

Effects of Sub-Cooling on the Performance of R12 Alternatives in a Domestic Refrigeration System

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Abstract

This paper presents experimental results of investigation of effects of sub-cooling on the performance of four ozone-friendly alternative refrigerants (R32, R152a, R143a, and R134a) in a domestic refrigeration system. The study was performed using a system designed for R12 with the aim of finding a drop-in replacement for the refrigerant. The results obtained showed that the sub-cooler in the refrigeration system positively affected the system performance and all the investigated refrigerants benefited from the performance improvement. An increase in sub-cooling effectiveness reduces the compressors work input and increases the system refrigeration capacity. Also, an increase in the degree of sub-cooling, reduces the pressure ratio, and increases both the refrigerant mass flow rate and coefficient of performance (COP) of the system. The comparison of the performance of R12 and the investigated alternative refrigerants showed that R152a and R134a have the most similar performance characteristics to R12, with R152a having a slightly better performance. These two refrigerants are the best replacements for R12 in a domestic refrigeration system. The performances of R32 and R143a were significantly lower than that of R12.

Keywords: alternative refrigerants, sub-cooling, refrigeration, performance, R12.

1. Introduction

Refrigerant 12 (R12) has been used for many decades as a working fluid in vapour compression refrigeration system. It was found that R12 and other chloro-fluorocarbon (CFC) refrigerants destroy the stratospheric ozone layer and also contribute significantly to the world's greenhouse warming problem [1, 2]. Table 1 indicates that ozone depletion potential (ODP) of R12 is 1.0, while its global warming potential (GWP) is 8100 over one hundred years. As a result, many environmental issues related to alternative

refrigerants and energy efficiency are reported in the literature [3 - 7].

The technology for replacing R12 in refrigeration systems has now been fully developed, but is still undergoing rapid changes where it concerns the selection of the appropriate refrigerant. Originally, a large number of refrigerant candidates were compared and the results of tests narrowed down the list of possible candidates to only one refrigerant (R134a), which is a HCF refrigerant [8]. The thermo-physical properties of R134a are very similar to those of R12 and the refrigerant is also a non-toxic

and ozone-friendly refrigerant (Tables 1 and 2).

Many research works have been done on R134a. It has been reported that the power consumption of a R134a system would be 10 - 15% more than an R12 system [9]. The performance study on a single evaporator domestic refrigerator indicated that the COP of R134a is 3% less than that of R12 [10]. Due to the reactive nature of the residual mineral oil with the lubricant polyol ester (POE) oil and R134a, a stringent flushing procedure should be adopted so that the mineral oil residue comes below 1% while retrofitting R12 systems with R134a [11, 12]. Experimental studies on the retrofitted R134a system indicated 5 - 8% lesser COP than that of a conventional R12 system [13].

However, while the ozone depletion potential (ODP) of R134a is zero, the global warming potential (GWP) is high (GWP = 1300). Due to this reason, some restrictions have already been placed on its use in Europe. Therefore, the production and use of R134a will be terminated in the near future [14 - 16].

OORG [17] reported that a preliminary (non-optimized) comparison of refrigerant candidates carried out between 1988 to 1990 showed poor performances of R134a compared to R12. However, the optimization of the compressor, the lubricant, and the cycle in 1991 resulted in comparable energy efficiency characteristics for both R134a and R12. Also, comparison of various refrigerants, including R32, R152a, R143a, R134a and hydrocarbons is still ongoing within the framework of a bilateral project in China [7, 18, 19].

Table 1 Environmental impact of investigated alternative refrigerants

Refrigerant	Ozone depletion potential (ODP)	Global warming potential (GWP)
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R12	1	8100
R32	0	650
R152a	0	140
R143a	0	3800
R134a	0	1300

Sources: [6]

Table 2 Physical properties of investigated alternative refrigerants

Refrigerant	Chemical Formula	Molecular Weight (g)	Boiling Point (°C)
R12	CF ₂ Cl ₂	121	-29.8
R32	CH ₂ F ₂	52	-51.7
R152a	C ₂ H ₄ F ₂	66	-24.0
R143a	C ₂ H ₃ F ₃	84	-47.2
R134a	C ₂ H ₂ F ₄	102	-26.1

Sources: [5]

According to Bitzer [6] the refrigerants R32, R152a, R143a and R134a are regarded as direct substitutes in domestic refrigeration system to the line of hydrofluorocarbon (HFC) refrigerants. These refrigerants belong to the chlorine free (ODP = 0) alternatives, the first two have been used for many years as components in blends but not as a single substance refrigerant until now. Especially advantageous is their very low GWP (650 and 140 for R32 and R152a, respectively).

Sub-coolers are commonly installed in refrigeration systems with the intent of ensuring proper system operation and increasing system performance. The desired increase in capacity is achieved by means of sub-cooling the condenser liquid. Sub-cooling removes any residual liquid that leaves the evaporator, thus protecting the compressor. It will also reduce the tendency toward the formation of flash gas at the entrance to the capillary tube by condensing any two-phase refrigerant that leaves the condenser [20, 21]. The performance analysis of the alternative refrigerants in domestic refrigeration system is important in order to find a drop-in replacement for the existing refrigerant in the system.

Domestic refrigerators and freezers are used for food storage in individual dwelling units and non-commercial areas such as offices throughout the world. As a result many global environmental issues related to refrigerants are illustrated through examples using domestic refrigerators and freezers. In this paper, the effects of sub-cooling on the performance of R12 alternatives in a domestic refrigeration system designed for R12 were investigated experimentally. Also, the performance parameters of the system working with alternative refrigerants were evaluated and compared with those of R12.

2. Materials and Methods

2.1 Refrigeration System with Sub-cooling

Sub-cooling in refrigeration implies cooling the refrigerant in liquid state, at uniform pressure, to a temperature that is less than the saturation temperature, which corresponds to condenser pressure. Degree of sub-cooling is the difference between the saturation temperature of the liquid refrigerant, corresponding to condenser pressure, and the temperature of the liquid refrigerant before entering to the expansion device.

Fig. 1 illustrates a refrigeration system with sub-cooling heat exchanger. The main components of the sub-cooling system include air-cooled condenser, evaporator, compressor, sub-cooler and expansion device.

Assumptions

The experimental analysis is based on the following relevant assumptions:

- (i) pressure losses due to friction and pipelines are considered to be negligible,
- (ii) heat losses to the surrounding through the system components are negligible, and

- (iii) the compression process is assumed to be isentropic.

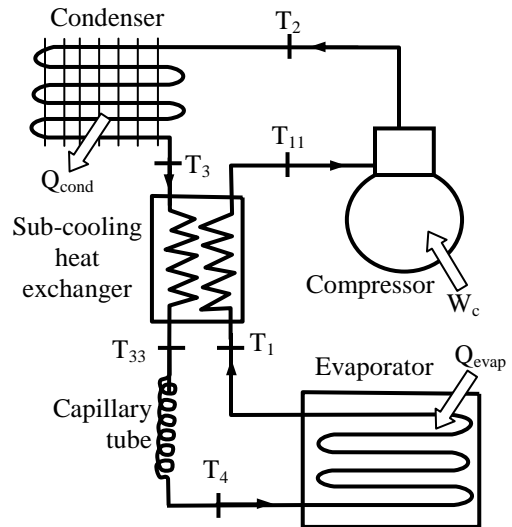


Fig. 1 Refrigeration system with sub-cooling heat exchanger

The refrigerant mass flow rate is characterized using eqn. (1) [22]:

$$m_R = \left[1 + C - C \left(\frac{p_{dis}}{p_{suc}} \right)^{\frac{1}{\gamma}} \right] \cdot \frac{A \cdot N}{V_{suc}} \quad (1)$$

where, m_R = refrigerant mass flow rate (kg/s); C = compressor clearance volume ratio; p_{dis} = compressor discharge pressure (kN/m^2); p_{suc} = compressor suction pressure (kN/m^2); V_{suc} = specific volume of refrigerant at the compressor suction (m^3/kg); A = flow area (m^2); N = compressor speed (m/s); and γ = isentropic index for the refrigerant at the suction conditions.

The thermal performance of the sub-cooling heat exchanger is presented in terms of heat exchanger effectiveness (ϵ_{sc}), and is expressed as [23]:

$$\epsilon_{sc} = \frac{T_{11} - T_1}{T_{33} - T_1} \quad (2)$$

where, T_1 = temperature of vapour refrigerant entering the sub-cooler ($^{\circ}\text{C}$); T_{11}

= temperature of vapour refrigerant leaving the sub-cooler ($^{\circ}\text{C}$); and T_{33} = temperature of liquid refrigerant leaving the sub-cooler ($^{\circ}\text{C}$). The following are the energy changes in each component of the refrigeration system as shown in Fig. 1 [22]:

The heat absorbed by the refrigerant in the evaporator or refrigerating effect (Q_{evap} , kJ/s) is expressed as:

$$Q_{\text{evap}} = m_R (h_1 - h_4) \quad (3)$$

where, h_1 = specific enthalpy of refrigerant at the outlet of evaporator (kJ/kg); and h_4 = specific enthalpy of refrigerant at the inlet of evaporator (kJ/kg).

The isentropic work input to compressor (W_{cs} , kJ/s) is expressed as:

$$W_{\text{cs}} = m_R (h_2 - h_1) \quad (4)$$

where h_2 is the specific enthalpy of refrigerant at the outlet of compressor (kJ/kg). The actual compressor work (W_c , kJ/s) is expressed as:

$$W_c = \frac{W_{\text{cs}}}{\eta_s} \quad (5)$$

where η_s is the isentropic efficiency. The heat rejected by the condenser to the atmosphere (Q_{cond} , kJ/s) is given as:

$$Q_{\text{cond}} = m_R (h_2 - h_3) \quad (6)$$

where, h_3 = specific enthalpy of refrigerant at the outlet of condenser (kJ/kg).

From the first law of thermodynamics, the measure of performance of the refrigeration cycle is the coefficient of performance (COP) and is defined as the refrigeration effect produced per unit of work required [24]. It is expressed as:

$$COP = \frac{Q_{\text{evap}}}{W_c} \quad (7)$$

Compressor pressure ratio (R_p) is given as:

$$R_p = \frac{P_{\text{dis}}}{P_{\text{suc}}} \quad (8)$$

2.2 Experimental Analysis

The schematic diagram of the vapour compression refrigeration system with sub-cooling heat exchanger is shown in Fig. 1. The refrigeration system, which

originally was designed to work with R12, was measured with two pressure gauges at the inlet and outlet of the compressor for measuring the suction and discharge pressures. The temperatures of the refrigerant at six different points, as indicated in Fig. 1, were measured with copper-constantan thermocouples.

Service ports were installed at the inlet of expansion device and compressor for charging and recovering the refrigerant. The evacuation of moisture in the system was also carried out through the service port. Initially, the system was flushed with nitrogen gas to eliminate impurities, moisture and other materials inside the system, which may affect the performance of the system. The system was charged with the help of a charging system and evacuated with the help of a vacuum pump. The refrigeration system was charged with 100 g of R12 and the base line performance was studied. After completing the baseline test with R12, the refrigerant was recovered from the system and the experimental procedures were repeated with R32, R152a, R143a and R134a. In the experiments, variations of degree of sub-cooling and sub-cooling effectiveness were obtained with the aid of adjustable output heat exchanger which provides precise control of sub-cooling.

Measurement of uncertainty

The testing of refrigeration system with sub-cooling heat exchanger using R12 and its alternatives involved the measurement of temperatures, pressures and power consumption. Measured quantities with their uncertainties are listed in Table 3.

Table 3 Measured quantities and their uncertainties

Quantity	Range	Uncertainty
Temperature	0 – 50 $^{\circ}\text{C}$	± 0.1 K
Pressure	0 – 2500 kPa	$\pm 1\%$
Power	0 – 5000 W	$\pm 1\%$

3. Results

With the aid of temperatures and pressures at different locations (Fig. 1) obtained for each refrigerant during the test, the sub-cooling (heat exchanger) effectiveness was determined using eqn. (2) and compressor work input was determined using eqns. (1), (4) and (5). The variation of compressor work input as a function of the sub-cooling effectiveness for R12 and its alternatives is shown in Fig. 2. Refrigeration capacity in kW is obtained using eqns. (1) and (3), and the variation of refrigeration capacity as a function of the sub-cooling effectiveness for the investigated refrigerants is shown in Fig. 3. The effects of the degree of sub-cooling ($T_3 - T_{33}$) on mass flow rate (eqn. 1), pressure ratio (eqn. 8) and COP (eqn. 7) for the investigated refrigerants are shown in Figs. 4, 5 and 6, respectively.

4. Discussion

The results obtained showed that the compressor work input for all the investigated refrigerants reduces as the sub-cooling effectiveness increases (Fig. 2). As shown in this figure, R32 and R143a required more work input than other investigated refrigerants, while R134a and R152a required almost the same work input as R12. Refrigeration capacity increases as sub-cooling effectiveness increases until the effectiveness becomes 0.8, above which the refrigeration capacity decreases with increase in sub-cooling effectiveness (Fig. 3). R152a has the highest refrigeration capacity which is almost the same as those of R134a and R12. Average capacities of R152a and R134a are 2.6% higher and 3.4% lower than that of R12, respectively, while average capacities of R143a and R32 are 22.4% and 31.3% lower than that of R12, respectively.

As shown in Fig. 4, the mass flow rate increases as the sub-cooling temperature increases, which implies greater liquid portion 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 and R32.

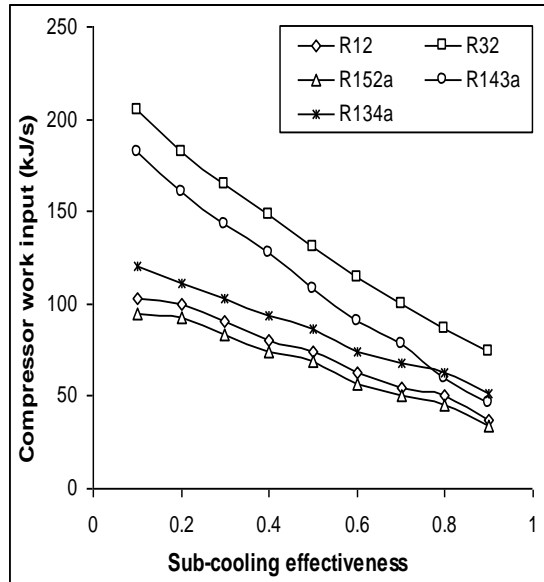


Fig. 2 Variation of compressor work input as a function of the sub-cooling effectiveness for R12 and its alternatives

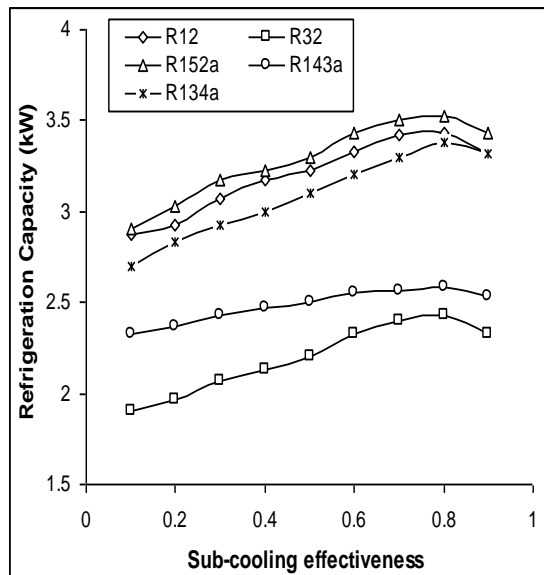


Fig. 3 Variation of refrigeration capacity as a function of the sub-cooling effectiveness for R12 and its alternatives

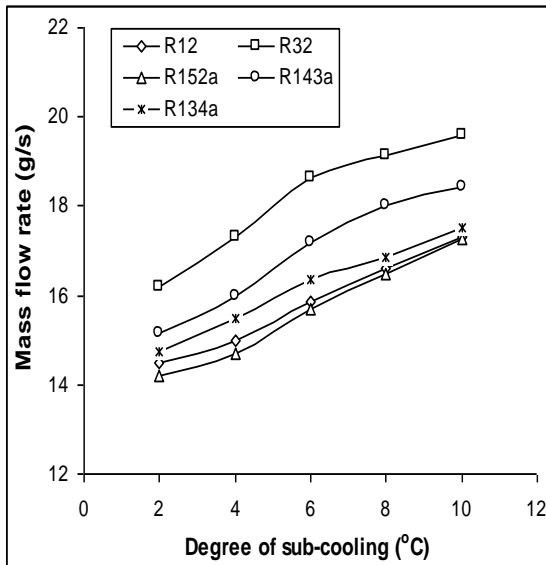


Fig. 4 Effects of the degree of sub-cooling on the mass flow rate of R12 and its alternatives

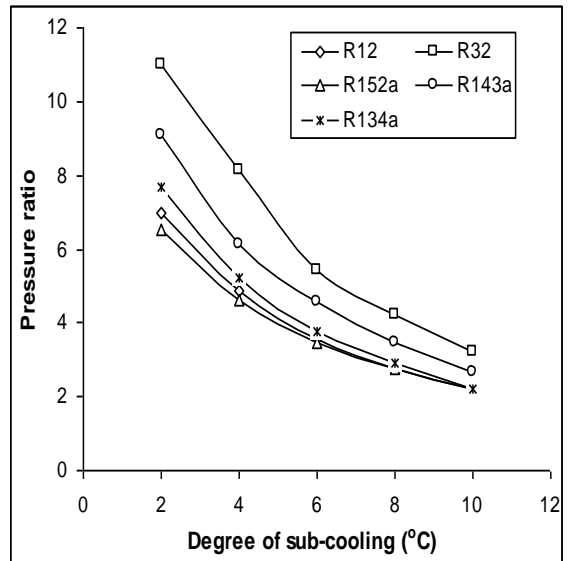


Fig. 5 Variation of pressure ratio with varying degree of sub-cooling for R12 and its alternatives

The results obtained showed that pressure ratio decreases with increase in degree of sub-cooling (Fig. 5). The average pressure ratios obtained using R32 and R143a were 56.4% and 26.6% higher, respectively, than when R12 was used, while the average pressure ratios using R134a and R152a were 6.6% higher and 4.2% lower, respectively, than when R12 was used. Therefore, heavy compressor work is required for employing R32 and R143a in the system, while the same compressor with little or no modification can be used for R12, R134a and R152a in the system. The results of COPs obtained showed that R152a has the highest COP (Fig. 6). The comparison carried out between the COPs of the investigated refrigerants showed that the COPs of R152a and R134a are very close to that of R12 over the considered range of operating conditions. The average COPs of R134a and R152a are 4.3% lower and 3.8% higher than that of R12 respectively, while the average COPs of R32 and R143a are 26.7% and 14.5% lower than that of R12, respectively.

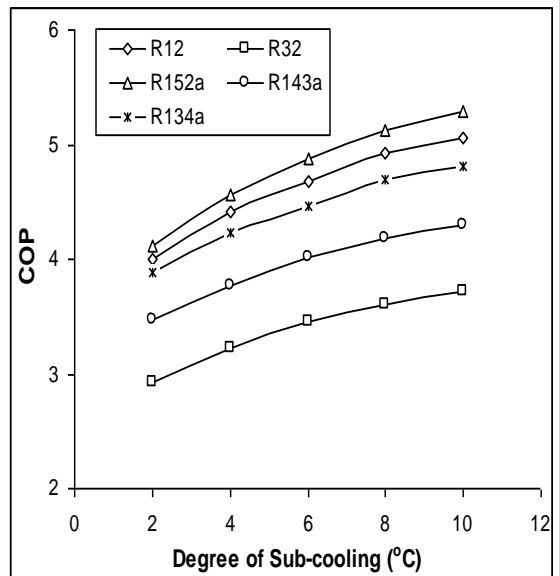


Fig. 6 Effects of degree of sub-cooling on the coefficient of performance (COP) for R12 and its alternatives

5. Conclusion

Refrigerant 12 (R12) has been used for many decades as a working fluid in vapour compression refrigeration systems.

R12 has many suitable properties such as non-flammability, non-toxicity, stability and material compatibility that have led to its widespread use. Unfortunately, it is among the chlorofluorocarbon (CFC) refrigerants that are now being phased out due to possible damage to the ozone layer. This has resulted in studies performed on four promising alternatives (R32, R152a, R143a and R134a) to replace R12 in a domestic refrigeration system. The effects of sub-cooling on the performance of these refrigerants in a refrigeration system originally designed to work with R12 were investigated. The performance parameters of the system working with alternative refrigerants were evaluated and compared with those of R12.

The application of a sub-cooler positively affected the system performance, and all the investigated refrigerants benefited from the performance improvement. An increase in sub-cooling effectiveness reduces the compressor work input and increases the system refrigeration capacity. Average refrigeration capacities of R152a and R134a were 2.6% higher and 3.4% lower than that of R12, respectively, while average capacities of R143a and R32 were 22.4% and 31.3% lower than that of R12, respectively. Also, the results obtained showed that as the degree of sub-cooling increases, the pressure ratio reduces, while both the refrigerant mass flow rate and the coefficient of performance (COP) increase. The COPs of R152a and R134a obtained at various degrees of sub-cooling are close to that of R12, while significant deviations in COPs of R32 and R143a were obtained when compared with that of R12. The overall assessment of the results showed that R152a and R134a refrigerants had the most similar performance characteristics to R12, with R152a having a slightly better performance, while the performances of R32 and R143a were significantly lower than that of R12.

6. References

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