubes with a larger tube size are generated on the inner surface of the condenser section, the condensed working fluid can flow back to the evaporator section more quickly, thereby accelerating the heat transfer effect and preventing heat accumulation in the evaporator section. It can be concluded that

a larger anodizing voltage has a smaller temperature variation in the heat pipe within the parameter range of this study.





In Figure 5, the temperature distributions T(X) under an input heat power of 100 W are plotted for different treatment times at an anodizing voltage of 50 V. It can be seen from the figure that for the same anodizing voltage, the longer the treatment time, the larger the temperature decreases in the evaporator section, but the temperatures in the condensation section increase slightly (more heat is carried from the evaporator section to the condenser section). Therefore, when AAO nanotubes with a longer tube length (with high specific surface area) are generated on the inner surface of the condenser section, the condensed working fluid can flow back to the evaporator section more smoothly, thereby improving the heat transfer performance of the heat pipe. It can be concluded that within the parameter range of this study, a longer treatment time has a smaller temperature variation in the heat pipe.



**Figure 5.** Temperature distributions under an input heat power of 100 W for different treatment times at an anodizing voltages of 50 V.

### 3.2. Overall Thermal Resistance

Figure 6 shows the overall thermal resistance versus the anodizing voltage at a treatment time of 3 h under an input heat power of 100 W. As shown in the figure, the overall thermal resistance of the heat pipe after anodic oxidation treatment is smaller than that of the heat pipe without anodic oxidation treatment ('normal' line). The reason may be that the larger the anodizing voltage of the anodic oxidation treatment, the larger the tube diameter of the resulting nanotubes and the better the hydrophobicity [20]. Therefore, when AAO nanotubes with a larger tube diameter are formed on the inner surface of the condenser section, the condensed working fluid can slide down the surface more quickly and accelerate its return to the evaporator section, thereby improving the overall heat transfer performance of the heat pipe, which is the same reason as the above-mentioned improvement in temperature distribution in the heat pipe.



**Figure 6.** Variation of the overall thermal resistance with the anodizing voltage under an input heat power of 100 W at a treatment time of 3 h.

Figure 7 shows the overall thermal resistance versus the treatment time at an anodizing voltage of 50 V under an input heat power of 100 W. It can be seen from the figure that when the anodizing voltage is fixed and the treatment time is increased, the overall thermal resistance of the heat pipe also tends to decrease. The reason may be that the longer the treatment time, the longer the AAO nanotubes (the larger the specific surface area), which gives more opportunities to take away heat in the condenser section, thereby improving the overall heat transfer performance of the heat pipe, which can also be applied to the explanation of the above-mentioned improvement in temperature distribution in the heat pipe.



**Figure 7.** Variation of the overall thermal resistance with the treatment time under an input heat power of 100 W at an anodizing voltage of 50 V.

From the above analysis, it can be known that the most significant effect occurs at 50 V and 9 h. Tables 1 and 2 show the experimental data of the heat pipe without anodic oxidation treatment and after anodic oxidation treatment at 50 V and 9 h, respectively. Further analysis of these experimental data shows that compared with the unprocessed heat pipe, the temperature difference between the average temperature of the evaporator section (the average of T7, T8, and T9) and the average temperature of the condenser section (the average of T1, T2, and T3) and the overall thermal resistance can be reduced by up to 58.83% and 58.79%, respectively, which occurs when the input heat power is 25 W. This implies that in the case of a lower heat source, a gravity heat pipe with AAO nanostructure generated on condenser section inner surface can better exert its performance.

|                         | $Q_{in} = 25 \text{ W}$ | $Q_{in} = 50 \text{ W}$ | $Q_{in} = 75 \text{ W}$ | $Q_{in} = 100 \text{ W}$ |
|-------------------------|-------------------------|-------------------------|-------------------------|--------------------------|
| T1 (°C)                 | 26.6                    | 34.5                    | 37.7                    | 42.1                     |
| T2 (°C)                 | 27.6                    | 35.2                    | 38.7                    | 42.2                     |
| T3 (°C)                 | 27.9                    | 35.4                    | 39.5                    | 42.8                     |
| T4 (°C)                 | 36.5                    | 42.7                    | 47.7                    | 51.5                     |
| T5 (°C)                 | 37.6                    | 43.3                    | 48.2                    | 52.4                     |
| T6 (°C)                 | 38.1                    | 44.3                    | 48.3                    | 52.7                     |
| T7 (°C)                 | 57.7                    | 64.6                    | 69.0                    | 84.3                     |
| T8 (°C)                 | 58.0                    | 65.3                    | 75.2                    | 84.5                     |
| T9 (°C)                 | 58.5                    | 65.6                    | 77.2                    | 85.6                     |
| $\overline{T}_{c}$ (°C) | 27.37                   | 35.03                   | 38.63                   | 42.37                    |
| $\overline{T}_e$ (°C)   | 58.07                   | 65.17                   | 73.80                   | 84.80                    |
| <i>R</i> (°C/W)         | 1.228                   | 0.603                   | 0.469                   | 0.424                    |

Table 1. Experimental data of the heat pipe without anodic oxidation treatment.

Table 2. Experimental data of the heat pipe after anodic oxidation treatment (50 V and 9 h).

|                         | $Q_{in} = 25 \text{ W}$ | $Q_{in} = 50 \text{ W}$ | $Q_{in} = 75 \text{ W}$ | $Q_{in} = 100 \text{ W}$ |
|-------------------------|-------------------------|-------------------------|-------------------------|--------------------------|
| T1 (°C)                 | 33.9                    | 37.9                    | 45.0                    | 44.9                     |
| T2 (°C)                 | 34.2                    | 38.2                    | 45.2                    | 45.3                     |
| T3 (°C)                 | 34.3                    | 38.4                    | 45.3                    | 45.6                     |
| T4 (°C)                 | 43.6                    | 47.6                    | 51.3                    | 60.9                     |
| T5 (°C)                 | 43.7                    | 47.8                    | 51.5                    | 61.4                     |
| T6 (°C)                 | 43.9                    | 48.2                    | 51.8                    | 61.7                     |
| T7 (°C)                 | 46.5                    | 51.7                    | 66.2                    | 70.1                     |
| T8 (°C)                 | 46.8                    | 51.9                    | 66.8                    | 70.6                     |
| T9 (°C)                 | 47.0                    | 52.3                    | 67.3                    | 70.9                     |
| $\overline{T}_{c}$ (°C) | 34.13                   | 38.17                   | 45.17                   | 45.27                    |
| $\overline{T}_{e}$ (°C) | 46.77                   | 51.97                   | 66.77                   | 70.53                    |
| <i>R</i> (°C/W)         | 0.506                   | 0.276                   | 0.288                   | 0.253                    |

#### 3.3. Single and Combined AAO Nanostructured Inner Surfaces

With reference to the previous literature, there have been studies on how to use the anodized inner surface of the evaporator section of a gravity heat pipe to improve the heat transfer performance of the heat pipe. Therefore, in addition to the anodic oxidation treatment on the inner surface of the condenser section (single AAO nanostructured inner surface treatment), this study also further considered the anodic oxidation treatment on the inner surfaces of the condenser and evaporator sections (combined AAO nanostructured inner surface treatment) to investigate the degree of improvement in heat transfer performance. In Figure 8, the temperature distribution under an input heat power of 100 W is plotted for single and combined AAO nanostructured inner surfaces at an anodizing voltage of 50 V and a treatment time of 9 h. As shown in the figure, the temperatures of the evaporator section of the heat pipe after combined AAO nanostructured inner surface treatment is lower than those of the heat pipe after single AAO nanostructured inner surface treatment, which shows that the generation of AAO nanostructure both on the

inner surfaces of the condenser section and evaporator section can further reduce the heat source temperature. The reason is that the generation of AAO nanostructure on the inner surface of the evaporator section makes more tube holes on the surface, which leads to an increase in nucleation site effect and then promotes boiling heat transfer, thereby improving the overall heat transfer performance of the heat pipe. Further analysis of the present experimental data shows that compared with the heat pipe after single AAO nanostructured inner surface treatment, the temperature difference between the average temperature of the evaporator section and the average temperature of the condenser section and the overall thermal resistance for the heat pipe after combined AAO nanostructured inner surface treatment can be further reduced by up to 13.70% and 13.83%, respectively. Figure 9 shows the case of combined AAO nanostructured inner surface treatment with the further reduction in the overall thermal resistance for different input heat powers at an anodizing voltage of 50 V and a treatment time of 9 h.



**Figure 8.** Temperature distributions of the heat pipes with single (condenser) and combined (evaporator + condenser) AAO nanostructured inner surfaces under an input heat power of 100 W at an anodizing voltage of 50 V and a treatment time of 9 h.



**Figure 9.** Variation of the overall thermal resistance with input heat power at an anodizing voltage of 50 V and a treatment time of 9 h.

### 4. Conclusions

Previous experimental studies have only investigated how to use the anodized inner surface of the evaporator section of a gravity heat pipe to improve its heat transfer performance. This study has been conducted to investigate the effect of anodic aluminum oxide (AAO) nanostructure generated on condenser section inner surface on the heat transfer performance of the heat pipe. An anodic oxidation treatment was performed to generate AAO nanotubes. The tube diameter can be enlarged by increasing the anodizing voltage, and the tube length can be extended by increasing the treatment time. The focus of this study is on the temperature distribution and overall thermal resistance under different anodizing voltages (20 V to 50 V) and treatment times (3 h to 9 h) for specific input heating powers (25 W, 50 W, 75 W, and 100 W). The experimental results obtained are as follows:

- 1. The larger the anodizing voltage, the larger the tube diameter of the resulting nanotubes and the better the hydrophobicity, thereby reducing the temperature variation in the heat pipe and the overall thermal resistance of the heat pipe.
- 2. The longer the treatment time, the longer the tube length of the resulting nanotubes and the larger the specific surface area, thereby reducing the temperature variation in the heat pipe and the overall thermal resistance of the heat pipe.
- 3. In the case of a lower heat source, a gravity heat pipe with AAO nanostructure generated on condenser section inner surface can better exert its performance. Compared with the unprocessed heat pipe, the temperature difference between the average temperature of the evaporator section and the average temperature of the condenser section and the overall thermal resistance can be reduced by up to 58.83% and 58.79%, respectively.
- 4. The generation of AAO nanostructure both on the inner surfaces of the condenser section and evaporator section can further reduce the temperature variation in the eat pipe and the overall thermal resistance of the heat pipe by 13.70% and 13.83%, respectively.

It can then be concluded that the generation of AAO nanostructure on the inner surface of the condenser section of a gravity heat pipe can effectively improve its overall heat transfer performance.

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