Int. J. Heat Mass Transfer. Vol. 28, No. 12, pp. 2323–2329, 1985
Printed in Great Britain

0017–9310/85 \$3.00 + 0.00

A study of economiser performance in a water–lithium bromide absorption cooler

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(*Received* 20 *March* 1985)

Abstract—The effectiveness of an economiser heat exchanger in a water–lithium bromide absorption cooler has been shown to decrease with increases in flow ratio and cooling capacity. Experiments have been carried out with six levels of cooling capacity and nine values of flow ratios.

INTRODUCTION

A CONVENTIONAL heat driven absorption cooler is shown schematically in Fig. 1. It consists of four basic components, an evaporator, a condenser, a generator and an absorber. In addition an economiser heat exchanger is normally placed between the absorber and the generator. The economiser makes the process more efficient without altering its basic operation.

In the evaporator heat exchanger, the working fluid evaporates at a temperature T_{EV} while extracting an amount of heat Q_{EV} from the source which may be in the gaseous, liquid or solid state. The working fluid is then compressed in the secondary or absorption circuit before giving up an amount of latent heat Q_{CO} at a higher temperature T_{CO} in the condenser heat exchanger. The condensed working fluid is then expanded through the expansion valve and returned to the evaporator to complete the cycle in the primary circuit.

The primary circuit of an absorption cooler is identical to that in a compressor driven unit. However in absorption systems, the work of compression is accomplished by a secondary circuit in which a liquid absorbent is circulated by a pump. An amount of heat Q_{GE} is added in a vapour generator at an absolute temperature T_{GE}, to produce high pressure working fluid vapour which is then fed to the condenser. The mechanical energy required to pump the liquid is usually negligible compared with the input of high grade heat energy Q_{GE}.

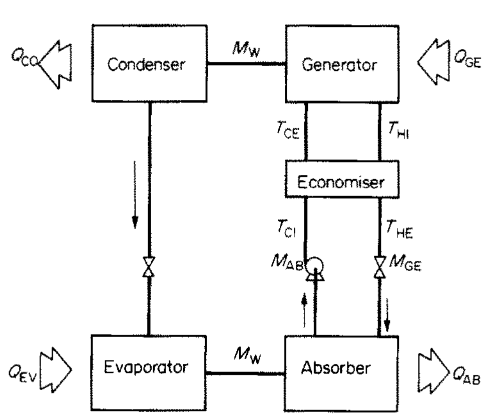

FIG. 1. Simplified block diagram of an absorption cooling system.

The actual coefficient of performance of an absorption cooler is defined as the ratio of the heat energy extracted in the evaporator Q_{EV} to produce the desired cooling, to the heat energy supplied to the generator Q_{GE}:

$$(COP)_{ACL} = \frac{Q_{EV}}{Q_{GE}}. \quad (1)$$

The performance of an absorption system is mainly dependent on the evaporator, condenser, absorber and generator temperatures (T_{EV}, T_{CO}, T_{AB} and T_{GE}, respectively) and the flow ratio (FR). The latter is essentially the ratio of the mass flow rate of solution M_{AB} in the secondary circuit linking the generator and absorber to the mass flow rate of pure working fluid M_W in the primary circuit linking the condenser and the evaporator [1]. It can be written as

$$(FR) = \frac{M_{AB}}{M_W}. \quad (2)$$

For water–lithium bromide absorption systems, the working fluid is pure water and the flow ratio can also be written in terms of concentrations as

$$(FR) = \frac{X_{GE}}{X_{GE} - X_{AB}} \quad (3)$$

where X_{GE} and X_{AB} are the weight fractions of salt in the generator and absorber solutions, respectively.

In a conventional absorption system there are two pressure levels

$$(P_{CO} = P_{GE}) > (P_{EV} = P_{AB})$$

and either three or four temperature levels

$$T_{GE} > T_{CO} \geqslant T_{AB} > T_{EV}$$

NOMENCLATURE

A	heat transfer area [cm^2 or m^2]
C	heat capacity, MC_p [$kJ\ K^{-1}$]
C_p	heat capacity per unit mass [$kJ\ kg^{-1}\ K^{-1}$]
(COP)	coefficient of performance [dimensionless]
(CR)	compression ratio, P_{CO}/P_{EV} [dimensionless]
E	effectiveness of heat transfer [dimensionless]
(FR)	flow ratio [dimensionless]
M	mass flow rate [$kg\ s^{-1}$]
M_{AB}	mass flow rate of solution leaving the absorber [$kg\ s^{-1}$]
M_{GE}	mass flow rate of solution leaving the generator [$kg\ s^{-1}$]
M_W	mass flow rate of working fluid [$kg\ s^{-1}$]
(NTU)	number of transfer units [dimensionless]
P	pressure [bar]
Q	heat load [kW]
R	heat capacity rate ratio [dimensionless]
T	temperature [°C or K]
T_{CE}	exit temperature of cold solution [°C]
T_{CI}	inlet temperature of cold solution [°C]
T_{HE}	exit temperature of hot solution [°C]
T_{HI}	inlet temperature of hot solution [°C]
ΔT	temperature difference [°C]
U	overall heat transfer coefficient [$W\ m^{-2}\ K^{-1}$]
X	weight fraction of salt [dimensionless].

Subscripts

A	actual
AB	absorber
C	cold
CL	cooling
CO	condenser
EV	evaporator
GE	generator
H	hot
min	minimum
max	maximum.

depending on whether the condenser and absorber are operated at the same temperature or not.

The compression ratio $(CR) = P_{CO}/P_{EV}$ produced by the secondary circuit is a function of the salt concentrations X_{GE} and X_{AB} in the generator and absorber, respectively. Aqueous solutions of lithium bromide exhibit large negative deviations from Raoult's law which make them particularly attractive for use in absorption systems. For a given solution vapour pressure, the fraction of water increases with increasing deviation from Raoult's law. This has the advantage of reducing the volume flow of the solution in the secondary circuit for a given water flow rate through the condenser and evaporator in the primary circuit.

The two main design parameters which determine the size and the performance of an absorption system are the flow ratio (FR) and the cooling capacity Q_{EV}.

THE ROLE OF THE ECONOMISER IN AN ABSORPTION SYSTEM

Smith *et al.* [2] have discussed the effect of the mass flow rate of the working fluid and the flow ratio (FR) on the required size of the economiser heat exchanger. They concluded that the performance of the economiser was critically affected by changes in concentration in the absorbent solution and in the mass flow rate of the working fluid.

The effect of the heat transfer area of the economiser is to decrease the total amount of heat transfer area required in the generator and the absorber. The heat transferred in the economiser reduces the heat loads in both the generator and absorber by an equivalent amount. This in turn improves the actual coefficient of performance $(COP)_{ACL}$.

Although an absorption cooling system is designed for a given maximum capacity, it should also be capable of adapting to changes in operating conditions such as the heat supplied Q_{GE} and the cooling load demanded Q_{EV}. It is therefore desirable to know the effect on the efficiency of the economiser heat exchanger of changes in operating conditions such as the flow ratio (FR) and the required cooling capacity Q_{EV}.

Heat is transferred in the economiser between the hot stream flowing from the generator with a mass flow rate M_{GE} and the cold stream flowing from the absorber with a mass flow rate M_{AB}. The mass flow rate of the cold stream is greater than that of the hot stream and the difference is given by the equation

$$M_{GE} = M_{AB} - M_W \tag{4}$$

where M_W is the mass flow rate of the working fluid in the primary circuit.

Figure 2 is a plot of heat capacity per unit mass C_p against weight fraction of salt X for the water–lithium bromide system. The salt concentration in the cold stream X_{AB} is less than the salt concentration in the hot stream X_{GE}. Figure 2 shows that the heat capacity per unit mass of the cold stream $(C_p)_{AB}$ is greater than the heat capacity per unit mass of the hot stream $(C_p)_{GE}$.

Thus since $(C_p)_{AB} > (C_p)_{GE}$ and $M_{AB} > M_{GE}$ from

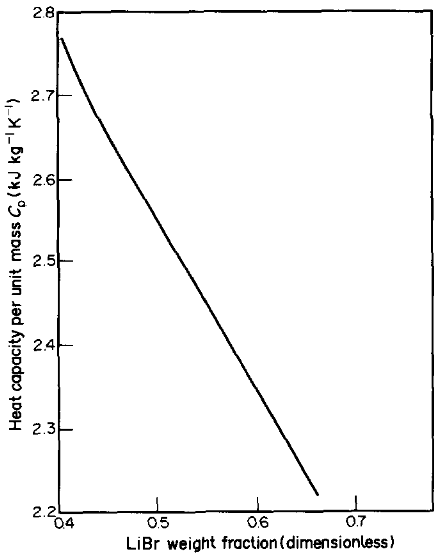

FIG. 2. Heat capacity per unit mass against lithium bromide concentration.

equation (4), the heat capacity rate of the cold stream C_C is always greater than the heat capacity rate of the hot stream C_H for this system where

$$C_C = M_{AB}(C_p)_{AB} \tag{5}$$

and

$$C_H = M_{GE}(C_p)_{GE}. \tag{6}$$

The effectiveness of heat transfer in any kind of heat exchanger is a function of the heat capacity rate ratio $R = (MC_p)_{min}/(MC_p)_{max}$ [3] which for this system can be written as

$$R = \frac{C_H}{C_C} = \frac{M_{GE}(C_p)_{GE}}{M_{AB}(C_p)_{AB}} < 1 \tag{7}$$

where R is always less than 1.

The heat load in the evaporator Q_{EV} determines the mass flow rate of working fluid M_W in the primary circuit. From equations (2) and (4) it can be seen that as the flow ratio (FR) increases for a fixed volume of M_W, M_{AB} and M_{GE} both increase. The ratio M_{GE}/M_{AB} also increases.

An increase in flow ratio (FR) also leads to a decrease in salt concentration X_{GE} in the hot stream [1] which in turn leads to an increase in the heat capacity per unit mass $(C_p)_{GE}$. At the same time, the salt concentration X_{AB} in the cold stream increases, which in turn leads to a decrease in the heat capacity per unit mass $(C_p)_{AB}$.

Equations (2), (4) and (7) show that as the flow ratio (FR) increases the heat capacity rate ratio R increases for this system.

The maximum theoretically possible rate of heat transfer between the two fluid streams in the economiser is given by the equation [3]

$$Q_{max} = (MC_p)_{min}(T_{HI} - T_{CI}) \tag{8}$$

which in this case can be written as

$$Q_{max} = M_{GE}(C_p)_{GE}(T_{HI} - T_{CI}) \tag{9}$$

where T_{HI} and T_{CI} are the inlet temperatures of the hot and cold streams, respectively, to the economiser.

The actual rate of heat transfer can either be written in terms of the hot stream

$$Q = M_{GE}(C_p)_{GE}(T_{HI} - T_{HE}) \tag{10}$$

or the cold stream

$$Q = M_{AB}(C_p)_{AB}(T_{CI} - T_{CE}) \tag{11}$$

where T_{HE} and T_{CE} are the exit temperatures of the hot and cold streams, respectively, from the economiser.

The effectiveness of heat transfer E in any kind of heat exchanger is defined as the ratio of the actual rate of heat transfer Q to the maximum theoretically possible rate of heat transfer Q_{max} [3], i.e.

$$E = \frac{Q}{Q_{max}}. \tag{12}$$

For this case, equation (12) can be written in terms of equations (9) and (10) as

$$E = \frac{Q}{Q_{max}} = \frac{M_{GE}(C_p)_{GE}(T_{HI} - T_{HE})}{M_{GE}(C_p)_{GE}(T_{HI} - T_{CI})} \tag{13}$$

$$E = \frac{(T_{HI} - T_{HE})}{(T_{HI} - T_{CI})}. \tag{14}$$

The number of transfer units (NTU) is a measure of a heat exchanger's ability to transfer heat. If the overall heat transfer coefficient U can be assumed to remain constant throughout the heat exchanger [3]

$$(NTU) = \frac{UA}{(MC_p)_{min}}. \tag{15}$$

For a particular type of heat exchanger, a mathematical relationship can be calculated between the number of transfer units (NTU), the effectiveness of heat transfer E and the heat capacity of rate ratio R. If two of these quantities are known, this mathematical relationship can be used to calculate the unknown.

Consider the effect of changes in operating conditions on the effectiveness of heat transfer E in the economiser heat exchanger.

An increase in the evaporator load Q_{EV} requires an increase in the mass flow rate of the working fluid M_W in the primary circuit. For an economiser with a fixed heat transfer area A, the increased mass flow rates will lead to a slight increase in the overall heat transfer coefficient U and in the heat capacity rate $C_{min} = (MC_p)_{min} = M_{GE}(C_p)_{GE}$. The same effect occurs if the flow ratio (FR) is increased. If C_{min} increases more rapidly than U, then (NTU) will decrease, which in turn will result in a decrease in the economiser effectiveness E [3].

If the heat capacity rate ratio R is increased for a fixed number of transfer units (NTU), the effectiveness of heat transfer E decreases. Alternatively if the number of transfer units is decreased for a fixed value of the heat capacity ratio R, then the effectiveness of heat transfer E also decreases. A combination of R increasing and (NTU) decreasing magnifies the rate of decrease in E. The above discussion applies to any type of heat exchanger.

The object of the current work is to study the effect of changes in cooling capacity Q_{EV} and flow ratio (FR) on the effectiveness of a fixed area countercurrent heat exchanger and on the efficiency of the overall system.

EXPERIMENTAL

Equipment

The experiments were carried out in a glass absorption cooler shown schematically in Fig. 3. Most of the components used were standard items supplied by Quickfit Ltd, U.K. Details of the equipment and operating techniques have been described by Landauro-Paredes *et al.* [4].

The use of standard, readily available glass components limited the choice of economiser heat exchanger. A type C3/12 multicoil unit equipped with thermocouple pockets was used. The total available heat transfer area was 600 cm^2. This heat exchanger was chosen because it could operate with a minimum hold up of concentrated salt solution. The more concentrated salt solution circulated outside the coils and the less concentrated salt solution inside the coils. This facilitated the removal of crystals in case of accidental crystallisation. The inlet and outlet temperatures of the

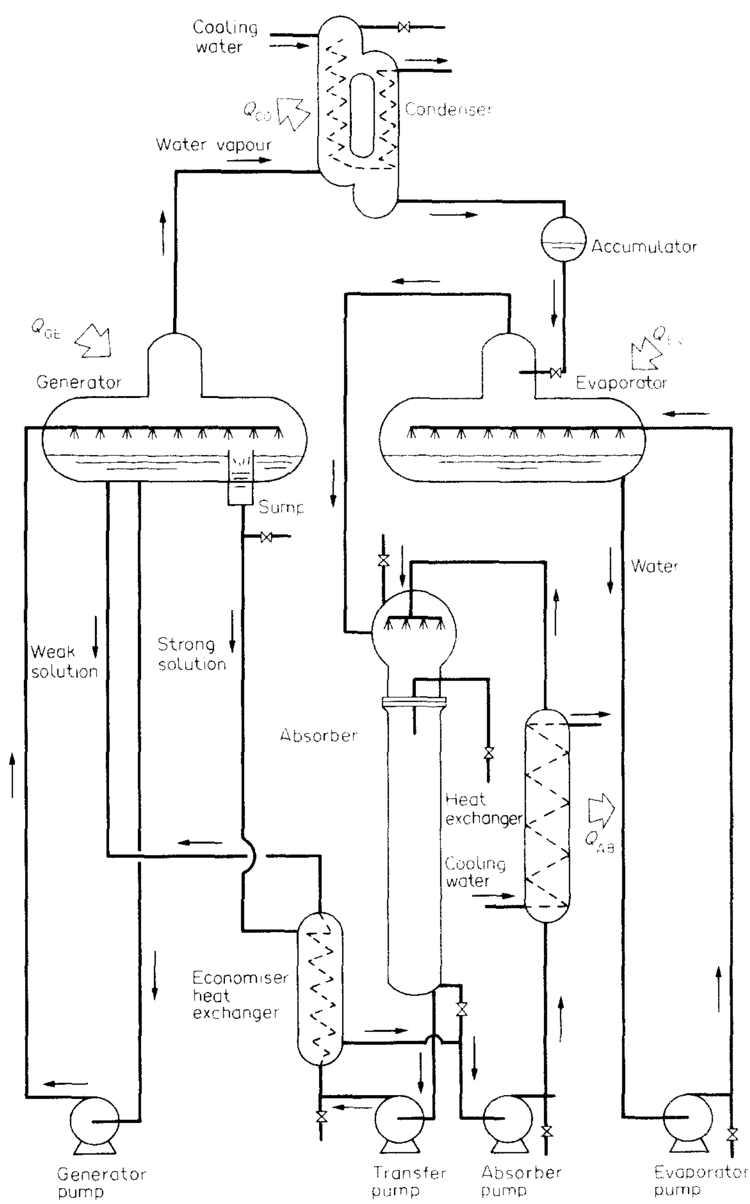

FIG. 3. Schematic diagram of the experimental absorption cooler.

more concentrated and less concentrated salt solutions were measured by thermocouples.

Experimental procedure

Experiments were carried out with six different cooling capacities Q_{EV}. These were 80.6, 163.3, 242.3, 326.0, 405.4 and 489.6 W, respectively. Nine different flow ratios (FR) were used for each value of the cooling capacity Q_{EV}. The heat transfer effectiveness E of the economiser heat exchanger was determined for each of the 54 sets of conditions. All other parameters were kept as constant as possible.

RESULTS AND DISCUSSION

Figure 4 gives plots of the ratio of mass flow rates M_{GE}/M_{AB} and the ratio of heat capacities per unit mass $(C_p)_{GE}/(C_p)_{AB}$ against the flow ratio (FR). Both ratios increase with an increase in flow ratio but the rate of increase is higher at the lower flow ratios.

Figure 5 is a plot of the heat capacity rate ratio

$$R = [M_{GE}(C_p)_{GE}/M_{AB}(C_p)_{AB}]$$

and the heat capacity of the hot stream $C_H = M_{GE}(C_p)_{GE}$ against the flow ratio (FR). C_H increases linearly with an increase in flow ratio but the rate of increase is greater for the higher value of the cooling capacity Q_{EV}. The heat capacity rate ratio R increases with an increase in flow ratio but the rate of increase is higher at the lower flow ratios. The relationship between the heat capacity rate ratio R and the flow ratio (FR) appears to be unaffected by changes in the cooling capacity Q_{EV}.

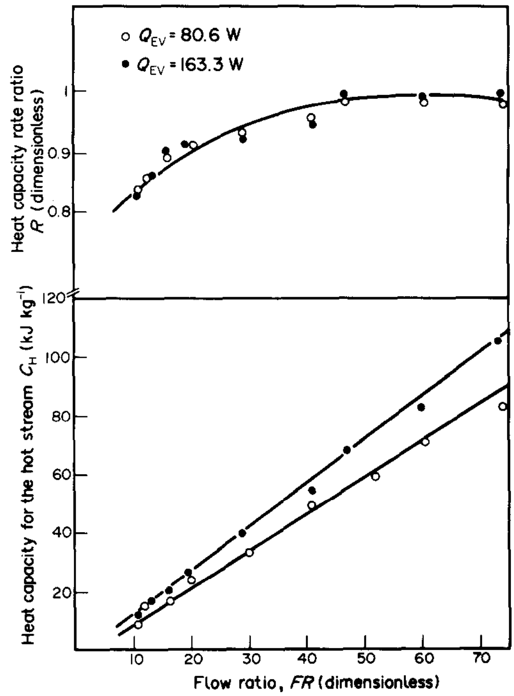

FIG. 5. Heat capacity for the hot stream C_H and heat capacity rate ratio R against flow ratio (FR).

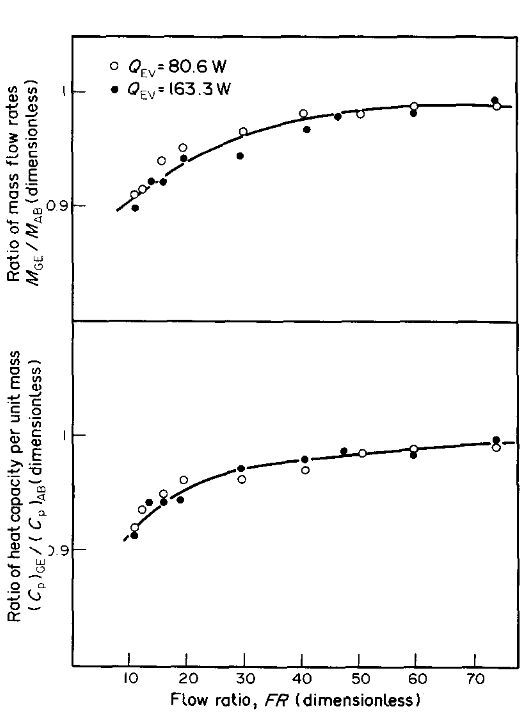

FIG. 4. Ratios of mass flow rates M_{GE}/M_{AB} and heat capacities $(C_p)_{GE}/(C_p)_{AB}$ against flow ratio.

Figure 6 is a plot of temperature change ΔT against flow ratio (FR) for the two streams in the economiser heat exchanger. The hot stream with a mass flow rate M_{GE} has a fall in temperature $(\Delta T)_H$ and the cold stream with a mass flow rate M_{AB} has a gain in temperature $(\Delta T)_C$. Figure 6 shows that the reduction in temperature of the hot stream $(\Delta T)_H$ is somewhat higher than the gain in temperature of the cold stream $(\Delta T)_C$. The

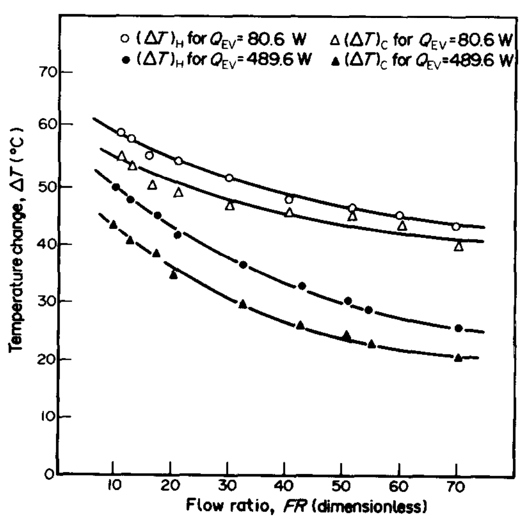

FIG. 6. Temperature change against flow ratio.

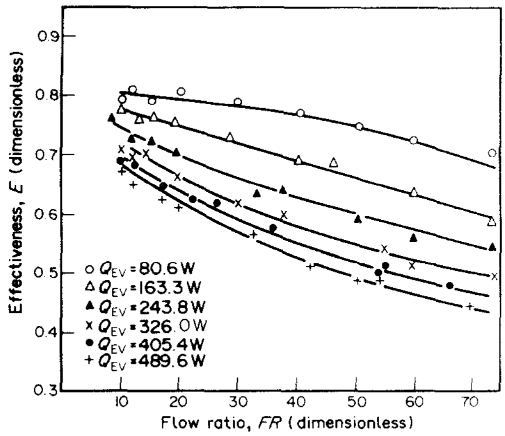

FIG. 7. Economiser heat exchanger effectiveness E against flow ratio (FR) for various cooling capacities Q_{EV}.

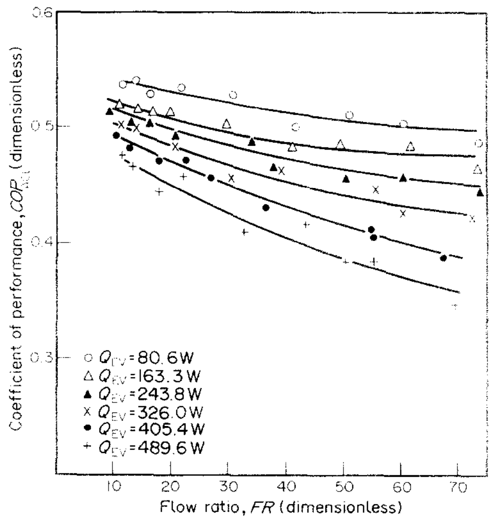

FIG. 8. Coefficient of performance $(COP)_{ACL}$ against flow ratio (FR) and cooling capacity Q_{EV}.

temperature changes $(\Delta T)_H$ and $(\Delta T)_C$ for both streams are smaller for the higher value of the cooling capacity Q_{EV}.

Figure 7 is a plot of the effectiveness E of the economiser heat exchanger against flow ratio (FR) for six different cooling capacities Q_{EV}. Figure 7 shows that the effectiveness E decreases with an increase in flow ratio (FR) and cooling capacity Q_{EV} and that the rate of decrease in E with an increase in (FR) becomes greater as the cooling capacity Q_{EV} is increased.

Increases in both the flow ratio (FR) and the cooling capacity Q_{EV} result in an increase in mass flow rates through the economiser heat exchanger. Figure 5 shows that this in turn leads to higher values of the heat capacity of the hot stream $C_H = M_{GE}(C_p)_{GE}$ and the heat capacity rate ratio $R = [M_{GE}(C_p)_{GE}/M_{AB}(C_p)_{AB}]$. This means that if insufficient heat transfer area is available in the economiser heat exchanger, the number of transfer units (NTU) decreases. A combination of a decrease in (NTU) and an increase in R, results in a decrease in the effectiveness E of the economiser heat exchanger.

Figure 8 is a plot of the actual coefficient of performance for cooling $(COP)_{ACL}$ against flow ratio (FR) for six different cooling capacities Q_{EV}. Figure 8 shows that $(COP)_{ACL}$ decreases with an increase in flow ratio (FR) and cooling capacity Q_{EV} and the rate of decrease in $(COP)_{ACL}$ with an increase in (FR) becomes greater as the cooling capacity Q_{EV} is increased. An increase in Q_{EV} results in a decrease in the economiser effectiveness E. The reduction in effectiveness ΔE increases with increases in both cooling capacity Q_{EV} and flow ratio (FR). The reductions in actual coefficient of performance $(COP)_{ACL}$ are because of higher heat losses.

The decision to carry out the experiments on a small absorption cooler, which was fabricated from standard glass components, limited the choice of heat exchanger which could be used as the economiser. However, this does not affect the conclusions that can be drawn. In practise, specifically designed economiser heat exchangers would be used in commercial and industrial size absorption coolers.

CONCLUSIONS AND OBSERVATIONS

The performance of an economiser heat exchanger in a water–lithium bromide cooler is critically affected by the cooling capacity Q_{EV} and the flow ratio (FR).

Although an absorption cooler would normally be designed for a specified maximum capacity, it should also be capable of adapting to likely changes in operating conditions such as the heat supplied and the cooling demanded. It is therefore necessary to know the effect on efficiency of changes in operating conditions. The correct choice of the economiser heat exchanger and its sizing is of vital importance in the design of an efficient and economic absorption cooler.

The required application will determine whether the economiser heat exchanger should be designed for extreme conditions or for typical operating conditions. The larger the heat exchanger the greater the capital cost. Correct sizing will result in the selection of the most economic heat exchanger which will meet the performance requirements. A unit designed for typical operating conditions will in general use less energy than one designed for extreme conditions.

Kumar *et al.* [1] demonstrated that by using high flow ratios in an absorption cooler it is possible, for a given evaporator temperature, to reduce the generator temperature. However, the work reported in this paper shows that unless the economiser heat exchanger has an adequate area, it is preferable to operate the system at a relatively low flow ratio.

This work confirms and extends that of Vliet *et al.* [5] who found that as the area of the economiser heat exchanger in an absorption cooler is increased, the cooling capacity Q_{EV} and the actual coefficient of performance $(COP)_{ACL}$ also increased.

REFERENCES

1. P. Kumar, S. Devotta and F. A. Holland, Effect of flow ratio on the performance of an experimental absorption cooling system, *Chem. Engng Res. Des.* **62**, 194 (1984).
2. I. E. Smith, C. O. B. Carey and G. F. Smith, Absorption heat pump research, Proceedings of a workshop in Berlin (Edited by W. Raldow), p. 149. Sponsored by the Swedish Council of Building Research, Stockholm, Sweden (April 1982).
3. F. A. Holland, R. M. Moores, F. A. Watson and J. K. Wilkinson, *Heat Transfer*. Heinemann, London (1970).
4. J. M. Landauro-Paredes, F. A. Watson and F. A. Holland, Experimental study of the operating characteristics of a water–lithium bromide absorption cooler, *Chem. Engng Res. Des.* **61**, p. 362 (1983).
5. G. C. Vliet, M. B. Lawson and R. A. Lithgow, Water–lithium bromide double-effect absorption cooling cycle analysis, *Trans. Am. Soc. Heat. Refrig. Air-Condit. Engrs* **88**, 811 (1982).

ETUDE DE PERFORMANCE D'UN ECONOMISEUR DANS UN REFRIGERATEUR A ABSORPTION EAU–BROMURE DE LITHIUM

Résumé—L'efficacité d'un économiseur thermique dans un réfrigérateur à absorption eau–bromure de lithium décroît quand augmentent le rapport de débit et la capacité de refroidissement. Des expériences sont menées avec six niveaux de capacité de refroidissement et neuf valeurs de rapport de débit.

UNTERSUCHUNG DER LEISTUNGSFÄHIGKEIT VON TEMPERATURWECHSLERN IN WASSER–LITHIUMBROMID-ABSORPTIONSKÄLTEANLAGEN

Zusammenfassung—Es konnte gezeigt werden, daß der Wirkungsgrad eines Temperaturwechslers im Lösungskreislauf einer Wasser–Lithiumbromid-Absorptionskälteanlage mit zunehmenden Durchsatzmengen und zunehmender Kälteleistung abnimmt. Es wurden Experimente mit sechs verschiedenen Kälteleistungen und neun Durchsatzraten durchgeführt.

ИССЛЕДОВАНИЕ ЭКСПЛУАТАЦИОННЫХ КАЧЕСТВ ЭКОНОМАЙЗЕРА В АБСОРБЦИОННОМ ВОДНО–БРОМИСТО-ЛИТИЕВОМ ОХЛАДИТЕЛЕ

Аннотация—Показано, что с ростом отношения потоков и охладительной способности уменьшается эффективность теплообменника-экономайзера в абсорбционном водно–бромисто-литиевом охладителе. Эксперименты проводились на шести уровнях охладительной мощности и девяти значениях отношения потоков.