Thermodynamic Process Simulation and Evaluation on Surface-Mounted Evaporative Cooling System

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Abstract. The change of exergy has a direct impact on the circulation head of the surface-mounted evaporative cooling system that relies on the change of vapor-liquid density for circulating cooling. In this paper, the circulation system of the surface-mounted evaporative cooling system is taken as the research object. Based on the second law of thermodynamics, an exergy analysis model of main equipment is established to analyze and evaluate the characteristics of exergy change of the system. The research results show that under different thermal loads, the exergy efficiency is less than 70%, the exergy loss in the liquid box is relatively large, and the main irreversible exergy loss in liquid box occurs in the vapor-liquid boiling process, which will restrict the cooling capacity of the system. This study provides a theoretical basis for further optimizing the flow heat transfer process of the surface-mounted evaporative cooling system.

Keywords: surface-mounted; boiling heat transfer; thermodynamic process; exergy loss;

1. Introduction

With the continuous advancement of science and technology, the miniaturization of electronic devices has become the mainstream trend in the development of electronic equipment and the heat flux of some electronic devices has reached the range of \(10^2-10^3\) W/cm\(^2\) [1]. The traditional air-cooled heat dissipation method can no longer meet the heat dissipation requirements of electronic equipment. Problems such as overheating of electronic equipment, reduced reliability, and even shortened lifespan have occurred frequently, and heat dissipation has become a bottleneck restricting its development. The surface-mount evaporative cooling technology is a passive boiling transfer technology with the advantages of self-circulation, no power consumption, self-adaption, and maintenance-free, and has been gradually applied to the cooling of electronic equipment [2-4].

Considerable researches have studied the thermodynamic of the cooling system from the aspects of exergy, rate of entropy generation. Wang et al. analyzed the effect of fin geometry and flow rate on exergy loss in heat exchanger based on the numerical method and found the exergy loss was always equal to 23.4% of the heat transfer rate [5]. Dizaji et al. investigated the effects of flow, thermodynamic and geometrical characteristics on exergy loss in the shell and coiled tubes heat exchangers experimentally and the result showed that exergy loss increases with the increased flow rate [6]. Bagheri et al. used comprehensive exergy-based analyses to study on a refrigeration cycle. It was found that the endogenous part of the exergy destruction is much larger than the exogenous part [7]. Bejan analyzed the entropy production during convective heat transfer and studied how to select the flow structure parameters to minimize the entropy production of the system [8]. Christian et al.
analyzed the entropy production of the boiling two-phase flow process in the evaporator and condenser. Studies have shown that when the heat transfer and the entropy yield caused by the flow are the same, it is not necessarily the best flow heat exchange system [9]. Bilicki et al. based on the second law, established the entropy yield model of a two-phase flow heat transfer process, which can quantitatively analyze the irreversible loss in the two-phase flow process [10]. Dong et al. used the second law of thermodynamics to evaluate the evaporative cooling system in the stator windings of turbo-generators. The results show that the irreversible loss of the system is affected by various factors such as heat exchange temperature difference and two-phase flow [11].

As shown in the literature review above, much attention has been paid to exergy loss of entropy production in circular pipes based on forced circulation which is limited to specific conditions. There is still little research on surface-mounted self-circulation evaporative cooling systems with large aspect ratios. So there is an urgent need to analyze the boiling flow thermosyphon process based on the second law of thermodynamics method. This article establishes the entropy production and exergy flow analysis models of the surface-mounted evaporative cooling system and quantitatively analyzes the factors that affect the exergy flow of each part. It provides a theoretical basis for further optimizing the boiling flow thermosyphon cycle process of the surface-mounted evaporative cooling system.

2. Mathematical Model

The surface-mounted evaporative cooling system is shown in figure 1, which is designed for the cooling of electronic equipment. The whole loop mainly includes four main parts: liquid box, condenser, riser, and downcomer. When the coolant is heated to become vapor-liquid mixture in the liquid box, the coolant begins to circulate due to the driving head caused by the difference in density between the riser and downcomer. The vapor-liquid mixture flows up through riser to the condenser, where condense into liquid. The liquid coolant return to the liquid box through a downcomer for the next cooling circulation. This boiling flow thermosyphon process is a passive heat transfer system without pump. Detailed structural dimension parameters of the system are found in the published literature 12.

2.1. Liquid Box

The liquid box is the main cooling device in the surface-mounted evaporative cooling system, which is a square structure with one-sided heating, as shown in Figure 3. Depending on the thermal load of the liquid box, the coolant state of the liquid box outlet may be unsaturated, saturated, or superheated. The
exergy loss of the thermal process mainly comes from preheating, boiling, superheating, and flow resistance. The exergy flow calculation process of the liquid box is as follows:

**Figure 3.** Physical model diagram of the liquid box.

Length of preheating:

\[ l_1 = \frac{m(h_3 - h_2)(l_1 + l_2 + l_3)}{Q} \]  

(1)

Entropy change production of preheating:

\[ S_{2:1} = c_v \ln \left( \frac{T_1}{T_{\text{in}}} \right) + \frac{\Delta p_{2:1}}{\rho_0 T_1} \]  

(2)

Exergy flow of preheating:

\[ E_{2:1} = h_2 - h_1 - T_0 S_{2:1} \]  

(3)

Length of boiling:

\[ l_2 = \frac{m(h_3 - h_2)(l_1 + l_2 + l_3)}{Q} \]  

(4)

Entropy change production of boiling:

\[ S_{3:2} = s T \ln \left( \frac{T_2}{T_{\text{in}}} \right) + \frac{\Delta p_{3:2}}{\rho_0 T_2} \]  

(5)

Exergy flow of boiling:

\[ E_{2:1} = h_1 - h_2 - T_0 S_{3:2} \]  

(6)

Length of superheating:

\[ l_3 = l - l_2 - l_1 \]  

(7)

The entropy change of superheating:

\[ S_{4:3} = c_p \ln \left( \frac{T_{\text{out}}}{T_3} \right) + R \ln \left( \frac{P_4}{P_3} \right) \]  

(8)

Exergy flow of superheating:

\[ E_{4:3} = h_4 - h_3 - T_0 S_{4:3} \]  

(9)
2.2. Condenser

In this system, the condenser is a tube and shell type, where the vapor-liquid mixture condenses into liquid on the shell side, releasing heat to the cooling water. The condensation process is an isothermal heat release process, and the pressure loss only considers the local resistance of the inlet and outlet. The calculation process is as follows.

\[
S_{x=0} = \frac{Y}{T_s} + \frac{\Delta \tilde{h}}{\rho \tilde{T}_s} \quad (10)
\]

\[
E_{s=0} = h_0 - h_s - T_0 S_{s=0} \quad (11)
\]

Where \( m \) is mass velocity; \( p \) is pressure; \( h \) is enthalpy; \( s \) is entropy; \( Q \) is heat flux; \( T_0 \) is environment temperature; \( E \) is exergy; \( c_p \) is specific heat capacity; \( T \) is temperature; \( x \) is vapor quality; \( Y \) is the heat of vaporization; \( \rho \) is density; subscripts in is inlet; out is outlet, \( s \) is saturated.

3. Results Discussion

To verify the correctness of the simulation model, simulation results were compared qualitatively with experimental results in the published literature [4], where the error was represented as the standard deviation. The system thermal load varies from 200 to 800W and the operating pressure of the condenser is maintained at about 10kPa. The standard deviation of parameters such as wall temperature and mass velocity are listed in figure 4 and figure 5. The average deviation of the wall temperature is only 2.49% with a maximum deviation of 4.21% in the figure 4. Meanwhile, the average deviation of the mass velocity is only 6.54% with a maximum deviation of 12.74% in the figure 5. It can be seen that the simulation model has a high degree of accuracy and can be used to evaluate and analyze the thermodynamic circulation of the system.

\[ \text{Figure 4. The standard deviation of wall temperature under different thermal loads.} \]

\[ \text{Figure 5. The standard deviation of mass velocity under different thermal loads.} \]

As can be seen from figure 6, the temperature of the wall is stable with an increasing trend, while the mass flow rate is gradually decreasing. This indicates that on the one hand, the boiling heat transfer is large, which keeps the wall temperature stable. On the other hand, the increase in the number of bubbles generated leads to a rapid increase in system flow resistance, which means that there is insufficient cyclic power in the system and the circulating power has become an important factor restricting the cooling capacity of the liquid box. The model better reflects the characteristics of temperature uniformity and self-circulation of the surface-mounted evaporative cooling system.
Figure 6. The trend of wall temperature and mass velocity under different thermal loads.

Figure 7. Comparison of thermal efficiency and exergy efficiency.

Figure 7 shows a comparison of the thermal efficiency and exergy efficiency in liquid box. It can be seen that the thermal efficiency is maintained at more than 90%, while exergy efficiency is less than 70%. This shows that although the system can take away most of the heat, the exergy flow obtained by the coolant is low, which indicates that the irreversible loss caused by heat transfer in the system is high. It is necessary to further improve the exergy value of the coolant to improve the cooling capacity of the system.

Meanwhile, figure 8 shows the exergy loss of the main equipment in the surface-mount evaporative cooling system. As the thermal loads increases, the exergy loss in the riser and downcomer is very small compared to the exergy loss in the liquid box and condenser. The exergy loss in the liquid box and condenser is gradually increasing with the increase of thermal load. The exergy loss in the condenser is mainly the exergy gained from the coolant circulation, which is necessary to promote the system circulation process. The exergy loss in the liquid box is mainly caused by irreversible heat transfer, which is the key factor to improve the exergy efficiency and cyclic head of the system. Therefore, it is necessary to further optimize the flow heat transfer process in the liquid box for improving the cooling capacity of the system.

Figure 8. Exergy loss comparison of the main equipment.

Figure 9. Comparison of entropy production of each process in the liquid box.

To further analyze the flow heat transfer process in the liquid box. The entropy change and exergy loss in the liquid box are analyzed respectively. Figure 9 is showing the changing trend of entropy increase in each process in the liquid box. The entropy production in preheating remains unchanged showing a decreasing trend. When the thermal load exceeds 600W, the entropy production in the superheating begins to increase continuously. The entropy production of boiling increases rapidly and
finally stabilizes, which is consistent with the boiling process of the coolant in the liquid box. The change of entropy production indirectly indicates the change of exergy loss in the liquid box.

The exergy loss changes of the main heat transfer process in the liquid box are shown in figure 10. As the thermal load increases, exergy loss in preheating presents the gradual decline trend while exergy loss in boiling shows a gradually increasing trend. When the thermal load exceeds 600w, the exergy loss in the superheating increases rapidly. It can be seen from the comparison of exergy loss of each flow heat transfer process in the liquid box that the main exergy loss is the vapor-liquid boiling process. The exergy loss of the boiling can be reduced by increasing the coolant boiling temperature. Besides, the superheating of coolant should be avoided as much as possible to prevent exergy loss caused.

![Figure 10](image)

**Figure 10.** Comparison of exergy loss of each process in the liquid box.

With the increase of the coolant boiling heat transfer in liquid box, the obtained exergy flow increases, a large number of bubbles are generated, the system flows friction resistance increases rapidly, and the vapor phase has occupied the main share of friction resistance, resulting in which leads to a further increase flow exergy loss in the system as shown in figure 11. This indicates that the exergy loss caused by the increase of circulation friction of the system exceeds the exergy flow obtained by the coolant, resulting in a further increase in the required exergy flow, and its growth rate exceeds the exergy flow taken away by the coolant. The way to reduce the frictional resistance in the liquid box can increase the exergy flow carried away by the coolant for improving the system cooling capacity further.

![Figure 11](image)

**Figure 11.** Comparison between the exergy flow carried away by coolant and the frictional resistance of the system.

4. Conclusion

In this paper, based on the boiling heat transfer and two-phase flow process in the surface-mounted evaporative cooling system, the entropy production and exergy loss models are established. Through the analysis of exergic and entropy under different thermal loads, the calculated results show that the
thermal efficiency exceeds 90%, exergic efficiency is still within 70%, which indicates there is room for further optimization of the system. Comparing the exergy loss of the main equipment in the system, the main exergy loss is in the liquid box and the condenser, and the exergy loss in the liquid box is the direct factor that restricts the exergy efficiency. Further analysis of the exergy loss in the liquid box, the main irreversible loss occurs in the vapor-liquid boiling process. Besides, the irreversible loss increases rapidly when the superheating appears in the liquid box.

References
[1] Mudawar I 2000 Assessment of high-heat-flux thermal management schemes in ITHERM 2000. Proceeding of The Seventh Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems (Cat. No.00CH37069) 1: 1-20.
[2] Gu G B and Ruan L 2014 Application and development of evaporative cooling technology in the field of hydroelectric generators Proceedings of the Chinese Society for Electrical Engineering 34(29): 5112-5119.
[3] Cao R Ruan L and Xu Y S 2019 Study on key components of evaporative cooling system of converter valve Journal of Engineering Thermophysics 40(10): 2373-2376.
[4] Shi Y T Cao R and Ruan L 2020 Experimental study on boiling heat transfer and flow of surface-mounted internal rib array self-circulating evaporative cooling system Proceedings of the Chinese Society for Electrical Engineering 40(06): 1997-2006.
[5] Juanping W Saeed H Saeideh A Mhosen M Mehti S and Ashkan A 2018 Analysis of Exergy and energy in shell and helically coiled finned tube heat exchangers and design optimization International Journal of Refrigeration 94: S0140700718302780-.
[6] Sadighi Dizaji H Jafarnadar S and Hashemian M 2015 The effect of flow, thermodynamic and geometrical characteristics on exergy loss in shell and coiled tube heat exchangers Energy 91: 678-684.
[7] Safarnezhad Bagheri B Shirmohammadi R Seyed Mahmoudi S M and Rosen M A 2019 Optimization and comprehensive exergy-based analyses of a parallel flow double-effect water-lithium bromide absorption refrigeration system Applied Thermal Engineering 152: 643-653.
[8] Bejan A 1948 Entropy generation through heat and fluid flow Journal of Applied Mechanics 50(2): 475.
[9] Hermes and Christian J L 2013 Thermodynamic design of condensers and evaporators: formulation and applications International Journal of Refrigeration 36(2): 633–640.
[10] Bilicki Z Giot M and Kwizdinski R 2002 Fundamentals of two-phase flow by the method of irreversible thermodynamics International Journal of Multiphase Flow 28(12): 1983-2005.
[11] Dong H H and Gu G B 2008 Research on the thermodynamic processes and performance evaluation of the evaporative cooling system in the turbine generator Proceedings of the Chinese Society for Electrical Engineering 28(20): 137-141.