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Research Article

The Pumping Up Phenomenon of Double-Stage Bubble Pump with Water and Aqueous LiBr Solution

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Abstract: The double-stage bubble pump, using thermal energy as driving force to transport the solution, can replace the mechanical solution pump in the double-effect lithium bromide absorption chiller. By building a bench, a lot of experimental research and analysis were conducted with water and different concentrations of lithium bromide solution as the working fluid of the bubble pump. The first-stage bubble pump in the experiment pumps up by the external heat source. The heat for driving the second-stage bubble pump is provided by refrigerant steam produced from the first-stage bubble pump. The experiment data shows that the heating of refrigerant vapor is only one of the elements of pump-up phenomenon. Another is that the intermediate solution flashes to vapor to become bubbles. The pump-up phenomenon of double-stage bubble pump has much to do with the pressure difference of intermediate solution and first-stage refrigerant vapor. With water as the working fluid, when the pressure difference between refrigerant vapor and the intermediate liquefied refrigerant is 3.5-3.9 kPa, the bubble pump can pump up and run for some time and the start-up time decreases with the driving head. When the working fluid is lithium bromide solution, the pressure difference of the double-stage bubble pump increases with the solution concentration and is bigger than that of water. The start-up time increases with the concentrations of lithium bromide solution within the range of 45.5 to 54% and decreases within the range of 54-59.5%. The start-up time is largest at 54% under this experimental condition. The experimental result is also compared with the single-stage bubble pump. The start-up time of double-stage bubble pump decreases with the driving height, which is contrary to the single-stage bubble pump.

Keywords: Absorption refrigeration, double-stage bubble pump, pressure difference, pump-up phenomenon, start-up time

INTRODUCTION

The driving force of the pump-free lithium bromide absorption refrigeration device is supplied by the bubble pump, which absorbs the external heat (hot water or steam) to lift the solution. Heat source can be reasonably utilized by using bubble pump in absorption refrigeration, reducing the dependence on high-quality energy (Liu *et al*., 2003). In recent years, many scholars, at home and abroad, have done a lot of researches about single-stage bubble pump, including the establishment of the mathematical model of the bubble pump operation and the construction of the single-stage bubble pump test setup to do some experimental studies on many factors affecting the bubble pump performance (Saravanan and Maiya, 2003; Pfaff *et al*., 1998; Deng and Ma, 1999). Peng and Xiao (1989) gave the theoretical formula on bubble pump. Gu and Wu (2006) and Gu *et al*. (2008) designed and used second generator in the bubble pump refrigeration cycle. But few researches on the double-stage bubble pump have been done, especially the pump-up phenomenon of the small-type double-stage bubble pump.

The solution in the high-pressure generator is directly heated and concentrated, thus the refrigerant vapor is generated. The solution in the low-pressure generator is heated by the refrigerant vapor from the high-pressure generator to generate bubbles to drive second-stage bubble pump, meanwhile the solution is concentrated again. The experiment shows that the heating of refrigerant vapor is only one of the elements of pump-up phenomenon. Another is that the intermediate solution flashes to vapor and becomes bubbles. In this study the pressure difference between the two stages bubble pump is presented, which will be helpful for further study of the double-stage bubble pump.

EXPERIMENTAL SETUP

The test setup includes high and low pressure generators, first and second stage gas-liquid separators,

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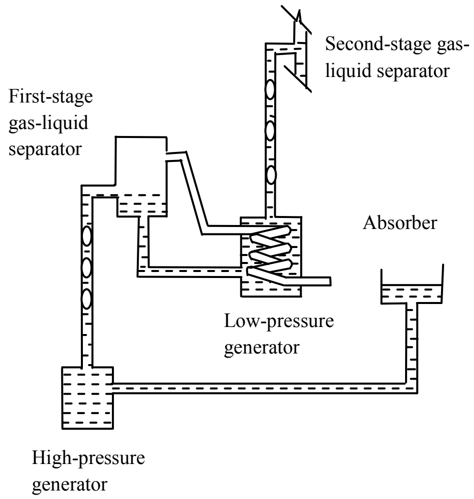

Fig. 1: Diagram of the experiment

Table 1: The experiment measurement equipment specifications

Measurement device	Specification
Thermocouple	Type T, 0-800°C
Pressure sensor	US10000, ±0.1%, 0-34.47 KPa
Data logger	FLUKE 2635A, 20 ch

absorber, condenser, needle valve pressure regulators and the interconnected pipelines. The system is shown in Fig. 1.

This experimental setup is designed to observe the performance of the bubble pump in the pump-free lithium bromide absorption refrigeration system. In order to analyze the influence of each parameter to the performance more clearly, two 1 m length see-through glass tubes are used in the first and second stage bubble pump respectively in this experiment. To simplify the experimental setup, the system eliminates the evaporator and other components. The heating bar is fixed in the high-pressure generator and it is electrified through additional power source. The heating input is controlled by changing the heating bar voltage and the heating input ranges from 0 to 4000 W. The driving height is adjusted of the range of 300-450 ~ 450-450 mm (the first and second stage bubble pump, respectively). The lift height is kept at 1250-1400 mm (the first and second stage bubble pump, respectively). The lithium bromide solution concentration ranges from 45.5 to 59.5%. Due to high requirement of air-tightness in the experimental operating, the connection of glass tubes and steel components as well as between steel components needs to be done very well.

Table 1 gives experiment measurement equipment specifications.

The process of bubble pump cycle: The solution in the high-pressure generator is heated by the heating bar to generate bubbles. The gas-liquid mixture is transported into the first-stage gas-liquid separator under the action of the pressure difference between the absorber and the generator. The refrigerant vapor goes into the low-pressure generator to exchange heat with the solution and then be transported into the condenser. The intermediate solution goes into the low-pressure generator. After pumping up of the second-stage bubble pump, the concentrated solution goes into gas-liquid separator and then into the absorber to be sprayed to absorb the refrigerant vapor from the second-stage gas-liquid separator. In order to enhance the absorption effect, the absorber is cooled. Theoretical cycle is shown in Fig. 2.

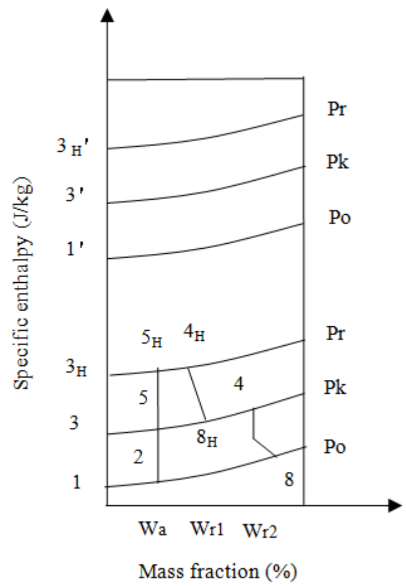

Fig. 2: Theory diagram of double-stage bubble pump

As shown in Fig. 2, the pressure of the high-pressure generator is Pr. The weak solution from the absorber flows into high-pressure generator, the inlet solution is in the sub-cooling state 2 and then reaches the point 5_H and begins to generate bubbles through the heating exchange, so the density of mixture in the bubble pump decreases and the bubble pump begins running, the outlet solution is concentrated to intermediate solution at the point 4_H. The intermediate solution goes through the pressure reducing valve into low-pressure generator and its pressure is P_k. Due to the sudden drop in pressure, the intermediate solution flashes to vapor, the formation of bubbles causes pumping up of the second-stage bubble pump. The solution absorbs heat to become a saturated concentrated solution of mass fraction of Wr_1 and this process is shown as 4_H-8_H in the diagram. The refrigerant vapor passes through the low-pressure generator coil to heat the solution, which is concentrated to the solution of mass fraction of Wr_2 and the process is shown as 8_H-4 in the diagram.

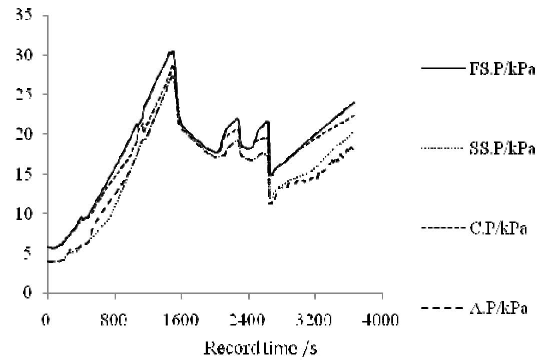

Fig. 3: Pressure diagram at the driving head of 350-450 mm

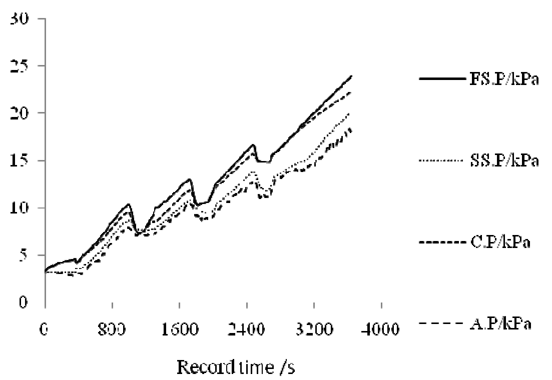

Fig. 4: Pressure diagram at the driving head of 400-450 mm

EXPERIMENTAL RESULTS

The experimental results and analysis with water as the working fluid:

The experimental results with the driving head 350-450 mm: When the heating input is 3000 W and the diameter is 7.7-7.7 mm, the experimental operation parameters are shown in Fig. 3.

The experimental results show that: when the driving height is 350-450 mm, the pump-up can last long time. The system can operate well and the pressure difference between the two stage gas-liquid separators tends to be a constant value of 3.6-3.8 kPa.

The experimental results with the driving height 400-450 mm: When the heating input is 3000 W, the high-pressure generator is heated continuously and in the meanwhile, the condenser and absorber are cooled continuously. By adjusting the two pressure regulators, the first and second stage bubble pump can be operated simultaneously. The operation pressure is shown in Fig. 4.

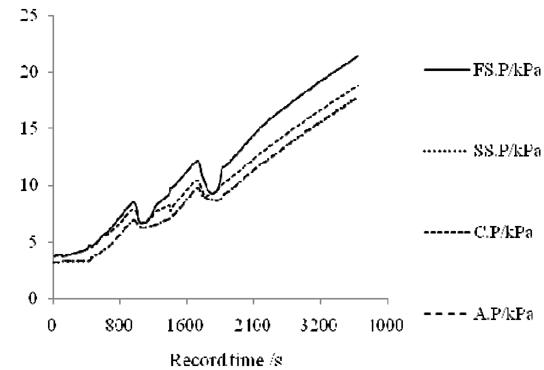

Fig. 5: Pressure diagram at the driving head of 450-450 mm

Table 2: The start-up time of bubble pump

Driving height/mm	350-450	400-450	450-450
Start-up time/s	480	220	190

The experimental results show that: when the driving height is 400-450 mm, the two stage bubble pump can maintain a stable operation finally and pressure difference between the two stage gas-liquid separators tends to stabilize, with the range of 3.6-3.8 kPa.

The experimental results with the driving head 450-450 mm: When the driving height is 450-450 mm and other conditions are unchanged, the device predation pressures are shown in Fig. 5.

As shown in Fig. 5, in the later operation period, the pressure difference between the two stage gas-liquid separators trend to be stable, with the range of 3.6-3.9 kPa.

The start-up time of bubble pump with different driving heights and water as the working fluid is shown in Table 2.

As shown in Table 2, the time of pumping up of the second-stage bubble pump becomes shorter with the increase of the driving height of first-stage bubble pump.

Comparison with the single-stage bubble pumps with the driving height 300, 380, 468 mm: Experimental data was gotten from single-stage bubble pump setup made in our work beforehand (Gao *et al*., 2012). The experiment was conducted under the condition: heating input is 471 W, tube diameter is 9.5 mm, lifting height is 1144 mm, the generator is heated continuously and in the meanwhile, the condenser and absorber are cooled continuously. The operation data at driving height of 300, 380, 468 mm are shown in Fig. 6-8, respectively.

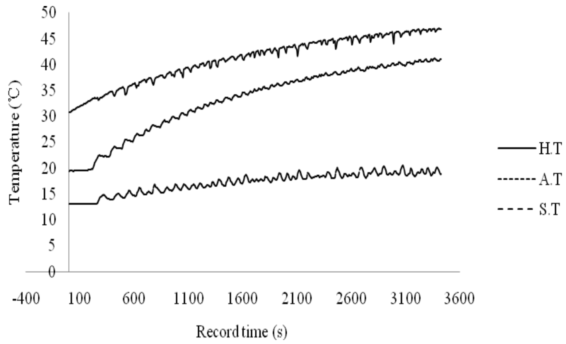

Fig. 6: Driving head 300 mm

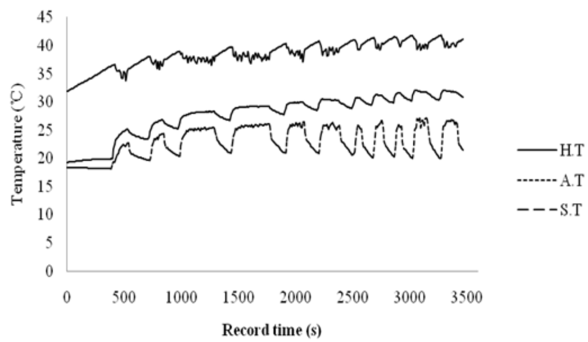

Fig. 7: Driving head 380 mm

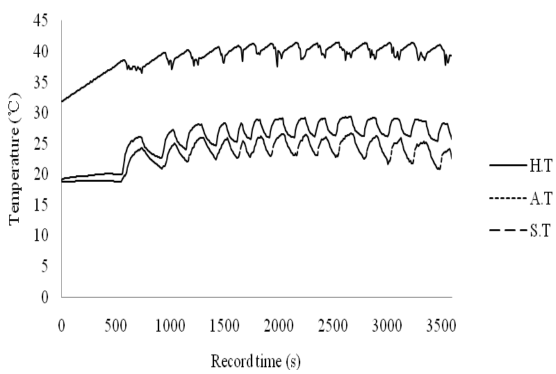

Fig. 8: Driving head 468 mm

According to comparison of the start-up time at different driving height, 270s (300 mm), 400s (380 mm), 560s (468 mm), the experimental results show that: when the driving height is larger, the single-stage bubble pump need more time to be started up. The result shows different trends compared with double-stage bubble pump. Because the potential energy of solution increases with the driving height, more power

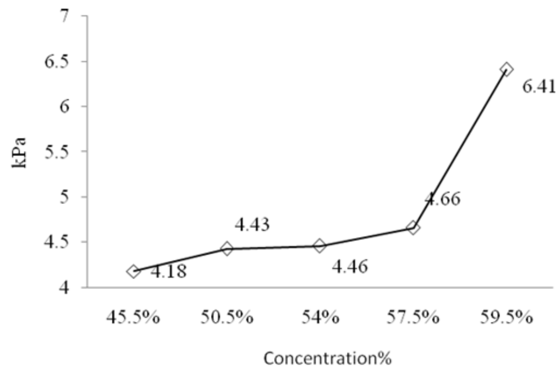

Fig. 9: Driving head 350-450 mm

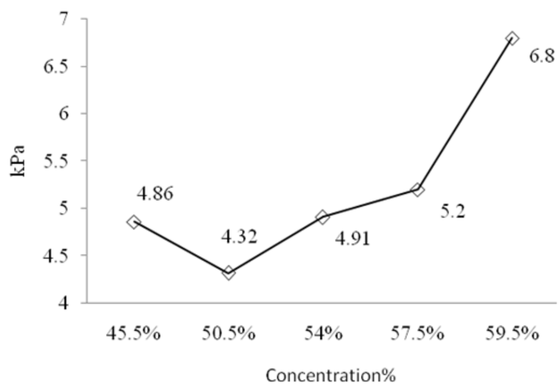

Fig. 10: Driving head 425-450 mm

input is needed to lift solution. It needs more time to generate bubble to supple stronger driving force, so the start-up time is longer at larger driving height. The first-stage of double-stage bubble pump lifting performance is enhanced with the increase in driving height, so driving force of the second-stage is stronger at larger driving height of first-stage bubble pump. Hence, the start-up time is shorter at larger driving height.

The phenomenon of pumping up and the pressure difference between the two stage gas-liquid separators with the lithium bromide absorption as the working fluid: The experiment is carried out with the lithium bromide solution as the working fluid. The driving height is unchanged, 350-450, 400-450, 425-450 and 450-450 mm, respectively. The experimental results are shown in Fig. 9 to 12.

When the heating input is 1800 W, according to statistics for the bubble pump start-up time under the condition of four driving heights above, with different concentrations of lithium bromide solution, the figure is

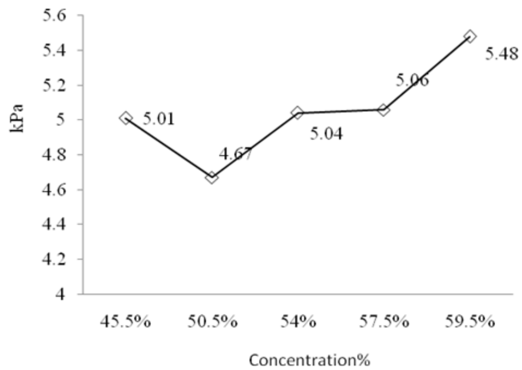

Fig. 11: Driving head 400-450 mm

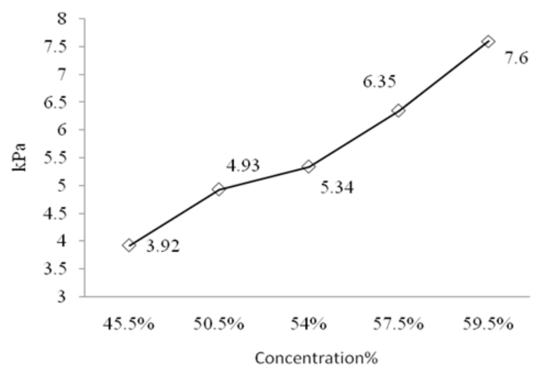

Fig. 12: Driving head 450-450 mm

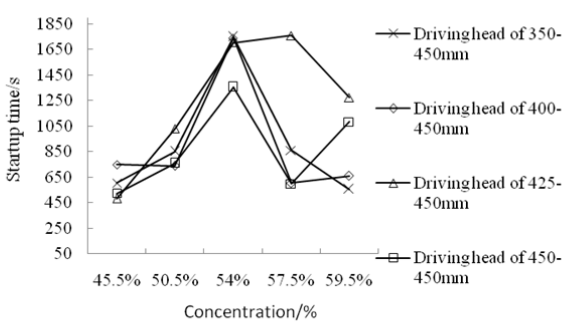

Fig. 13: The startup time of bubble pump at different LiBr solution concentrations

shown in Fig. 13. The startup time is set 0s when high-pressure generator solution temperature is 38°C.

Figure 13 shows that the bubble pump start-up time increases with the increase in concentration within a range of 45.5 to 54%. The start-up time of the bubble pump basically decreases with the increase in concentration within a range of 54 to 59.5%. At the concentration of 54%, the start-up time is the longest.

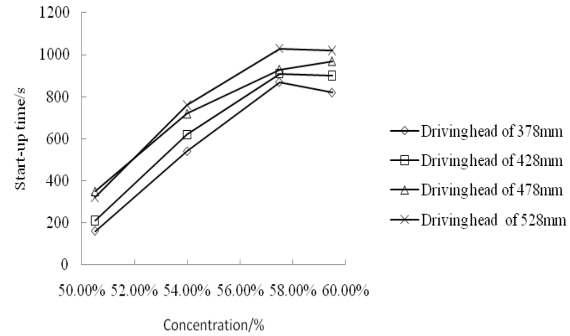

Fig. 14: The startup time of bubble pump at different LiBr solution concentrations

Comparison with single-stage bubble pumps with different concentrations lithium bromide solution: For single-stage bubble pump, the experiment was carried out as the heating input is 961 W, the lifting height is 1244 mm, the tube diameter is 7.7 mm and startup time is set 0s when the generator temperature is 60°C.The start-up time is shown in Fig. 14.

According to the Fig. 14, for the single-stage bubble pump, the start-up times, under the condition of four driving heights of 378, 428, 478, 528 mm, respectively with different concentrations of lithium bromide solution, show that: when the driving height is larger, the start-up time is longer at the same solution concentration. The effect of solution concentration is similar to the double-stage bubble pump, but the effect of driving head, shows different impact compared to the double-stage bubble pump.

CONCLUSION

When the heating input, working fluid and tube diameter of bubble pump remain unchanged, the greater driving height of first-stage bubble pump has a positive effect on the pump up of the second-stage bubble pump. The pump-up phenomenon has a close relationship with the pressure of the intermediate solution. The experimental data indicates that the second-stage pump can run up, when working fluid is water and the pressure difference, between the refrigerant vapor from first-stage bubble pump and the intermediate solution, is between 3.5 and 3.9 kPa. It is shown that intermediate solution flashes to vapor and heating refrigerant vapor from first-stage bubble pump are very important factors of the pump-up phenomenon. By adjusting two pressure regulators, the bubble pump can pump up and run for some time ultimately. The pressure difference increases with the increase in solution concentration and the start-up time increases with the increase in the concentration of 45.5 to 54% when working fluid is lithium bromide solution. In the range 54 to 59.5%, with the increase of the concentration, the start-up time decreases. At the concentration of 54%, the start-up time reaches the maximum point. The bubble pump start-up time decreases with the increase in the driving height, which is contrary to the single-stage bubble pump.

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NOMENCLATURE

FS.P = First-stage gas-liquid separator pressure (kPa)
SS.P = Second-stage gas-liquid separator pressure (kPa)
C.P = Condenser pressure (kPa)
A.P = Absorber pressure (kPa)
H.T = Heater temperature (°C)
A.T = Absorber temperature (°C)
S.T = Separator temperature (°C)

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