CHAPTER VI

Test Results and Discussion

This chapter provides the experimental and calculation results obtained from the experimental DAR. The effects of heat input to the generator, rectifier temperature, and auxiliary gas pressure on the system performance are presented. During the tests, while one parameter was varied the other two were maintained. It was tested with the generator heat input between 1000 to 2500 W, helium pressure of 6.0 to 10 bar. The rectification temperature was set between 50 and 90°C.

Cooling capacity between 100 to 200 W and COP between 0.07 to 0.17 was obtained. The actual results are compared with calculated values based on the model developed in chapter 5. Actual performances were found to depend on the evaporator and absorber mass transfer performance. The bubble pump characteristic was also found to be an important parameter.

6.1 Experimental procedure

During the tests, performance parameters such as temperatures, pressures, heat input to the generator, and cooling capacity were recorded. The heat input to the generator was equal to the electrical power supplied to the heater. Cooling load to the evaporator was provided by mean of circulation of water through the evaporator coil. For each test, 30 kg of fresh water in a well-insulated icebox was chilled from 30°C down to 0°C. A small aquarium pump (17 W) was used to circulate the water. During the tests, it was found that temperature of the chilled water decreased at an almost constant rate. Thus it might be considered that the cooling capacity was independent from the water temperature or constant throughout the operating period. Therefore, the cooling capacity at the evaporator could be determined as:

$$\dot{Q}_{evap} = \frac{m_{water} Cp(T_2 - T_1)}{\Delta t} + 17\,\mathrm{W} \tag{6.1}$$

where

m_{water}	mass of water in the icebox (30 kg)
C_P	specific heat capacity of water (4200 J·kg^{-}1·K^{-1})
T_1	the starting temperature (30°C)
T_2	the final temperature (0°C)
Δt	time (second)

Coefficient of Performance was then obtained from:

$$COP = \frac{\dot{Q}_{evaporator}}{\dot{Q}_{generator}} \tag{6.2}$$

COP obtained from the above equation was a measure of overall performance and included all the unwanted heat losses and gains to the system.

Before the tests, the system was evacuated. The absorber and generator were filled with 7 liters aqueous solution of ammonia with mass concentration of 0.25. The system was left to reach equilibrium with surrounding. Then it was charged with helium until the required pressure was achieved.

6.2 Effect of the generator heat input to the system performance

Figures 6.1 and 6.2 show plots of cooling capacity and COP of the experimental refrigerator. It was operated over a range of generator heat input. It was charged with helium pressure of 6.8 bar and operated within rectification temperature range of 75-80°C. It was discovered that there was a minimum generator heat input required to start the experimental refrigerator. Below the minimum heat input, it would not operate or produce any cooling effect. When the heat input was increased beyond the minimum value, the obtained cooling capacity increased sharply. As the heat input was increased further, the cooling capacity increased slightly. Variation of the COP was similar to the cooling capacity when the heat input was low. However, the COP increased to a maximum value, then it dropped as the heat input continued to increase. It contrasted with the case of the cooling capacity, which continued to increase.

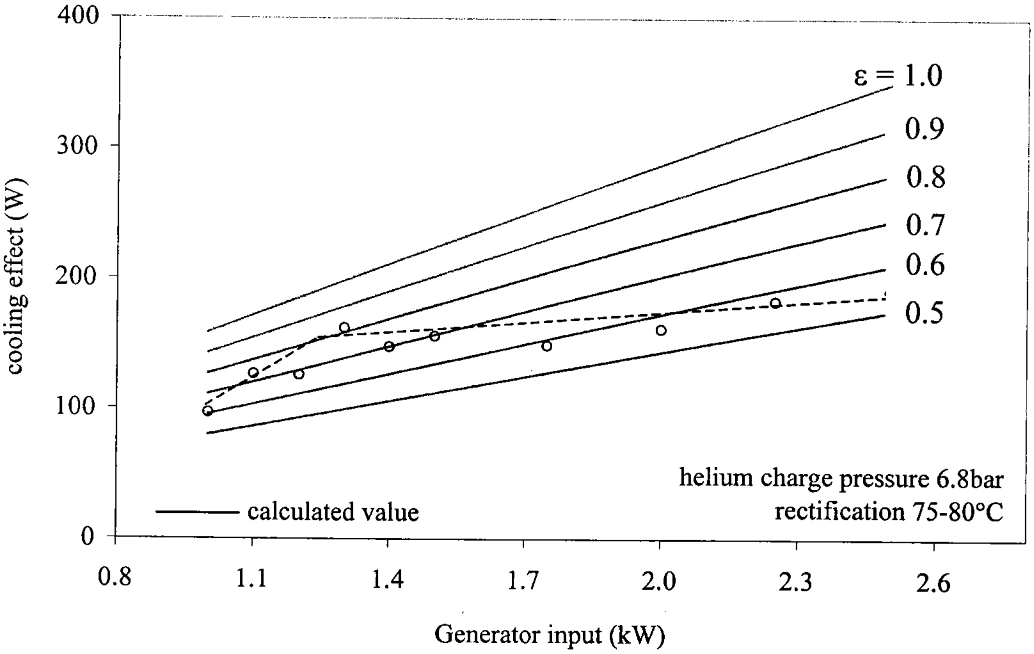

Figure 6.1 Cooling effect of the system with variation of input heat at the generator.

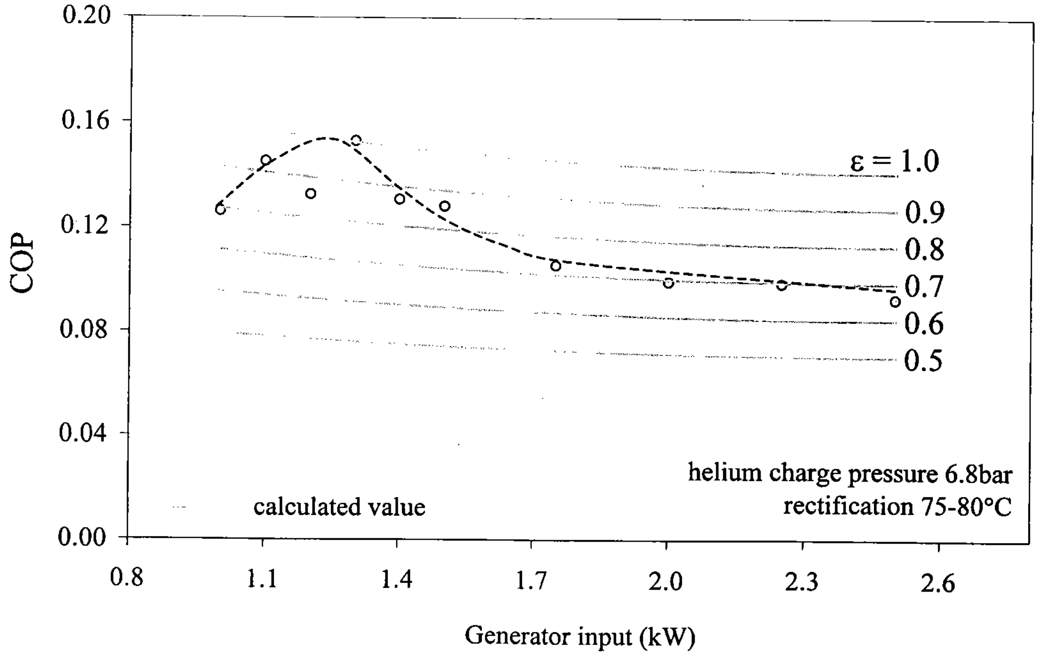

Figure 6.2 COP of the system with variation of input heat.

When the generator heat input is lower than the minimum value, the system cannot produce any cooling effect. This is due to the bubble pump characteristics. To obtain a pumping effect, a minimum vapor generated is required. When the heat input is too low, there is not enough vapor to drive the pump. This means that only the refrigerant vapor is produced. This refrigerant will be liquefied and enter the evaporator. However, it cannot evaporate and produce any cooling effect since there is no liquid flowing to induce absorption of the refrigerant vapor. When the heat input is increased beyond the minimum value, the pumping effect occurs. The liquid will be circulated to the absorber and absorb the refrigerant vapor. Thus, a cooling effect is produced. Further increase in heat input will produce a higher cooling effect as more refrigerant vapor is generated and more liquid is pumped to the absorber. This also causes the COP to increase. From figure 6.1, it can be seen that when the heat input continues to increase beyond a certain point (about 1300 W), the cooling capacity will increase with a lower rate. This implies that the cooling capacity is limited by the evaporator or absorber mass transfer performance. As the increased rate of cooling capacity does not match with the rate of heat input, this results in a drop of the COP.

Cooling capacity is strongly dependent upon the evaporation and absorption rates, which depend on area of wetted surface. To evaporate all refrigerant, there must be enough surface for evaporation (the evaporator coil on which the liquid refrigerant is evaporated) and enough surface for absorption (absorber column on which the ammonia vapor is absorbed). When there is an increase in the generator heat input the mass flow of ammonia is increased. However, the evaporator and absorber surfaces are fixed. This may not be enough for all the ammonia to evaporate or to be absorbed. When the refrigerant flow is increased due to the increased generator heat input, the cooling capacity might not increase. This is because it cannot be completely evaporated or absorbed. It should be noted that during the tests, it was observed through the sight glass that the absorber column and evaporator coil were not completely covered with liquid.

When the liquid refrigerant is completely evaporated in the evaporator, the concentration of solution obtained at the end of the absorber column is equal to that accumulated at the bottom of the absorber. If the ammonia cannot completely evaporate, the concentration of solution obtained at the end of the absorber column is lower than that accumulated at the bottom of the absorber. For the first case, the absorber-evaporator effectiveness (equation 5.18) is exactly equal to unity. For the second case, the effectiveness is lower than one.

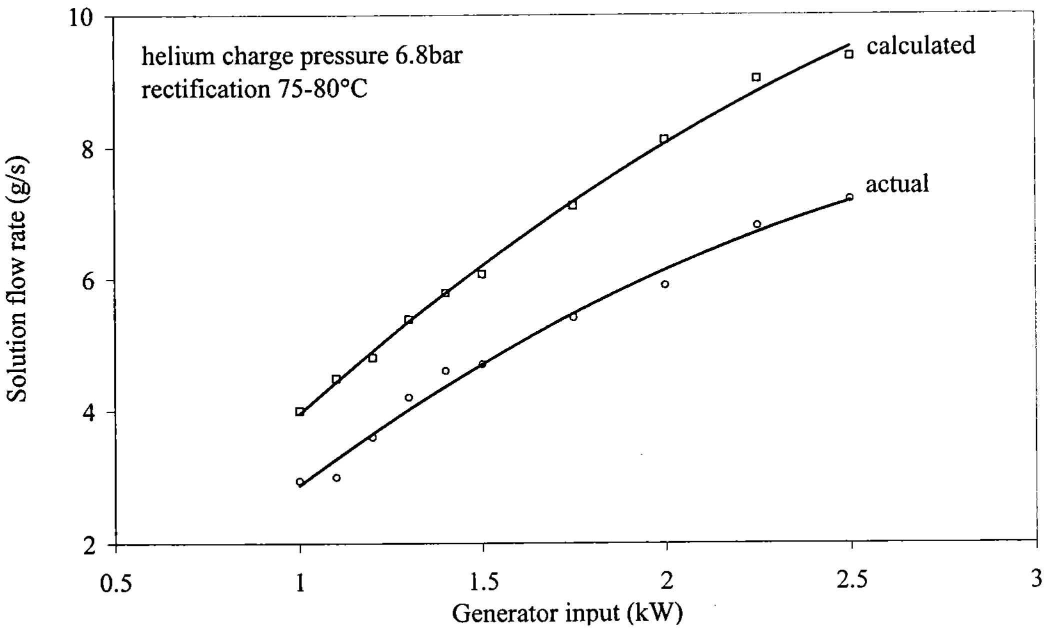

Figure 6.3 Calculated VS actual solution flow rate at various heat input.

Comparisons of actual and calculated mass flow rate of liquid solution through the pump tube versus generator input are provided in Figure 6.3. The actual results were found to lie between 70 to 80% of the calculated values. The difference may result from heat loss from the generator and pump tube. At the generator, it causes less vapor to be generated. At the pump tube, it causes condensation of the vapor. Other reasons may be the properties of the fluid. The pump performance (equation 5.3) was obtained using air and water as the test fluid rather than aqueous ammonia solution. It must be noted that if 10% heat loss is included, the calculated values will be closer to the actual values.

Referring to the figures 6.1 and 6.2, it can be seen that the calculated cooling capacity increases almost linearly with the generator heat input. When there is an increase in the generator input, more vapor is generated and more liquid is pumped. This causes more refrigerant to enter the evaporator and more liquid to enter the absorber. Based on the model developed with an effectiveness of one, all liquid refrigerant is evaporated in the evaporator and maximum cooling capacity is obtained. When the effectiveness is reduced, all liquid refrigerant does not completely evaporate in the evaporator. The cooling capacity drops and the unevaporated liquid just returns to the absorber without producing any cooling effect.

At a heat input approximately below 1300 W, both actual and calculated cooling capacity increase with the generator heat input. It can be noted that the actual cooling capacity is compatible with calculated value with effectiveness between 0.5 and 0.7. It could be implied to be a result of the absorber and evaporator performance. To absorb refrigerant vapor into solution or to evaporate liquid refrigerant, a certain amount of wetted surface area is required. With low heat input, the amount of liquid refrigerant entering the evaporator and liquid solution entering the absorber is small. Liquid film cannot be formed properly on the evaporator coil as well as on the absorber column. This reduces the evaporation and absorption rates, which effects the cooling capacity. Thus the actual cooling capacity is compatible with the calculated value of low effectiveness. As the heat input increases, more refrigerant and solution are circulated in the system, and a better liquid film on the absorber column and on the evaporator coil will be obtained, this results in better evaporation and absorption rates. Therefore, the actual cooling capacity is compatible with calculated values having high effectiveness.

For the generator input greater than 1300 W, the actual cooling capacity was almost constant (slightly increasing with heat input). Even though more refrigerant is generated with increased heat input, the cooling capacity is fairly constant due to limited mass transfer surfaces of the evaporator and the absorber. The slight increment may result from higher mass transfer coefficient due to an increase of solution flow rate. This resulted in a drop of effectiveness when compared with the calculated value.

6.3 Effect of helium charged pressure on the system performance

Helium charge pressure is a key parameter in the operation of the DAR. The system will fail to operate if the charge is too low. However, overcharge of helium will cause too high operating pressure due to existence of partial pressure of ammonia in the condenser. This can be realized by comparing the actual system pressure and ammonia saturation pressure at the condenser temperature.

The bubble pump can be driven by vaporized solution in the generator. According to the actual results and mathematical model discussed in chapters 4 and 5, performance of the bubble pump depends on the amount of vapor volume. The higher the generator heat input, the more vapor is generated. Knowing that specific volume of any vapor varies with its pressure, for the same mass of vapor generated, its volume should be less when the system pressure is increased. Therefore, the helium charge pressure should affect performance of the bubble pump. For a given heat input to the generator, when the helium charge pressure is increased, the amount of liquid being pumped is decreased.

The experimental refrigerator was charged with helium pressure of 6.1, 6.8, and 10.2 bar. These pressures were measured when the system was not operated. It was found that helium charge pressure caused effect on system performance, cooling capacity, COP, and minimum generator heat input requirement.

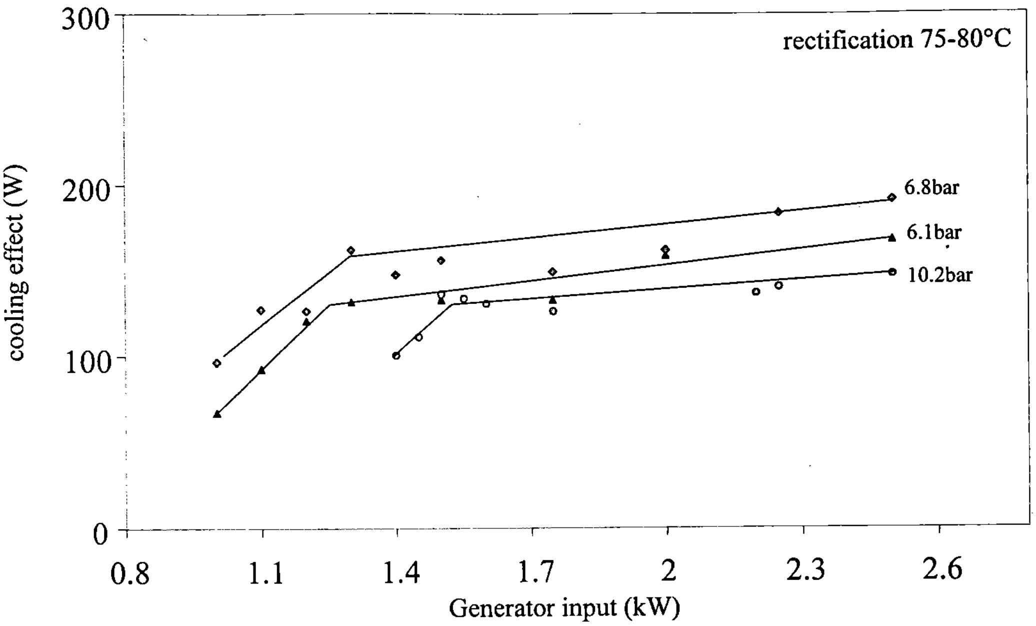

Figure 6.4 Cooling capacity with variation of heat input at various helium charge pressure.

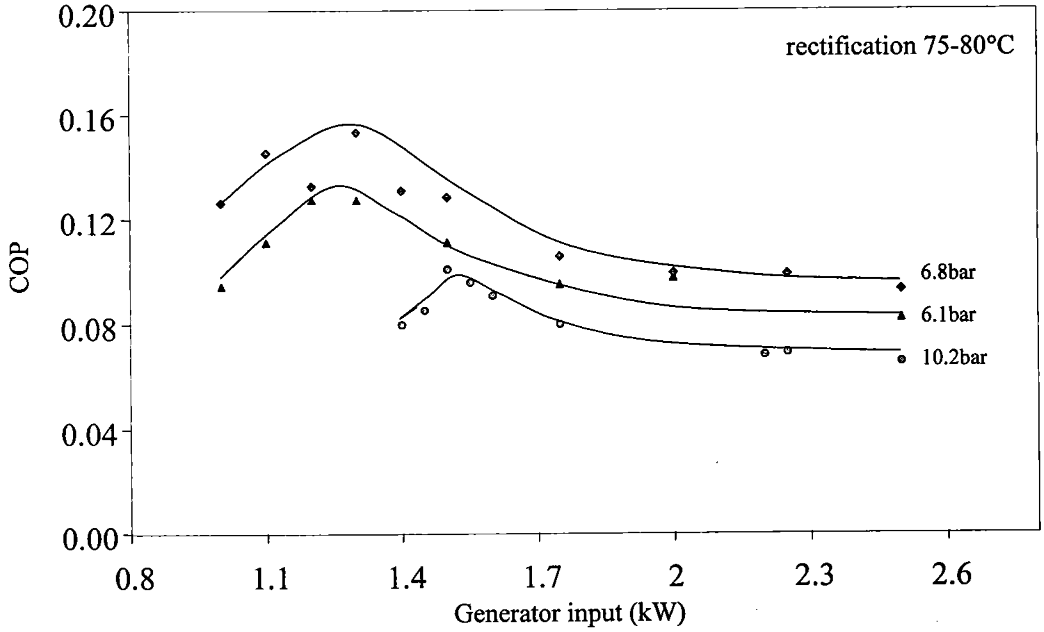

Figure 6.5 COP with variation of heat input at various helium charge pressure.

The minimum heat input required was shifted to the higher value when the helium charge pressure was increased from 6.8 to 10.2 bars as shown in Figure 6.4. For the same amount of heat input to the generator, the amount of refrigerant generated was slightly increased (as less liquid was pumped and more heat was used to generate the vapor) when the helium charged pressure increased. However, the cooling capacity dropped with increased helium charge pressure. It would result from less liquid solution circulating in the absorber. Thus less ammonia could be absorbed and so a reduction of cooling effect was obtained.

When the helium charge pressure was increased from 6.1 to 6.8 bar, the effect of helium charge pressure to the minimum heat input required was not significant. It is not clearly shown on the figures. However, it can be expected that the effect of helium charge pressure to the bubble-pump performance would be similar to that for the previous case. In contrast with the previous case, it was found that the cooling capacity and COP dropped with decrement of helium charge pressure from 6.8 to 6.1bar. The drop of cooling capacity (even more liquid solution is pumped and circulated in the absorber) could result from increment of ammonia evaporation temperature in the evaporator. With decreased helium charge pressure, the ammonia partial pressure in the evaporator will increase. It causes a higher ammonia evaporation (saturation) temperature. As the differential temperature between ammonia (evaporate outside the coil) and chilled water (circulate in the coil) is reduced, the heat transfer rate will drop. This causes less ammonia to evaporate and certainly less cooling effect is produced.

Too much helium charged will reduce the liquid solution entering the absorber. It reduces the absorption capability and cooling capacity. Too low helium charge pressure, the ammonia partial pressure in the evaporator is high. This results in the ammonia evaporating at high temperature in the evaporator. As the differential temperature between refrigerant and chilled water reduce, less heat transfer capability to the ammonia and less cooling capacity would exist. It may be implied that for each operating condition, there is an optimum helium charge pressure.

6.4 Effect of rectification temperature on the system performance

The major disadvantage of using ammonia/water as working fluid is that at the generator water always evaporates with ammonia. Without a rectifier, the contaminated ammonia vapor will be liquefied and passed into the evaporator. In the evaporator, water causes ammonia to evaporate at a higher temperature for a given pressure. Thus, the unwanted evaporated water vapor will degrade the system performance. To enhance the system performance, a rectifier is needed to purify ammonia vapor before being liquefied in the condenser.

Figure 6.6 shows rectification process on a P-T-X-h diagram. The ammonia vapor leaving the separator (4) contains some water. The vapor is purified by being cooled in the rectifier (6). It condenses some ammonia and some water vapor as condensate (5). Therefore, the concentration and purity of vapor ammonia exiting the rectifier is increased (7). Relations between the mass entering and exiting the rectifier are:

$$\frac{\dot{m}_5}{\dot{m}_6} = \frac{X_7 - X_6}{X_7 - X_5} = \frac{h_7 - h_6}{h_7 - h_5} \qquad (6.3)$$

$$\frac{\dot{m}_7}{\dot{m}_6} = \frac{X_6 - X_5}{X_7 - X_5} = \frac{h_6 - h_5}{h_7 - h_5} \qquad (6.4)$$

These mass ratios can be obtained graphically as,

$$\frac{\dot{m}_5}{\dot{m}_6} = \frac{\overline{67}}{\overline{57}} \qquad (6.5)$$

$$\frac{\dot{m}_7}{\dot{m}_6} = \frac{\overline{56}}{\overline{57}} \qquad (6.6)$$

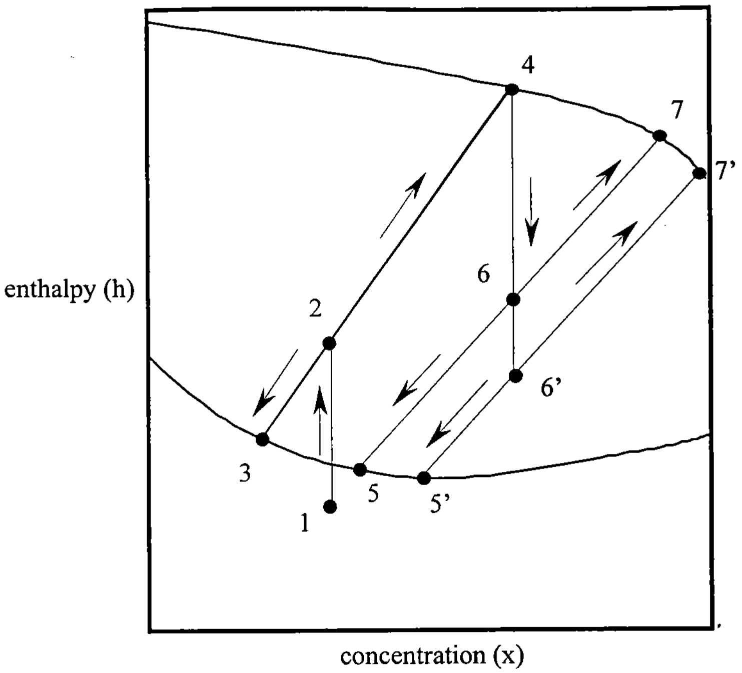

Figure 6.6 Generator and separator's process on P-T-X-h diagram.

Referring to Figure 6.6, if the rectification temperature is reduced from 6 to $6'$, the vapor will leave the rectifier at a higher concentration ($7'$) but at a lower quantity. The variation of rectification temperature effects the system performance. A higher rectification temperature yields more ammonia vapor having lower purity, while a lower rectification temperature gives less amount of ammonia but having higher purity.

Figures 6.7 and 6.8 show effects of rectification temperature on the system performance. They also show the calculated results compared with the actual values. From these Figures, it can be seen that the calculated cooling capacity and COP increase with the rectification temperature. This implies that, at a higher rectification temperature, more ammonia enters the evaporator and produces a higher cooling effect than at a lower rectification temperature. However, from the tests, the cooling capacity was fairly constant. The constant of the cooling capacity may result from low mass transfer performance of the absorber and the evaporator.

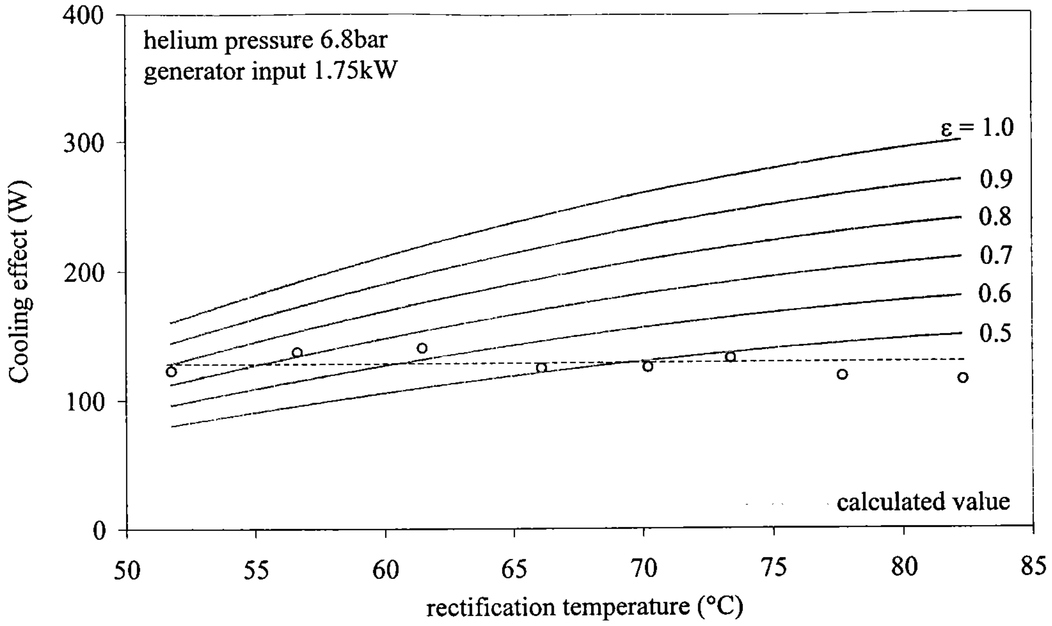

Figure 6.7 Comparison of experimental and calculated cooling capacity with variation of rectification temperature.

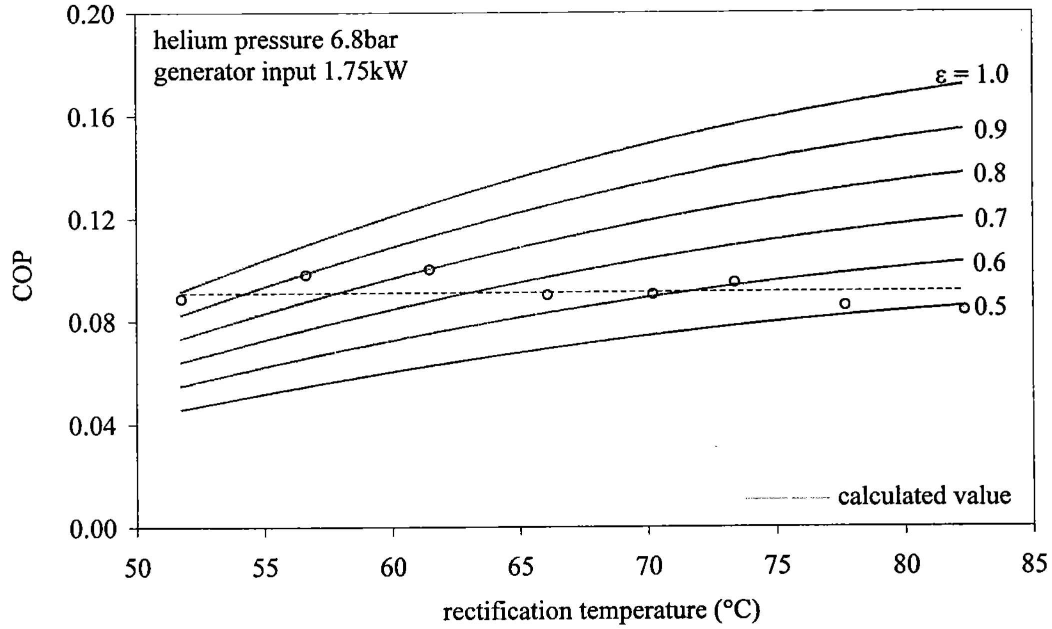

Figure 6.8 Comparison of experimental and calculated COP with variation of rectification temperature.

Alternatively, at a high rectification temperature, the purity of ammonia is low thus it evaporates at relatively high temperature in the evaporator. This results in a low differential temperature between the ammonia and the chilled water. Therefore, the cooling capacity remained unchanged even though there was more ammonia entering the evaporator.

6.5 Conclusion

The tested DAR was clearly found to be affected by variation of heat input at the generator and auxiliary gas charge pressure. There were related to each other. There was a minimum heat input level required to start the system operation. At a lower heat input than the minimum value, the system could not be operated. Increment of heat input increased the cooling effect until a transition point (maximum COP) was reached. Increased heat input beyond this point would not increase the cooling effect much. Thus, the COP was reduced with greater heat input beyond the transition point.

The minimum heat input required to start the system operation is affected by the auxiliary gas charge pressure. The required heat input level to start the system was greater with higher auxiliary gas charge pressure. It could occur as a result of less specific volume of vaporized solution in more pressurized system for a given mass of solution. Therefore, the onset of the bubble pump operation was shifted to a higher heat input level. However, with low helium charge pressure, the system was found to operate with lower performance. It could result from high partial pressure of ammonia in the evaporator, which increased the evaporation temperature of ammonia. Heat transfer performance should be reduced due to less temperature different between evaporated ammonia and chilled water circulated through the evaporator coil.

There was no significant effect obtained from the experimental results with variation of the rectification temperature. It was found that variation of the rectification temperature did not cause any effect on the bubble pump. The increased rectification temperature gave more refrigerant at the condenser but with less purity. It did not cause any increment of the absorption capability as the pumped solution was consistent. Therefore, there was no effect to the cooling capacity due to increased rectification temperature. Reduction of the rectification temperature did not affect the actual cooling capacity either.