Studies on an Ejector-Absorption Refrigeration Cycle with New Working Fluid Pairs

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Abstract

The Ejector-Absorption Refrigeration System (EARS) combines the advantages of conventional absorption system and ejector refrigeration system. This paper makes a comparative study of EARS operating on new working fluid pairs such as R124-DMAC, R134a-DMAC and R32-DMAC. Results show that R124-DMAC and R134a-DMAC give good performance at low values of generator and evaporator temperatures. R32- DMAC has drawbacks such as high generator pressures and high circulation ratios. Since R124 is a HCFC and has to be phased out in the near future, R134a-DMAC may be the preferred working pair for low heat source temperature applications.

Key words: absorption cycle, ejector cycle, new working fluids.

1. Introduction

Heat operated cooling systems are attractive when thermal energy is available freely or at low cost, and high-grade electrical energy is expensive. Both absorption and ejector refrigeration systems are heat powered. From the energy and environmental points of view, considerable scope exists for employing new working fluids in these systems. Conventional fluids being used in vapour absorption refrigeration systems (VARS) namely, water-LiBr and NH_3-water, have certain drawbacks and limitations in terms of physical characteristics and operating temperatures. In order to overcome these, many new working fluid pairs for VARS based on HFCs and HCFCs have been suggested [1- 3]. Multi-stage, multi-effect and cascade systems have also been suggested for improving the efficiencies and for utilizing high temperature heat sources effectively [4,5]. Combination of the VARS and ejector cycles by placing an ejector at the exit of generator of the conventional VARS resulting in increased mass flow rate of refrigerant, termed as Ejector-Absorption Refrigeration System (EARS), has also been suggested [6- 8]. In this paper, a comparative study of EARS with HFC32, HFCI34a and HFCI24 as refrigerants and Di-Methyl Acetamide (DMAC) as absorbent is presented.

2. Theoretical analysis

The analysis is carried out for steady state operation of the EARS shown schematically in Figure 1. It is assumed that the pressure drops at various system components, the pump work and the heat losses to the surroundings are negligible.

Pressures at the condenser, evaporator and generator are respectively calculated from,

$$P_c=P_r\left(t_c\right);P_e=P_r\left(t_e\right);P_g=P_r\left(t_g\right) \qquad (1)$$

Concentrations of weak and strong solutions are respectively obtained as

$$X_{ws}=X_s\left(t_g,P_g\right);\ X_{ss}=X_s\left(t_a,P_e\right) \qquad (2)$$

Mass flow rates of strong and weak solutions entering generator and absorber are respectively obtained as

$$m_{ss}=m_l\left(1\text{-}X_w\right)/\left(X_s\text{-}X_w\right);m_{ws}=m_l\left(1\text{-}X_s\right)/\left(X_s\text{-}X_w\right) \qquad (3)$$

where m_l is the refrigerant flow rate.

Enthalpies of refrigerant at the exit of generator (superheated vapour state), condenser (saturated liquid) and evaporator (saturated vapour state)are respectively calculated as

$$h_l=h_r\left(t_g,P_g\right);\ h_5=h_r\left(t_e,P_e\right);h_3=h_r\left(t_c,P_c\right) \qquad (4)$$

Across the expansion valve, we have

$$h_4=h_3 \qquad (5)$$

Enthalpies of solutions at the exit of generator and absorber are respectively obtained as

$$h_{10}=h_s\left(t_g,P_g\right) \qquad ;\ h_7=h_s\left(t_a,P_a\right)$$

(6)

Effectiveness of solution heat exchanger is given as

$$E_{hx}=\left(h_{10}\text{-}h_{11}\right)/\left(h_{10}\text{-}h'_{11}\right)\ \text{ where } h'_{11}=h_s\left(t_a,X_w\right) \qquad (7)$$

As pump work is negligible, one can write

$$h_8=h_7 \qquad (8)$$

Enthalpy of solution entering generator through solution heat exchanger is calculated as

$$h_9=h_8+\left(m_w/m_s\right)\left(h_{10}\text{-}h_{11}\right) \qquad (9)$$

Entrainment ratio, $?\left(=m_{13}/m_l\right)$ is determined from the following relationship,

$$?=f\left(p_g,t_g,p_e,t_e,p_c,A_t/A_k\right) \qquad (10)$$

which is obtained by applying conservation of mass and energy equations across ejector, assuming constant pressure mixing theory Keenan et al [1950], from the following equations:

$$M_j^*=\frac{M_{1i}^*+?\,M_{13i}^*\sqrt{t}}{\sqrt{\left(1+?\,t\right)\left(1+?\right)}} \qquad (11)$$

where M_{1i}^* and M_{13i}^* are functions of P_g and P_e respectively and $t=T_e/T_g$

$$\frac{A_t}{A_k}=\frac{p_2}{p_l}\sqrt{\frac{1}{\left(1+?\,t\right)\left(1+?\right)}}\,\frac{\left(\frac{p_k}{p_2}\right)^{1/?}\sqrt{1\text{-}\left(\frac{p_k}{p_2}\right)^{(?\text{-}1)/?}}}{\left(\frac{2}{1+?}\right)^{1/(?\text{-}1)}\sqrt{1\text{-}\left(\frac{2}{?\text{-}1}\right)}} \quad \text{where } P_2=P_c,P_1=P_g \qquad (12)$$

In order to obtain the COP of the cycle, energy balances at the generator and evaporator are made. Thus,

$$Q_g=m_wh_{10}+m_lh_l\text{-}m_5h_9\,;Q_e=m_l\left(1+?\right)\left(h_5\text{-}h_4\right);COP=Q_e/Q_g \qquad (13)$$

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3. Results and Discussion

The working fluids studied here are R32-DMAC, R124-DMAC and R134a-DMAC, the properties of which are taken from the Borde et al [1-3]. System performance for three working pairs are compared for specified operating conditions and unit mass flow rate of refrigerant vapour leaving generator. The results were obtained for constant values of nozzle efficiency, $?_{n}=0.85$, diffuser efficiency, $?_{d}=0.85$ and heat exchanger effectiveness, E_{hx}= 0.9. The generator pressures corresponding to dew point temperature for the three working fluid pairs are listed Table 1.

The variation of COP for three pairs with generator temperature under different generator dew point temperature (generator pressure) is depicted in Figure 2(a). For each generator pressure, there is an optimum temperature at which COP is maximum. This optimum temperature is minimum for R124-DMAC. Hence low heat source temperature is required for R124-DMAC compared to the other two pairs. R134a-DMAC and R124- DMAC exhibit nearly the same COP values in the range of generator temperatures considered here. R32-DMAC gives the best COP values, but operates at high generator pressures.

In EARS, the generator pressure is an independent parameter. For a given generator temperature, there also exists an optimum generator pressure at which the COP is maximum. For R124-DMAC, COP values are high as depicted in Figure 2(b) because of its operation near critical conditions i.e. saturation condition of generator pressure for given generator temperature at which maximum refrigerant vapour is generated. R32-DMAC, the pressure corresponding to same dew point temperature is high as seen in Table 1. For the generator temperatures 100 °C and 110 °C, R32-DMAC works at far below critical value where as RI24-DMAC operates near to critical temperature and pressure values. Hence RI24-DMAC shows better COP at these conditions.

R32-DMAC has low entrainment ratio values compared to others. Entrainment ratio remains nearly constant with generator temperature. But it is more sensitive to generator pressure because high-pressure primary fluid can entrain relatively larger amount of secondary refrigerant vapour from the evaporator compared to high temperature vapour. All three pairs have similar variation with generator temperature as observed in Figure 2(c). The concentration of weak solution leaving generator decreases with generator temperature and pressure. Since the concentration of strong solution remains unchanged, the concentration width reduces. Hence circulation ratio for EARS decreases with increase in generator temperature and pressure. Figure 2(d) shows that R32-DMAC has high CR values compared to RI24-DMAC and RI34a-DMAC.

Since the geometry of the ejector is kept constant, as generator pressure increases, incomplete expansion of primary fluid through the primary nozzle will occur. This means that the expansion of primary fluid continues outside the nozzle outlet and therefore, part of mixing section serves as primary nozzle. As a result, flow area for secondary fluid reduces and this causes entrainment ratio to fall. Hence, the ejector area ratio should increase with generator pressure to provide sufficient area for expansion, mixing and compression.

But this effect is less pronounced with generator temperature. RI24-DMAC has high ejector area ratio values among the three working fluids and also offers more geometry variation in ejector with generator pressure. As shown in Figure 2(e), R32-DMAC shows the least effect on ejector performance.

Figure 2(f) illustrates the effect of evaporator temperature on COP under different generator pressures. The rate of increase in COP with evaporator temperature is high for R32-DMAC among three working fluid pairs. Also at higher evaporator temperatures, it gives the higher COP compared to other two pairs RI24-DMAC is superior to other two pairs at low evaporator temperatures.

The entrainment ratio increases with evaporator temperature due to increase in flow rate of secondary fluid and its variation is similar for three working fluid pairs as seen Figure 3(a). This increase in entrainment ratio causes sharper increase in COP of the EARS system with evaporator temperature on higher side compared to that of simple VARS. In order to cope up with the increase in entrainment ratio, mixing section area should slightly increase. Hence ejector area ratio increases with evaporator temperature. One may also observe that RI24-DMAC requires high ejector area ratio values where as R32-DMAC demands has low values as seen in Figure 3(b).

At higher evaporator temperatures, circulation ratio (CR) is nearly the same for the three pairs. But CR is higher at low evaporator temperatures for R32-DMAC as depicted in the Figure 3(c). Hence due to low COP and high CR, R32-DMAC is not suitable at lower evaporator temperature applications. At these conditions, RI24-DMAC shows better COP and CR than the other two pairs.

Figure 4(a) shows that COP decreases with increasing condenser temperature due to decreasing in entrainment ratio. R32-DMAC gives the highest COP values in the given conditions. RI34a-DMAC has the least COP values.

Entrainment ratio decreases with condenser temperature. R32-DMAC has least values for entrainment ratio at low condenser temperature. At higher condenser temperature the three pairs have nearly the same values of entrainment ratio as shown in Figure 4(b). Entrainment ratio increases appreciably with generator pressure. R124-DMAC and R134a-DMAC have similar variation with condenser temperature. Figure 4(c) shows the effect of condenser temperature on ejector geometry. R32-DMAC has the least effect on ejector geometry while R124-DMAC has the highest.

4. Conclusions

Analysis of ejector-absorption cycle is made with R134a-DMAC, R32-DMAC and R124-DMAC as working fluids. It is found that R32-DMAC gives the best COP value with the least variation in ejector geometry. However, it needs higher circulation ratio and cannot operate at low generator pressures. R124-DMAC can operate at low heat source temperatures. At low evaporator and generator temperatures, R124-DMAC and R134a-DMAC show nearly similar performance.

Nomenclature

General	
A	Area of cross section (m2)
h	Specific enthalpy (kJ/kg)
m	Mass (kg/S)
M	Mach number (-)
E	Effectiveness (-)
p	Pressure (MPa)
Q	Heat quantity (kW)
T, t	Temperature (K,°C)
y	Specific heat ratio (-)
?	Efficiency (%)
?	Entrainment ratio (-)

Subscripts	
a	Absorber
c	Condenser
e	Evaporator
g	Generator
gd	Generator dew point
r	Refrigerant
s	Solution
ss	Strong solution
t	Throat section
ws	Weak solution
1,2...13, i,j, k	State points as in figures

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Table 1 Pressures corresponding to dew point temperature for the working fluid pairs

Working fluid	T_{gdew}= 40 °C	t_{gdew}= 50 °C	t_{gdew}= 60 °C
R32-DMAC	24.783 bar	27.946 bar	31.412 bar
R124-DMAC	5.935 bar	6.801 bar	7.758 bar
R134a-DMAC	10.166 bar	11.599 bar	13.179 bar

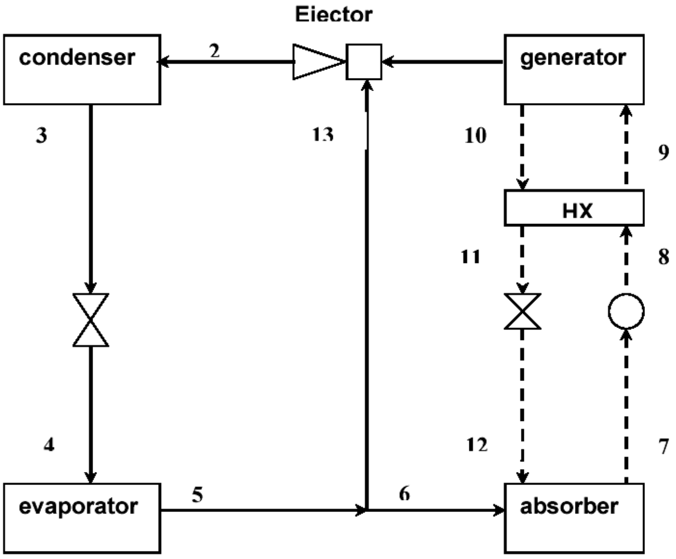
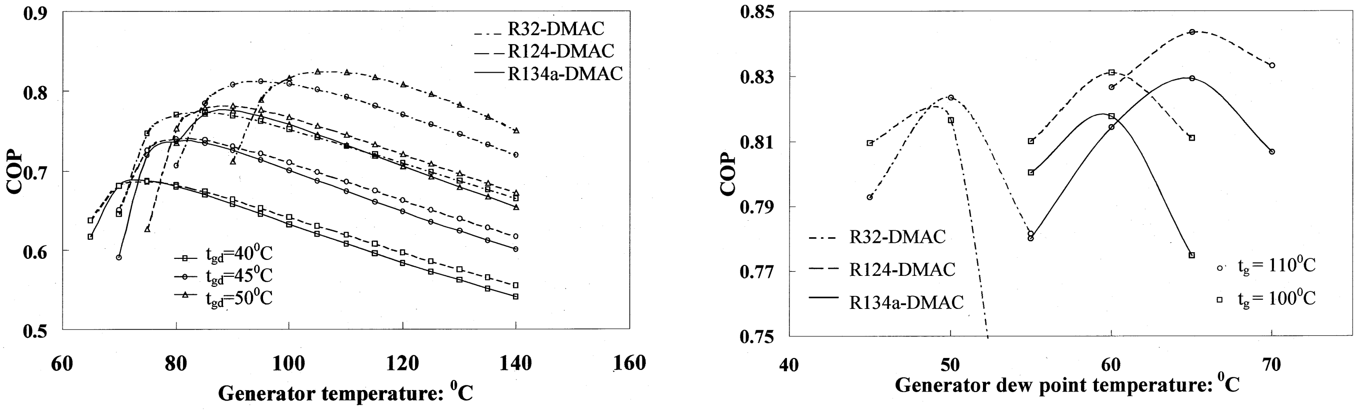
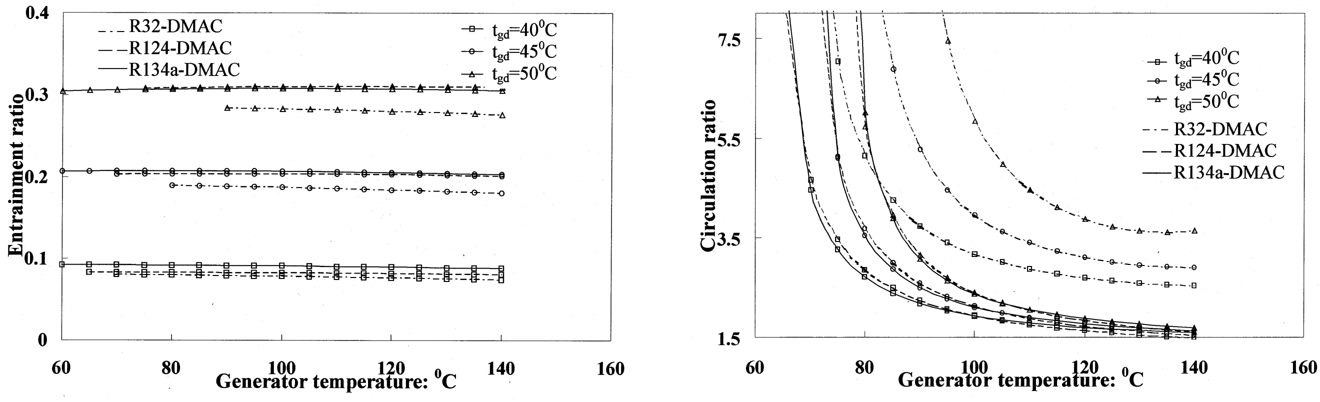


Figure 1 Schematic representation of the EARS



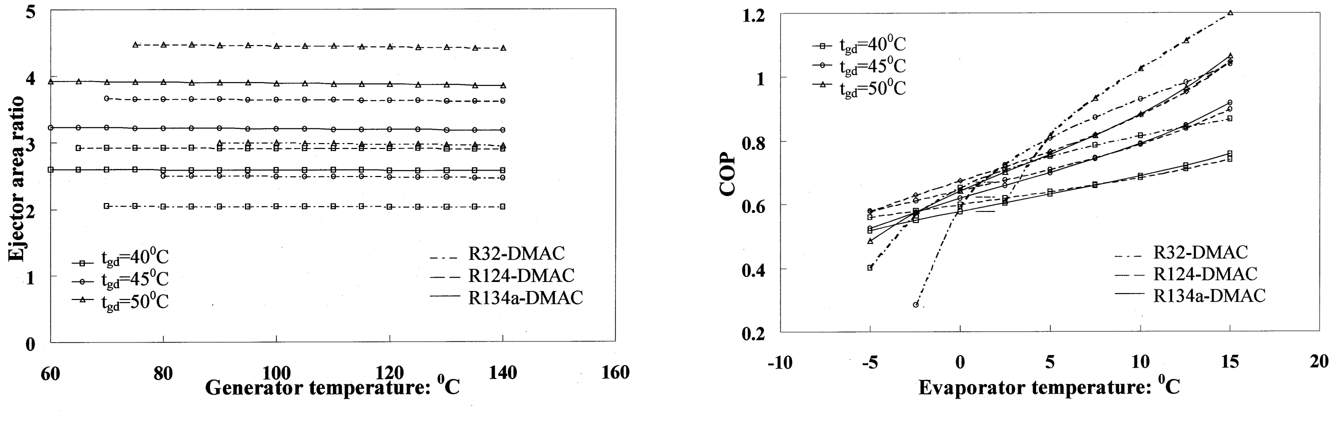
(a) COP vs Generator temperature

(b) COP vs Generator dew point temperature



(c) Entrainment ratio vs Generator temperature

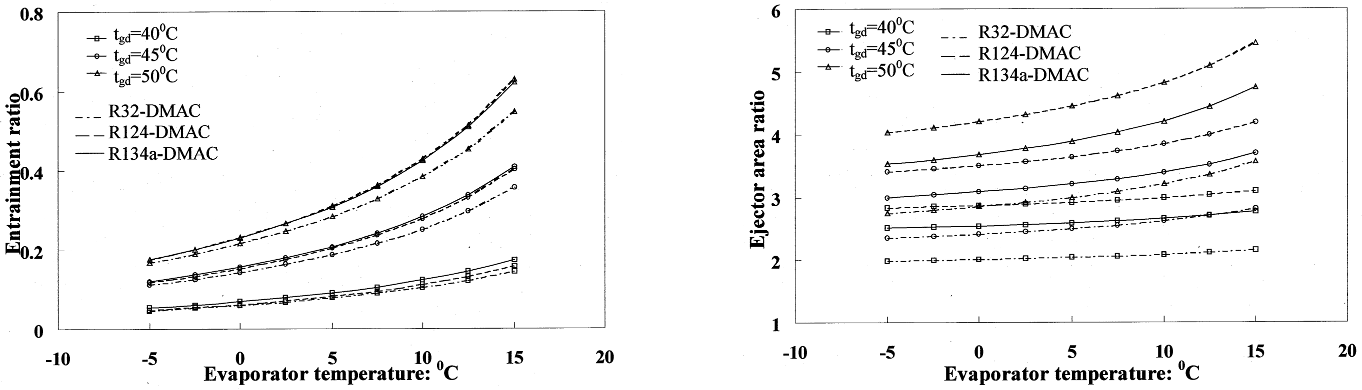
(d) Circulation ratio vs Generator temperature



(e) Ejector area ratio vs Generator temperature

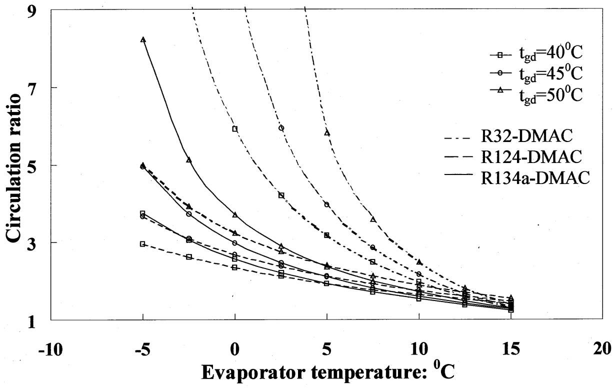
(f) COP vs Evaporator temperature (t_g=100°C)

Figure 2 Effect of generator temperature at t_e=5°C,t_c=25°C,t_a=20 °C,$?_n$=0.85, $?_d$=0.85 and E_{hx}=0.9



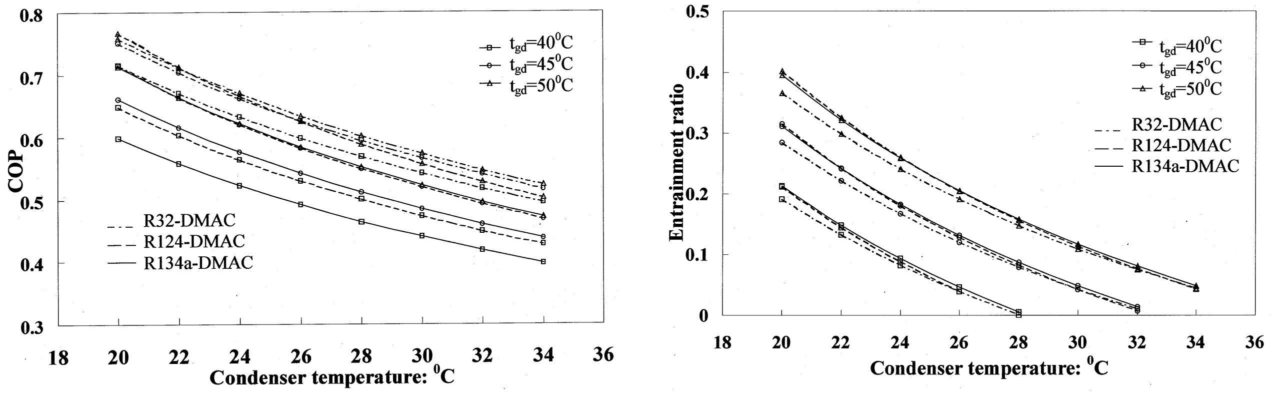
(a) Entrainment ratio

(b) Ejector area ratio



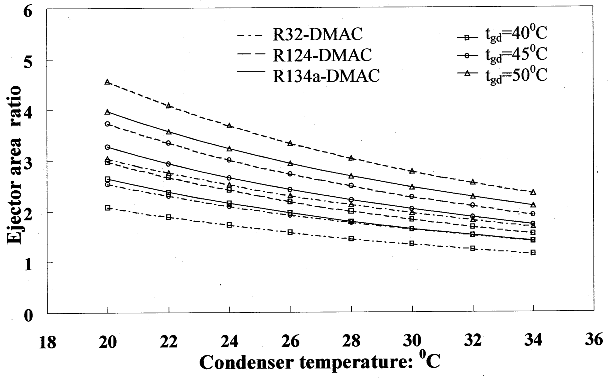
(c) Circulation ratio

Figure 3 Effect of evaporator temperature under different generator dew point temperatures (pressures) t_g=100 °C,t_c=25 °C,t_a=20°C,?$_n$=0.85,



(a) COP

(b) Entrainment ratio



(c) Ejector area ratio

Figure 4 Effect of condenser temperature under different generator dew point temperatures (pressures) t_g=100°C,t_c=25°C,t_a=20°C,$?_n$=0.85, $?_d$=0.85 and E_{hx}=0.9