INTRODUCTION

This paper is the first part of a two paper series. It provides theoretical studies of an absorption refrigerator using aqueous lithium bromide as the working fluid. Mathematical model was developed and used to study an absorption system over the range of operating temperature. In the second part, design and experimental studies of a 2 kW cooling capacity experimental refrigerator will be provided, [Aphornratana 1996]. Literature review on absorption refrigerators and heat pumps are already provided in the literature, [Aphornratana 1995].

A practical absorption refrigerator was first introduced in 1859 by Ferdinand Carré. The working fluids used were ammonia (as a refrigerant) and water (as an absorbent). These machines were used to make ice and store food. As the absorbent used is volatile, the system requires a rectifier to strip away the water normally evaporated with the ammonia as shown in Figure 1. To overcome this problem, a system using an aqueous lithium bromide solution (water is a refrigerant and lithium bromide is an absorbent) was introduced in the 1950's for industrial applications.

Figure 2 shows a schematic diagram of an absorption refrigeration cycle using aqueous lithium bromide. Refrigerant vapour flows from the evaporator to the absorber where it is taken into solution by the absorbent. A flow of refrigerant vapour is maintained by a boiling process within the evaporator, thus creating the necessary refrigeration effect. The absorption process is usually exothermic and, therefore, the absorber requires constant cooling to maintain its temperature. As the refrigerant enters the solution with the absorbent, the ability of the latter to absorb decreases. To maintain the strength of the absorbent, a quantity of the solution is continuously pumped, at high pressure, to the generator where it is heated causing the refrigerant to be driven out of the solution. The concentrated solution is then returned to the absorber via a pressure regulator valve. The high pressure refrigerant vapour flows from the generator to the condenser where it is liquefied and returned, via an expansion valve, to the evaporator, thus completing the cycle. A solution heat exchanger may be added to preheat the solution leaving the absorber using the hot solution returning from the generator. Thus the generator input and the absorber output are reduced and the Coefficient of Performance (COP) is improved. Normally the work input required by the solution pump is negligible relative to the energy input at the generator, therefore, the pump work is often neglected. The COP for the refrigeration cycle, is equal to the ratio of the heat absorbed at the evaporator to the heat input at the generator, therefore:

$$COP = \frac{\dot{Q}_{evap}}{\dot{Q}_{gen}} \quad (1)$$

MATHEMATICAL MODEL DESCRIPTIONS

For each component of an absorption refrigerator shown in Figure 2, their thermodynamic performance can be determined from mass and energy balances, thus, the following equations can be applied:

Heat input to the generator:

$$\dot{Q}_{gen} = \dot{m}_1 h_1 + \dot{m}_{10} h_{10} - \dot{m}_9 h_9 \quad (2)$$

Heat rejected from the condenser:

$$\dot{Q}_{con} = \dot{m}_3 h_3 - \dot{m}_2 h_2 \quad (3)$$

Energy balance at the refrigerant throttling valve:

$$\dot{m}_3 h_3 = \dot{m}_4 h_4 \quad (4)$$

Heat input to the evaporator (cooling capacity):

$$\dot{Q}_{evap} = \dot{m}_5 h_5 - \dot{m}_4 h_4 \quad (5)$$

Heat rejected from the absorber:

$$\dot{Q}_{abs} = \dot{m}_7 h_7 - \dot{m}_{12} h_{12} - \dot{m}_6 h_6 \quad (6)$$

Energy balance at the solution throttling valve:

$$\dot{m}_{11} h_{11} = \dot{m}_{12} h_{12} \quad (7)$$

Work input to the solution pump:

$$W_{pump} = \frac{\dot{m}_7}{\rho_7} (P_8 - P_7) \quad (8)$$

Solution Circulation Ratio:

$$SCR = \frac{\dot{m}_7}{\dot{m}_6} = \frac{X_{12}}{X_{12} - X_7} \quad (9)$$

The model together with the following assumptions was used to analyse thermodynamic performance of an absorption refrigerator over the range of temperatures.

- Lithium bromide solutions in the generator and the absorber were assumed to be in equilibrium at their respective temperatures and pressures.
- Refrigerant (water) in the condenser and the evaporator was saturated.
- Thermodynamic properties of non-equilibrium (subcooled) solutions were the same as the equilibrium values at the state with the same temperature and concentration.
- Pressure losses due to the friction in heat exchangers and pipe lines were neglected.
- Heat exchange between the system and surroundings other than that prescribed by heat transfer at the generator, evaporator, condenser and absorber do not occur.
- The solution heat exchanger has a minimum temperature difference of 20°C or the concentrated solution entering the absorber must have a temperature at least 10°C above crystallisation. If the temperature is reduced below the its saturated value, the crystallisation of solution will occur.
- Thermodynamic properties of lithium bromide solution were obtained from the correlation given by Patterson & Perez-Blanco [1988]. Thermodynamic properties of steam and water were obtained from correlations given by Irvine & Liley [1984].

DISCUSSION

Figures 3 to 6 show theoretical performance of an absorption refrigerator using aqueous lithium bromide. Based on the assumptions made, for the given operating temperatures, the calculated results present the best COP values for an absorption system. From the figures, the Solution Circulation Ratio (SCR) also has a strong effect on the COP; the lower the SCR, the higher the COP. This is because an increase in SCR requires more heat input at the generator (per unit mass of the refrigerant generated). This extra amount of heat is required to heat the subcooled solution (from the solution heat exchanger) to an equilibrium temperature, and is rejected to the environment at the absorber. This amount of energy may be defined as a circulation loss. The SCR can be reduced by increasing the concentration of solution in the generator or decreasing the concentration of solution in the absorber (see Equation 9). The concentration of solution increase when the temperature increases or the pressure decreases, and vice versa. From the figures, when the generator and evaporator temperatures increase or the condenser and absorber temperatures decrease, the SCR is decreased and improves the COP.

The use of a solution heat exchanger improves the performance as it reduces the circulation loss. As the diluted solution enters the generator, it is preheated by the concentrated solution returning to the absorber. Thus the heat input at the generator and the heat rejected at the absorber are reduced, and the result is an increase of the COP. The use of the solution heat exchanger becomes more important when the system is operated with high SCR.

From this, it can be said that the input to the generator depends on SCR and heat recovery at the solution heat exchanger. However, reducing the SCR by increasing the concentration of solution in the generator is not always possible. At temperatures above 100°C, lithium bromide solution is saturated at a concentration around 70% and decreases to 64 % at 0°C. If the solution is already saturated, reducing the pressure or increasing the temperature will cause the crystallisation, and the system can be no longer operated. Experiments conducted in the second part [Aphornratana 1996] show that crystallisation normally occurs at the inlet section of the throttling valve. The temperature of concentrated solution leaving the solution heat exchanger must be above its saturated value. When the cycle is operated with the solution in the generator close to the saturated condition, the effectiveness (heat transfer area) of the solution heat exchanger must be reduced to avoid crystallisation before it enters the throttling valve. For example, at the concentration of 62%, the solution from the generator can reject heat (via a solution heat exchanger) to a temperature as low as 30°C, while at the concentration of 65%, the solution temperature must be kept above 50°C in order to avoid the crystallisation.

CONCLUSIONS

In this paper, theoretical studies of an absorption refrigerator were described. A simple mathematical model was developed to analyse thermodynamic performance of an absorption refrigerator using aqueous lithium bromide as the working fluid over the range of operating temperatures. The results showed that the Solution Circulation Ratio (SCR) has a strong effect on the system performance. The Coefficient of Performance (COP) can not always be improved by raising the generator temperature due to the problem of crystallisation. In the second part of this paper series, experimental studies of an absorption refrigerator will be described.

NOMENCLATURES

COP	Coefficient of Performance
$\dot{m}$	mass flow rate ($kg.sec^{-1}$)
h	specific enthalpy ($kg.kg^{-1}$)
P	absolute pressure (kPa)
Q	heat energy rate (kW)

SCR	Solution Circulation Ratio (Equation 9)
W_{pump}	power input to the pump (kW)
X	mass concentration
ρ	density ($kg.m^{-3}$)

SUBSCRIPTS

1, 2, 3,...	see Figure 2
abs	absorber
gen	generator
con	condenser
evap	evaporator

REFERENCES

Aphornratana, S. (1994), "Theoretical and experimental investigation of a combined ejector absorption refrigerator", Ph.D. thesis, The University of Sheffield.

Aphornratana, S. (1995), "Research on absorption refrigerators and heat pumps", RERIC International Energy Journal, Vol. 17, No. 1, pp 1-19.

Aphornratana, S. (1996), "An aqueous lithium bromide absorption refrigerator: part II experimental studies", to be published.

Herold, K. E., and Radermacher, R. (1989), "Absorption heat pumps", Mechanical Engineering, Aug., pp 68-73.

Irvine, T. F., and Liley, P. E. (1984), "Steam and gas table with computer equations", Acade- mic Press, U.S.A..

Patterson, M. R., and Perez-Blanco, H. (1988), "Numerical fits of the properties of lithium-bromide water solutions", ASHRAE Trans., Vol. 94, Part 2, pp 2059-2077.

LIST OF FIGURES

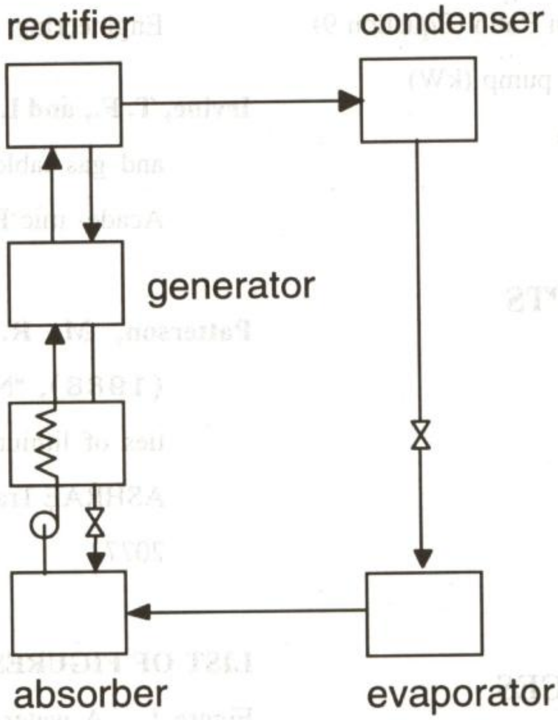


Figure 1

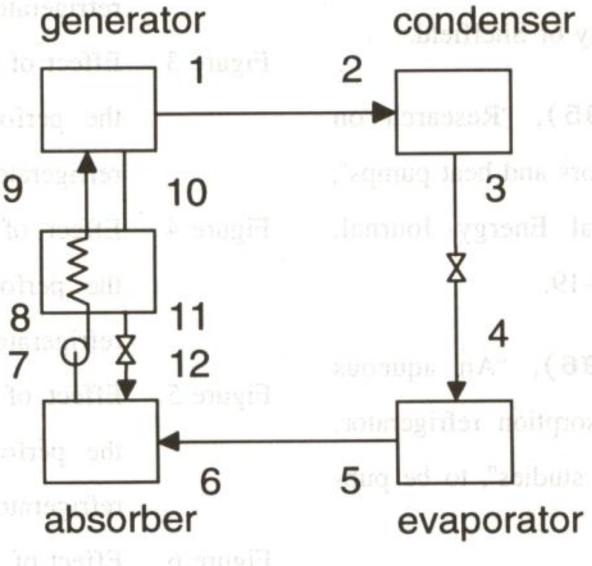
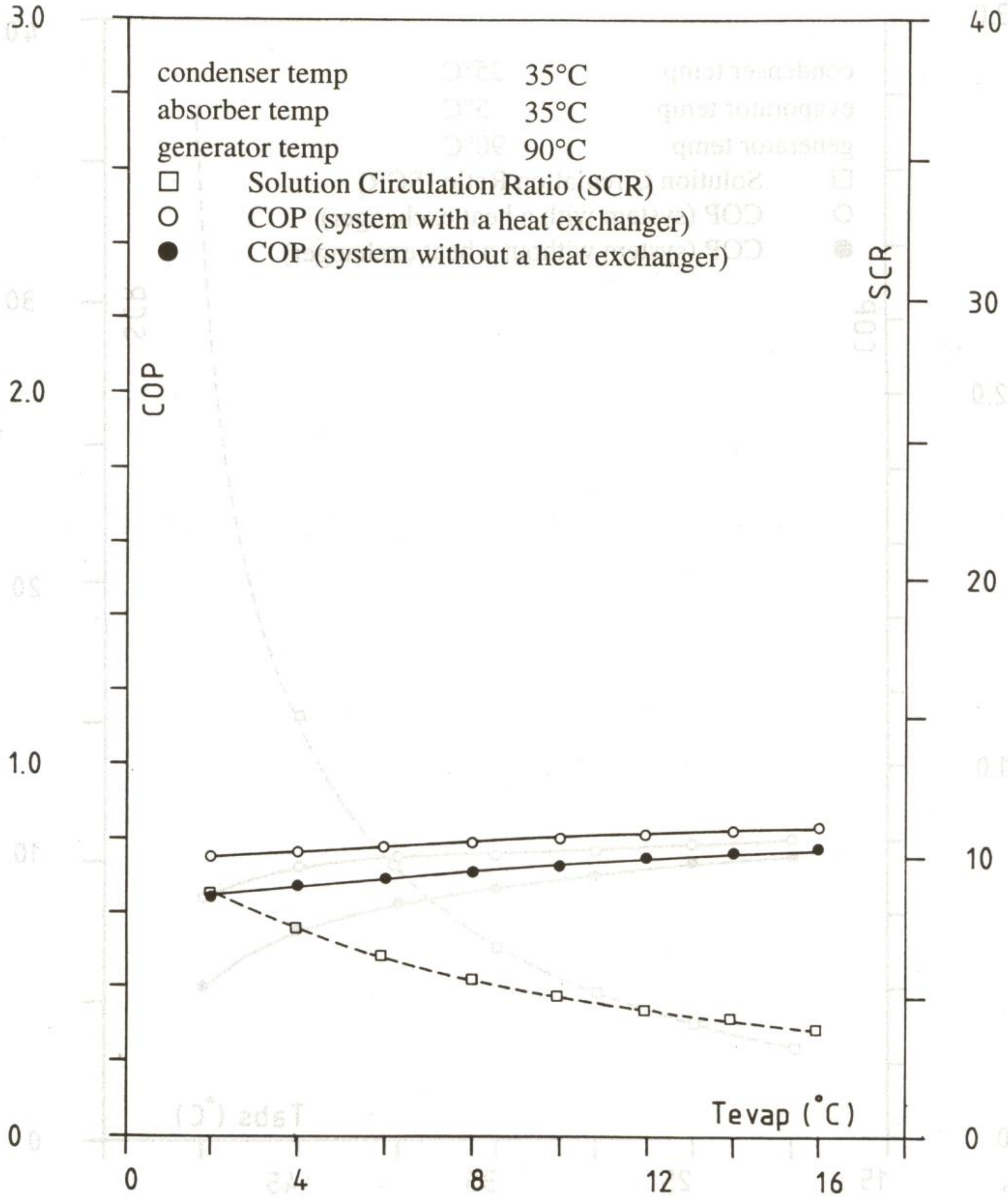


Figure 2



3.0
2.0
1.0
0
COP
40
30
20
10
0
SCR
condenser temp 35°C
absorber temp 35°C
generator temp 90°C
Solution Circulation Ratio (SCR)
COP (system with a heat exchanger)
COP (system without a heat exchanger)
Tevap (°C)
0
4
8
12
16

Figure 3

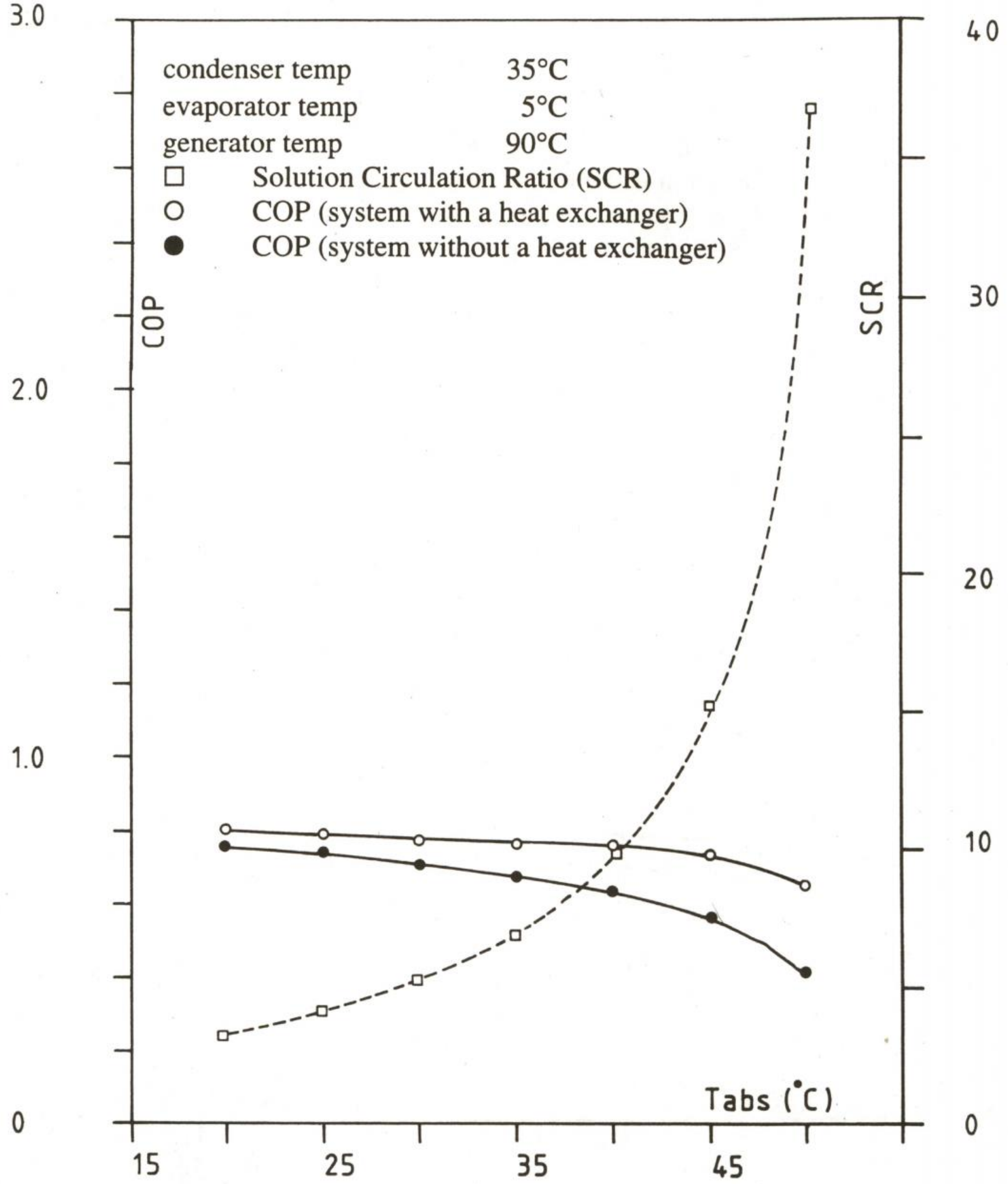

condenser temp 35°C
evaporator temp 5°C
generator temp 90°C
Solution Circulation Ratio (SCR)
COP (system with a heat exchanger)
COP (system without a heat exchanger)
COP
SCR
Tabs (°C)
3.0
2.0
1.0
0
40
30
20
10
0
15
25
35
45

Figure 4

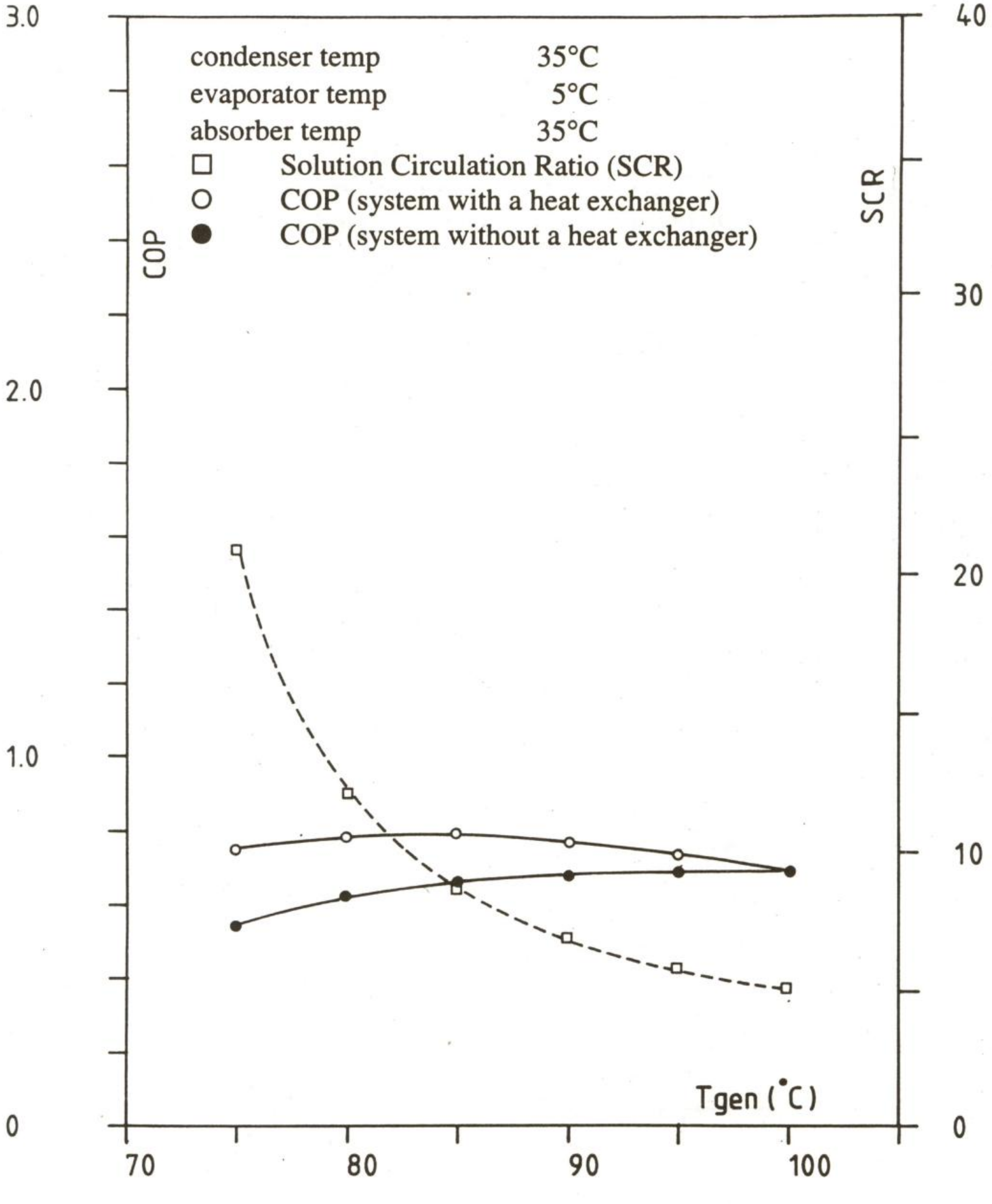
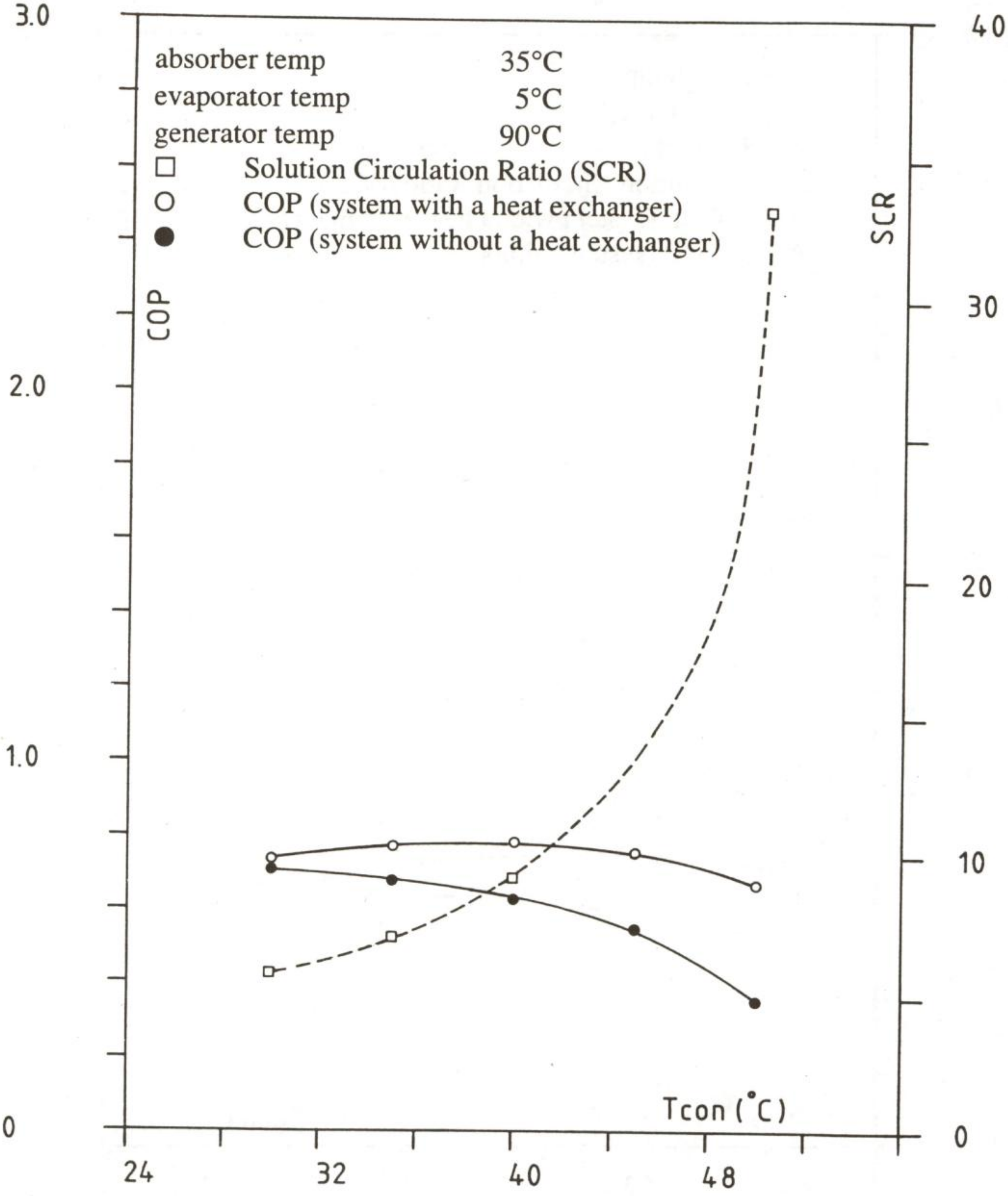

3.0
2.0
1.0
0
40
30
20
10
0
condenser temp 35°C
evaporator temp 5°C
absorber temp 35°C
Solution Circulation Ratio (SCR)
COP (system with a heat exchanger)
COP (system without a heat exchanger)
COP
SCR
Tgen (°C)
70
80
90
100

Figure 5



3.0
2.0
1.0
0
COP
absorber temp 35°C
evaporator temp 5°C
generator temp 90°C
Solution Circulation Ratio (SCR)
COP (system with a heat exchanger)
COP (system without a heat exchanger)
SCR
40
30
20
10
0
24
32
40
48
Tcon (°C)

Figure 6