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EXPERIMENTAL STUDY ON TWO-PHASE LIQUID-IMMERSION COOLING SYSTEM FOR DATA CENTER

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ABSTRACT

In this study, a two-phase liquid-immersion cooling system was developed for ICT (Information communication technology equipment) cooling. The PUE energy efficiency of the two-phase cooling system was evaluated under various IT loads, and the annual PUE was calculated dependent on the meteorological parameters in Shanghai. Then, exergy analysis of the two-phase cooling system was taken based on the second law of thermodynamics. The observations and conclusions in this study can be valuable references for the study of cooling systems in data centers.

Keywords: Two-phase, Air cooling, Data center, Exergy efficiency, Immersion, PUE

NONMENCLATURE

Abbreviations	
PUE	Power usage effectiveness
ICT	Information communication technology
VLSI	Very large scale integration
Symbols	
Q	Heat exchange (W)
η	Exergy efficiency
T	Temperature (K)
P	Power(W)
dex	Input exergy(J)
δex	Exergy loss (J)
δq	Quantity of heat(W)

1. INTRODUCTION

With the development of digital technologies (e.g., IoT, artificial intelligence, big data, 5G, cloud computation), the demand for data center construction is growing rapidly, and massive amounts of servers are generating tremendous energy consumption. As of the end of the third quarter of 2019, there were 504 hyperscale data centers worldwide, and the data centers are expected to grow at an annual rate of 12-14% over the next five years[1]. Data centers typically consume large amounts of energy, the energy consumption of the data centers in the United States takes approximately 1.8% of the total electricity in the USA in 2014[2]. In the United Kingdom, the energy consumption of the data centers accounted for 1.5% of electricity consumption in 2016[3]. In China, data centers consumed 160.8 billion kWh of electricity in 2018, an annual growth rate of more than 12%, which is more than the total electricity consumption of Shanghai, and data centers accounted for about 2% of the total electricity consumption in China[4]. On the other hand, the server heat flow density brought about by VLSI (Very Large Scale Integration) technology is also increasing, with the local heat flow density on the surface of the chip much higher than 100 W/cm^2 and up to 1000 W/cm^2[5]. Conventional air-cooled heat exchanger system has been unable to meet the cooling needs of high heat density servers and seriously affect the performance and service life of electronic components. Statistics show that more than 55% of chip failures are caused by high temperature[4].

The two-phase liquid-immersion cooling system is a novel technology for ICT cooling. Comparing with the air cooling system that server is cooled by air, the ICT equipment is completely submerged in the dielectric liquid bath， which has no compressor that takes an amount of energy. Therefore, the two-phase liquid-immersion cooling system was more efficient than the

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air cooling systems. In this study, an innovative cooling structure and procedure for a two-phase liquid-immersion cooling system were developed, and the thermal management performance of the system was evaluated by exergy analysis. The study seeks to provide valuable data collected from the two-phase cooling system, with the results and conclusions serving as valuable references for researchers and engineers.

2. METHODOLOGY

2.1 Experiment instrument and measurements

A novel, innovative cooling structure, and procedure of a two-phase liquid-immersion cooling system was developed to study the thermal management performance of the phase change liquid cooling system for the submerged server cooling. It consists of a tank contained coolant with server boards, an external cooling system, and data collection system, and the scheme of the two-phase cooling system was shown in Fig. 1. Figure 2 is the corresponding system diagram, the main instruments, and equipment including server motherboard, pumps, fans, temperature sensors, manometers, power meters, etc. The server board of the server is submerged in Novec7100 electronic fluoride solution which was supplied by 3M company.

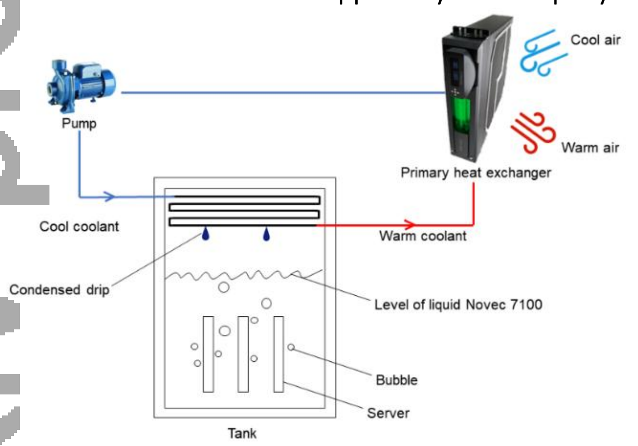

Fig. 1 Scheme of the two-phase liquid-immersion cooling system

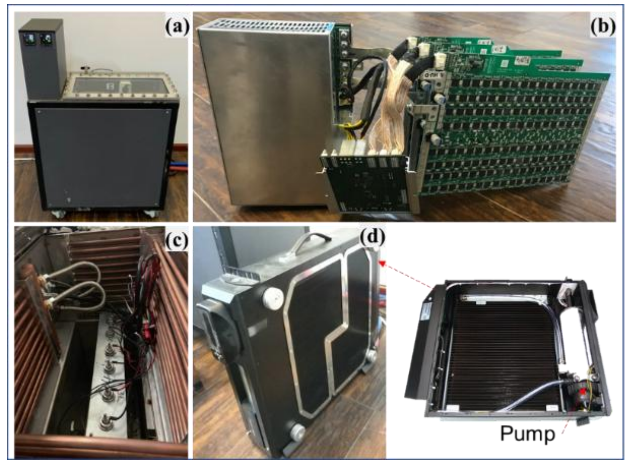

Fig 2 Two-phase liquid-immersion cooling system：(a) The tank (b) Servers (c) Condenser coil (d) Primary heat exchanger

The size of the tank was 650 × 450 × 1050 mm^3 (length × width × height), and three server boards (ASIC T2T-25T) that contained 140 T2T CPUs were ranged in the middle of the tank as Fig. 2(b) showed. The parameters of the motherboard were displayed in Table 1.

Table 1 The parameters of the motherboard

Size of the sever boards (mm)	Number of the CPU	Size of CPU (mm)	Hashrate (TH/S)	Power of motherboard (W)	Average heat flow (W/cm²)
235×182	140	8×8	23±5%	750	8.37

The heat from the coolant was removed by a heat exchanger (ERM-3K3UC Liquid Cooling System) as Fig. 2(d) showed. The cooling system contains a fan, a water pump, and a brass radiator (9×120mm), without a compressor. The power of the server board was controlled by loading a computing program to change the server's operation mode, which affects the output power of the server's main board.

Table 2 Operating conditions and experimental results

Mode	Power of the external cooling system and the motherboard (W)		Temperature of the CPU (℃)		Heat exchanger coolant temperature (℃)		PUE
	External cooling system	Mother board	Core	Surface	Inlet	Outlet	
efficiency	73.2	1130.3	67.1	65.6	29.0	29.9	1.065
efficiency+	73.3	1187.5	67.2	64.4	28.9	29.8	1.062
efficieny++	73.1	1193.2	67.2	64.2	28.8	29.6	1.061
balance--	73.3	1213.7	70.6	68.3	29.5	30.4	1.060
blance-	73.2	1251.4	71.5	68.6	29.3	30.4	1.058
blance	73.2	1299.6	70.4	67.2	30.2	31.5	1.056
blance++	73.3	1300.9	70.6	69.3	30.2	31.5	1.056
factory-	73.4	1462.5	72.8	70.2	30.9	32.3	1.050
factory+	73.4	1462.1	72.7	70.3	31.0	32.4	1.050
performance--	73.4	1529.0	73.3	71.8	31.2	32.8	1.048
Performance	73.4	1531.6	73.5	70.1	31.8	33.3	1.048

2.2 Energy efficiency evaluation of the system

Power usage effectiveness (PUE) is an industry-preferred index for evaluating the infrastructure energy efficiency of data centers[6]. When the PUE value close to 1.0, that's means the data center has optimal energy efficiency. In the experiment, the temperature and the power were tested by the thermocouples and power monitoring equipment, respectively. Then the PUE value was calculated by *Eqs. (1)*.

$$PUE = \frac{P_{fan} + P_{pump} + P_{IT}}{P_{IT}} \qquad (1)$$

Where P_{fan}, P_{pump} and P_{IT} is the power of the server, pump, and IT equipment, respectively.

The annual *PUE* of the system was calculated by *Eqs. (2)*

$$PUE_{an} = \sum PUE_i \times \frac{n_i}{8760} \qquad (2)$$

Where PUE_i is the instantaneous *PUE* under the weather at that time; n_i represents the number of the hour in the full-year.

2.3 Exergy snalysis

For any reversible process, the total amount of exergy remains constant. For an irreversible process, the exergy will shift to useless energy inevitably, and reduce the total amount of exergy, which is called exergy loss of the irreversible process. In this study, the exergy balance equation was established according to the exergy loss mechanism of the system, and then the exergy analysis of the system was carried out. The liquid submerged two-phase cooling system was taken as an open-ended system, and the exergy flow was displayed in Fig. 3.

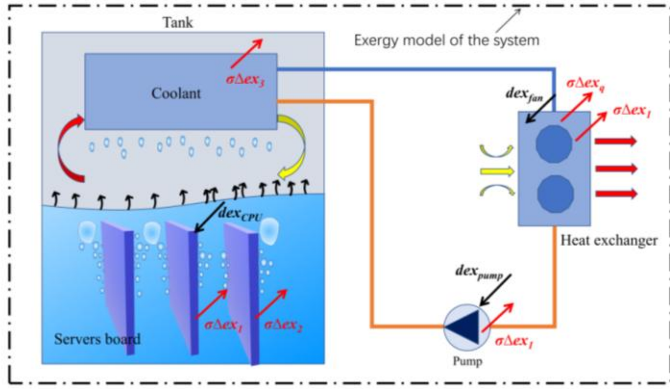

Fig 3 Exergy flow of the two-phase cooling system

The electric energy obtained from the system can be converted into exergy value. Some of these exergy quantities were converted to internal losses, and the other part was dispersed into the environment by the external heat exchanger. The exergy equation was displayed in *Eqs. (3)*:

$$dex_{fan} + dex_{pump} + dex_{CPU} = \delta ex_{loss} + \delta ex_q \qquad (3)$$

where dex_{fan} is the exergy of fan; dex_{pump} is the exergy of the pump; dex_{CPU} is the exergy of CPU; δex_q is the dissipation of the system exergy as the *Eqs. (4)* showed.

$$\delta ex_q = \delta W_{\max} = \left(1 - \frac{T_0}{T}\right)\delta q \qquad (4)$$

There was no energy dissipation in the system except the external heat exchanger, and all the electric energy was converted into heat without any other dissipation. δex_{loss} was defined as the *Eqs. (5)* showed.

$$\delta ex_{loss} = \delta\Delta ex_1 + \delta\Delta ex_2 + \delta\Delta ex_3 \qquad (5)$$

where $\delta\Delta ex_1$ is the exergy loss from the fan, pump and the heat converted from the CPU; $\delta\Delta ex_2$ is the exergy loss from the heat transfer between the CPU and the coolant; $\delta\Delta ex_3$ is the heat transfer exergy loss from the coolant (tank side) and the cooling water (heat exchanger side).

For the exergy loss $\delta\Delta ex_1$, when the electric energy was converted to heat, part of the electric exergy became the exergy loss, and the other part became the exergy value from the electric energy converted to heat, as the *Eqs. (6)* displayed.

$$dex_{fan} + dex_{pump} + dex_{CPU} = \delta\Delta ex_1 + \sum\left(1 - \frac{T_0}{T}\right)\delta q \qquad (6)$$

For the exergy loss $\delta\Delta ex_2$ from the heat transfer between the CPU and the coolant, some of the heat exergy input by CPU became exergy loss, and the other part became the increment of exergy value of the coolant(mineral oil), as the *Eqs. (7)* showed.

$$dex_{CPU} = \delta\Delta ex_2 + \delta ex_{out,oil} - \delta ex_{in,oil} \quad (7)$$

The exergy value of the liquid at the inlet and outlet can be obtained by the *Eqs. (8)- (9):*

$$Ex_{in,oil} = c_{oil}\left(T_{in,oil} - T_0\right) - c_{oil}T_0 \ln\frac{T_{in,oil}}{T_0} + T_0 R_v \ln\frac{P_{v,0,b}}{P_{v,0}} \quad (8)$$

$$Ex_{out,oil} = c_{oil}\left(T_{out,oil} - T_0\right) - c_{oil}T_0 \ln\frac{T_{out,oil}}{T_0} + T_0 R_v \ln\frac{P_{v,0,b}}{P_{v,0}} \quad (9)$$

For the heat transfer exergy loss $\delta\Delta ex_3$ between the coolant (tank side) and the cooling water (external exchanger side), the exergy of inlet liquid steam of the cooling water and the cooling water became the exergy and exergy loss of the outlet liquid and cooling water of the external heat exchanger. The equation was described as the *Eqs. (10):*

$$\delta\Delta ex_3 = \delta ex_{in,oil} + \delta ex_{in,water} - \delta ex_{out,oil} - \delta ex_{out,water} \quad (10)$$

Here, the exergy efficiency η was defined as the ratio of profit exergy to expenditure exergy. For the exergy efficiency of the coolant, the η is the ratio of the output heat exergy of the coolant to input electric energy exergy.

$$\eta = \frac{\left(1 - \frac{T_0}{T}\right)\delta q}{dex_{fan} + dex_{pump} + dex_{CPU}} \quad (11)$$

Similarly, the energy equation of the system was given by *Eqs. (12)*.The system input energy is electric energy. Because the system does not exist heat dissipation except the condenser, all the electric energy converted to heat and dissipated to the environment by the heat exchanger.

$$den_{fan} + den_{pump} + den_{CPU} = \delta Q \quad (12)$$

where den_{fan}, den_{pump} and den_{CUP} are the energy consumption of fan, pump, and CPU, respectively.

From the energy equation, when the input electric energy is all transformed into heat, the utilization rate of the electric energy is 100%. However, for the exergy equation, exergy loss is large under this condition. Therefore, it is not comprehensive to analyze thermodynamic problems only dependent on the energy equation, and it is more accurate to analyze energy loss from the perspective of exergy loss. The exergy analysis is to obtain the maximum exergy efficiency and find out the exergy loss, to realize the maximum utilization of energy, and optimize the main dissipation points.

3. RESULTS AND DISCUSSION

3.1 PUE analysis

Figure 4 showed the PUE and inlet/outlet water temperature variation under different IT load. It shows that the temperature difference between the inlet and outlet water of the cooling water increased with the increase of the IT load. However, the PUE of the system was decreased. The average PUE of the system was 1.055. Based on the stable operation of the system, the temperature of the environment was varied according to the outdoor air temperature variation in Shanghai. The annual PUE energy consumption was calculated based on the weight of outdoor temperature distribution, and the results were displayed in Table 3.

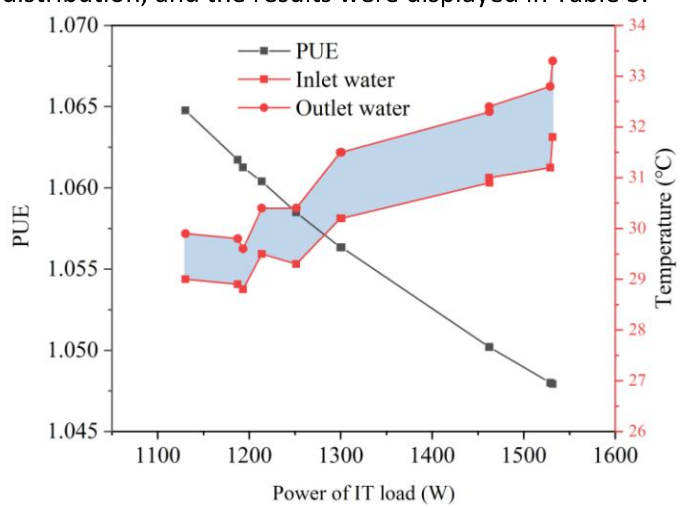

Fig 4 PUE and inlet/outlet water temperature variation under different IT load

Table 3 Annual PUE of the system under different temperature rangs in Shanghai

Experimental setting value (℃)	10	15	20	25	30	33	36	39
Tempertaure range	Below 10	10-15	15-20	20-25	25-30	30-33	33-36	36-39
Hours	2351	1185	1298	1711	1572	404	206	33
Instantaneous PUE	1.058	1.059	1.060	1.058	1.065	1.057	1.057	1.056

From Table 3, the annual PUE of the two-phase liquid-immersion cooling system under the Shanghai climate decreased to 1.184, which was much lower than that of the air cooling system (1.786)[7], and the degree of reduction reached to 33.7%. In addition, the energy efficiency of refrigeration increases with the increase of IT load and load rate, which made the actual annual PUE lower than that of the air-cooling system. Due to the two-phase liquid-immersion cooling system uses the high-temperature liquid to dissipate from the IT equipment, and it does not need the air conditioning refrigerator to carry the heat from the server room to outdoor, the efficiency of the system was improved greatly. The refrigeration energy consumption decreased from 34 % to 6 %, the reduction amplitude up to 82.4 %, as shown in Fig. 5.

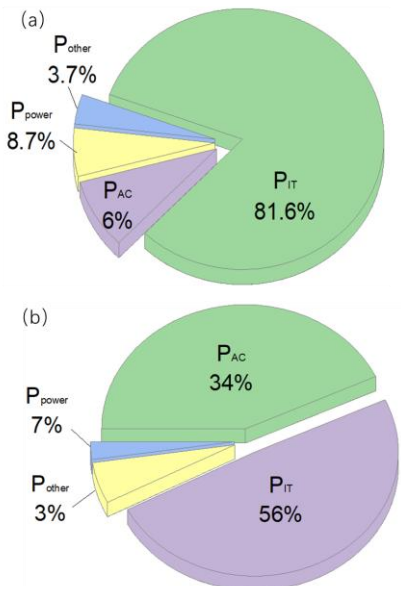

Fig 5 Energy consumption distribution of (a) The two-phase cooling system (b) Air cooling system [7]

Kanbur et al.[8] studied the cooling system of two-phase liquid-immersion data center by experimental and thermal economic analysis. They found that when the IT load was at the maximum or minimum value, the PUE reached the highest value of 1.15 and 1.4, respectively. The most studies focus on the instantaneous PUE, and without considering the meteorological characteristics of the whole year. The PUE given in this study was based on the meteorological parameters of Shanghai, therefore the annual PUE was more significant.

3.2 *Exergy snalysis*

Table 4 lists the partial exergy losses in the exergy balance equation of the two-phase liquid-immersion cooling system. Figure 6 shows the exergy efficiency of the cooling system under experimental conditions, ranging from 12.65% to 18.96%, with an average of 14.84%. Kanbur et al.[8] also analyzed the exergy efficiency of the liquid cooling system. The lowest exergy efficiency in there study is about 7% lower than that of our study. The difference may be due to the difference in operating temperature. The operating temperature of Kanbur is 3-5 °C higher, and the working temperature will affect the heat transfer of the system, thus affecting the exergy efficiency of the system. DíAZ[9] calculated the exergy efficiency of a typical air cooling system in a data center. The upper limit of exergy efficiency is about 12%, which is about 3% lower than the value in our study. Relatively small power input is one of the reasons for the improvement of exergy efficiency of the two-phase liquid-immersion cooling system. Comparing with air cooling system, the two-phase liquid-immersion cooling system involves less heat transfer processes, which also helps to reduce the exergy loss. Another advantage of the cooling system is that it can generate high-quality waste heat, which can be further used to improve the energy efficiency of the whole system. As the boiling point of the liquid is as high as 61 °C, it brings high-quality waste heat, which can be used for absorption refrigeration system or direct heating. In contrast, the typical air-cooling system of the data center has a hot channel temperature of 35 °C[10], which is lower than that of the two-phase liquid-immersion cooling system, so the further recycling of waste heat is limited.

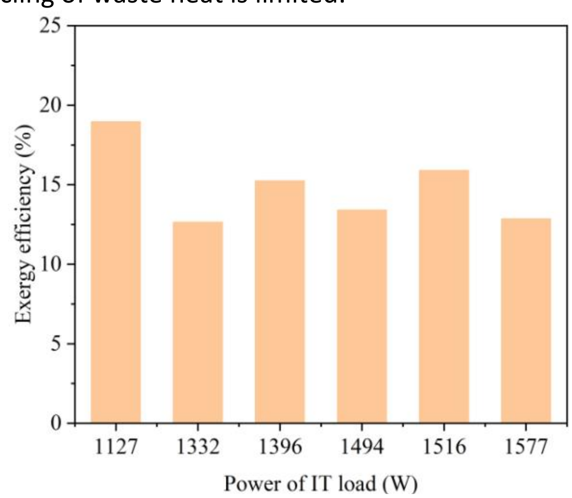

Fig 6 The exergy efficiency of the two-phase cooling system

Table 4 Partial exergy losses statistics of cooling system

	W_{server}	$E_{d,1}$ (W)	$E_{d,2}$ (W)	$E_{d,3}$ (W)	$E^{d,4}$ (W)
Case 1	1127	864.91	19.8	27.27	14.28
Case 2	1396	1092.95	19.54	74.99	45.64
Case 3	1332	1038.41	29.85	70.79	38.37
Case 4	1494	1163.08	37.61	45.91	60.92
Case 5	1516	1176.93	46.45	33.15	31.86
Case 6	1577	1190.93	56.82	107.42	33.01

4. *CONCLUSION*

In this study, a series of experiments were carried out to verify the reliability of the two-phase liquid-immersion cooling system. The energy efficiency of the system is obtained by analyzing the experimental data, and through the exergy analysis of the open-ended system, the thermodynamic exergy efficiency of the system is given. The conclusions of this study are as follows:

(1) The cooling PUE of the system can be lower than 1.048, and the PUE of the whole year is 1.184, which is significantly lower than that of the current air cooling data center, with a reducted rate of 33.7%. The refrigeration energy consumption is reduced from 34% to 6%, the reduction amplitude up to 82.4%. And with the increase of server power, the energy efficiency increases.

(2) The exergy efficiency of the system ranges from 12.65% to 18.96%, with an average of 14.84%, which is relatively higher than that of the conventional air cooling data center. One of the main reasons for the efficiency improvement of the two-phase liquid-immersion cooling system is that there is no need to use chiller for cooling, less CPU fan power consumption, and other factors. Reduce the energy consumption of the system, which is the main reason for efficiency improvement.

(3) It can be seen from the partial exergy analysis of the system that most of the exergy loss of the two-phase liquid-immersion cooling system occurs at the tank side. For a certain cooling system, we only need a few parameters such as temperature and flow rate to achieve the current maximum exergy efficiency. However, for the design of the cooling system, we need to consider all the parameters that may affect the system, which is a major difficulty in exergy efficiency analysis.

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