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PERFORMANCE STUDY OF A DOUBLE-ABSORPTION WATER/CALCIUM CHLORIDE HEAT TRANSFORMER

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SUMMARY

In order to increase the temperature lift and efficiency of single-absorption heat transformers there are other possible arrangements. Double-absorption heat transformers have a relatively simple design and smaller size compared to two-stage heat transformers. In this work, the thermodynamic performance of the water/calcium chloride system was modelled for a double-absorption heat transformer. Results indicate that temperature lifts of up to 40 °C are possible with coefficients of performance close to 0·3. © 1998 John Wiley & Sons, Ltd.

KEY WORDS heat transformers; absorption systems; energy recycling

1. INTRODUCTION

Absorption heat transformers enable the temperature of a low grade heat source to be raised to a higher level. This process takes place by means of the absorption of a vaporized working fluid into a substance which has a strong affinity for the vapour. The absorption process is based on the physicochemical and thermodynamic properties of the substances and solutions. The absorption principle utilizes the physical phenomenon in which, at same pressure, the equilibrium temperature for the absorbent solution is higher than that corresponding to the saturated working fluid. Absorption processes are considered to be thermodynamically more reversible and hence potentially more efficient than mechanical cycles (Rebello, 1988). The temperature lift and the coefficient of performance depend on the thermodynamic properties of the working pair which is constituted by the working fluid and the absorbent. Those design characteristics also depend on the configuration of the equipment.

In order to increase the temperature lift of heat transformers there are various possible designs. Basically the heat delivered by the absorber of one heat transformer can be supplied to a second heat transformer connected to the first. This heat can be supplied to the evaporator, to the generator or can be divided into the evaporator and the generator of the second unit. This new arrangement is called the two-stage heat transformer. An analysis of this kind of equipment was carried out by Ciambelli and Tufano, (1988a), Kripalani *et al.* (1984), Alefeld *et al.* (1990) and Stephan and Seher (1984). The results indicated that for the first case it is possible to have a wide range of operating conditions with a relatively simple design. For the second case, it is necessary to have a more complex design, which is justified because of the higher coefficients of performance that can be obtained. At present, for the third case there are technical and economic constraints. For the three cases mentioned, it was concluded that the equipment was very expensive and their coefficients of performance values were not as high as expected.

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Double-absorption heat transformers present some important advantages with regard to two-stage heat transformers. They have a relatively simple design and are smaller. They are able to increase the temperature lift to the same degree as the two-stage heat transformers (Ciambelli and Tufano 1988b; Rivera *et al.*, 1994a, b).

At present, all industrial heat transformers use the water/lithium bromide system as the working pair. Although this system has many advantages, corrosion has limited its application in advanced heat transformers. Recently, new working pairs, able to provide high-temperature lifts in absorption heat transformers, have been reported (Herold *et al.*, 1991; Zhuo and Machielsen, 1993).

In this work, the water/calcium chloride system was selected to study the performance of a double-absorption heat transformer. Calcium chloride is readily available in México and is not expensive. It is safe and non-toxic. It has also been used as working pair in single-absorption heat transformers by Sidding *et al.* (1983) and Barragán *et al.* (1996). Eisa *et al.* (1986) obtained theoretical design parameters for the water/calcium chloride system in a single absorption heat transformer. Barragán *et al.* (1991) studied the theoretical and experimental performance of this system in an absorption heat transformer with an economiser.

2. DOUBLE-ABSORPTION HEAT TRANSFORMER PROCESS

Figure 1 shows the components of a double-absorption heat transformer. The process sequence is as follows. Heat is supplied to the generator to concentrate the absorbent solution by removing refrigerant (water). The refrigerant vapour is condensed in the condenser which is maintained at a low pressure and heat is rejected. The condensed refrigerant is divided into two streams. One of them is pumped at high pressure to the absorber–evaporator in order to be evaporated inside the tubes. This process requires that heat be supplied. The other stream of refrigerant is pumped to the evaporator which is maintained at an intermediate pressure in order to evaporate. For this process heat has to be supplied. After the refrigerant has been vaporized it is led to the absorber–evaporator on the shell side. The vaporized refrigerant (from the tubeside of the absorber–evaporator) is fed to the absorber where it is absorbed by the concentrated absorbent solution from the generator. In this process useful heat is delivered. The solution from the absorber is divided into two streams. One of them is used to provide heat to the absorbent solution from the generator in an economiser and is then fed to the generator via an expansion valve. The second solution stream from the absorber is fed to the absorber–evaporator to absorb the refrigerant vapour from the evaporator. This process takes place outside the tubes and provides the heat required to vaporize the refrigerant inside the tubes. The diluted solution from the absorber–evaporator is fed to the generator to close the process cycle. A schematic pressure against temperature diagram for the process is shown in Figure 2.
General considerations:

(a) Thermodynamic equilibrium conditions were assumed.
(b) Steady-state operation was considered.
(c) For the operating temperature range the absorbent does not evaporate. A rectifier was not needed.
(d) The absorbent solution outlet streams from the absorber, generator and the absorber–evaporator were saturated. The refrigerant outlet streams from the condenser and the evaporator were saturated.
(e) Heat losses were negligible.
(f) Pressure drops were negligible.

Taking into account the above considerations, a computer programme was developed in order to calculate the variables of the system. The program was written in FORTRAN-77 and compiled on a VAX/VMS computer. The water/calcium chloride solution was selected as a working pair since thermodynamic data for

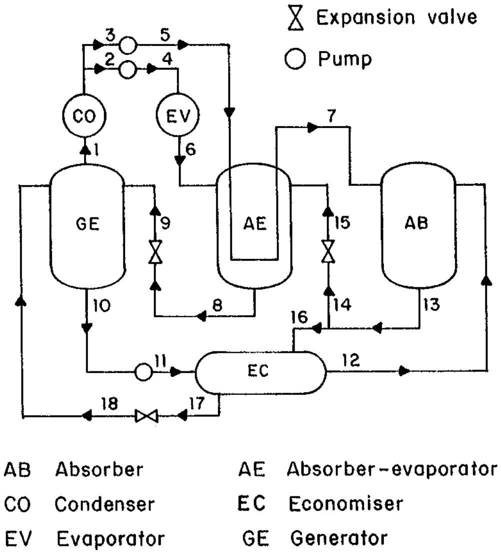

Figure 1. Double-absorption heat transformer

solutions are available, (Sidding *et al*., 1983). The input data were the temperature for the absorber, the heat supplied to the evaporator and the concentration of the absorbent solution in the generator, absorber and absorber–evaporator. It is possible to select the temperature of the generator as a function of the temperature of the evaporator. A description of the main design variables is given as follows. The flow ratio for the absorber–evaporator (FRAE, dimensionless) is defined as

$$\mathrm{FRAE} = X_{\mathrm{AE}}/(X_{\mathrm{AB}} - X_{\mathrm{AE}}) \tag{1}$$

where X_{AE} is the concentration of the absorbent solution (in % by weight) in the absorber–evaporator and X_{AB} is that corresponding to the absorber.

The flow ratio for the absorber (FRAB, dimensionless) is defined as

$$\mathrm{FRAB} = X_{\mathrm{GE}}/(X_{\mathrm{GE}} - X_{\mathrm{AB}}) \tag{2}$$

where X_{GE} is the concentration of the absorbent solution (in % by weight) in the generator.

The flow ratio leaving the condenser (BCO, dimensionless) is defined as

$$\mathrm{BCO} = M_2/M_3 \tag{3}$$

where M_2 is the mass flow rate of refrigerant leaving the condenser towards the evaporator and M_3 is the mass flow rate of refrigerant leaving the condenser towards the absorber–evaporator.

The flow ratio leaving the absorber (BAB, dimensionless) is defined as

$$\mathrm{BAB} = M_{16}/M_{14} \tag{4}$$

where M_{16} is the mass flow rate of absorbent solution entering the economiser and M_{14} is the mass flow rate of absorbent solution entering the absorber–evaporator.

For all cases the subscripts refer to Figure 1.

Coefficients of performance (COP, dimensionless) were calculated from

$$(\mathrm{COP})_{\mathrm{E}} = Q_{\mathrm{AB}}/(Q_{\mathrm{GE}} + Q_{\mathrm{EV}}) \tag{5}$$

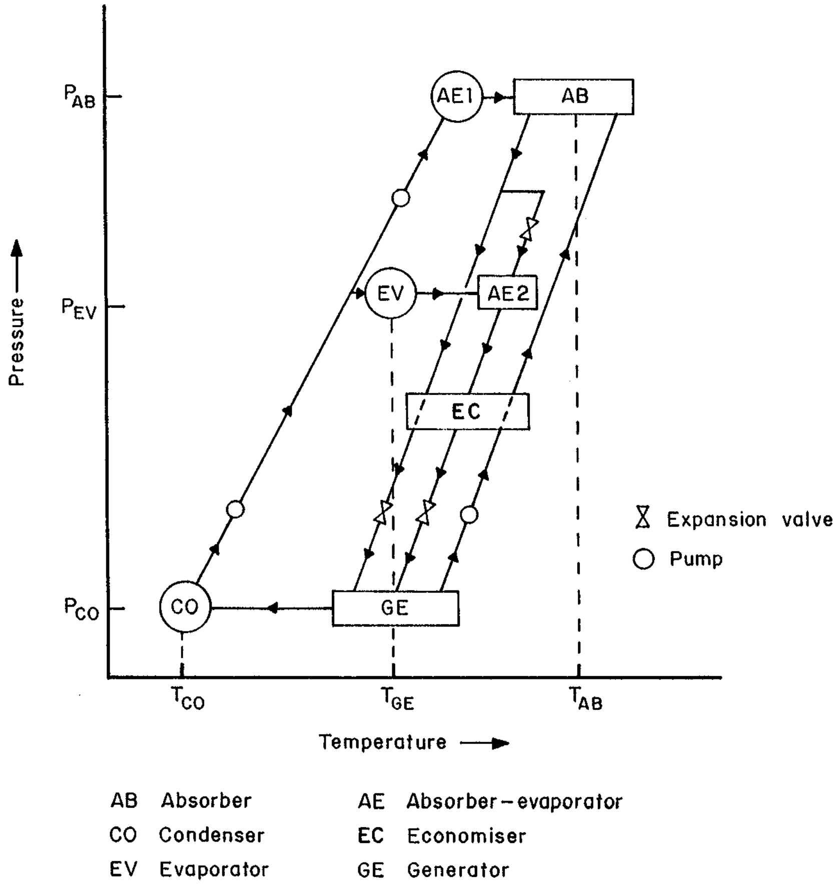

Figure 2. Pressure–temperature diagram for a double-absorption heat transformer

$$(\mathrm{COP})_{\mathrm{C}} = T_{\mathrm{AB}}(T_{\mathrm{EV}} - T_{\mathrm{CO}})/[T_{\mathrm{GE}}(T_{\mathrm{EV}} - T_{\mathrm{CO}}) + T_{\mathrm{EV}}(T_{\mathrm{AB}} - T_{\mathrm{GE}})] \tag{6}$$

where the subscripts E and C refer to the enthalpic and Carnot coefficients of performance, respectively. Q is the heat provided and T is the absolute temperature. The subscripts AB, GE, EV and CO refer to absorber, generator, evaporator and condenser, respectively. It is important to point out that for the enthalpic coefficient of performance $(\mathrm{COP})_{\mathrm{E}}$ calculation, the values for heat (Q) were those calculated taking into account the thermodynamic equilibrium. For practical purposes, in order to calculate the actual coefficient of performance $(\mathrm{COP})_{\mathrm{A}}$, the values for Q should be experimentally obtained.

3. RESULTS AND DISCUSSION

3.1. Varying the concentration of the absorbent solution in the absorber–evaporator and the temperature of the absorber

The temperature of the generator was taken equal to the temperature of the evaporator. This temperature was calculated under equilibrium conditions for given concentrations of the absorbent solution in the

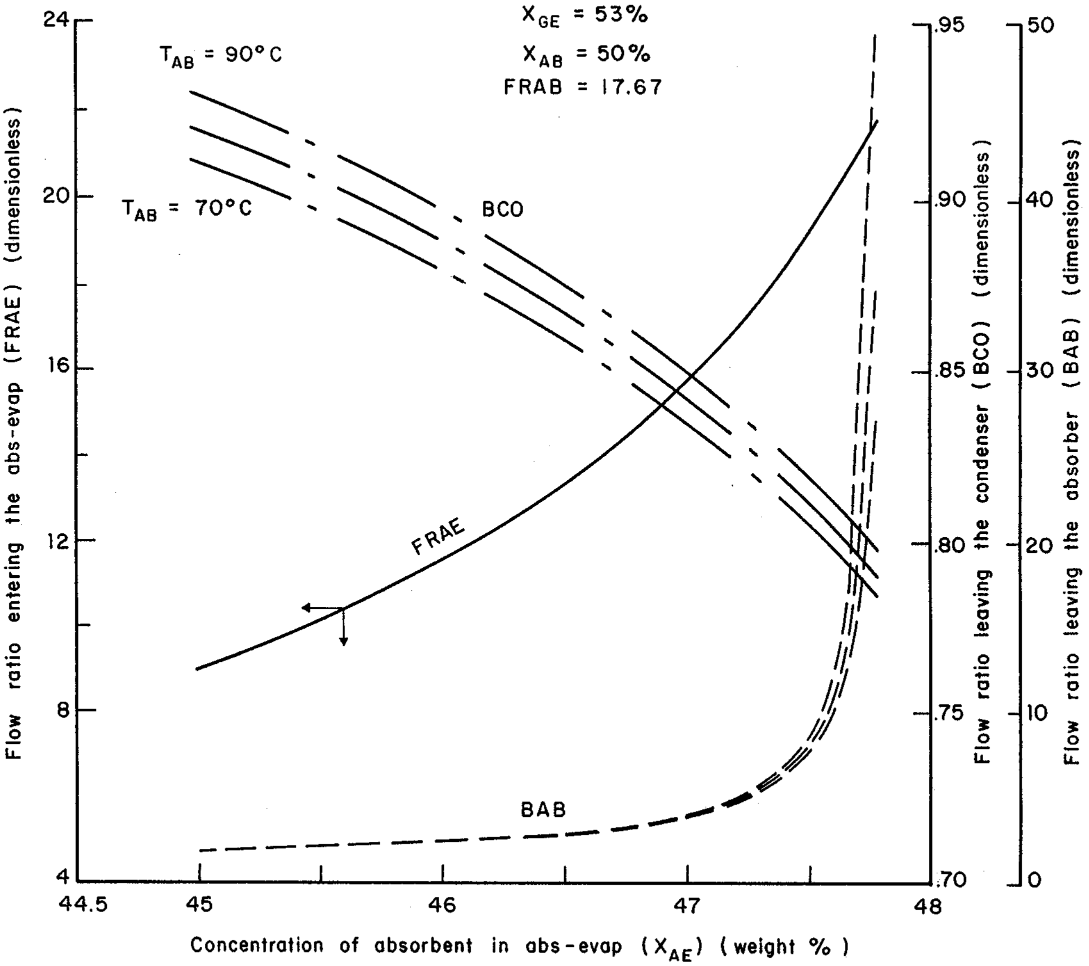

Figure 3. Flow ratio entering the absorber–evaporator, flow ratio leaving the condenser and flow ratio leaving the absorber against the concentration of absorbent in the absorber–evaporator

generator, absorber and absorber–evaporator, the temperature of the absorber and the heat supplied to theevaporator. The temperature of the absorber varied from 70 to 90°C. The concentration of the absorbent solution in the generator was selected as 53% (by weight), the concentration in the absorber was taken as 50% (by weight), whilst the concentration of the solution in the absorber–evaporator varied from 45 (by weight) to 47.8% (by weight). For this situation the flow ratio for the absorber (FRAB) was maintained as a constant, whilst the flow ratio for the absorber–evaporator (FRAE) increased as the concentration of the absorbent solution in the absorber–evaporator increased. This is shown in Figure 3. Also in Figure 3, it can be observed that the flow ratio for the condenser (BCO) decreased as the concentration of the absorbent in the absorber–evaporator increased. Figure 3 shows that the flow ratio for the absorber (BAB) increased as the concentration of the absorbent solution in the absorber–evaporator increased. Carnot and enthalpic coefficient of performance values varied slightly showing an opposite tendency, as can be seen in Figure 4. The enthalpic coefficient of performance increased whilst the Carnot coefficient of performance decreased. Gross temperature lifts obtained were about 35°C.

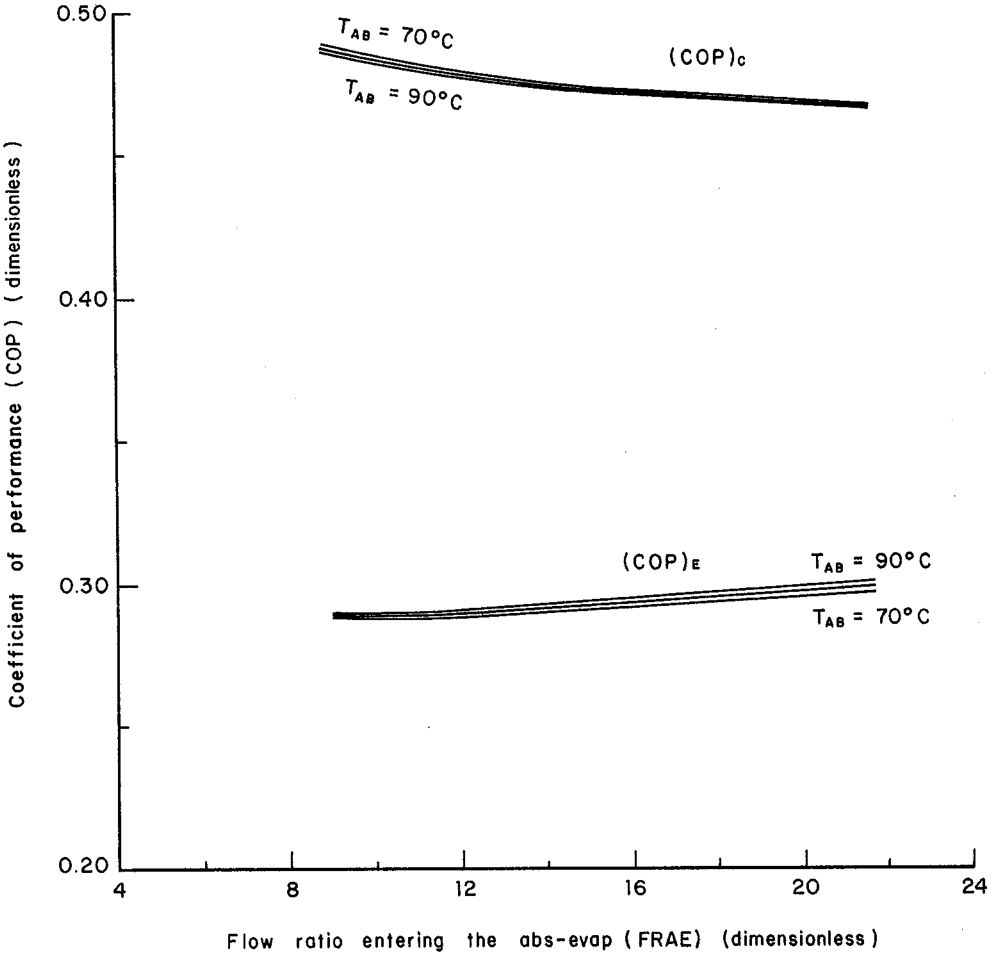

Figure 4. Coefficient of performance against the flow ratio entering the absorber–evaporator

3.2. Varying the concentration of the absorbent solution in the absorber and the temperature of the absorber

For this set of runs, the temperature of the generator was maintained equal to the temperature of the evaporator. The concentration of the absorbent solution in the generator was taken as 53% (by weight), the concentration corresponding to the absorber–evaporator was maintained as 45% (by weight) and the concentration of the solution in the absorber varied from 48·6 to 51·8% (by weight). The temperature of the absorber varied from 70 to 120°C. In Figure 5 it is shown that as the concentration of the solution in the absorber increased and for a given temperature of the absorber, the flow ratio for the condenser (BCO) increased slightly. The flow ratio for the absorber (BAB) decreased as the concentration of the absorbent increased. The flow ratio for the absorber–evaporator (FRAE) decreased whilst the flow ratio for the absorber (FRAB) increased, as the concentration of the solution in the absorber increases (Figure 6). Also, in Figure 6, it can be seen that both the enthalpic and the Carnot coefficient of performance decreased as the concentration of the absorbent increased. The enthalpic coefficient declined drastically as the concentration of the absorbent increased, but the Carnot coefficient decreased slightly. Figure 7 is a plot of the Carnot and enthalpic coefficients of performance against the flow ratio for the

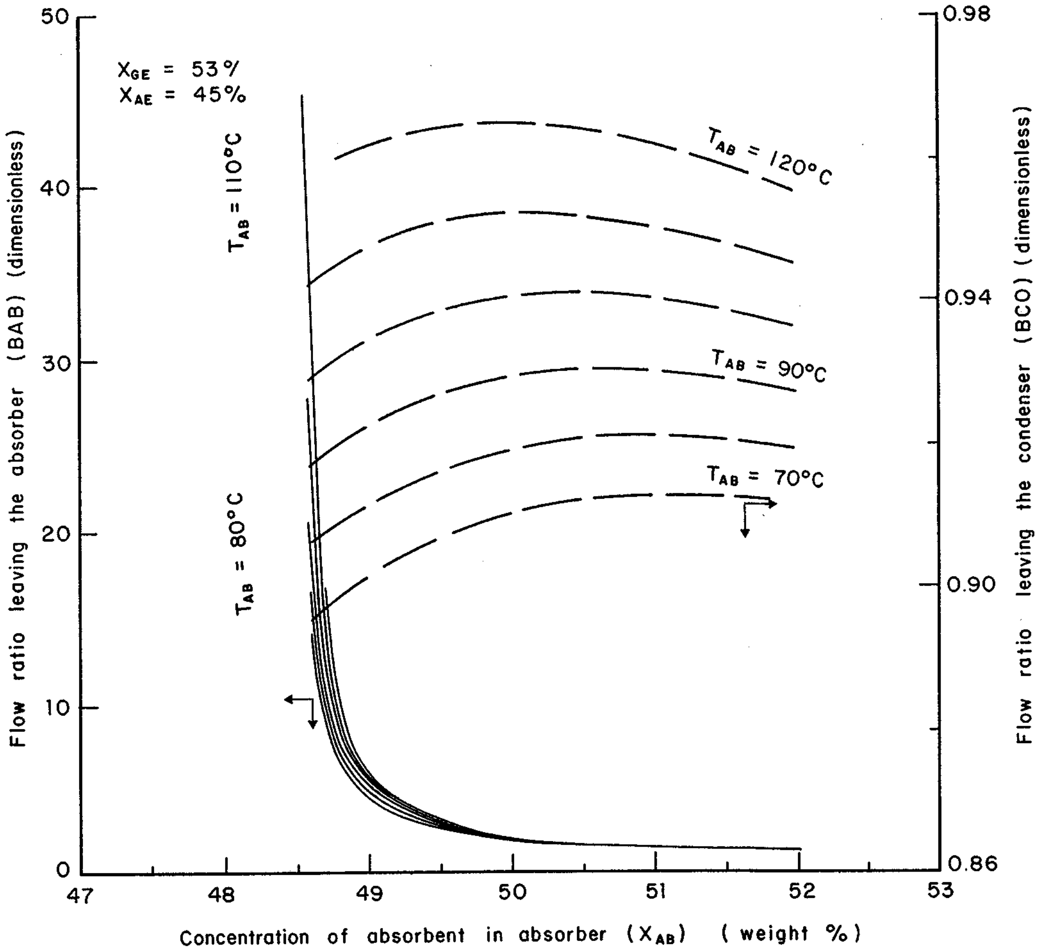

Figure 5. Flow ratio leaving the absorber and flow ratio leaving the condenser against the concentration of absorbent in the absorber

absorber–evaporator (FRAE), and the flow ratio for the absorber. The temperature lifts obtained had values in the range 35–40°C. For higher-temperature lifts the enthalpic coefficient values were lower.

3.3. Varying the temperature of the absorber and maintaining the concentrations of the absorbent solution in the generator, absorber and absorber–evaporator constant

The temperature of the absorber varied from 60 to 120°C and the concentrations of the absorbent solution in the generator and in the absorber–evaporator were 53 and 45% (by weight), respectively. The concentration of the absorbent in the absorber was maintained at 48·6 and 51·6% (by weight), in order to observe the bahaviour of the system under each set of conditions. The flow ratio for the absorber (FRAB) and that corresponding to the absorber–evaporator (FRAE) were constant, since they were defined as a function of the concentrations. As the temperature of the absorber increased, the flow ratio for the absorber (BAB) increased (Figure 8). An opposite behaviour is shown for the enthalpic coefficient of performance, which

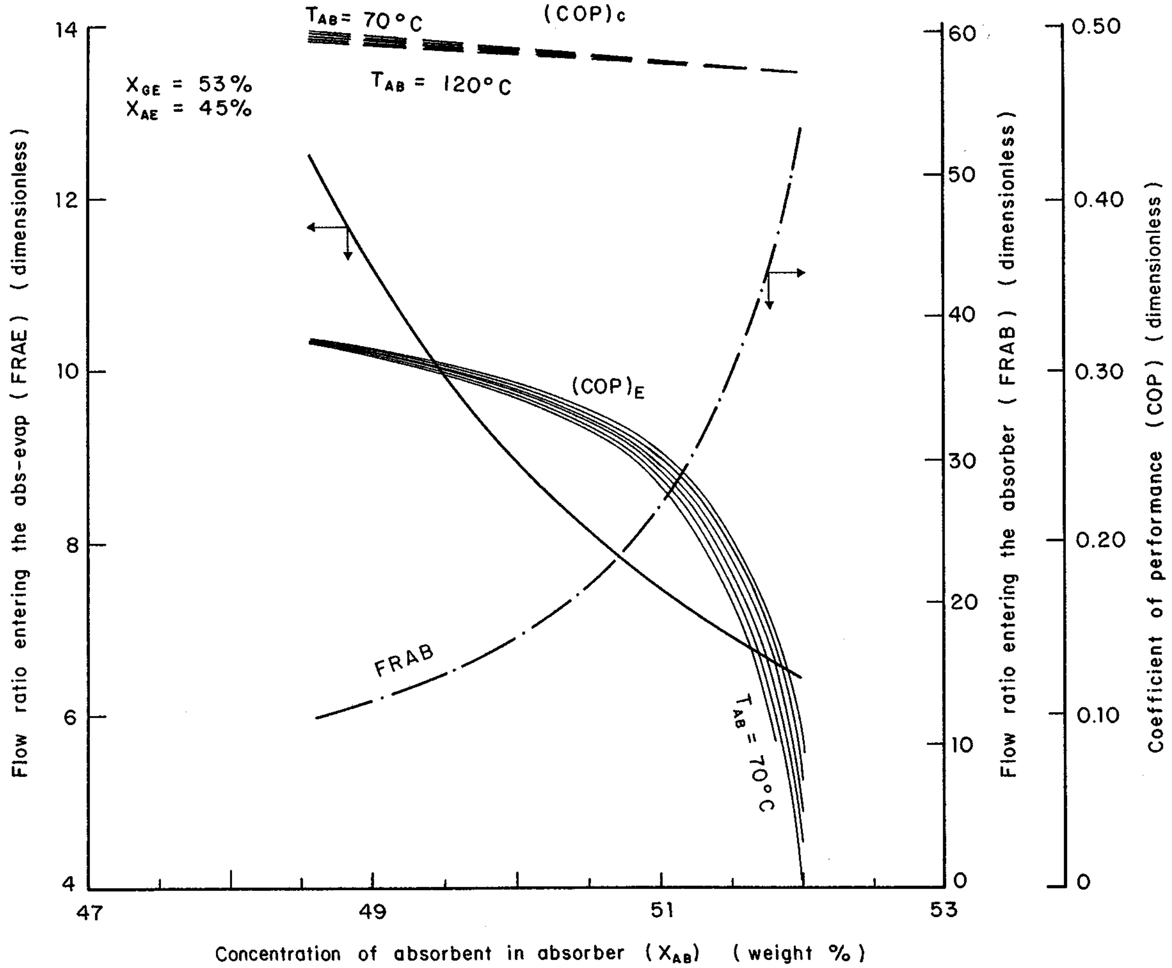

Figure 6. Flow ratio entering the absorber–evaporator, flow ratio entering the absorber and coefficient of performance against the concentration of absorbent in the absorber

slightly decreased as the temperature of the absorber increased. The gross temperature lifts obtained were in the range of 33–40°C. Higher gross temperature lifts were obtained for higher concentrations of the absorbent in the absorber. For the same temperature of the absorber, a lower temperature of the evaporator is calculated (Figure 9).

3.4. Varying the temperature of the absorber and considering the temperature of the generator 5°C higher and 5°C lower than the temperature of the evaporator

For these conditions, the concentrations of the absorbent solution in the generator, absorber and absorber–evaporator were taken as 53, 48.6 and 45% (by weight), respectively. In Figure 9 the calculated temperatures for the generator and the condenser are presented.

Figure 10 is a plot of the flow ratio leaving the condenser (BCO) and that corresponding to the absorber (BAB) against the temperature of the absorber. For both cases, the flow ratio increased as the temperature of

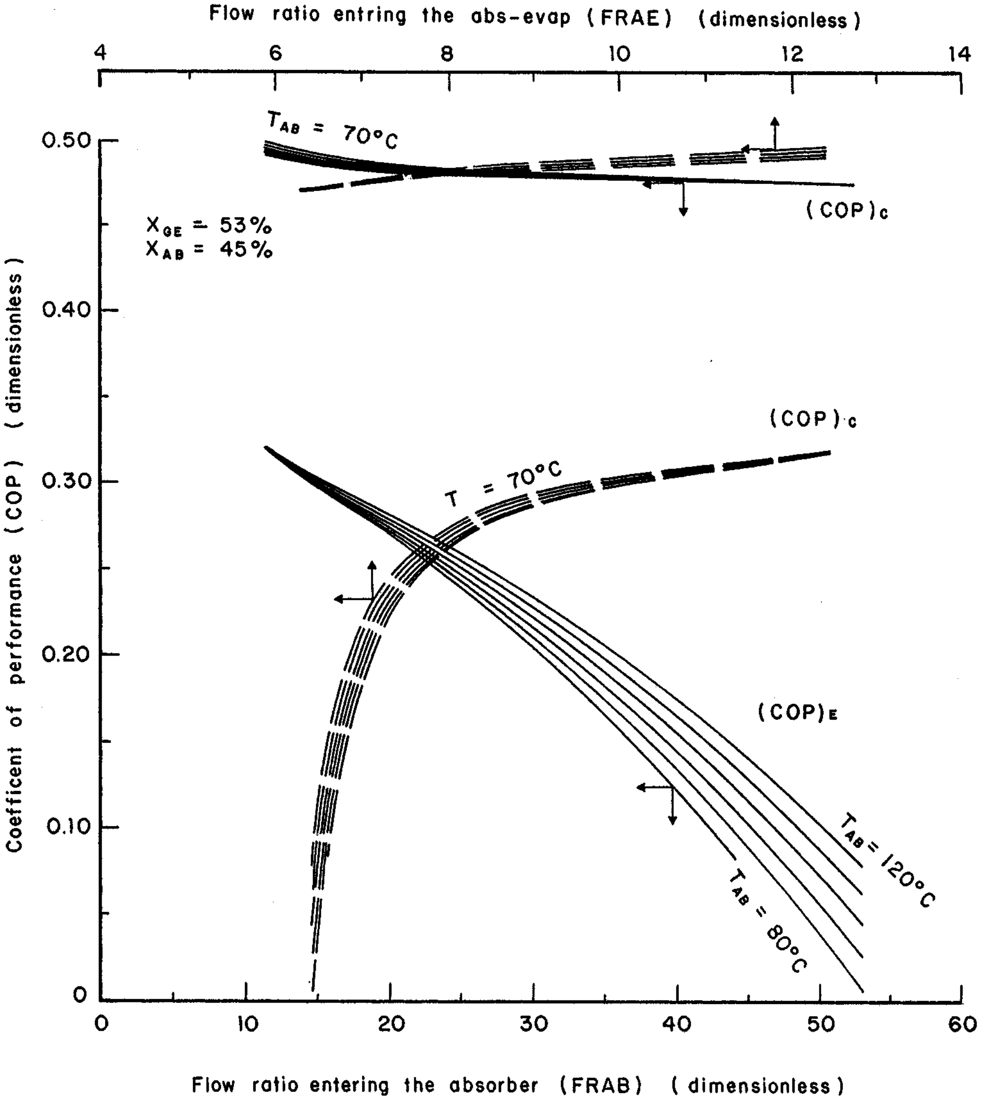

Figure 7. Coefficient of performance against the flow ratio entering the absorber and the flow ratio entering the absorber–evaporator

the absorber increased. Higher values for flow ratio were obtained for lower temperatures in the generator. Figure 10 is a plot of the calculated Carnot and enthalpic coefficients of performance against the temperature of the absorber. The higher values for both coefficients were obtained for higher temperatures in the generator. Both coefficients decreased as the temperature of the absorber increased.

4. CONCLUSIONS

Theoretical modelling for the system water/calcium chloride in a double-absorption heat transformer provided useful information. The calculated values of the coefficient of performance are a measure of the

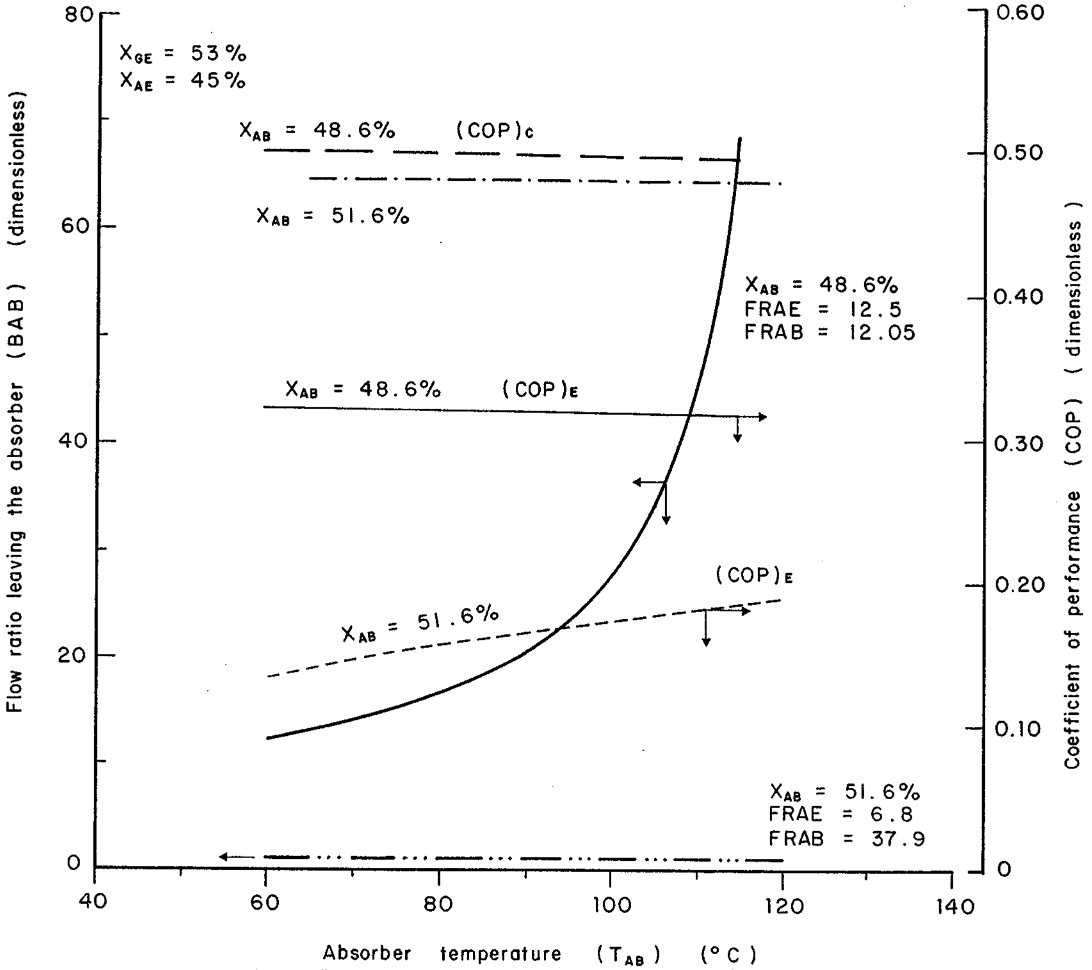

Figure 8. Flow ratio leaving the absorber and coefficient of performance against the absorber temperature

system efficiency. The recirculation flow ratio affects the size of the equipment. Interactions among these important design parameters have been presented in graphic and tabulated forms. Derived data that include temperatures for the units will facilitate the design of heat transformers for specific applications.

Double-absorption stage heat transformers provided lower coefficient of performance values compared to single-stage heat transformers. The temperature lifts obtained for double-stage absorption heat transformers are higher than the values obtained for single-stage heat transformers. As heat transformers utilize waste heat as thermal input, low coefficient of performance values are not a severe constraint.

NOMENCLATURE

BAB	flow ratio leaving the absorber (dimensionless)
BCO	flow ratio leaving the condenser (dimensionless)
COP	coefficient of performance (dimensionless)
FRAB	flow ratio for the absorber (dimensionless)

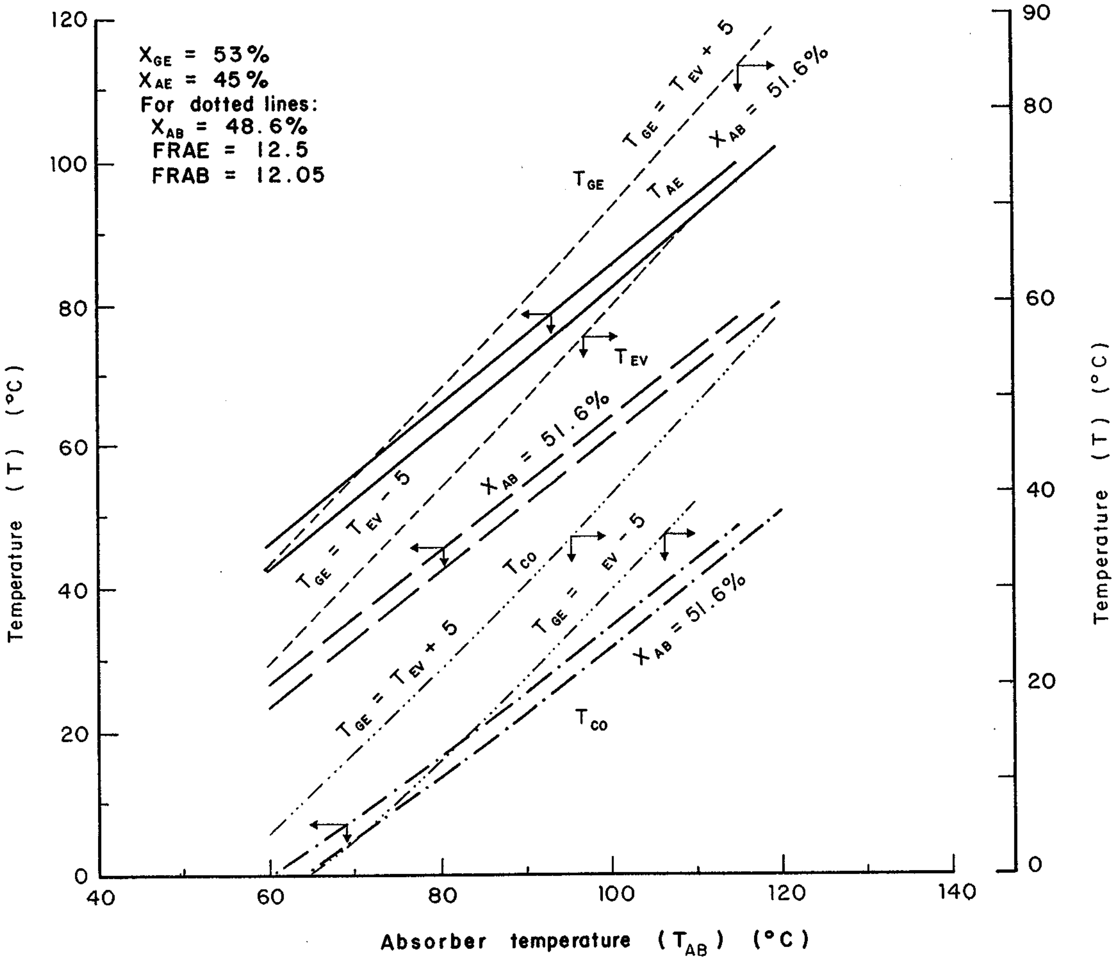

Figure 9. Temperature for the generator, evaporator, absorber–evaporator and condenser against the absorber temperature

FRAE	flow ratio for the absorber–evaporator (dimensionless)
M	mass flow rate (g s^{-1})
Q	heat load (W)
T	temperature (°C, K)
X	concentration of solution (wt %)

Subscripts

AB	absorber
AE	absorber–evaporator
C	Carnot
CO	condenser
E	enthalpic
EV	evaporator
GE	generator

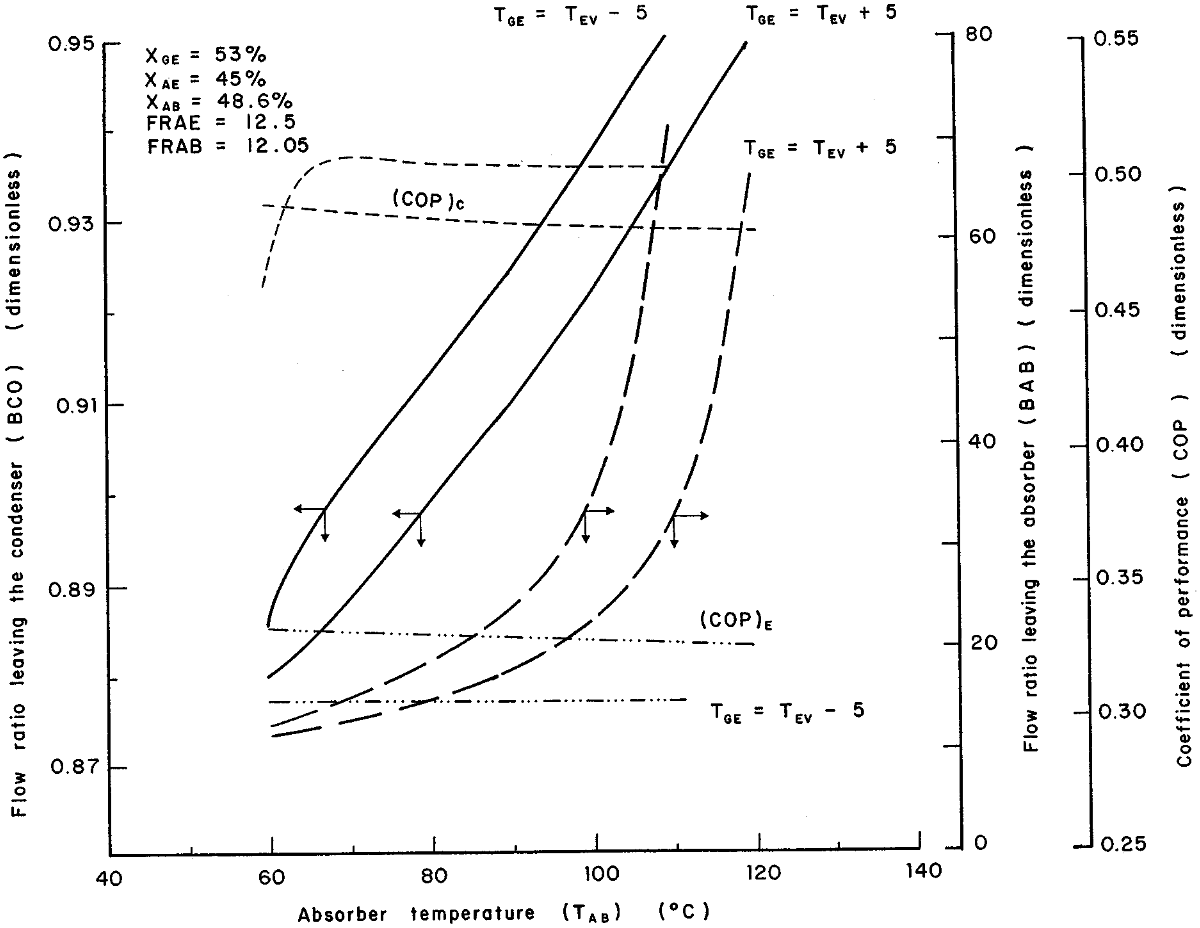

Figure 10. Flow ratio leaving the condenser, flow ratio leaving the absorber and coefficient of performance against the absorber temperature

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