THEORETICAL INVESTIGATION OF THE PERFORMANCE OF SOME ENVIRONMENT-FRIENDLY REFRIGERANTS IN A SUB-COOLING HEAT EXCHANGER REFRIGERATION SYSTEM

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ABSTRACT
As a result of global concerns over the depletion of the earth's protective stratospheric ozone layer by the atmospheric release of chloroflurocarbons (CFCs) and hydrochlorofluoro-carbons (HCFCs) refrigerants, their production has been restricted and they are no longer choices for new equipment. This paper presents theoretical investigation of the performance of some environment-friendly refrigerants in a sub-cooling heat exchanger refrigeration system. Five promising environment-friendly refrigerants (R23, R32, R134a, R143a and R152a) were selected from methane and ethane derivatives and they were investigated theoretically. Sub-cooling heat exchanger was used to evaluate the impact of selected refrigerants on the exchanger effectiveness, system capacity and coefficient of performance (COP). The results obtained showed excellent performance of R152a and R134a, and fair performance of R143a when compared with R12 in vapour compression refrigeration system. The results also showed that using R23 and R32 in the refrigeration system will be detrimental to the system performance.

Keywords: *environment-friendly, heat exchanger, sub-cooling, refrigerant performance, refrigeration system.*

INTRODUCTION
There is continued growing awareness at the international level with particular focus on the working fluids of refrigerating and air-conditioning systems. Chlorofluorocarbons (CFCs) have a long and successful association with the refrigeration industry due to their pre-eminent properties such as stability, non-toxicity, non-flammability and good thermodynamic properties (Calm and Didion, 1998; Calm *et al.*, 1999; Bolaji, 2005). However, they also have harmful effect on the Earth's protective ozone layer. Therefore, they have been forbidden in developed countries since January of 1996. In 2010 production and usage of CFCs will be prohibited completely all over the world (Radermacher and Kim, 1996; Kim *et al.*, 2002; UNEP, 2003).

As a consequence, a lot of research has been done to find the suitable replacement for CFCs. Transitional alternative compounds, such as HCFCs (hydro-chlorofluorocarbons), which are less harmful to the ozone layer, are to be used in their place until the year 2020. Also, HCFCs will be phased out internationally by 2020 and

2030 in developed and developing countries respectively, because their ozone depletion potentials (ODPs) are in relatively high levels though less than those of CFCs. By 2020, compounds such as HFCs (hydro-fluorocarbons), which are benign to the ozone layer are expected to have replaced HCFCs (Devotta *et al.*, 2001; McMullan, 2002; Sekhar *et al.*, 2004 and 2005). As a result it became a very urgent issue to investigate the performance of candidate refrigerants that will serve as CFCs and HCFCs substitutes.

Sub-cooling heat exchangers are commonly installed in refrigeration systems with the intent of ensuring proper system operation and increasing system performance. Specifically, ASHRAE (1998) states that sub-cooling heat exchangers are effective in: (i) increasing the system performance; (ii) sub-cooling liquid refrigerant to prevent flash gas formation at inlets to expansion devices; and (iii) fully evaporating any residual liquid that may remain in the compressor suction line. Therefore, sub-cooling heat exchanger is a tool that can be used to evaluate the impact of refrigerants on refrigeration system's capacity and performance.

This tool has been used by some researchers (Domanski and Didion, 1993; Domanski *et al.*, 1994; Klein *et al.*, 2000) to evaluate some alternative refrigerants to R22. Therefore, in this paper, the performance of some environment-friendly refrigerants selected as alternatives to R12 in vapour compression refrigeration system is investigated theoretically employing a sub-cooling heat exchanger refrigeration system. The impacts of these refrigerants on the system are quantified in terms of relative capacity index and relative coefficient of performance.

MATERIALS AND METHODS

Selection of Environment-Friendly Refrigerants

The range of possible alternative fluids is extensive; it includes hydro-fluorocarbons (HFCs), refrigerant mixtures, hydrocarbons, and natural fluids. Among these groups of alternatives, HFCs are the most useful. According to Calm (2002), possible environment-friendly refrigerants with zero ODP and lower global warming potential (GWP) could be selected from derivatives of methane and ethane. In this work, full array of methane and ethane derivatives were considered and trade-off in flammability, toxicity and chemical stability concerning atmospheric lifetime with changes in molecular chlorine, fluorine and hydrogen content were carried out (Bolaji, 2008). Therefore, five promising alternative refrigerants (R23, R32, R134a, R143a and R152a) that contain no chlorine and that have short atmospheric lifetime were selected and investigated theoretically using sub-cooling heat exchanger.

Refrigeration System with Sub-cooling Heat Exchanger

Vapour compression refrigeration system with a sub-cooling heat exchanger is shown in Fig. 1. In this system, high temperature liquid from the condenser is sub-cooled in the heat exchanger before entering the expansion device where it is being throttled to the evaporator pressure. The sub-cooling heat exchanger is an indirect liquid-to-vapour heat transfer device where high temperature and pressure liquid refrigerant transfers heat to the low temperature refrigerant vapour leaving the evaporator. The heat exchanger also prevents the carrying-over of liquid refrigerant from the evaporator to the compressor.

Heat Exchanger Effectiveness

The sub-cooling heat exchanger performance is expressed in terms of effectiveness (e), which is the ratio of the actual heat transfer rate to maximum possible heat transfer rate and is expressed as:

$$\varepsilon = \frac{T_{1'} - T_1}{T_3 - T_1} = \frac{T_{vapour,out} - T_{vapour,in}}{T_{liquid,out} - T_{vapour,in}} \quad (1)$$

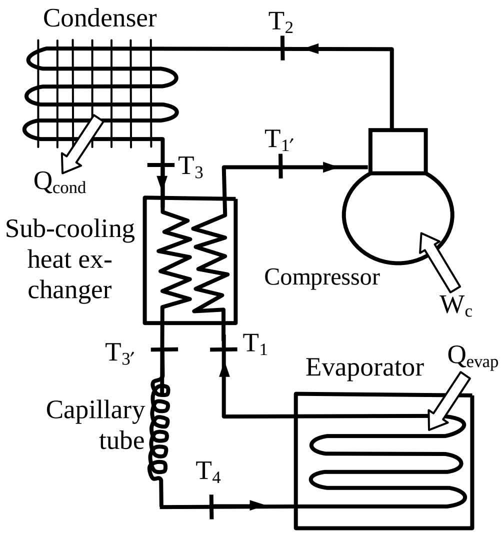

Fig. 1: Refrigeration system with a sub-cooling heat exchanger

The numeric subscripted temperature (T) values correspond to locations as shown in Fig. 1. The effectiveness is related to the surface area of the heat exchanger. A zero surface area represents a system without a sub-cooling heat exchanger whereas a system having an infinite heat exchanger area corresponds to an effectiveness of unity (Klein *et al.,* 2000).

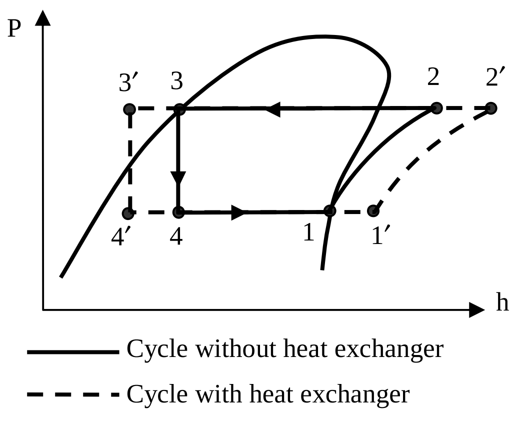

Fig 2: Pressure-enthalpy diagram showing effect of an idealized sub-cooling heat exchange

The sub-cooling heat exchanger affects the performance of a refrigeration system by influencing both the high and low pressure sides of a system. Fig. 2 shows the key state points for a vapour compression cycle utilizing an idealized sub-cooling heat exchanger on a pressure-enthalpy diagram. The enthalpy of the refrigerant leaving the condenser (state 3) is decreased prior to entering the expansion device (state 3′) by rejecting energy to the vapour refrigerant leaving the evaporator (state 1) prior to entering the compressor (state 1′). The cooling of the condensate that occurs on the high pressure side serves to increase the refrigeration capacity and reduce the likelihood of liquid refrigerant flashing prior to reaching the expansion device. Another major benefit of the sub-cooling heat exchanger is that it reduces the possibility of liquid carry-over from the evaporator which could harm the compressor.

Relative Capacity Index (*RCI*)

Without a sub-cooling heat exchanger, the refrigerating effect per unit mass flow rate of circulating refrigerant is the difference in enthalpy between states 1 and 4 in Fig. 2. When the heat exchanger is installed, the refrigeration effect per unit mass flow rate increases to the difference in enthalpy between states 1′ and 4′. If there were no other effects, the addition of a sub-cooling heat exchanger would always lead to an increase in the refrigeration capacity of a system. The extent of the capacity increase is a function of the specific heat of refrigerant, the heat exchanger effectiveness, and the system operating conditions. According to Klein and Reindl (1998), the effect of a sub-cooling heat exchanger on refrigeration capacity can be quantified in terms of a relative capacity index (*RCI*) as defined in equation (2):

$$RCI = \left(\frac{RC_{hx} - RC_{nohx}}{RC_{nohx}} \right) \times 100\,\% \qquad (2)$$

where, RC_{hx} = the refrigeration capacity with a sub-cooling heat exchanger; and RC_{nohx} = the refrigeration capacity for a system operating at the same condensing and evaporating temperatures without a sub-cooling heat exchanger.

Refrigeration cycle performance calculations were carried-out with assumption that refrigerant exits the evaporator as a saturated vapour at the evaporator pressure (state 1) and exits the condenser as a saturated liquid at the condenser pressure (state 3). When a sub-cooling heat exchanger is employed, the refrigerant entering the compressor (state 1′) has been superheated by heat exchange with the liquid exiting the condenser which causes the liquid to enter the expansion device in a sub-cooled state (state 3 ′).

A critical element not included in the calculation of *RCI* in Eq. (2) is the effect of superheating the refrigerant at the compressor suction on the mass flow of refrigerant delivered by the compressor. Most compressors are fixed volumetric flow devices (i.e. they operate at a fixed displacement rate); consequently, the mass flow of refrigerant the compressor delivers will be a function of the specific volume of refrigerant. The refrigeration capacity without heat exchanger (RC_{nohx}) can be expressed in terms of the compressor displacement rate V_r and a volumetric efficiency, h_v, density of refrigerant at compressor suction, r_1, and change in enthalpy across the evaporator ($h_1 - h_4$) as indicated in Eq. (3) (Adegoke *et al.*, 2007):

$$RC_{nohx} = V_r \eta_v \rho_1 (h_1 - h_4) \quad (3)$$

where, $V_r\rho_1 = V_r/v_1 = m_R$; V_r = compressor displacement rate (m^3/s); r_1 = (kg/m^3); v_1 = refrigerant specific volume at the compressor suction (m^3/kg); and m_R = refrigerant mass flow rate (kg/s).

Similarly, the refrigeration capacity with heat exchanger (RC_{hx}) is given as:

$$RC_{hx} = \eta_v m_R (h_{1'} - h_{4'}) \quad (4)$$

The volumetric efficiency, η_v, in Eq. (3) can be approximately represented in terms of injection ratio, R_{inj}, (the ratio of the clearance volume to the displacement volume) and the refrigerant specific volumes at the compressor suction and discharge, v_1 and v_2, as indicated in Eq. (5):

$$\eta_v = 1 - R_{inj}\left(\frac{v_1}{v_2} - 1\right) \quad (5)$$

In addition to the influence of sub-cooling heat exchangers on system capacity, it is also important to consider their influence on the system coefficient of performance (COP). COP is the ratio of refrigeration capacity to the compressor power input. This requires knowledge of how the refrigeration system power varies with sub-cooling heat exchanger performance. The following approximate expression for compressor work W_c (on a per unit mass flow rate basis) assuming an isentropic process is given in Eq. (6) (Gutkowski, 1996):

$$W_c = \frac{\gamma P_{1'} v_{1'}}{(\gamma - 1)}\left[\left(\frac{P_{2'}}{P_{1'}}\right)^{\frac{\gamma-1}{\gamma}} - 1\right] \quad (6)$$

where γ = adiabatic index; $P_{1'}$ = absolute pressure at the compressor suction (kN/m^2); $P_{2'}$ = absolute pressure at the compressor discharge (kN/m^2); and $v_{1'}$ is the refrigerant specific volume at the compressor suction (m^3/kg). The compressor power W_p can be calculated knowing the refrigerant mass flow rate (m_R) and the motor efficiency (h_{motor}) using Eq. (7):

$$W_p = m_R \cdot \frac{W_c}{\eta_{motor}} \quad (7)$$

Substitution of expression for m_R and Eq. (6) in Eq. (7) gives:

$$W_p = \frac{V_r}{v_{1'} \eta_{motor}} \cdot \frac{\gamma P_{1'} v_{1'}}{(\gamma - 1)}\left[\left(\frac{P_{2'}}{P_{1'}}\right)^{\frac{\gamma-1}{\gamma}} - 1\right] \quad (8)$$

The COP of system with sub-cooling heat exchanger is obtained from the ratio of Eq. (4) to

Eq. (8) and the effect of a sub-cooling heat exchanger on the system COP is given as:

$$COP_{RS} = \left(\frac{COP_{hx} - COP_{nohx}}{COP_{nohx}} \right) \times 100\% \qquad (9)$$

where, COP_{RS} = relative system coefficient of performance; COP_{hx} = system COP with a sub-cooling heat exchanger; and COP_{nohx} = system COP without a sub-cooling heat exchanger.

RESULTS AND DISCUSSIONS

Calculated relative capacity indices are presented in Fig. 3 for different alternative refrigerants and heat exchanger effectiveness values at a fixed saturated evaporator temperature of -5°C and a saturated condensing temperature of 40°C. Performance parameters were also obtained for R12 for comparison purpose. R12 is the most widely used convectional CFC refrigerant in the household refrigerator that needs urgent replacement. These calculations assume the refrigerant flow rate to be constant and the effects of this are considered in Figs. 4 to 6.

As shown in Fig. 3, an increase in capacity is observed for all refrigerants, although there is considerable variation in the magnitude of the effect. The relative capacity increase for R152a at a heat exchanger effectiveness of unity is 42.5%, while the increase in relative capacity for R23 under the same condition is only about 15.5%. The relationship between the relative capacity index and sub-cooling heat exchanger effectiveness is nearly linear.

The effects of the heat exchanger effectiveness on mass flow rate for the investigated refrigerants are shown in Fig. 4. As the effectiveness of the heat exchanger increases, the refrigerant entering the compressor at state 1′ (Fig. 2) achieves a greater degree of superheat which reduces both its density and the compressor volumetric efficiency. Consequently, the refrigerant flow rate decreases with increasing effectiveness of the heat exchanger (Fig. 4). Higher mass flow rate implies greater liquid refrigerant in the capillary tube, this will retard the flashing of refrigerant and reduce the mass quality of the refrigerant vapour at the exit of capillary tube. Therefore, R152a, R134a and R12 refrigerants with lower mass flow rates will perform better in the system than R143a, R32 and R23 with higher mass flow rates (Fig. 4).

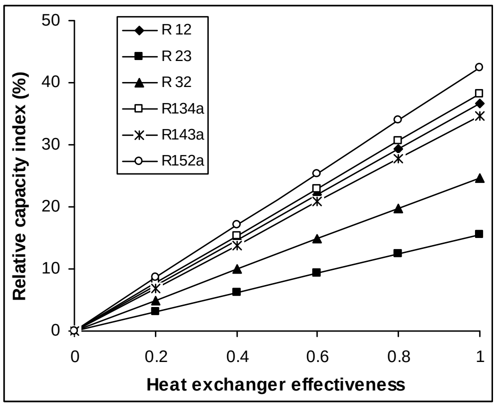

Fig. 3: System capacity change as function of the sub-cooling heat exchanger effectiveness ignoring the effect of mass flow rate for various refrigerants.

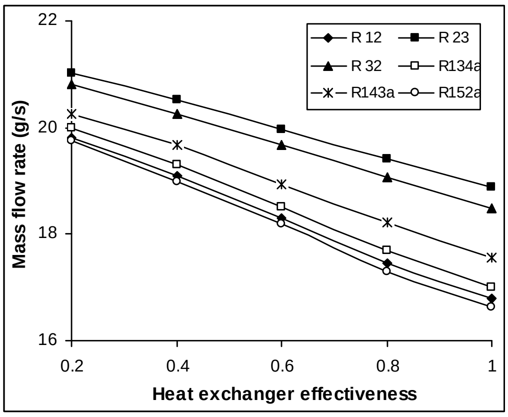

Fig. 4: Effects of the heat exchanger effectiveness on mass flow rate for the investigated refrigerants

Relative capacity index as a function of sub-cooling heat exchanger effectiveness considering the effect of mass flow rate for various refrigerants at -5°C evaporating temperature and 40°C condensing temperature is shown in Fig. 5.

As shown in this figure, the presence of a sub-cooling heat exchanger produces opposing effects on refrigeration capacity. R23 and R32 performed poorly with negative relative capacity indices, while better performance was obtained for R152a and R134a, and fair performance for R143a when compared with that of R12.

Relative system COP as a function of sub-cooling heat exchanger effectiveness considering the effect of mass flow rate for various refrigerants at -5°C evaporating temperature and 40°C condensing temperature is shown in Fig. 6. Since the system COP change is directly related to the change in capacity, the percentage change in system COP is equivalent to the percentage change in system capacity. The effect of a sub-cooling heat exchanger on COP with various refrigerants, as shown in Fig. 6, is identical to that found for capacity in Fig. 5. The application of sub-cooling heat exchanger reduces the COPs of R23 and R32, but increases the COPs of R12, R134a, R143a and R152a by 9.38, 11.1, 6.94 and 14.7%, respectively, at a heat exchanger effectiveness of unity.

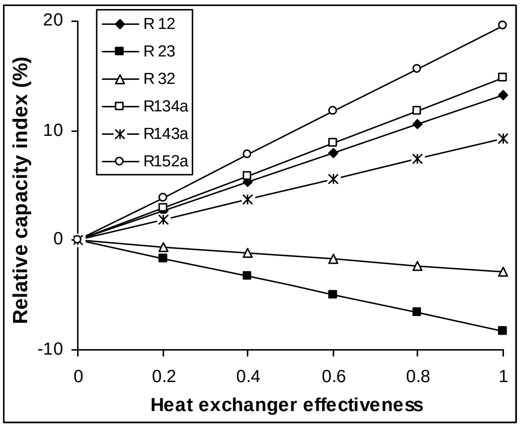

Fig. 5: Relative capacity index as a function of sub-cooling heat exchanger effectiveness considering the effect of mass flow rate for various refrigerants.

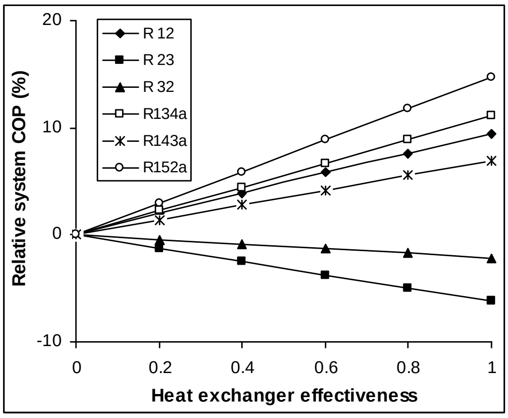

Fig. 6: Relative system COP as a function of sub-cooling heat exchanger effectiveness considering the effect of mass flow rate for various refrigerants.

CONCLUSION

Chlorofluorocarbon (CFC) that have been widely used as refrigerants in vapour compression refrigeration system due to their preeminent properties since 1931 have been phased out because they are the principal cause of stratospheric ozone depletion and global warming. Production and usage of these chemicals will be prohibited completely all over the world by the year 2010. Five promising alternative refrigerants (R23, R32, R134a, R143a and R152a) were selected based on the criteria of inflammability, toxicity and atmospheric lifetime from the compounds of methane ethane derivatives. Sub-cooling heat exchanger was used as a tool to evaluate the performances of the selected refrigerants in terms of heat exchanger effectiveness, capacity index and coefficient of performance in vapour compression refrigeration system.

The performance of R12 was also evaluated along with the five selected refrigerants to serve as basis for comparison. The results obtained showed that R152a. R134a and R143a will perform better than R23 and R32 as alternatives to R12 in vapour compression refrigeration system. The results also showed that using

R23 and R32 in the system will degrade the system performance.

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