

EXPERIMENTAL ANALYSIS OF MICROCHANNEL CONDENSER USING R134a AND DROP IN SUBSTITUTE HYDROCARBON MIXTURE OF R290 AND R600a

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ABSTRACT

Microchannel condensers are widely used in automobile and household air conditioners with R134a as a refrigerant. In order to reduce the global warming potential as well as the refrigerant charge, hydrocarbon mixture of R290 and R600a (50:50 % by mass) was used as a drop in substitute to R134a in the vapour compression refrigeration system. Versatile vapour compression refrigeration system of 1 ton of refrigeration capacity was designed, developed and fabricated for testing different refrigerants. Various parameters such as ambient temperature in the condenser cabin, different condensation and evaporation temperatures, different mass flow rates of refrigerant and air can be controlled precisely in the test rig. Experiments were performed using R134a and hydrocarbon mixture of R290 and R600a (50:50 % by mass) for condensation temperature of 44°C and evaporation temperature ranging from -15 to 15 °C. Refrigerant charge was reduced by 45 % with the hydrocarbon mixture of R290 and R600a (50:50 % by mass) over R134a. Performance parameters such as compressor power consumption increases by 13.3 %, coefficient of performance reduced by 43 %, refrigeration capacity increased by 140.8 %, condenser capacity increased by 185.4 % and the product of overall heat transfer coefficient and surface area of condenser was increased by 243.7 % by using hydrocarbon mixture of R290 and R600a (50:50 % by mass) over R134a with the microchannel condenser at condensation temperature of 44°C and evaporation temperature of 0°C. It is suggested to use an environmental friendly refrigerant, hydrocarbon mixture of R290 and R600a (50:50 % by mass) as a drop in substitute to the conventional refrigerant R134a in the automobile, household air conditioning and refrigeration systems.

Keywords: Coefficient of performance; hydrocarbon mixture; refrigerant; condenser capacity; compressor power consumption.

INTRODUCTION

Presently hydrofluorocarbon (HFC) 134a refrigerant is used in the automobile and household air conditioning systems in most of the countries. Thermodynamic properties of R134a are good but the global warming potential (GWP) is 1430 which is quite high considering the human health and environmental norms. Keeping in view the GWP of R134a, it is an urgent need to find the alternative refrigerants [1, 2]. As per latest European norms, the refrigerants which are having GWP more than 150 cannot be used in the automobile air conditioning systems [3]. Hydrocarbons (HCs) are natural refrigerants, having negligible GWP of 4, environmentally friendly, non-toxic, chemically stable, compatible with many materials and miscible with mineral oils. Major hydrocarbons under consideration are propane (R290), iso-butane (R600a), n-butane and mixture of propane and iso-butane in different proportions by mass. Besides this, the zeotropic refrigerant mixtures of hydrocarbon refrigerants have potential to enhance the performance and efficiency of a vapour compression refrigeration (VCR) system due to the temperature gliding effect [4, 5]. Latent heat of hydrocarbon refrigerant is nearly twice than that of HFC and hydrochlorofluorocarbon (HCFC) refrigerants. Performance of HC refrigerant is better than R134a but the problem with these refrigerants is that they are flammable. Density of hydrocarbon refrigerant is nearly 40 % of HFCs and HCFCs, thus the refrigerant required in the system reduces drastically [6]. In the household refrigerators, the possibility of explosion by flammability is negligible because half amount of HC's can be charged compared HFC's and HCFC's [7]. Some simple safety devices such as a ventilation system and a leakage detector can be installed to overcome the flammability problem in large size refrigeration and air conditioning systems [8]. The improvement in refrigeration cycle performance can be done by lowering the compressor power consumption, increasing the condenser heat rejection capacity or reducing the difference between condenser and evaporator pressures [9-12]. Microchannels are viewed as being responsible for reducing the ozone depletion potential by enabling the use of smaller amounts of environmentally harmful fluids, decreasing the green house gas emissions by improving component and system energy efficiencies [13-15]. The successful applications of microchannel heat exchangers in automotive industries also opens up a new frontier and creates a positive momentum for other industries such as residential and commercial heating, ventilating, air conditioning and refrigeration (HVACR) [3]. Several types of compact heat exchangers are employed in small refrigeration, air-conditioning and heat pump systems [16].

There are significant differences between large round tubes and the smaller non-circular tubes in the relative magnitudes of gravity, shear and surface tension forces, which determine the flow regime established at a given combination of liquid and vapor-phase velocities [17]. A microchannel tube with heat transfer enhancement characteristics is taken as one potential solution for system performance enhancement with reduction in the refrigerant charge. The pressure drop in flat tubes is expected to be less than circular tubes due to a smaller wake area. For the same reason, noise and vibration are less in flat tube heat exchangers as compared to circular tubes [18-21]. In recent years, new condenser design concept called sub-cooling parallel flow (SPF) is provided in the microchannel condenser which enhances the system performance in which the receiver-dryer is integrated with condenser core before the last one or two refrigerant passes. The performance of microchannel condenser is dependent on different parameters such as refrigerant charge, size of the receiver, sub-cooling area,

pass structure, position of the receiver with respect to the condenser passes and liquid-vapor separation in the receiver [22]. If the hydrocarbon refrigerant charge in the VCR system is below 150 g the chances of explosion are nil even though all the refrigerant comes out of the system, as the lower flammability limit dose not reach to the flammable level even though the room size is very small ($4\text{m} \times 4\text{m} \times 4\text{m}$) [23]. Pure propane has high pressure and pure iso-butane has low pressure at the working conditions so both are not perfect drop in substitute for R134a. In the experimental investigation of substituting R134a with R436A (a mixture of R290 and R600a with a mass ratio of 56/44) in a 238 L domestic refrigerator without any modification in a refrigeration cycle, results showed that in comparison to the base refrigerator working with R134a, the energy consumption per day was reduced by 5.3 % [24].

EXPERIMENTAL SET UP

Design of Experiment

Experimental set up was designed and fabricated for 1TR (ton of refrigeration) VCR system with the air cooled condenser as shown in Figure 1. Air heaters were provided in the condenser compartment for increasing the condensation temperature, ethylene glycol (25 % by mass in water) was used in evaporator with stirrer to get the desired evaporation temperature with the manual controlled expansion valve. Microchannel condenser was designed, developed and fabricated for heat rejection capacity of 4.86 kW with aluminium material for rectangular tubes and fins with the integral receiver and drier as shown in Figure 2. Each condenser tube was containing 10 microchannels with hydraulic diameter of 0.9144 mm. Four pressure gauges (range 0 to 2 MPa) were attached before and after the evaporator as well as condenser for measuring the pressure drop across the two heat exchangers with an accuracy of $\pm 0.007\text{MPa}$. Voltmeter (range 0 to 400 Volts) was used for measuring voltage with an accuracy ± 1 Volt. Ammeter (range 0 to 100 Ampere) was used for measuring the current with an accuracy of ± 1 Amp. Rotameter (range 13.8-138 Kg/hr) was used to measure the flow rate of refrigerant with an accuracy of ± 0.5 Kg/hr. Refrigerant temperatures were recorded at various points such as suction and discharge of compressor, sub-cooled liquid at the exit of condenser, glycol in the evaporator, ambient air flow and exhaust of air over the condensers with the help of PT-100 thermal sensors with an accuracy of $\pm 0.1^{\circ}\text{C}$.



Figure1. Experimental set up.



Figure 2. Microchannel condenser.

Velocity of air across the condenser was measured with the help of anemometer with an accuracy of ± 0.1 m/s. Power consumption of compressor, air heaters, condenser fan, water heaters, stirrer were measured separately with the help of digital energy meters in kW with an accuracy of ± 0.01 kW.

Experimental Procedure

The objective of the research was to study, analyze and compare the performance of the VCR system with R134a and HC mixture of R290/R600a (50:50 % by mass) with aluminium microchannel condenser in terms of actual compressor power consumption, coefficient of performance, refrigerating capacity, condenser capacity and the product of overall heat transfer coefficient (U) and surface area (A) of the condenser. In the experimentation, HC mixture of propane and isobutane (50:50 % by mass) was used as a drop in substitute to R134a and experiments were performed with microchannel condenser for condensation temperature of 44°C . For each condensation temperature, evaporator temperature was varied from -15°C to 15°C . Desired condensation pressure corresponding to saturation temperature was obtained by controlling the air heater temperature and multi speed fan regulator. Evaporator temperature was controlled with the help of manually controlled expansion valve and setting the suction temperature of the refrigerant with the help of proportional, integral and derivative (PID) controller. Degree of sub-cooling at the exit of condenser was maintained at 7°C and degree of suction superheating to compressor was maintained 10°C throughout the experimentation for both the refrigerants.

RESULTS AND DISCUSSION

Experiments were performed on versatile VCR system using microchannel condenser at condensation temperature of 44°C while the evaporation temperature was varying from -15°C to 15°C for R134a and HC mixture of R290/R600a (50:50 % by mass). It was observed that the performance of the VCR system enhanced by using HC mixture of R290/R600a (50:50 % by mass) as compared to R134a. As the density of hydrocarbon refrigerant is around 40 % of HFC refrigerants, refrigerant charge was reduced by 45 % for HC mixture of propane and isobutane (50:50 % by mass) over R134a. Performance parameters such as actual compressor power consumption, COP, refrigeration capacity, condenser capacity and the product of overall heat transfer coefficient and area of

condenser for R134a and HC mixture of R290/R600a (50:50 % by mass) were analyzed and plotted for condensation temperature of 44⁰C and the evaporation temperature ranging from -15⁰C to 15⁰C.

Actual compressor power consumption

Compressor is one of the most important component of VCR system. Actual compressor power consumption for microchannel condenser with R134a and HC mixture of R290/R600a (50:50 % by mass) at 44⁰C condensation temperature and evaporation temperature ranging from -15 to 15 ⁰C is shown in Figure 3. As the microchannel condenser has different geometrical structure and uniform air distribution over the condenser tubes than conventional condenser, the condensation temperature drops by 2 to 3 ⁰C for same ambient condition. Thus the microchannel condenser works efficient in the high ambient conditions. Actual compressor power consumption was more in HC mixture of R290/R600a (50:50 % by mass) than R134a. It was seen that the compressor power consumption increases as the evaporation temperature increases from -15⁰C to 15⁰C for a condensation temperature of 44⁰C. It was observed that compressor power consumption is more by 13.3% for R134a than HC mixture of R290/R600a (50:50 % by mass) at condensation temperature of 44⁰C and evaporation temperature of 0⁰C.

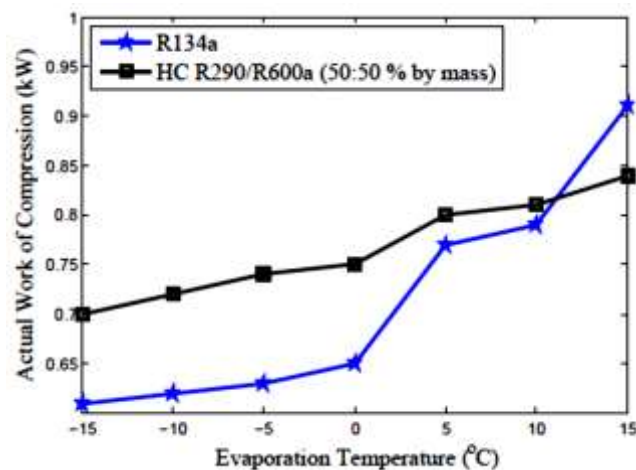


Figure 3. Actual compressor power consumption for microchannel condenser.

Coefficient of performance

Coefficient of performance of the VCR system is the ratio of desired refrigeration effect to the work supplied to the compressor. COP is one of the most important performance parameter of the VCR system. Figure 4 shows the values of COP for condensation temperature of 44⁰C and evaporation temperature were ranging from -15⁰C to 15⁰C using microchannel condenser with R134a and HC mixture of R290/R600a (50:50 % by mass). It was observed that, COP increases for evaporation temperature ranging from -15⁰C to 15⁰C for condensation temperatures of 44⁰C. It was seen that as the condensation temperature increases, COP decreases due to more compressor power consumption. It was also observed that COP values with the microchannel condenser were more for R134a than HC mixture of R290/R600a (50:50 % by mass) from -15⁰C

to 15°C. COP of HC mixture of R290/R600a (50:50 % by mass) at condensation temperature 44°C and evaporation temperature of 0°C was less by 43 % than R134a.

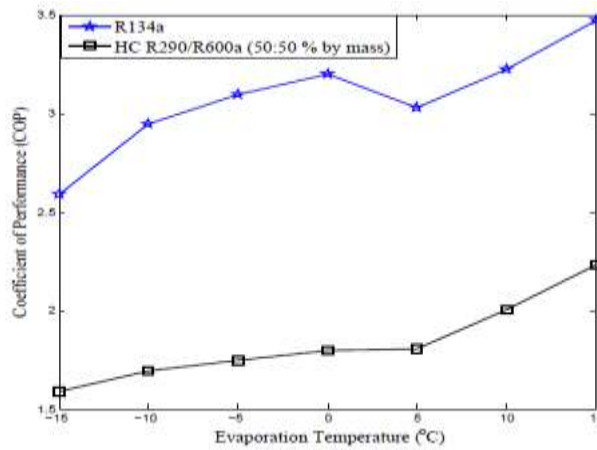


Figure 4. Coefficient of performance for microchannel condenser.

Refrigerant capacity

Refrigerant capacity of any refrigerating system is the rate at which it will remove heat from the refrigerated space. Refrigeration capacity is the total refrigeration effect produced in the evaporator which is given as the product of mass flow rate of refrigerant in kg/s and the enthalpy difference (kJ/kg) between the exit and inlet of evaporator. Refrigeration capacity of R134a and HC mixture of R290/R600a (50:50 % by mass) is shown in Figure 5 for condensation temperature of 44°C while the evaporator temperature ranges from -15°C to 15°C. It was observed that the refrigerating capacity of HC mixture of R290/R600a (50:50 % by mass) was higher than R134a from evaporation temperature ranging from -15°C to 15°C. As the latent heat of HC refrigerant is more than R134a, the cooling was fast for HC mixture of R290/R600a (50:50 % by mass) than R134a. It was seen that the refrigeration capacity increased by 140.8 % for HC mixture of R290/R600a (50:50 % by mass) than R134a at condensation temperature of 44°C and evaporation temperature of 0°C.

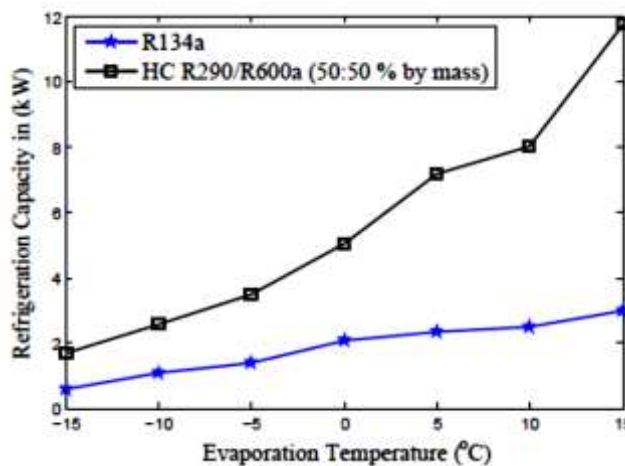


Figure 5. Refrigerating capacity for microchannel condenser.

Condenser capacity

Condenser capacity is the total heat rejected by the condenser which is equivalent to the addition of refrigeration effect in the evaporator and the heat generated by the mechanical compression. Thus condenser of VCR system is always larger than evaporator. Condenser capacity is given as the product of mass flow rate of refrigerant (kg/s) and the enthalpy of conversion from vapour to liquid (kJ/kg) at that condensation temperature. Figure 6 shows the condenser capacity for microchannel condenser with R134a and HC mixture of R290/R600a (50:50% by mass) at condensation temperature of 44°C while evaporation temperature ranging from -15°C to 15°C. Condenser size with the hydrocarbon refrigerants reduces for the same tonnage capacity of the refrigeration system as compared R134a due to large latent heat of hydrocarbons. This is beneficial for the automobile air conditioning systems as weight is reduced. It was observed that the condenser capacity of HC mixture of R290/R600a (50:50 % by mass) were more than R134a by 185.4 % at condensation temperature of 44°C and evaporation temperature of 0°C.

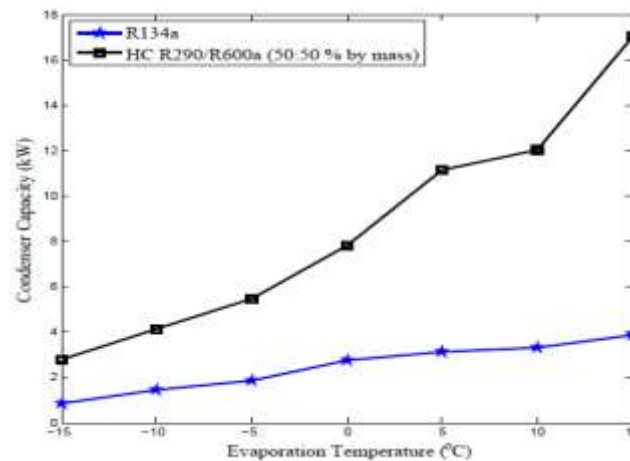


Figure 6. Condenser capacity for microchannel condenser

Product of Overall Heat Transfer Coefficient and Surface Area of Condenser

Product of overall heat transfer coefficient and surface area of condenser represents the heat exchanger capacity per degree of mean temperature difference. Product of overall heat transfer coefficient and surface area of condenser signifies the performance of the heat exchanger, higher the UA value, superior is the thermal performance of the heat exchanger. Figure 7 shows the product of overall heat transfer coefficient and the area of the condenser for microchannel condenser with R134a and HC mixture of R290/R600a (50:50 % by mass) at 44°C condensation temperature while evaporation temperatures ranging from -15°C to 15°C. Experimental UA value was more by 243.7 % for HC mixture of R290/R600a (50:50 % by mass) than R134a at condensation temperature of 44°C and evaporation temperature of 0°C.

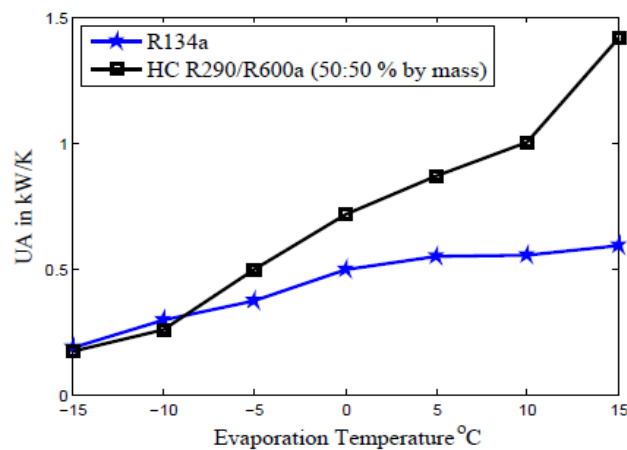


Figure 7. Product of overall heat transfer coefficient and surface area of condenser.

CONCLUSIONS

Performance analysis of VCR system was done using aluminium microchannel condenser tubes with aluminium fins using R134a and drop in substitute HC mixture of R290/R600a (50:50 % by mass) for condensation temperature of 44°C while the evaporator temperature ranges from -15°C to 15°C. It was concluded that the performance parameters such as compressor power consumption increased by 13.3 %, coefficient of performance reduced by 43 %, refrigeration capacity increased by 140.8 %, condenser capacity increased by 185.4 % and the product of overall heat transfer coefficient and surface area of condenser was increased by 243.7 % by using hydrocarbon mixture of R290 and R600a (50:50 % by mass) over R134a with the microchannel condenser for condensation temperature of 44°C and evaporation temperature of 0°C. As microchannel condensers are more compact in size, the refrigerant charge needed for HC refrigerants is around 42 to 45 % of R134a. Further the performance of the microchannel condenser can be enhanced by optimizing the passes in the condenser and number of tubes per pass, by providing proper position and size of inlet and outlet in the condenser. Thus it is concluded that microchannel condensers can be used in household refrigerators, air conditioners and in automobile air conditioning systems using HC mixture of R290/R600a (50:50 % by mass) as drop in substitute to R134a with proper care to prevent the leakage.

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