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Experimental Study of a Bubble Pump Operating with a Set of Parallel Lift Tubes and a Binary Solution of R134a-DMAC

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Abstract **-**An alternative utilization of a compressor or a mechanical pump in the traditional refrigeration cycles is the diffusion absorption refrigeration (DAR) cycle operating with a bubble pump to circulate the binary working fluid. The bottle neck of the DAR cycle is the bubble pump and its performance is determined by the amount of separated refrigerant leaving the bubble pump and the circulation ratio (i.e., the ratio between the mass flow rates of separated refrigerant and rich solution). This work investigated the possibility of increasing bubble pump performance by using a set of parallel bubble pump lift tubes. A modular experimental continuous system was designed to characterize the performance of three parallel bubble pump lift tubes with an environmentally friendly binary solution of R134a-DMAC. The dependence of the number of bubble pump lift tubes and various operating conditions (i.e., refrigerant mass concentration and heat input) on the amount of the desorbed refrigerant was determined. The results showed that in comparison to a single lift tube, the use of two or three parallel lift tubes when the bubble pump was operated with optimum heat input could double or triple, correspondingly, the amount of desorbed refrigerant.

Keywords**:** bubble pump, DAR cycle, multiple lift tubes, binary solution.

1. Introduction

Conventional vapour compression and absorption refrigeration systems are dual pressure cycles where the saturation temperature difference between the condenser and evaporator is produced by a system pressure difference. This requires a mechanical input to drive the compressor or the pump needed to generate this change in pressure, which adds significantly to the noise level and cost of the system while reducing its reliability and portability. To circulate the working fluids without a mechanical pump the diffusion absorption (DAR) cycle relies on a bubble pump (Fig. 1) which is a heated tube (length L and diameter D) communicating with two reservoirs, one higher than the other. The motive head (H) is the difference between the height of the liquid in the reservoir and the point where heat is applied. Heat is applied at the bottom of the bubble pump at a rate sufficient to evaporate some of the refrigerant from the rich solution. The resulting vapor bubbles rise in the tube, carrying the liquid above them to the higher reservoir. The bulk density of the fluid in the tube is reduced relative to the liquid in the lower reservoir, thereby creating an overall buoyancy lift. The desorbed gaseous refrigerant is separated from the binary solution, and flows to the condenser where heat exchange with colder surroundings occurs. Auxiliary gas is charged into the evaporator and the absorber. The auxiliary gas should be a non-condensable gas such as hydrogen or helium. The presence of the inert gas reduces the partial pressure of the refrigerant, while keeping the system pressure almost constant.

This mixture of refrigerant and auxiliary gas flows through the evaporator tubes, where it absorbs heat from the cooling chamber at higher temperature. The heated refrigerant and the inert gas flow to the absorber, where exothermal mixing occurs between the refrigerant and the poor solution. The inert gas is separated from this binary solution. Due to the motive head, this mixture flows to the lower reservoir of the bubble pump unit, where heat is applied.

The bottle neck of diffusion absorption cycles is the bubble pump unit, because for constant environmental conditions, the cooling capacity of the cycle is dependent on the amount of the separated refrigerant and solution circulation. These are limited by the DAR unit configuration. Most DAR systems operate with ammonia-water-H_2 or He are inefficient comparing to the conventional absorption system. DAR system operating with organic working fluid, such as R134a-DMAC-H_2, are even less efficient (Zohar et al. (2009)). This work focuses only on the bubble pump unit, since it is mainly responsible for the performance of DAR cooling systems. The aim of the work is to examine the possibility of increasing the cooling capacity (not the COP) of a DAR unit by suggesting modifying the traditional bubble pump tube with a set of parallel bubble pumps tubes.

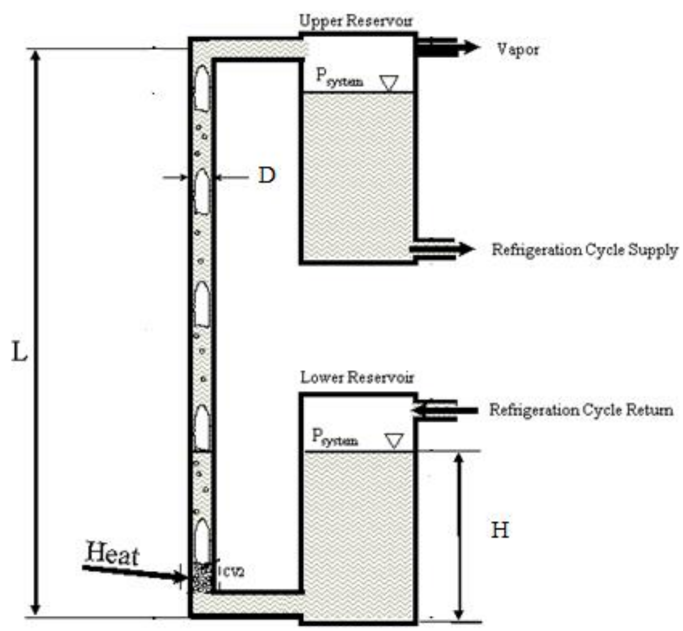


Fig. 1. Bubble pump schematic design.

Bubble pump performance has been investigated in many works that studied the effects of varying tube diameter, pump lift, motive head and heat input to the bubble pump. Delano (1998) and White (2001) found that the bubble pump operated most efficiently in the slug flow regime, in which vapor bubble diameter was approximately equal to that of the lifting tube. In the slug flow pattern, however, tube diameter is a limitation by the Chisholm (1983) correlation.

The effects of varying bubble pump heat input have been tested extensively (Delano (1998), Sathe (2001) and Koyfman et al. (2003)). These studies showed that the mass flow rate of the vapor increased linearly with the heat input while the mass flow rate of the pumped liquid first increased until it reached a maximum value (in the range of 150-200 W), after which it decreased with the increase in heat input. The results implied that each bubble pump setup had an optimum heat input at which the amount of pumped liquid reached a maximum. The experimental results of Pfaff et al. (1998) indicated that the rich solution and refrigerant flow rates increased with pump heat input after the minimum pump heat input was reached. This system operated under low heat input values (up to 80 W) due to the use of water-LiBr as the working fluid pair.

Delano (1998) analytically modeled a thermally driven, triple working fluid Einstein refrigeration cycle. The model showed that widening tube diameter would reduce the friction factor, thereby increasing the flow rate through the bubble pump. In another experimental work, Sathe (2001) showed that an increase in tube diameter was accompanied by a corresponding rise in the optimal heat input to the bubble pump.

Several experimental studies on the influence of the motive head on the bubble pump performance found that increasing the motive head caused an increase in the rich solution flow rate (Delano (1998), White (2001), Sathe (2001), Koyfman et al. (2003) and Pfaff et al. (1998)). Koyfman et al. (2003) experimental results also showed that a much longer time was required for the system pressure to reach a steady state than was needed for the measured temperatures.

Multiple lift tube configurations were experimentally investigated by Vicatos and Bennett (2007) and Monsef et al. (2012). Their results indicated that an addition of lift tubes increased the pump's ability to handle larger heat loads and flow rates before the flow pattern changed from slug to annular. Vicatos and Bennett (2007) used water as the working fluid and Ni as the pressure equalizer, whereas Monsef et al. (2012) used the water-LiBr fluid pair.

Previous works that investigated bubble pump performance did not test a set of parallel lifting tubes with R134a-DMAC environmentally friendly working pair.

2. Experimental System

The experimental system shown in Fig. 2 was designed to analyse the performance of bubble pump with several parallel lift tubes at steady state.

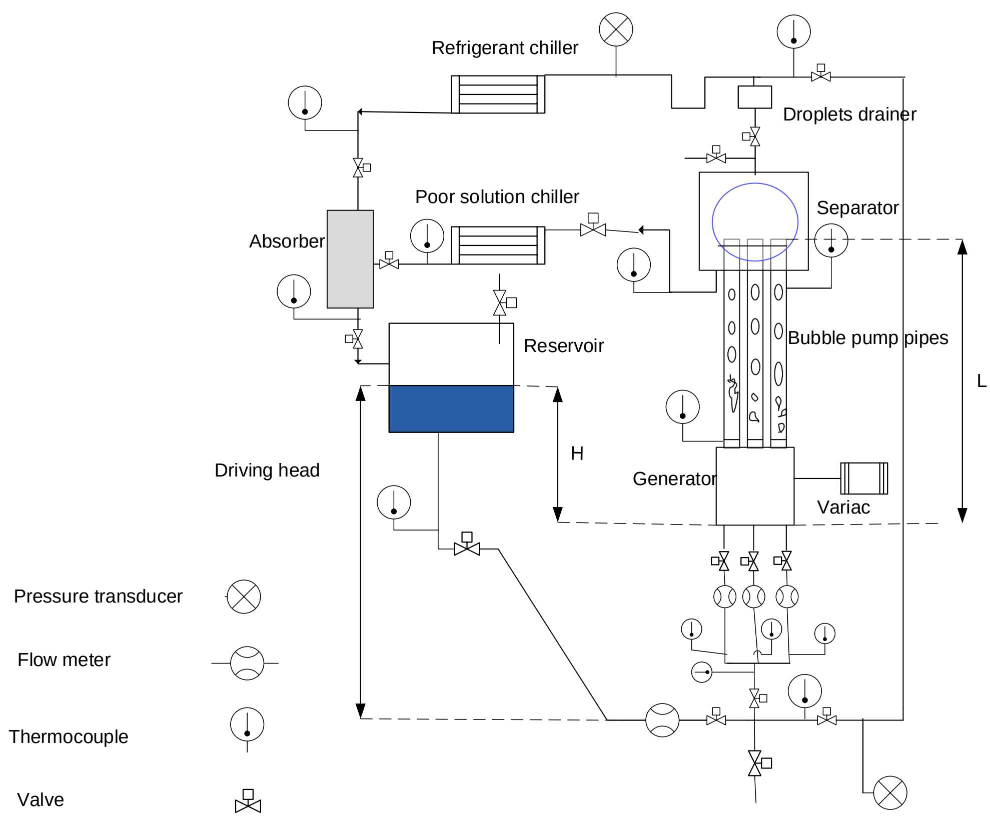


Fig. 2. Layout of the experimental system.

A standard single bubble pump configuration commonly used in previous works was replaced by a modular set of parallel bubble pumps operating with an environmentally friendly solution of R134a-DMAC. Consideration in choosing the working fluids was based on work done by Borde et al. (1993)

The design of the experimental system is modular, making it possible to change the number of pipes where the flow takes place by using the installed valves. In addition, the design of the system allows changing the heat input, the motive head by changing the height of the reservoir and enables insertion of additional R134a to change the concentration of the solution. Combination of the operating conditions and number of pipes are expected to define the performance of the bubble pump unit.

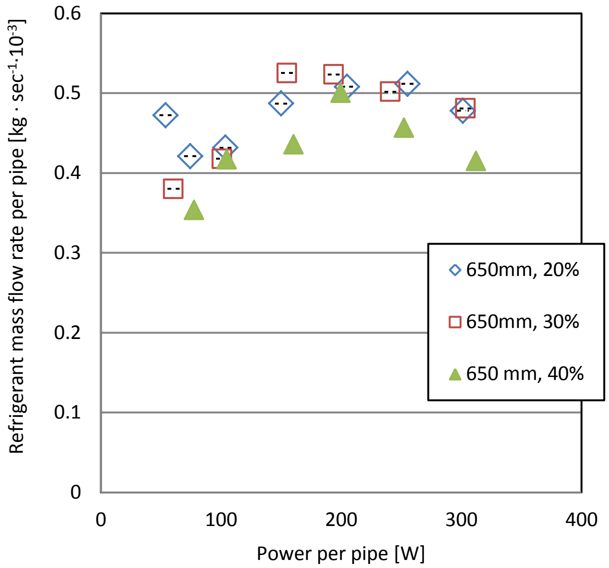
An experimental system lacks an evaporator, a condenser and the inert gas since it focuses only on the performance of the bubble pump and it is not considered a complete diffusion absorption cooling system. This setup comprises a reservoir, a heating unit (generator), a separation unit (separator), and an absorption unit, all of which are schematically illustrated in Fig.2. From the reservoir, the rich solution flows downwards to the manifold where valves could be opened or closed to direct the flow into one, two or all three of the pipes. The heat for refrigerant evaporation is supplied by a manually operated variac powered by an electrical DC current. Vertical flow is driven by the evaporated refrigerant bubbles, which carry the liquid solution up the lifting pipes to the separation unit. The separator special double-outlet design enables upward flow of the gaseous refrigerant and downward flow of the liquid poor solution. The liquid binary solution contains solvent and refrigerant that is not separated during evaporation (poor solution). The amount of separated refrigerant defines bubble pump performance. Both the hot refrigerant and the hot poor solution flow through bent copper tubes where they are cooled by heat exchange with the environment. The pipes for refrigerant and poor solution then merge into a single pipe, resulting in absorption of the refrigerant into the poor solution, a reaction accompanied by an exothermal effect and further heat exchange with the environment. The combined solution of refrigerant and poor solution then flows back into the reservoir. The inclusion of metering devices in the system makes it possible to know in real time the temperature, pressure, and flow rate at points of interest.

2. 1. Experimental Results

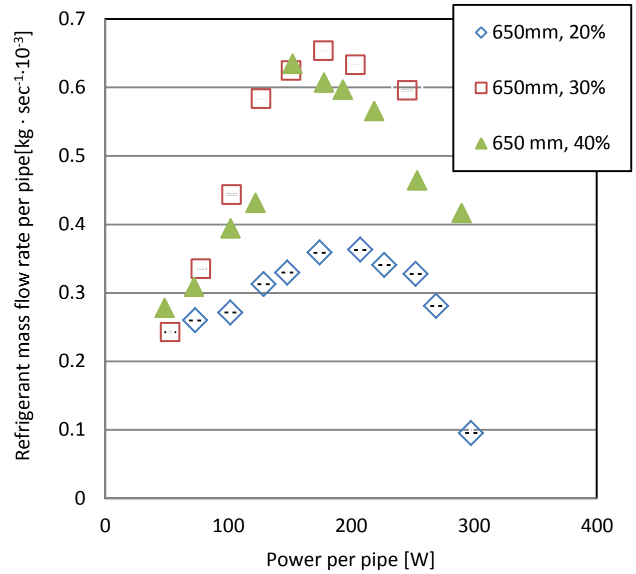
The aim of the experimental work is to operate the system under different operational conditions and to deduce the effect of each operating condition on system's performance, i.e. the amount of the desorbed refrigerant. The modular design of the experimental system enables its operator to change relevant operational conditions such as the number of pipes where the flow takes place, the motive head, the concentration of the solution and the heat input in the generator. In order to obtain better comparison, all the results are normalized by the number of pipes, i.e. for a case of flow in two parallel pipes, the values of the separated refrigerant and the required heating input are divided by two, same for the case of three parallel pipes which values are divided by three. This normalization is performed in all the following results.

In order to initiate circulation, heat inputs of 50-75 Watts were required for each one of the pipes where flow takes place.

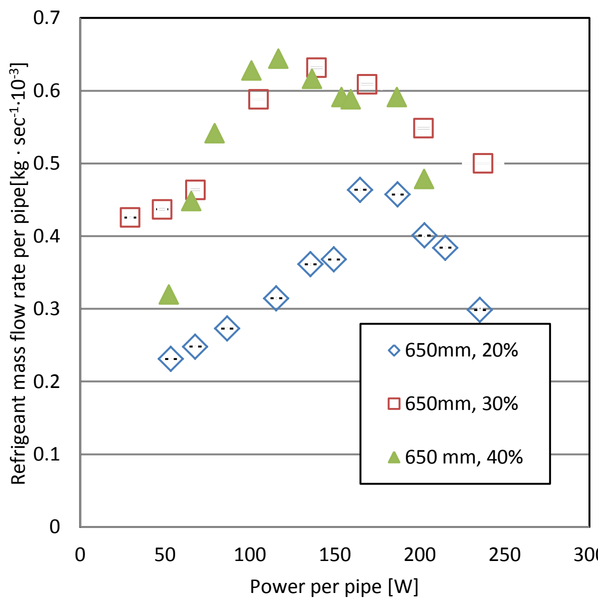
The nominal mass concentration of the refrigerant varies from 20%, 30% and 40%. Fig 3(a) -3(c) show that for input power of about 150 to 200 Watts, maximum amount of refrigerant is desorbed. Further increase in the input power results in a decrease of the refrigerant's mass flow rate. It can be seen from the following figures that for a case of a single pipe (Fig. 3(a)) there are no major differences in the performance of the bubble pump operating with concentration in the range of 20% to 40% within the specific motive head. As the number of bubble pump pipes increase from one to two or three, the influence of the concentration becomes more noticeable (Fig. 3(b)-3(c)). Significantly more refrigerant is separated for higher concentrations of 30% and 40%. There is no much difference in the results for concentration of 30% and 40% within the optimal heat input for the same amount of pipes.



(a)



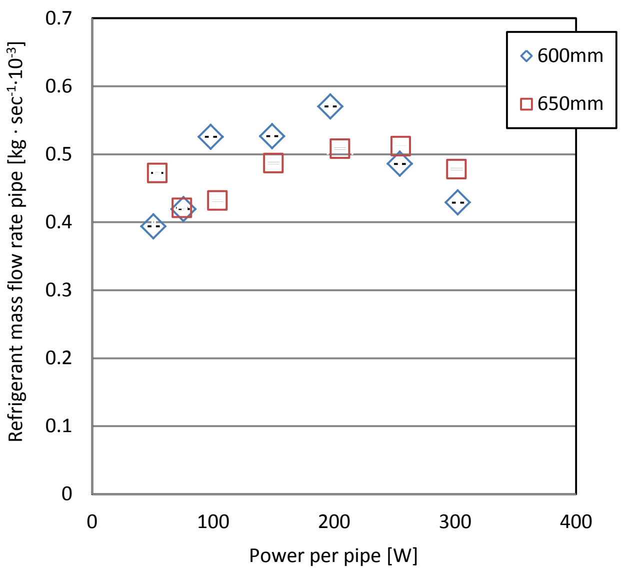
(b)



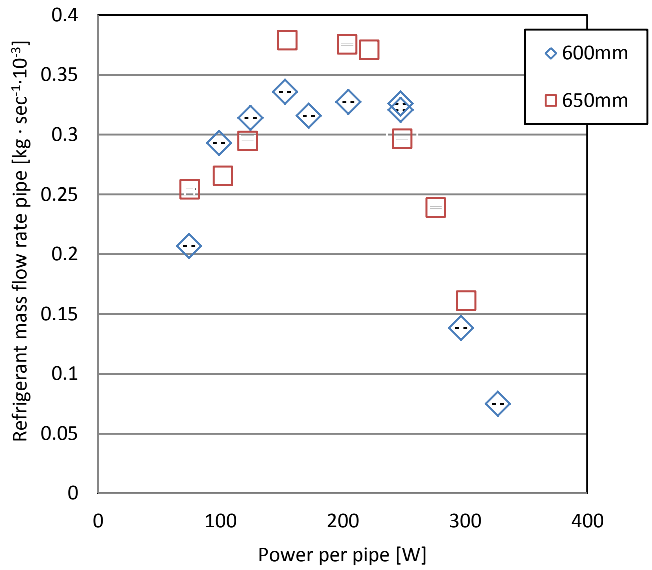
(c)

Fig. 3. Refrigerant mass flow rate vs. power input for various concentrations of the rich solution, single lift tube (a), two parallel lift tubes (b) and three parallel lift tubes (c), motive head of 650 mm.

The motive head's influence is also examined. Due to the system's physical restrictions, the motive head is set to be 600 mm and 650 mm. For the case of a single pipe at all concentrations (Fig. 4(a),), one can notice the weak influence of the motive head on the refrigerant's mass flow rate. The amount of the separated refrigerant is maintained pretty much constant with an increase in the heat input. As the number of pipes increases (Fig 4(b) and Fig. 4(c)) to two and three pipes, the influence of the motive head is more evident. An increase in the motive head results in an increase in the refrigerant's mass flow rate mainly at values of 150-200 Watts power per pipe heat input. The same tendency is observed while examining the rich solution's dependence on the motive head.



(a)



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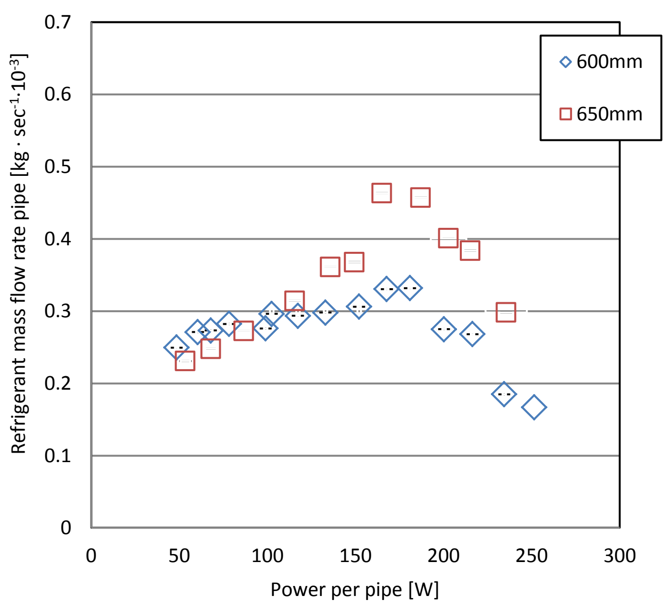
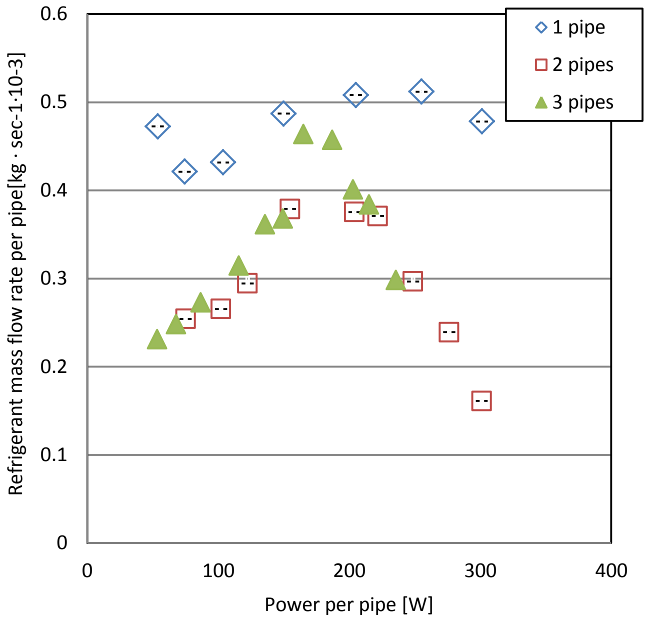


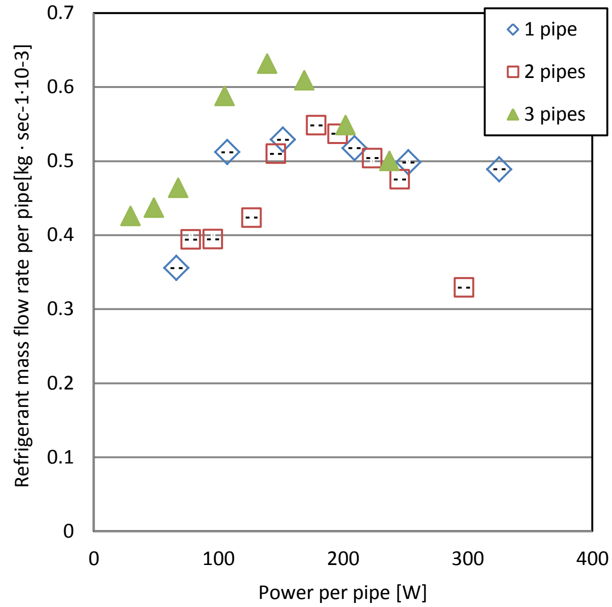
(c)

Fig. 4. Refrigerant mass flow rate vs. power input for 600 mm and 650 mm motive head, two parallel pipes, (a) 20% concentration, (b) 30% concentration, (c) 40% concentration.

The experimental system is operated with a single tube, two and three parallel bubble pump tubes. For cases of low nominal concentration of 20%, it is evident that the single pipe is more efficient than each one of the parallel pipes separately (Fig. 5(a)). As the concentration of the rich solution increases the differences between the pipes become less evident with a slight lead to results of three pipes (Fig. 5(b) and Fig.5(c)). For concentrations of 30% and 40%, it can be stated that an increase in the number of pipes increases the amount of the separated refrigerant especially in the range of input power of 150 to 200 Watts.



(a)



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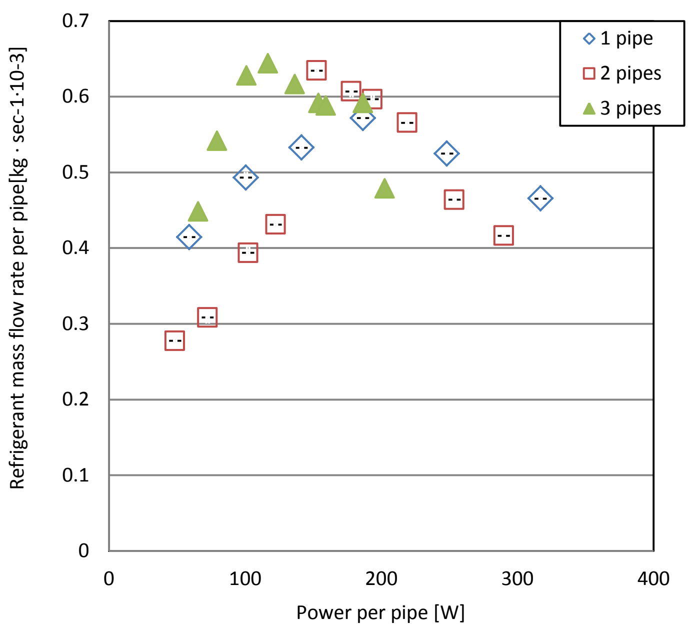

(c)

Fig. 5. Refrigerant mass flow rate vs. power input for one, two and three parallel lift tubes, motive head of 650 mm,20% concentration (a), 30% concentration (b) and 40% concentration (c).

4. Conclusion

A Performance of a set of parallel bubble pump pipes operating with a binary solution of R134a and DMAC was investigated experimentally. A continuous modular experimental system was successfully designed, assembled and operated. The operator was given an option to change the number of pipes where the flow took place, the concentration of the solution, the motive head and the heat input in the generator.

In order to initiate circulation, heat inputs of 50-75 Watts are required for each one of the pipes where flow takes place. It is important to control the temperature of the generator in order to avoid the evaporation of the solvent DMAC (which at atmospheric pressure evaporates at 165°C) and high system pressure. Also the higher the heat inputs slug to annular flow transition occurs. Therefore very high heat inputs are not recommended. The optimal power per pipe at which more refrigerant is separated from the solution is in the range of 150-200 Watts where slug flow occurs.

The change of 50 mm in the motive head causes an increase in the values of the rich solution for flow in two or three parallel pipes at concentrations in the range of 30% to 40%. As a result, more refrigerant is desorbed when the motive head is higher.

When operating in the optimal power per pipe range, for higher concentrations of 30% and 40%, the amount of the separated refrigerant in two and three parallel pipes is almost doubled or tripled correspondingly in comparison to a single pipe. Note that the cooling capacity is determined as $\dot{m}_{ref} \cdot h_{fg}$ in the evaporator. Such a configuration of the bubble pump unit can increase the cooling capacities of a DAR system, since more refrigerant participates in the cooling cycle. In addition it enables to operate the system at higher heat inputs (300-400 Watts and 450-600 Watts for a system of two and three parallel pipes correspondingly).

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