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Design and performance analysis of bubble pump with water-based multi lifting tubes

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ABSTRACT

Designing any refrigeration system is critical because it should be more efficient than the previous designs. In this article, a bubble pump which is an essential equipment of an integrated cooling system, has been designed. The design conditions were assumed that a hot surface released different amounts of heat 550 W and 1500 W is to be cooled and maintain the temperature under the desirable limit. The experiments have been conducted under the atmospheric pressure used many configurations such as a different number of 8 mm diameter lifting tubes from one to four tubes and different submergence ratios 0.3, 0.4, and 0.5. The efficiency has been calculated, and at the last step, the conclusion has been extracted that the slug flow pattern could be noticed in the experiments as the desired flow type where the maximum mass flow rate is about 63 g/s at a configuration of four lifting tubes and the heat power is 1500 W. It was concluded that the performance was directly proportional to the submergence ratio and lifting tubes.

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1. INTRODUCTION

Heat removal in daily life plays a significant role in the industry and the electronic devices people use, such as computers and servers. This importance stems from its impact on production levels, product quality and the efficiency of these devices work. Rapid cooling is required in many daily uses; correspondingly, cooling systems such as bubble pumps are needed to provide this instant cooling effectively.

Bubble pumps generally consist of a single vertical lifting tube heated at the bottom with any heat source. Continuous heating produces vapour slugs that carry the liquid slugs of the mixture to a higher level. The advantage of the bubble pump is that there are no mechanical moving parts such as pumps. When the bottom of the bubble pump is exposed to heat, it converts the liquid into vapour due to evaporation. When the vapour bubbles go up, they carry some fluid with them. According to previous studies, there are four common flow types in the lifting tubes: bubbly, slug, churn, and annular [1-3].

Furthermore, the flow types evolve from bubbly to annular while raising the heat. The experimental results were compared with the analytical models of the bubble pump. The study aimed to find out the differences in the amount of mass flow rate resulting from the change of some variables such as the submergence ratio, the number of lifting tubes, and the amount of the heating power input to the generator in the bubble pump that uses the saturated water as the working fluid and working under the atmospheric pressure [4-6]. To reach the slug flow type, the consistency of the bubbles slug depends mainly on the input heat power in the experiment (the amount of heat dissipated by the pump) and the refrigerant boiling point [1, 3, 6] for the present work. It was nearly 99°C for water; ammonia or R134a as refrigerant could also be used. However, this study focused not on refrigerants but the submergence ratio and the multi-lifting tubes.

The performance of a bubble pump depends on the refrigerant–absorbent solution properties and the bubble pump parameters. Aman J. et al. [1] performed a dimensional analysis, considering bubble pump geometry and the solution properties. They concluded that the highest efficiency of the bubble pump as 79% was achieved at a high liquid Froude number at the beginning of the slug flow regime when the non-dimensional pressure was low. According to many previous works, the slug flow is the most efficient flow pattern in the airlift pump and the bubble pump, as they share the basic work principle to lift liquid via bubbles without mechanical parts [1]. However, the flow through the bubble pump's lifting tubes is much more complicated to analyse than the airlift pump because of the condensation of the steam bubble inside the lifting tubes away from the bottom due to heat loss in some cases, poor insulation of the lifting tubes. So

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each bubble pump needs to have its pumping cycle [2], which is the time required for the pump to form a bubble with enough buoyancy force to lift the liquid slugs. When condensation inside the lifting tubes happens, the bubble pulls down the water slugs to the bottom of the tubes, affecting the flow from reaching the steady-state flow. Benhmidene A. et al. [2] presented a numerical model developed to simulate steady-state refrigerant flow along a tube of a bubble pump by considering one-dimensional flow and the non-metastable flow was neglected and numerically examined the influence of the heat source on the flow characteristics

In this experimental study, the bubble pump performance was examined at two different heat sources as low and high, with 1-4 units lifting tubes and different submergence ratios of 0.3, 0.4, and 0.5 as in other previous works. A bubble pump cooling system is designed for typical local conditions to provide cooling for electrical appliances during operation, such as servers and electrical transformers. Assuming the X device, it should dissipate at least 550 W of power through the cooling system using water flow. The system relies on the bubble pump's concept, a rarely used device for cooling.

2. EXPERIMENTAL

The cooling load can be defined as the amount of heat energy that has to be removed from a given space. In the case of this system, the cooling load is the heat to be removed from the hot surface by conduction, and it was chosen to be 550 W and 1500 W, respectively.

2.1. The Path of the Coolant in the Cooling Cycle

The device withdraws the heat from hot surfaces by absorbing it, throwing the water, and releasing it as steam to the environment.

As the water enters the cooling cycle from the water supply network to the water reservoir at an ambient temperature of nearly 23°C, and then have to be heated to the saturated temperature at about 99°C, with the lowest cost and highest efficiency through designing an integrated cooling system in terms of bubble pump configurations. To ensure that the device is working smoothly and minimising human mistakes, the working lift tubes were designed using the most reliable material and an automatic control system, as shown in Figure 1.

2.2. The Bubble Pump Performance

The protocol of the process was by using the 550 W electric heater as a simulator of the hot surface to be cooled, by using the total number of the lifting tubes firstly and taking the readings of the mass flow rate by utilising a stopwatch along with measuring the weight of the hot water returning from the separator. The water reservoir by taking samples with a small bottle and measuring the weight in grams via an electronic balance, and to obtain a more precise reading, the process has been repeated five times. Then the average number has been taken as the required data. Furthermore, it is resetting the water level sensor location to obtain different submergence ratios for comparing the result using 0.3, 0.4, and 0.5 submergence ratios. The previous process has been repeated three times after removing one of the lifting tubes to measure the device's performance with less than four lifting tubes. To compare the results of the low energy, hot surface with higher energy, the 550 W electric heater has been replaced with a 1500 W electric heater, and the whole process has been repeated.

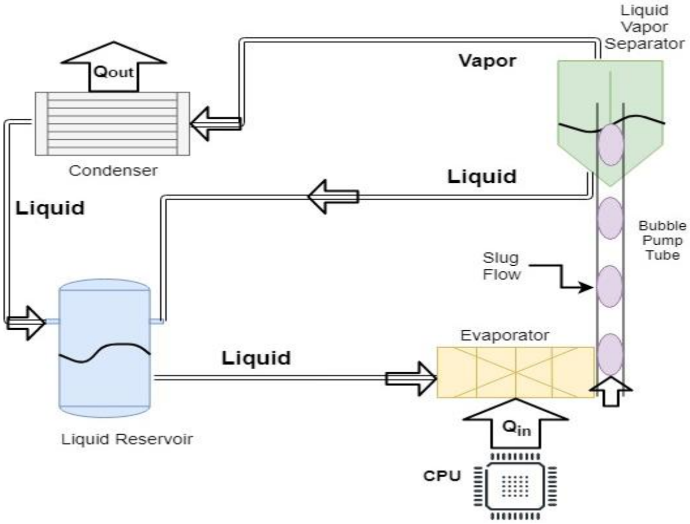

Fig. 1. Working principle of bubble pump to cool the hot surfaces.

3. RESULTS

The liquid mass flow rate as hot water returning from the separator to the water reservoir is determined by the submergence ratio, which is defined as the ratio of the height of the liquid inside the lifting tube (H) to the whole length of the lifting tube (L). The experiments were to use different submergence ratios from 0.3 to 0.5. Figure 2 shows liquid mass flow rate as a function submergence ratio in a different number of lifting tubes (N=1, 2, 3, and 4) with a diameter of 8 mm for two other heating power inputs, 550 and 1500 W.

According to the experiments, the bubble pump curves move upward when the submergence ratios increase. The mass flow rates are directly proportional to the submergence ratio at the same input heating power. The higher the submergence ratio, the higher (H), which means the liquid travels less distance to the separator. Besides, to achieve the same liquid mass flow rate value at high heating power, the submergence ratio and the number of lifting tubes at low input heating power must be increased. For example, the heating power required for liquid mass flow rates of about 18 g/s at a submergence ratio of 0.5 is about 1500 W with N=1 and 550 W with N=4, as shown in Figure 2.

To examine the effect of lifting tubes, experiments were carried out with lifting tube numbers, N= 1, 2, 3 and 4 as shown in Figure 2 and concluded that the performance curves have a similar trend. With the increase in the number of lifting tubes, the peak liquid mass flow rate occurs when the lifting tube number is N=4 because there is a regular heat dissipation under the generator. Nevertheless, according to the results, for the input heating power of 550 W at a submergence ratio of 0.4, when N=2. It can be noticed that the mass flow rate is slightly more than the mass flow rate of the same submergence ratio when N=3, for the same heating power, the highest performance value for N=4 is 18.7 g/s. The increase in the number of lifting tubes and the higher submergence ratio mean that lifting tubes have a different effect on performance, as shown in Figure 2. In the 550 W input heating power, the number of lifting tubes does not affect the pump's capacity.

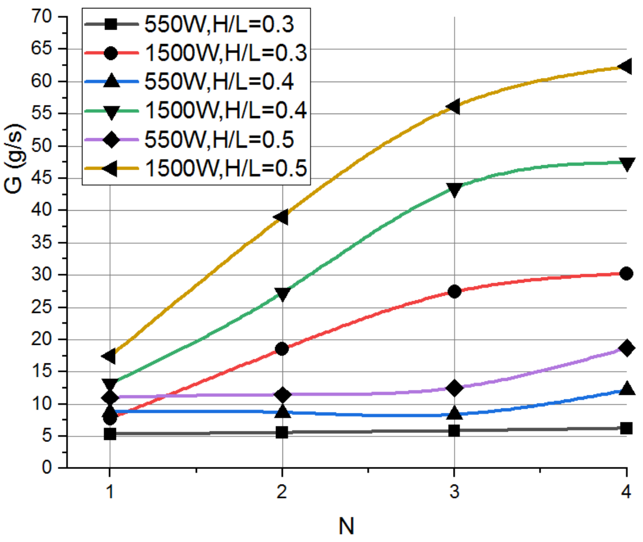

Fig. 2. The effect of submergence ratio, input heating power, and lifting tubes on the mass flow rate.

That means that the heating power assigned to each lifting tube is reduced by adding more lifting tubes and then increasing the time for each tube to reach the slug flow pattern. With the increase of heating power, the liquid mass flow rate increases with the number of lifting tubes. That means that increasing the heating power of each tube allows the tube flow pattern to approach the slug flow and then improve the lifting capacity as seen in Figure 2. 1500 W shows that at a higher heating power input, the number of lifting tubes (*N*) affects the overall performance of the bubble pump by comparing it with the peak mass flow rate of 62.3 g/s at a submergence ratio of 0.5 and when N=4, and the minimum mass flow rate of 7.8 g/s at N=1 and the submergence ratio of 0.3.

3.1. The bubble pump's efficiency

Let the efficiency of the pump be η. As in previous literature, it is defined as follows: the mass flow rate of the liquid refrigerant pumped per unit of input heating power to the bubble pump or can be defined as the ratio of the power output to the input heating power [4]:

$$\boldsymbol{\eta} = \frac{\boldsymbol{G}g(\boldsymbol{L}-\boldsymbol{H})}{\boldsymbol{P}_{\boldsymbol{in}}} \tag{1}$$

G is the liquid mass flow rate, (*L-H*) is the net lifting height, *and* P_{in} is the input heating power under the generator. In Figure 3, the experimental results show the efficiency of the bubble pump of a submergence ratio of 0.5 of the 8 mm diameter lifting tubes (*N*) for both 550 W and 1500 W input heating power, regardless of the submergence ratio. The trends of the efficiency curves are consistent, and the pumping efficiency increases when the heating power rises, and the same when the number of lifting tubes increase [3].

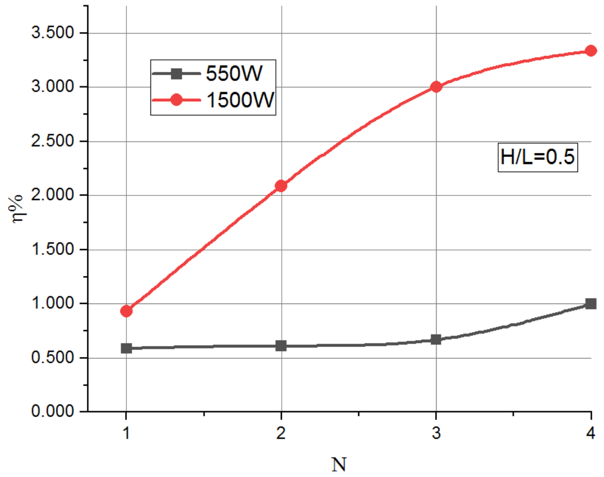

Fig.3. The effect of input heating power and the number of lifting tubes on efficiency

In general, the increase in the power input enhanced the heating efficiency, as shown in Figure 3. However, for a few cases, cooling can be done using a lower heating power input and gives the same efficiency for a higher input power heating, related to the higher number lifting tube. For example, when N=4 with the input heating power 550 W, the efficiency is more significant than 1500 W and N=1.

In the experiment, as seen in Figure 3, when the number of the lifting tubes is 1, 2, or 3 and at low input heating power 550 W, the liquid mass flow rate and the efficiency remain almost constant without a significant increase. For the higher heating power input 1500 W, the rise in the number of the lifting tubes at the same submergence ratio enhanced the efficiency; also, the mass flow rate of the fluid increases with the increase of the submergence ratio. Low efficiency is required for the multi-lifting tubes bubble pump to achieve a more mass flow rate. Furthermore, less heating power is demanded to achieve higher efficiency. Therefore, how to choose between the liquid mass flow rate and the efficiency of the pump should be selected according to the specific requirements of the pump system [5].

3.2. The flow patterns in the bubble pump

The flow in the lifting tube of a bubble pump is a complex two-phase rather than a single-phase flow, which is a direct use; the flow is upstream flow in vertical tubes. Standard vertical upstream models vary with the gas mass flow rate corresponding to the power input. In previous studies [4, 6, 7, 12, 15], flow patterns were analysed and categorised into four main classes: bubbly, slug, churn, and annular. The significant flow pattern in the vertical lifting tubes of the bubble pump is slug flow. In this experiment, gas-liquid two-phase flow is observed in four lifting tubes with a diameter of 8 mm for a tube length of 600 mm and a submergence ratio of 0.5. Flow types for 550 W and 1500 W heating power are shown in Figure 4, were photographed. For large distorted bubbles with interaction, combination, unique shapes, and system behaviours, churn flow is not enough; the number of bubbles interacting with each other is also not enough. This flow regime is created when a large gas fraction has high gas and low liquid velocity. These churn bubbles occur with a relatively low heating power of 550 W, as shown in Figure 4 (a-d). The bubbles are gathered together and grouped up into a stream in the slug flow. In Figure 4 (e-h), bullet-shaped slug bubbles act as pistons that drive liquid to the top of the lifting tubes. These slug bubbles are relatively stable in high heating power of 1500 W, however, after increasing the heating power from 550 W to 1500 W, the inner volume covers more gas, and longer slug bubbles are formed. Discomfort and fracture are detected in slug bubbles, which can be avoided by gently shaking the lifting tubes. Lifting tubes have an uneven gas distribution from bottom to top, leading to a different flow pattern for each.

When the heating power was 550 W, in Figure 4 (a-d), churn flow occurs, in Figure 4(a), when N=1, the bubbles occurred, and the steam was fast and big, in Figure 4(b), when N=2, the heat generator at the bottom of the distribution was not equal. Therefore, the removal was faster in the lifting tube closest to the water reservoir, and giant bubbles did not occur. In Figure 4(c), when N=3, the steam has become slower than before, and at the same time, the bubbles were giant, in Figure 4(d), when N=4. It has been noticed that the steam bubbles are larger at the bottom of the lifting tubes and become smaller and faster at the top of the lifting tubes.

At the heating power of 1500 W, slug flow occurs in Figure 4(e-h). When N=1, slug bubbles were short and fast, as shown in Figure 4(e), on the other hand in Figure 4(f), when N = 2, there were differences in slug bubbles length, and the flow rate of liquid water was lower and faster at the nearest lifting tube to the water reservoir. Also, when N = 3, slug bubbles were somewhat similar in terms of length and flow rate as shown in Figure 4(g), but when N = 4, the slug in Figure 4(h) is slower and longer than other configurations of bubbles. According to experiments, a multi-tube bubble pump can lead to the problem of uneven gas distribution.

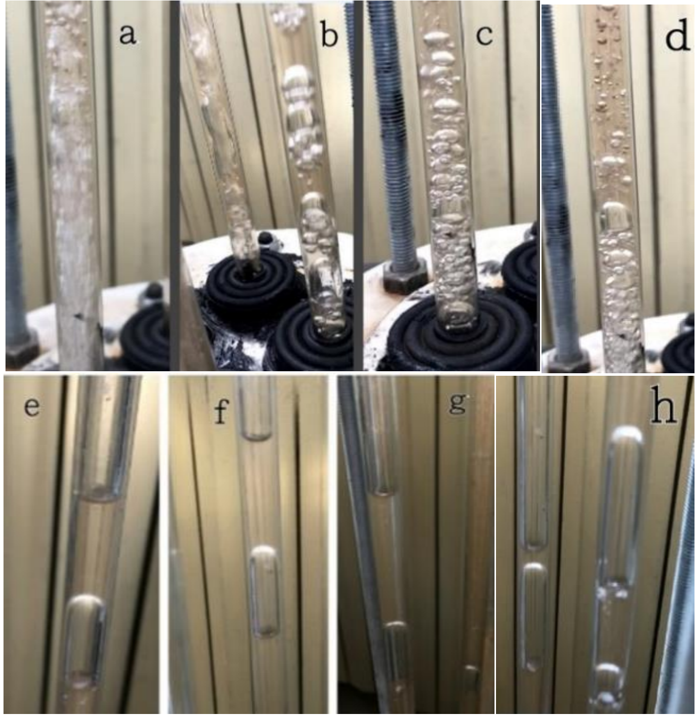

Fig. 4. The flow pattern inside the lifting tubes (heating power 550W); (a) N = 1, (b) N=2, (c) N = 3, (d) N=4; (heating power 1500 W); (e) N = 1, (f) N=2, (g) N=3, (h) N=4.

4. CONCLUSION

This article designed and tested a prototype of the open-guided multi-lifting tube pump system as the saturated water was the working fluid under atmospheric pressure. Experimental results show that the regime is slug flow when N=4 is linear. Besides, the liquid mass flow rate becomes insensitive to heating power as the input heating power increases beyond linear. For liquid lifting capacity, a higher submergence ratio is good. As this ratio increases, less energy will be used to remove heat from the water. However, if the submergence ratio continuously increases to unity, the importance of the bubble pump will be lost. When the liquid mass flow rate increases with higher heating power, the pumping efficiency, defined as the output power ratio to input power, has the same dependence on heating power. Maximum pumping efficiency occurs with the maximum mass flow rate of the fluid. For a multi-lifting tubes bubble pump, it is necessary to achieve more liquid mass flow rate and less heating power to achieve higher efficiency.

Therefore, how to choose between the liquid mass flow rate and the efficiency of the pump should depend on the specific requirements of the pump system. Multi-lifting tubes bubble pump performance increases when the submergence ratio or the number of lifting tubes increases; the pumping efficiency can also be up to 4%. Increasing the number of lifting tubes does not cause the lifting capacity and efficiency to be directly proportional. The highest performance value for lifting tubes when N=1, 2, 3 and 4 is 17.4 g/s, 39.06 g/s, 56.12 g/s and 62.34 g/s, respectively, at a 0.5 submergence ratio of 1500 W input heating power. The flow regime is mainly slugged flow within high input heating power while churn flow for 550 W input heating power. At the same time, a multi-lifting tubes bubble pump can solve the problem of uneven gas distribution. Ammonia or other common refrigerants such as R134a with the presence of the condenser can be replaced with a closed-cycle cooling bubble pump that runs on a commercial basis and would work well under pressure higher than atmospheric pressure. To use it to dissipate the heat emitting from large electrical transformers and many electrical devices such as central computers to save on costs resulting from the cooling of traditionally. While initial prices are not high, efficiency will be better in the long run by providing an endless cooling system without using electricity.

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