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Multiple lift tube pumps boost refrigeration capacity in absorption plants

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Abstract

The technology of the diffusion absorption refrigerator is receiving renewed attention due to its ability to use exclusively, low-grade heat to produce cooling or heating. Its capacity, however, has been largely restricted to small domestic-type units because of the flow rate limitations imposed by its single lift-tube pump. To increase its refrigeration capacity, a multiple lift-tube bubble pump can be used, in order to increase the volume flow rates of the fluids, which are directly related to the amount of refrigerant produced. Testing on a diffusion absorption plant using a multiple lift tube bubble pump, and the effects of additional tubes on the system's performance have been recorded. Although a full range of heat inputs could not be implemented, because of the limitations of the components of the unit itself, it was observed that the refrigeration cooling capacity was increased without a significant drop in Coefficient of Performance (COP). It was concluded that the multiple lift tube bubble pump has no limitation to the fluid flow rate and depends solely on the amount of heat input. This gives the freedom to design the lift tube pump according to the refrigeration demand of the unit, and not the other way round which is the current approach by the manufacturers world wide.

Keywords: bubble pump, coefficient of performance, multiple lift tube pumps, refrigeration capacity, tube configuration flow rates, water lift tube

1 Introduction

With the current concern for the environment and the sustainability of the planet's energy resources, there is an increased focus towards energy efficient and environmentally friendly technologies. A refrigeration cycle with good potential in this regard is the diffusion absorption refrigeration cycle, because it can use exclusively, heat energy to produce cooling. The heat energy can be obtained from a number of different sources, for example: LPG, natural gas or kerosene flames, electricity and waste heat (Abed 1997; Chisholm 1983; Clark & Dabolt 1986). The system has suffered, however, from two major disadvantages, which are its low efficiency and small refrigeration capacity.

The refrigerator's small refrigeration capacity is a result of the physical limitations on the bubble pump system. The bubble pump in the three fluid systems has a double-fold purpose:

- To create vapour for pumping action.
- To raise the solution to a higher level in order for gravity effects to maintain circulation.

The vapour which is released by boiling the solution will eventually become the condensed refrigerant, and its mass rate will dictate the refrigeration capacity of the refrigerator. According to established theory of absorption refrigeration, this mass rate of refrigerant is supported by the circulation rates of the strong and week solutions and their concentration difference. The bubble pump maintains the circulation of the solutions and up to date, the pump rate has been the very limiting factor of these three-fluid absorption units. Therefore, the main purpose of this study and in particular of the experiments performed, is to investigate the possibility of increasing the pump rate by a combination of multiple lift tubes and increased power input.

2 The bubble pump

A bubble pump is simply a vertical tube into which liquid and vapour is added at the lower end from the boiler or generator. The liquid fills the lift tube to a designed depth. The vapour travelling upwards through this section forms bubbles that act like pistons driving liquid slugs up the remainder of the tube.

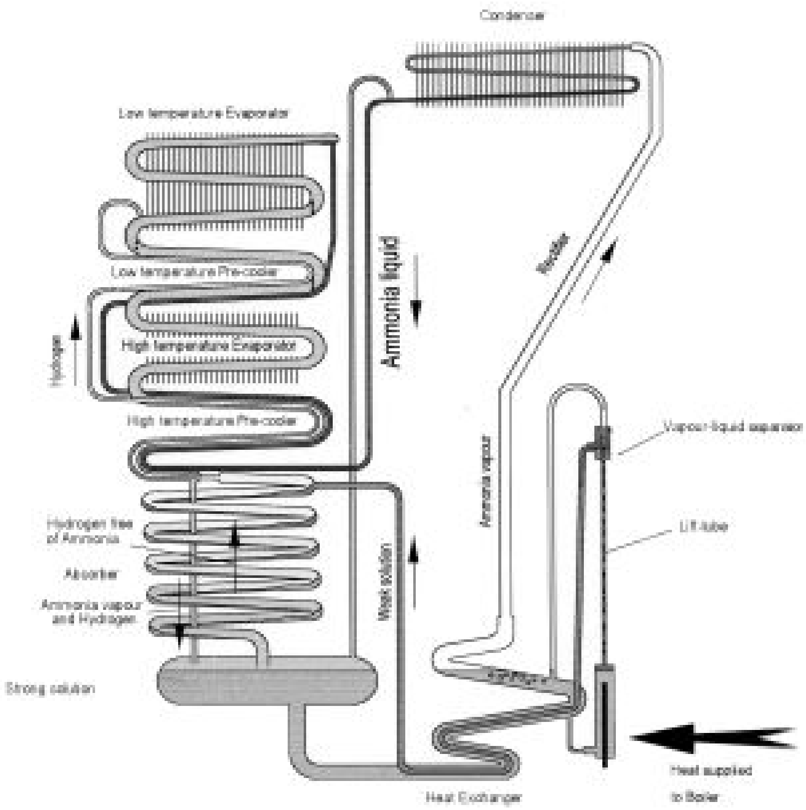


Figure 1: Diagram of a diffusion absorption refrigerator

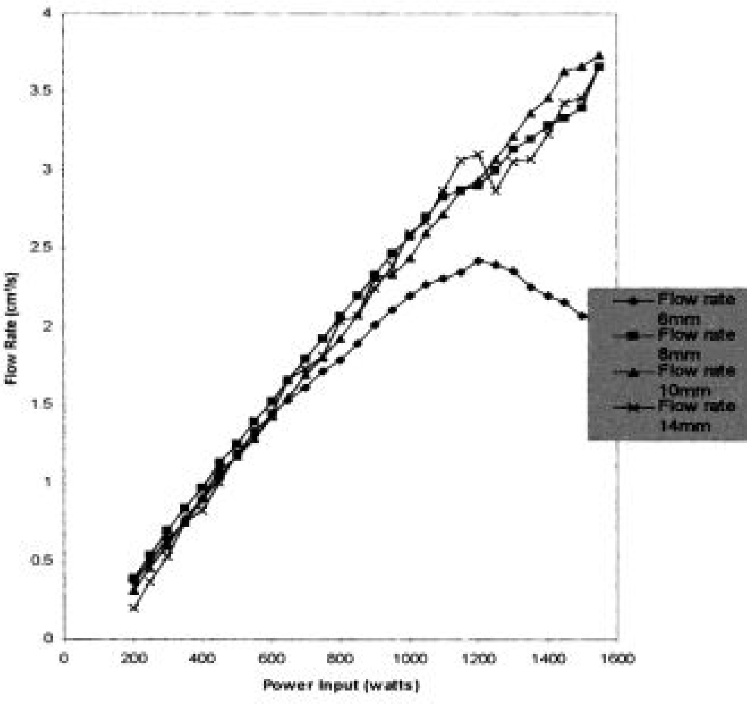


Figure 2: Characteristics of a single lift tube bubble pump
Source: Lister (1996)

It has been shown through experiment (Figure 2) and theoretical considerations that the diameter of the lift tube has no effect on the pumping rate if the pump is running in the slug or churn flow regimes, for a specific heat input (Lister 1996; Nicklin 1963).

It is observed in Figure 2 that the efficiency of the pump will eventually decrease as the vapour volume rate, which is directly related to the heat input, is increased. This is a result of the flow pattern within the lift tube, changing from slug to annular flow with increased vapour volume rate.

There is a maximum tube diameter above which slug flow will not occur. Equation 1 predicts this occurrence (Chisholm 1983), indicating a restriction on the use of larger diameter lift tubes at high vapour volume rates whilst retaining pumping ability.

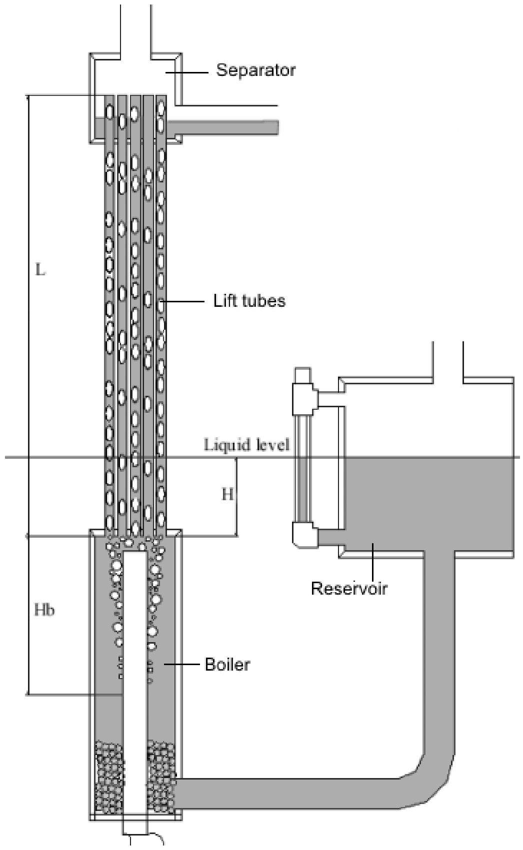
$$d = 19\left(\frac{\dfrac{\sigma}{\rho_f}}{g\left(1-\dfrac{\rho_v}{\rho_f}\right)}\right) \tag{1}$$

The phenomenon predicted by the above equation has also been observed in experimentation, and was found that after a maximum lift-tube diameter has been exceeded, there is a change in the flow pattern from slug flow to an intermittent churn-type flow [Jeong *et al.* 1998; Lister 1996; Pfaff 1998). Excessively large tube diameters caused pumping to stop altogether. Pfaff et al [12] found it to be an 18 mm diameter tube for their particular set-up. Jeong *et al.* (1998) found a similar type of phenomena, and classified this restriction as the discharge limit. They also found that after a certain pumping height is exceeded, the pumping action stopped. They noted that as the lift tube diameter increases the maximum pumping height decreases. This further restricts the diameter of the lift tubes if it is to be used on tall machines.

3 Findings and discussions

Two types of apparatus were built to test a multiple lift tube bubble pump.

- A closed circuit water rig was designed to maintain a constant pressure and also to accommodate a number of lift tubes. The constant pressure was maintained by regulating nitrogen from a high-pressure cylinder. The results aided to the development of a mathematical model that enabled the prediction of liquid and vapour rates for multiple lift tube bubble pumps.
- A locally manufactured diffusion absorption refrigerator was adapted to utilise a multiple lift tube pump in order to view its effect on the refrigerator's performance.



L = 445 mm, H = 65 mm H_b=approximately 100 mm, lift tube diameter = 0.006 m, heating element 20 mm and boiler diameter 65 mm

Figure 3: Diagram of the experimental multiple lift tube bubble

3.1 Findings and discussion of the water lift tube results

The layout of the experimental bubble pump rig is seen in Figure 3, and consists of a boiler, lift tube and separator. The remainder of the water rig (not shown in Figure 3) is designed to recover heat and return the water to the reservoir. A submergence ratio (ratio of initial head to pumping head, H/L) of 0.15 was chosen to allow comparison with Lister's experiments in Figure 2.

The boiler was heated by using a variable power electric heater submerged in the liquid, with sufficient power to change the flow pattern within a single lift tube from bubble to annular flow (see Figure 2).

3.1.1 Test results for increased lift tubes numbers and pressure

All four graphs of Figure 4 (overleaf) show that, for every pressure set-up, adding lift-tubes, it increases the pump's ability to handle larger heat loads and flow rates before a flow pattern change occurs. These graphs form the focal point of this investigation because they can be extrapolated to cater for increased pressure, more tubes, more power input and therefore more liquid flow rate.

Comparing these results, it can be seen that more energy is needed, for a given flow rate, as the pressure is increased. It is also noted that with an increase in pressure, the curves indicate an increase in the discontinuity at the flow pattern transition region. It is therefore expected that at even higher pressures (the operating of the fridge) the discontinuity will be severe. This region is to be avoided in the operating conditions of the unit, and the prediction model must indicate this critical region and calculate the bubble pump performance at maximum liquid flow.

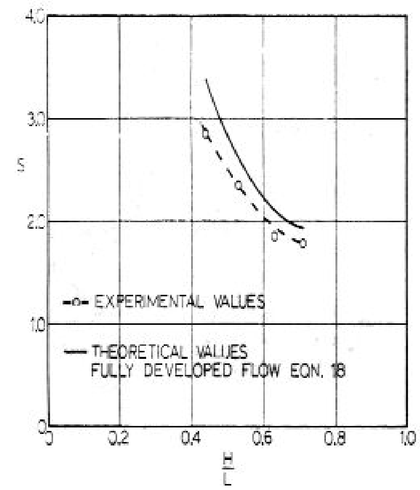


Figure 5: Graph of Slip values for specific submergence ratio values 's'
Source: Stenning et al. (1968)

3.1.2 Mathematical solution

The mathematical prediction model proposed by Stenning and Martin (1968) shows good correlation with experimental data found by other researchers (Delano 1998; Schaefer 2000). This model has been modified for the use with the current bubble pump arrangement.

The overall equation for the prediction is:

$$\frac{(H+\Delta h)}{L}-\left(\frac{1}{1+\frac{\dot{V}_g}{s\times\dot{V}_f}}\right)=\frac{\left(\frac{\dot{V}_f^2}{n\times(A_t^2)}\right)}{2\times g\times L}\times\left((K+1)+(K+2)\times\frac{\dot{V}_g}{\dot{V}_f}\right) \quad (2)$$

and must be solved iteratively. Where s is the slip ratio defined as:

$$s=\frac{V_g}{V_f} \quad (3)$$

and can be found in figure 7. The loss coefficient K is:

$$K=\frac{4\times f\times L}{n\times d} \quad (4)$$

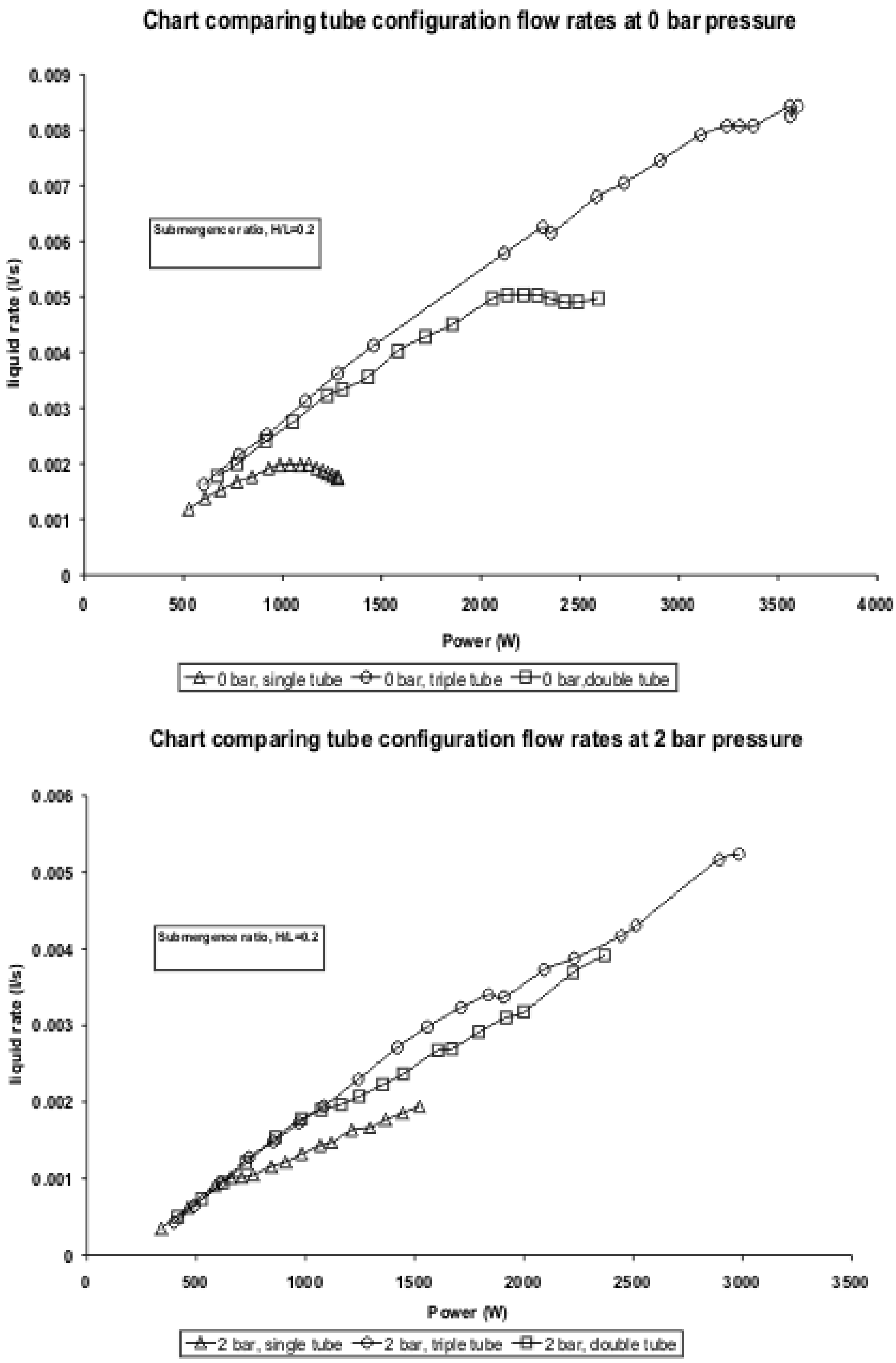


Figure 4 (first part): Comparison of tube configuration for 0, 2, 4 and 6 bar pressures

The coefficient K accounts for losses in the pump. It can also be found by experiment [5].

$$\Delta h = H_b \times \left(1 - \frac{\rho_b}{\rho_f}\right) \tag{5}$$

H_b is the depth that vapour occurs within the boiler and Δh is the added pumping effect of the boiler, accounted for by increasing the submergence ratio.

$$\rho_b = \frac{\dot{V}_g \times \rho_g}{V_{bg} \times A_T \times 3} + \rho_f - \frac{\dot{V}_g \times \rho_f}{V_{bg} \times A_T \times 3} \tag{6}$$

$$V_{bg} = 1.53 \times \left(\frac{g \times \sigma \times (\rho_f - \rho_g)}{\rho_f^{\,2}}\right)^{\frac{1}{4}} \tag{7}$$

V_{bg} is the gas rising velocity. [15]

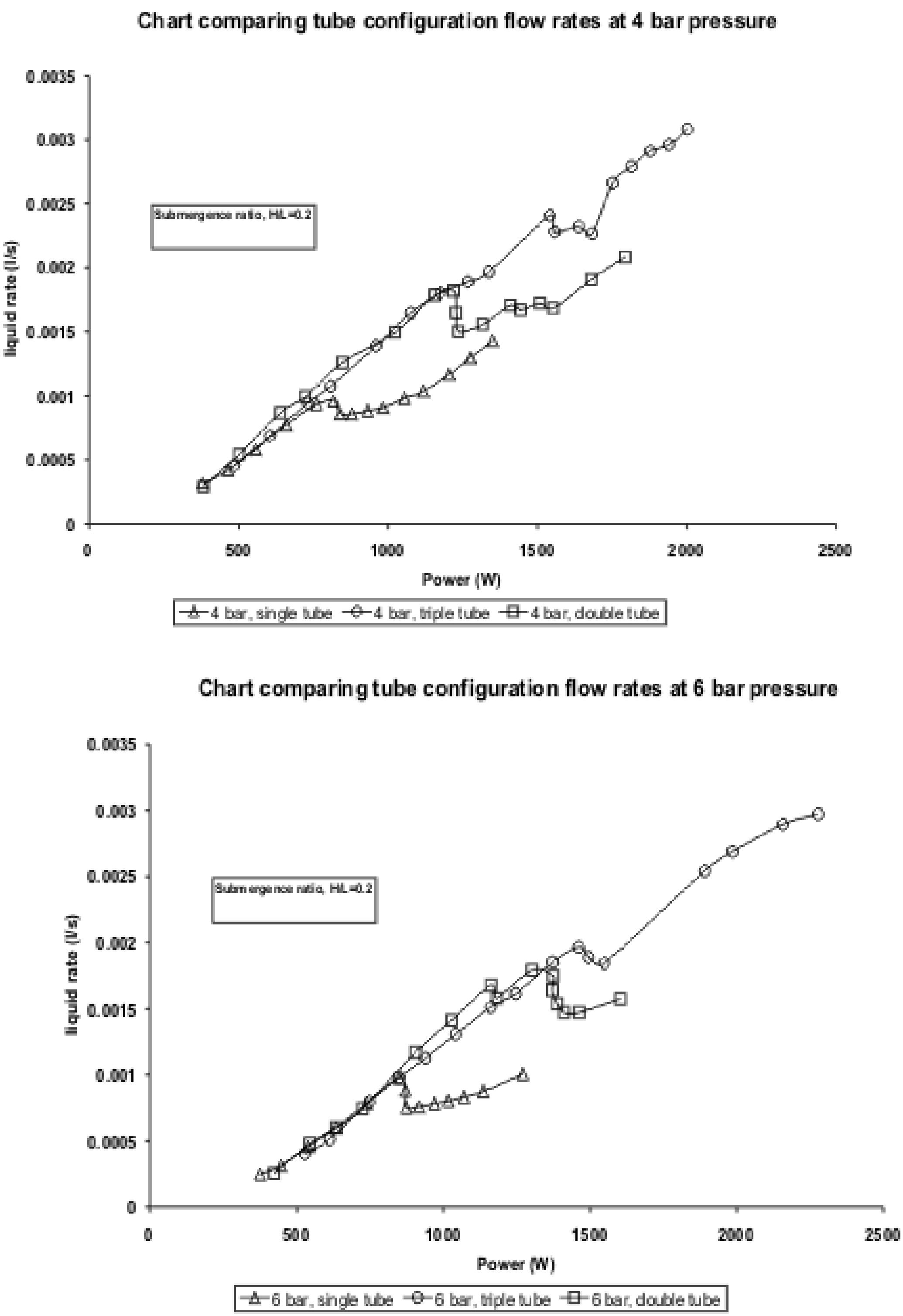


Figure 4 (continued): Comparison of tube configuration for 0, 2, 4 and 6 bar pressures

Once the volume rates are predicted, the energy necessary to heat and create these rates can be calculated. This is done using the properties of water and basic heat equations, knowing that:

$$Q_{total} = Q_{temp\_rise} = Q_{boil} + Q_{loss} \qquad (8)$$

The graphs plotted in Figure 6 are for 1 tube, 2 tubes and 3 tubes respectively. The data points have been plotted against the mathematical model predictions. The graphs show the model's capability in predicting volume rates for multiple lift tube pumps as well as changes in the flow regimes thus setting the upper limit of operating power input.

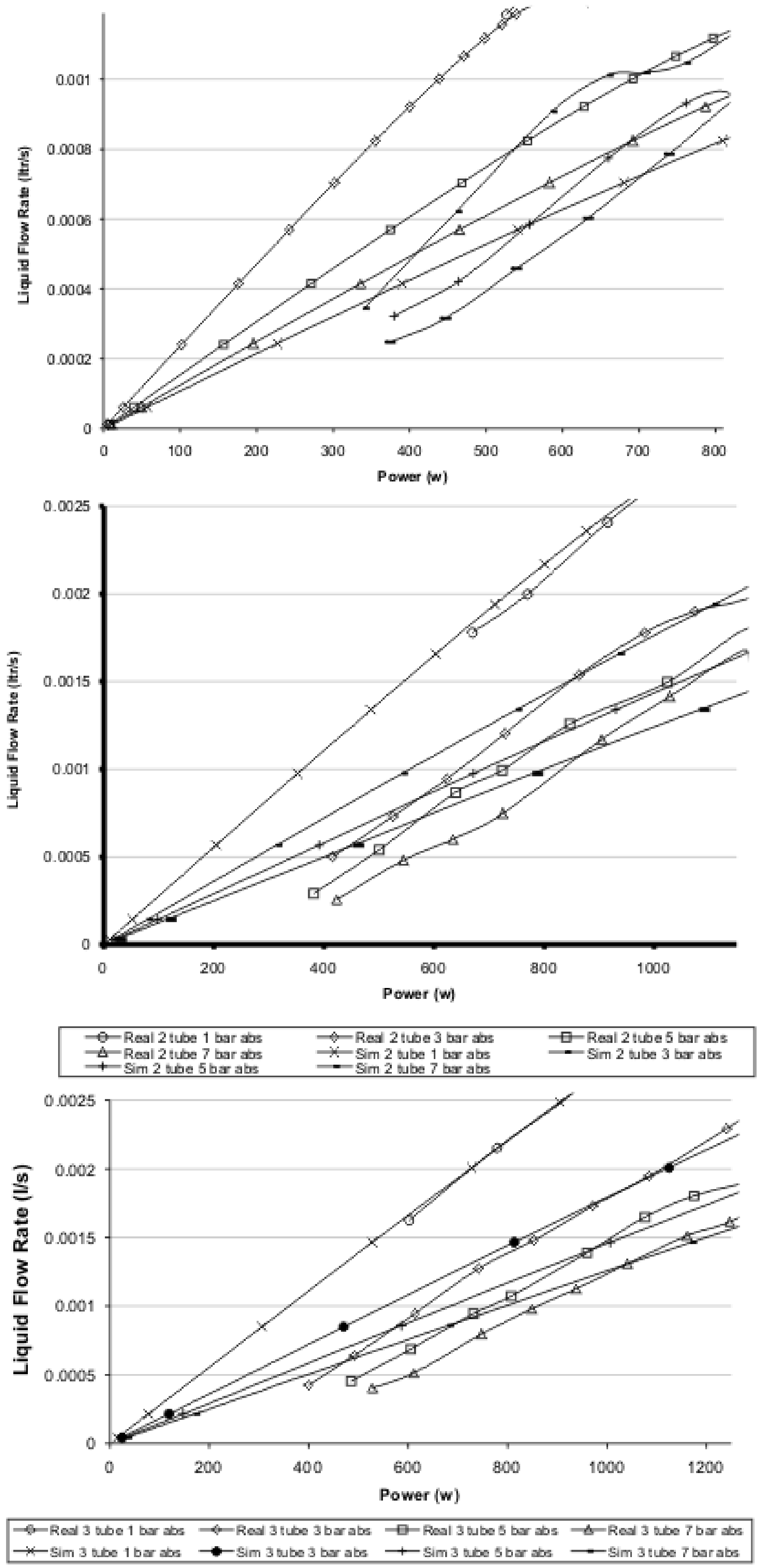


Figure 6: Graphs comparing the real and the mathematical data

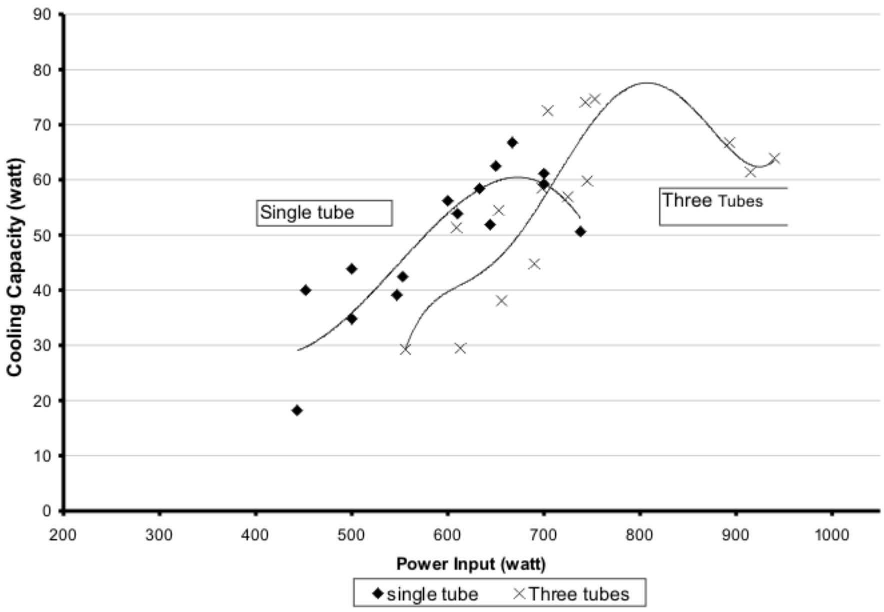


Figure 7: Performance of the refrigerator with respect to the heat input

3.2 Findings and discussion on the refrigerator's performance

According to Vicatos (1995), modifying an existing unit to accommodate major changes affecting fluid circulation, leads to invariably poor performance and unpredictable behaviour of the unit's components. Despite this, the authors felt necessary to perform experiments on the absorption rig to corroborate the expected increase in capacity with an increase in fluid circulation.

3.2.1 Refrigeration performance

Figure 7 shows the cooling performance of the refrigerator as heat input and is varied. From the graph it can be deduced that the COP of the refrigerator is low, constantly less than 10%.

The general trends of the curves indicate a cooling capacity increase with an increase in the number of lift tubes. It also shows a steep drop in performance after certain power input has been reached, which is a culmination of:

1. The rectifier is unable to cope with the increased water vapour and heat flux.
2. The absorber's inability to cool the solutions.
3. The absorber's inability to absorb the vapours from the evaporator.

3.2.2 Performance of the absorber

Having as a reference the problematic behaviour of the three-fluid-system due to the inadequate design of the absorber as described by Vicatos (1995), particular importance was given to the adequate cooling of the absorber.

A temperature rise within the absorber would slow the ammonia absorption rate, resulting in an ammonia build up in the evaporator, increased ammonia partial pressure, an increased temperature, and a drop in refrigeration effect and capacity. In addition to this, inadequate cooling of the heat generated due to absorption and the heat carried by the weak solution, would result in a hotter cold-strong solution and subsequently a poor performance of the liquid heat exchanger.

3.2.4 Performance of the liquid heat exchanger

The function of the liquid heat exchanger is to recover heat energy from the weak solution coming from the boiler, enabling a large heat input saving. One would expect a liquid-liquid heat exchanger to have an average effectiveness higher than 0.95 (Vicatos & Zulu 2002) but only 0.82 was achieved. Its performance worsened as the number of lift tubes and heat input was increased, showing that the heat exchanger was outside its designed characteristics.

3.2.5 Boiler response to increased number of lift tubes

Referring to Figure 8, it is noted that the boiler temperature is reduced with the addition of lift tubes. This is a result of a combined effect of the heat exchanger's performance and a higher liquid flow rate as indicated by Figure 4.

4 Conclusions

From the data and results obtained it can be seen that a multiple lift tube bubble pump is a viable and workable solution to increase the refrigeration capacity in diffusion absorption refrigeration plants. The addition of extra lift tubes supply a constant fluid/vapour ratio as the single lift tube does, but at

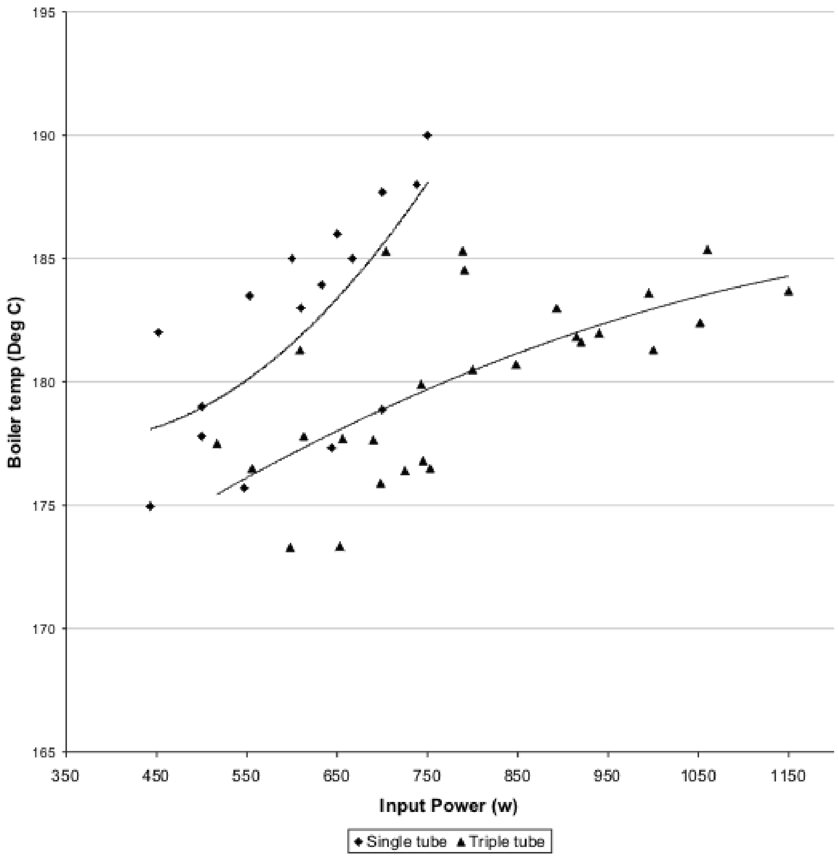


Figure 8: Temperature of the boiler

increased heat inputs beyond the single lift tube capabilities.

Previous studies such as (Vicatos 1995; Vicatos & Zulu 2002; Zulu 2000) indicate that the absorption machines are sensitive to their working environment and produce the desired performance only if the components operate within their designed parameters. Therefore, it can be strongly stated that the poor performance of the experimental refrigeration unit was not due to experimental errors and construction inaccuracies, but due to taxing the performance of each component of the unit beyond its design characteristics. Nevertheless, the fact that the unit showed an increasing refrigeration capacity with increasing the heat input and number of tubes, the authors believe that a much better response would have been obtained, if three separate units were build and tested for each of the number of tubes in the experiment. In addition, all the components should have been sized accordingly, to accommodate the maximum heat fluxes in the system.

Research has shown (Vicatos 1995) that absorption systems could attain COP values as high as 0.6, while the experimental rig attained a maximum of 0.1. It is therefore felt that with a redesigned system, a much higher COP can be achieved.

For refrigerator design purposes it is necessary to know the refrigerant flow rates, as it will be the parameter determining the desired cooling required and the sizing of all the components of the unit. The refrigerant flow rate is translated to the vapour flow released from the rectification column, which in turn, is linked to the vapour produced by the boiler. This in turn is associated with the solution flow rates, of which the weak solution depends on the bubble pump performance. Therefore, a refrigeration demand must meet a new design with a specific weak solution flow rate. The mathematical model will be able to predict the required tube diameters, tube numbers and submergence ratio that will result in a successful pump design and hence a refrigeration unit.

Nomenclature

A	Area m^2
d	Diameter m
f	Friction factor
g	Gravitational constant m/s^2
H	Initial head m
H_b	Bubble depth in boiler m
h	Height m
K	Loss coefficient t
L	Length of the lift tube m

n	Number of lift tubes
Q	Heat energy Watt
s	Slip ratio
V	Velocity m/s
Vol	Volume m^3
$\dot{V}$	Volume flow rate m^3/s
μ	Viscosity
ρ	Density kg/m^3
σ	Surface tension

Subscript

b	Boiler
g	Gas
f	Fluid
l	Lift tube

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