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Heat Transfer Analysis of Environment-Friendly Refrigerants Using Conventional and Minichannel Condensers in Versatile Refrigeration Systems

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ABSTRACT

The refrigeration system is fabricated so that it can control multiple input and output parameters for testing different refrigerants in the same system at the same condenser and suction pressure and temperature. The suction temperature in the evaporator was varied with controlled water heaters, the condenser temperature was controlled by air heaters and a multispeed fan, and different temperatures at salient points were precisely varied by the PID controller, expansion valve was used to use different refrigerants. The conventional copper tube condenser and aluminum mini channel parallel flow condenser were used to test R134a, R152a, R600a, R290, and a mixture of R290/R600a (50/50% by mass) refrigerants for varying condensation temperatures in the range of 30℃ to 55℃ and evaporation temperatures in the range of -10℃ to 15℃. The refrigerant charge was drastically minimized by 35% for R152a, 60% for R600a, R290, and a mixture of R290/R600a (50/50% by mass) with the minichannel condenser over conventional round tube plate fin condenser due to compact minichannel condenser. It was observed that volumetric refrigerating capacity was higher by 8%, power input to the compressor was reduced by 9%, coefficient of performance was increased by 14%, refrigeration capacity was decreased by 9%, and condenser capacity was reduced by 15% for minichannel condenser over conventional condenser at a condensing temperature of 44℃ and evaporative temperature of 0℃.

1. INTRODUCTION

The environment is degrading day by day due to the adverse impact of refrigerants on the atmosphere. The refrigerants commonly used as R134a, R22, R404a, and others are responsible for climate change in terms of global warming potential (GWP), ozone depletion potential (ODP), and carbon emissions. The global warming potential of R134a is 1320, very large considering global environmental standards. Total equivalent warming impact (TEWI) is an indicator employed to quantify refrigerants' direct and indirect impacts. The refrigerants are selected based on environmental, operating, and economic aspects of the refrigeration and air conditioning system. No refrigerant is the perfect choice for refrigeration or air conditioning applications. The compromise is to be made between properties for specific applications.

Hydrocarbon (HC) refrigerants, (R600a), propane (R290), and a mixture of R290/R600a (50/50% by mass) produced better performance than R134a. R152a (Difluoroethane) has having GWP of 120, classified by ASHRAE as A2L, producing more cooling performance over R134a. Figure 1 shows the saturation pressure and temperature of R152a, a mixture of R290/R600a (50/50% by mass) closed with R134a and is dropped in substitute to R134a.

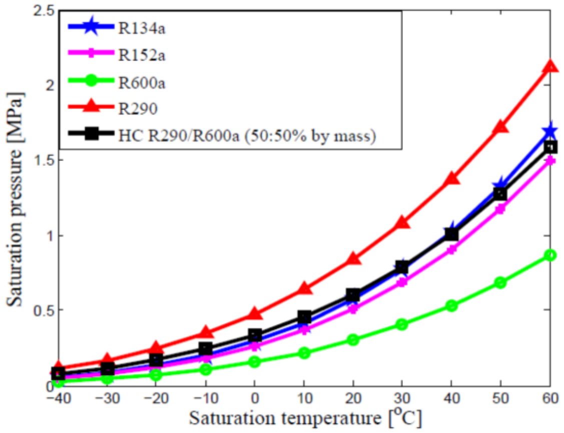

Figure 1. Pressure vs. temperature at saturated conditions

The saturation pressure and temperature are directly proportional to each other. The curve indicates the behavior of refrigerant in the actual system as a drop-in substitute or retrofit. The saturation pressure of R134a, R152a, and HC mixture of R290 and R600a (50/50%) matches closely with R134a from the initial to final temperature. Thus, they can be considered as a drop-in substitute. The volumetric refrigerating capacity of R152a, a mixture of R290/R600a (50/50%) matches with R134a, same compressor can be used while the volumetric refrigerating capacity of R600a is smaller while for R290 it is larger than R134a, thus some modification in the existing compressors is required. Minichannel condensers reduce ozone depletion due to their compact size and increased efficiency. It was found that with the reduction in hydraulic diameter of the tube, enhancement in heat transfer and penalty in pressure along the condenser.

2. MATERIAL AND METHODS

The hydrocarbons are low GWP and environmentally friendly refrigerants with flammability which can be controlled in smaller systems with proper precautions [1]. The hydrocarbon mixture available is 50% R290 and 50% R600a which replaces R134a [2]. Using a 50/50 HC mixture of R290/R600a and R134a, Jwo et al. [3] analyzed the effectiveness of a freezer by mass-producing more energy-efficient solutions with an additional cooling impact than R134a. Miyara [4] simulated the HTC performance of different refrigerants over R134a. Hydrocarbons have higher HTCs than R134a with a minichannel condenser over a conventional condenser.

Dalkilic et al. [5] performed experiments for alternative refrigerants with different retrofitted minichannel condensers and evaporators. They found that the refrigeration effect improved by 5% and COP by 8% over the existing system [6]. They investigated the performance of the minichannel condenser and found condenser temperature dropped by 3℃ and a drastic drop in pressure due to passes [7]. The minichannel condensers and evaporators are primarily used in automobiles which can be used in residential and household applications [8, 9]. Bhatkar et al. [10] studied the performance of VCR systems for air-side HTC with aluminium heat exchangers. They studied the performance concerning passes provided in the condenser for pressure and HTC concerning different flow rates [11-13]. Fernando et al. [14] performed experiments at different condenser temperatures and studied the performance of refrigeration systems. It is found that different refrigerants are used by different researchers for different applications such as drop-in or retrofit [15-21]. A flexible refrigeration system is established, developed, and assembled in recent research to regulate input and output parameters. The temperatures are recorded with temperature sensors with ± 0.1℃, pressure gauges with ± 1 PSIG, a flow meter of ± 1 kg/hr, and ±0.1 m/s of velocity over the condenser for maintaining the same experimental conditions for both the condensers. The experimental input parameters were measured such as voltage and current, air velocity, pressure gauge across the condenser and evaporator, and different temperatures like suction, discharge, subcooling, glycol, and airflow at the inlet and outlet whereas the outcome parameters were calculated in terms of refrigerant effect, condenser capacity, work input to compressor and COP at all pressure and temperature for both the condensers using mathematical formulae applied to the refrigeration cycle. The refrigerants are selected based on saturation pressure and temperature for different refrigerants related to R134a considering ecological and operating properties.

Refrigerant charge R134a, R152a, R290, R600a, and a 50/50% blend of R290/R600a were evaluated in a refrigeration system to identify the best performance with both conventional and minichannel condensers. Table 1 shows the quantity of refrigerant used in the system with both condensers.

Table 1. Refrigerants used in refrigeration system (g)

Refrigerant	RTPF	Minichannel
R134a	1010	915
R152a	810	655
R600a	405	355
R290	408	358
R290/R600a (50/50% by mass)	480	410

Figure 2 shows the front view of an actual versatile refrigeration test rig in which different input and output parameters are controlled. The suction pressure and temperature are controlled by glycol temperature and water heaters in the evaporator The condensation pressure and temperature are controlled by regulating fan speed and air temperature with the help of a heater bank provided in the compartment.

The PID controller regulates subcooling, while the expansion valve modulates the refrigerant circulation rate to attain varying condenser and suction pressure temperatures.

Figure 2. Actual fabricated VCR

Pressure gauges are installed across the condenser and evaporator stages of phase change heat exchange systems to monitor the pressure differential across the input and the outlet. The actual and theoretical parameters like compressor work, refrigerating effect, and COP, energy consumption of air heaters, water heaters, and compressors are recorded utilizing various energy meters. The safety-controlled parameters for the compressor, water and air heaters, glycol level in evaporator and compressor in terms of discharge temperature, and cutoff and cut in speed used are used to achieve the desired conditions without failure. Figure 3 shows the actual aluminium minichannel condenser fitted on the VCR system and Figure 4 shows the conventional condenser. The minichannel condenser was designed to operate at a condensation temperature of 50℃ and an evaporation temperature of 0℃, with R134a as the base refrigerant. Subcooling at the condenser's outlet was evaluated at 7℃, whereas superheating at the compressor's entry was regarded as 10℃.

Figure 3. Minichannel condenser

Figure 4. Conventional condenser

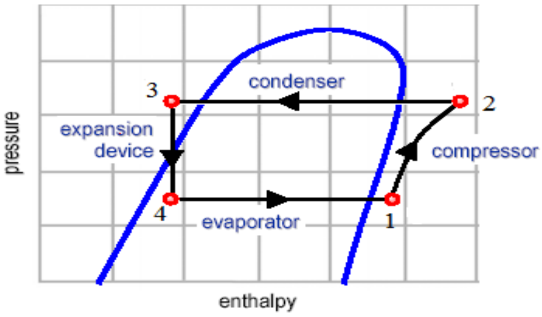

Figure 5. VCR cycle on p-h diagram

To fit into the system's condenser region, a minichannel condenser with a 4.86 kW capacity was developed employing 31 tubes, each measuring 470 mm in length and 310 mm in height. The condenser was divided into three parts: the de-superheating, two-phase region, and subcooling section. A minichannel condenser with a 4.86 kW capacity was developed in line with the space provided for the system. It includes 31 tubes, each measuring 470 mm in length and 310 mm in height. The minichannnel air-cooled condenser is manufactured with aluminium material with four passes from the inlet to the exit. The number of tubes is 14, 10, 4 and 3 are provided in each pass as the phase changes from vapor to liquid. The hydraulic diameter for each rectangular tube is 1 mm. The header tank is provided as a reservoir. The pressure drop in each pass is maintained constant in the parallel flow minichannel condenser. The conventional condenser is used with a round tube and plate fin. The tube material is copper and the fins are made of aluminium. The tube diameter was 9.6 mm with a single pass [22-26].

Different equations were used to accomplish performance parameters like COP, refrigeration and condenser capacity, and work input to the compressor [27-31]. The following parameters apply to Figure 5. Table 2 shows the geometrical parameters of conventional, Round Tube Plate Fin (RTPF), and omnichannel condensers.

Table 2. Geometrical parameters of conventional and mini channel condenser

Dimensions	RTPF	Minichannel
Surface area (sq m)	0.169	0.165
Tube	Copper	Aluminum
Fin	Aluminum	Aluminum
Size (m)	0.47 × 0.36 × 0.09	0.47 × 0.32 × 0.02
Internal volume	1865 cm^3	383 cm^3
Weight (g)	5600	1600
Fins	1/ 2 mm	1/ mm
Fin height	25 mm	8 mm
Fin width	90 mm	15 mm
Fin thickness	0.5 mm	0.3 mm
Tube diameter	9.6 mm	0.92 mm
Rows	56	31
Airside area (m^2)	11.8	4.94
Refrigerant side area (m^2)	0.925 m^2	0.418 m^2
No of channels	1	10
Passes provided	2	4
Header diameter	NA	15 mm

$$Wc = m_r(h_2 - h_1) \tag{1}$$

$$Rc = m_r(h_1 - h_4) \tag{2}$$

$$COP = \frac{(h_1 - h_4)}{(h_2 - h_1)} \tag{3}$$

$$Qc = m_r(h_2 - h_3) \tag{4}$$

$$U = \frac{Qc}{A\,\Delta T} \tag{5}$$

where, h_1: Enthalpy of vapor refrigerant at entry to the compressor, h_2: Enthalpy at condenser entry, and $h_3 = h_4$: Enthalpy across expansion valve and m_r: refrigerant mass per second (kg/sec). Wc is the work of the compressor, Rc is refrigeration capacity, Qc is condenser heat rejected and U is overall HTC.

3. RESULTS AND DISCUSSION

The refrigerants, R290, R600a, R290/R600a (50/50), R134a, and R152a were selected depending on the ODP, GWP, and carbon emissions. Experimental trials were conducted for both condensers for all refrigerants at different evaporation temperatures that varied from -10°C to +15°C with a 5°C interval and variable condensation temperatures spanning from 36°C to 54°C. Performance parameters for a typical condensation temperature of 44°C are used to display the results.

3.1 Volumetric cooling capacity

Volumetric cooling capacity is important for the selection of drop-in refrigerants in the compression refrigeration system. R600a and R290 are not dropped in substitute to R134a due to saturation pressure at different temperatures. They need separate compressors considering volumetric capacities.

R600a and R290 were determined to possess volumetric refrigerating capacities that are more than half and twofold that of R134a, respectively. Consequently, R600a and R290 cannot be used as replacements that drop in for R134a. Volumetric cooling capacity improves because of a reduction in specific volume and an increase in cooling effect; therefore, the smaller the compressor size necessary the higher the volumetric cooling capacity. Larger displacement compressors are required for R600a; however, smaller displacement compressors are necessary for R290. Volumetric refrigerating capacity was observed to increase as the evaporator's temperature increased. At -10°C evaporation temperature, the volumetric refrigerating capacity of R600a was less by 42.22%, for R290/R600a (50/50%) it was less by 15.64%, and for R152a it was less by 2.08% while for R290 it was more by 34.98% than R134a. It was seen from Figure 6 that R152a, R290/R600a (50/50%), and R134a are producing equal refrigerating effect. As the operating pressures for R290 are much higher while lower for R600a than R134a component changes are necessary to prevent leakage into the system.

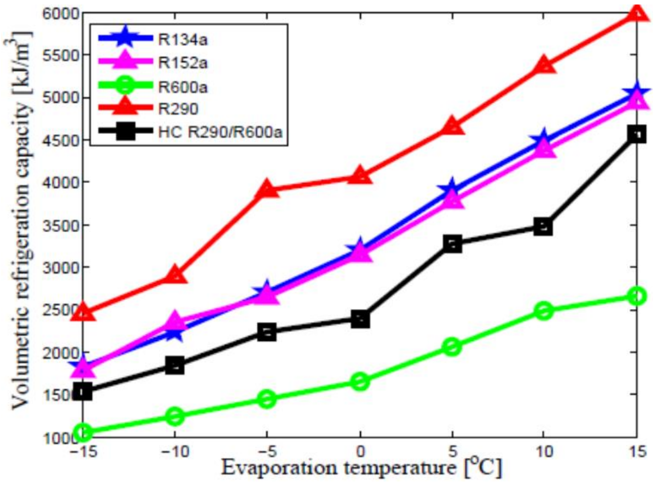

Figure 6. Volumetric refrigeration capacity vs. evaporation temperature

3.2 Actual work of compression

Due to the lower refrigerant charge in the system for different alternative refrigerants, the work of compression was reduced for the minichannel condenser than the conventional condenser by ± 10%. Figure 7 illustrates the following result: compressor work increases as the bulk flow rate of refrigerant increases. In all the trials, the power consumption of the compressor with a minichannel condenser was less than conventional condenser. R290/R600a (50/50%) HC combination can consequently be used as a drop-in replacement for R134a. Because the charge of HC refrigerant in the refrigeration system is lower compared to that of HFC refrigerants, the actual compressor work is less than that of R134a. In contrast to a typical condenser, the minichannel condenser's geometrical shape reduces the condensation temperature by 2 to 3°C, which lowers the work of compression for all refrigerants. It was discovered that, at a specific condensation temperature, the work of compression increases as the rate of evaporation rises due to the refrigerant's improved mass flow and the system's cooling capacity. In each test, the minichannel condenser-equipped compressor consumed less electricity than the conventional condenser. It was observed that, given the same condensation temperature, the compressor's specific effort (kJ/kg) decreases when the evaporation temperature increases from -10 to 15°C and the pressure ratio decreases. Due to high working circumstances, R290 has consumed more work than R600a, which uses less because it is a low-pressure refrigerant. Applying azeotropic or non-azeotropic refrigerant mixes (NARMs), which have energy-efficient and environmentally friendly components, is one way to maintain the compressor size. The HC blend of R290/R600a (50/50% by mass) can be used successfully in home refrigerators even if it has almost the same pressure as R134a.

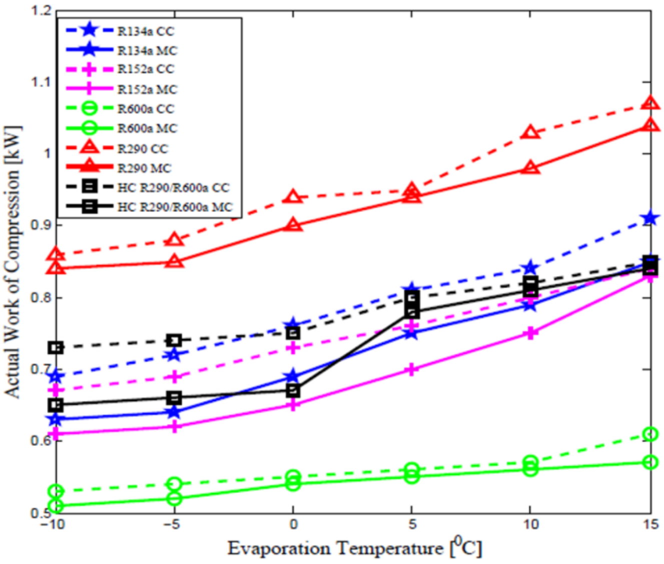

Figure 7. Actual work of compression vs. evaporation temperature

3.3 Coefficient of performance (COP)

The operational efficiency of the refrigeration system is influenced by the compressor's actual electricity consumption, which COP might measure. The work consumption of the minichannel condenser was less over round tube plate fin condenser due to the reduced pressure ratio between evaporator and condenser for minichannel condenser than the conventional condenser because of the lower condensation temperature, the COP for minichannel condensers was higher than that of traditional condensers for all condensation and evaporation temperatures. COP of R152a was the highest of all refrigerants while R290 shows the minimum COP concerning R134a as shown in Figure 8.

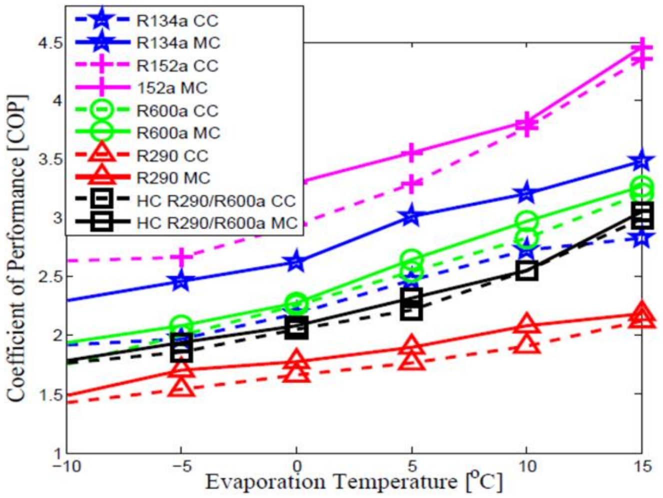

Figure 8. COP vs. evaporation temperature

The greater value of COP indicated a lower energy consumption. It was found that COP depends on the effective cooling medium and suction temperature. The suction temperature is to be maintained as per the cooling demand of the product or comfort air conditioning. Consequently, the minichannel condenser was shown to provide more efficient cooling than the standard condenser.

3.4 Condenser capacity

Figure 9 shows the condenser capacity in kJ/kg for all the refrigerants used with conventional and minichannel condensers. HC refrigerants have higher latent heat than HFC refrigerants. Out of all the refrigerants used in the system, R152a had the highest discharge temperature. The discharge temperature has an impact on the stability of lubricants and compressor components. For all alternate refrigerants, the compressor discharge temperature decreases by 10 to 20°C as compared to R134a for minichannel condensers. Even though the internal volume of the minichannel condenser is around one-fifth that of the traditional condenser, the condenser capacity of the former was marginally lower. Compared to HFC refrigerants, HC refrigerants have a larger latent heat and a larger condenser capacity. Because it was discovered that as the condensation temperature increases, the condenser capacity decreases as the latent heat transfer diminishes towards the critical point in the p-h diagram, minichannel condensers are a good option for operating at lower condensation temperatures as opposed to conventional condensers that increase Carnot COP.

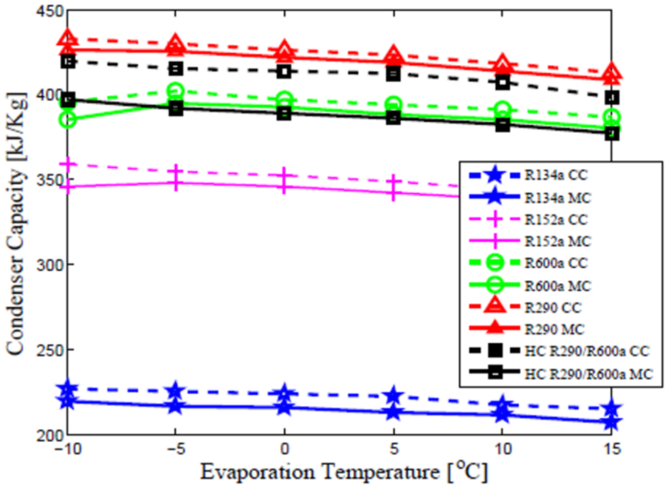

Figure 9. Condenser capacity vs. evaporation temperature

3.5 Refrigeration capacity

The refrigeration capacity in kJ/kg for all refrigerants is displayed in Figure 10 at an evaporation temperature of -10 to 15°C for both condensers and a condensation temperature of 44°C. When compared to other refrigerants, R152a has performed better overall. The refrigeration capacity for the minichannel condenser was more than the round tube plate fin condenser for all refrigerants at different condensation and evaporation temperatures as seen in Figure 10.

The refrigeration capacity of hydrocarbon refrigerants was more due to large latent heat over HFC refrigerants. It was shown that refrigeration capacity rises with evaporation temperature. Additionally, it was noted that R152a and all hydrocarbon refrigerants cooled more quickly than R134a. For every refrigerant at each condensation and evaporation temperature, the minichannel condenser's refrigeration capacity was marginally higher than that of the traditional condenser.

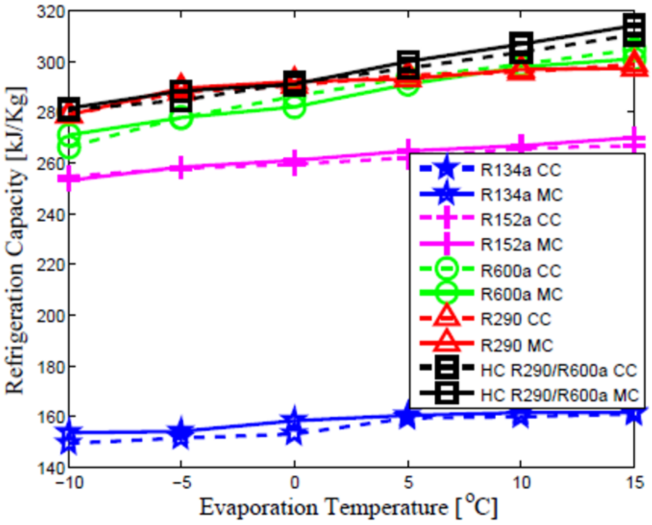

Figure 10. Refrigeration capacity vs. evaporation temperature

4. CONCLUSIONS

•R152a and R290/R600a (50/50% by mass) can be replaced directly with R134a concerning saturation pressure and temperature from starting to a final temperature as well as from the experimental results.

•R290 is having higher operating pressure than R134a. Thus, needs a different compressor, Therefore, it is a retrofit refrigerant.

•Refrigerant charge was reduced by 35% with R152a and 60% for R600a, R290 and R290/R600a (50/50% by mass) against R134a with minichannel condenser over conventional condenser.

•In summer when electricity demand is higher, minichannel condenser works efficiently due to a reduction in condenser temperature over conventional condenser by 2 to 3°C.

•Compressor power consumption of all the refrigerants was lesser for minichannel condenser than conventional condenser.

For all condenser pressures and temperatures, the COP of the refrigeration system using a minichannel condenser was more than 15% higher than that of a round tube plate fin condenser.

•The refrigeration and condenser capacity of all the alternating refrigerants was more than R134a due to larger latent heat, more than 45% at all pressure and temperature conditions.

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NOMENCLATURE

A	surface area of condenser, m^{-2}
COP	coefficient of performance
HC	hydrocarbon
m	mass flow rate of refrigerant, kg s^{-1}
RTPF	round tube plate fin
U	overall heat transfer coefficient, $Wm^{-2} K^{-1}$
VCR	vapor compression refrigeration
ΔT	temperature difference across condenser, K

Subscripts

c	condenser
CC	conventional condenser
MC	minichannel condenser
r	refrigerant