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Performance of heat pumps charged with R170/R290 mixture

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ABSTRACT

In this study, thermodynamic performance of R170/R290 mixture is measured on a heat pump bench tester in an attempt to substitute R22. The bench tester is equipped with a commercial hermetic rotary compressor providing a nominal capacity of 3.5 kW. All tests are conducted under the summer cooling and winter heating conditions of 7/45 °C and −7/41 °C in the evaporator and condenser, respectively. During the tests, the composition in R170/R290 mixture is varied from 0% to 10% with an interval of 2%. Test results show that the coefficient of performance (COP) and capacity of R290 are up to 15.4% higher and 7.5% lower, respectively than those of R22 for two conditions. For R170/R290 mixture, the COP decreases and the capacity increases with an increase in the composition of R170. The mixture of R170/R290 mixture at 4%/96% composition shows the similar capacity and COP as those of R22. For the mixture, the compressor discharge temperature is 17–28 °C lower than that of R22. For R170/R290 mixture, there is no problem with mineral oil since the mixture is composed of hydrocarbons. The amount of charge is reduced up to 58% as compared to R22. Overall, R170/R290 mixture is a good long term ‘drop-in’ candidate from the view point of energy efficiency and greenhouse warming to replace R22 in residential air-conditioners and heat pumps.

1. Introduction

Chlorofluorocarbons (CFCs) and Hydrochlorofluorocarbons (HCFCs) have been used extensively for the past few decades due to their excellent thermodynamic properties and chemical stability in various refrigeration and air-conditioning applications. Due to their stratospheric ozone layer depletion, however, CFCs and HCFCs are now controlled substances by the Montreal protocol [1]. Because of the international regulation, non-ozone depleting hydrofluorocarbons (HFCs) have been used in most of the refrigeration and air-conditioning applications for the past two decades.

These days, greenhouse warming has become one of the most important global issues and Kyoto protocol was proposed to resolve this issue, which classified HFCs as one of the greenhouse warming gases [2]. Consequently, in the long run refrigerants with low greenhouse warming potential (GWP) and zero ozone depletion potential (ODP) are to be used in refrigeration and air-conditioning applications. At the same time, the performance of refrigeration and air-conditioning equipment has to be improved to reduce the indirect green house warming caused by the use of electricity generated mainly by the combustion of fossil fuels. In fact, for most of the refrigeration and air-conditioning equipment, the indirect warming effect is more than 80% of the total warming.

R22 has been used predominantly in residential air-conditioners and heat pumps and has the largest sales volume among all refrigerants. R22, however, is an HCFC containing the ozone depleting chlorine atom and hence has to be phased out eventually. As part of the environmental protection effort, R22 can not be used in newly manufactured air-conditioners from 2010 in the United States. Likewise, most of the developed countries expend research and development efforts to replace ozone depleting R22 with environmentally friendly refrigerants.

One of the best ways of solving energy and environmental problems in refrigeration industry is the use of such natural refrigerants as hydrocarbons. Hydrocarbons have zero ODP and very low GWP. In general, hydrocarbons offer 10–15% increase in energy efficiency in various refrigeration and air-conditioning applications. In spite of these advantages, hydrocarbon refrigerants have been prohibited in normal refrigeration and air-conditioning applications due to a safety concern for the past few decades. These days, however, this trend is somewhat relaxed because of an environmental mandate. Therefore, some of the flammable refrigerants have been applied to certain applications.

Purkayastha and Bansal [3] measured the performance of R290 (propane) and R22 in a heat pump of 15 kW capacity and found that the coefficient of performance (COP) of R290 is 18% higher than that of R22 with a decrease in heating capacity of 15%. The refrigerant mass flow rate of R290 was half that of R22 and the compressor discharge temperature of R290 was much lower than that of R22. Granryd [4] also performed thermodynamic cycle

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Nomenclature

COP	coefficient of performance
GTD	gliding temperature difference
GWP	global warming potential
HTF	heat transfer fluid
$\dot{m}$	mass flow rate (kg/s)
ODP	ozone depletion potential
Q	capacity (W)
T	temperature (°C)
Subscripts	
c	condenser
dis	discharge
e	evaporator
w	water

and heat transfer analysis for R290 and R22 and arrived at a similar conclusion as that of Purkayastha and Bansal [3]. Chang et al. [5] measured the performance of four pure hydrocarbons of R600a (isobutene), R600 (butane), R290 and R1270 (propylene) and two binary mixtures of R290/R600a and R290/R600 and discovered that both R290 and R1270 have better performance than R22. Fernaldo et al. [6] used R290 in a heat pump of 5 kW capacity and determined the optimum amount of charge for the use of mini-channel aluminum heat exchangers. Recently, Hwang et al. [7] carried out a research to determine energy consumption for HFC mixtures of R404A and R410A and R290 in walk-in refrigeration systems and observed that the COP of propane is up to 10% higher than those of R404A and R410A.

Reflecting the recent interest in the use of hydrocarbons, ASHRAE listed many refrigerant mixtures such as R429A, R430A, R431A, R432A, R433A, which contain hydrocarbons and some other flammable refrigerants for better energy efficiency and environmental protection [8]. Due to these continuing efforts, certain hydrocarbons were proposed for household refrigeration applications [9]. Jung et al. [10] showed that R290/R600a mixture was good for domestic refrigerators. At this time, propane is being used in small scale air-conditioners, heat pumps, and vending machines because of the good material and lubricant compatibility and low cost [11].

It has been known that zeotropic refrigerant mixtures can increase the energy efficiency of certain refrigeration equipment under optimized conditions. For zeotropic refrigerant mixtures, a good temperature matching between the refrigerant and secondary heat transfer fluid (HTF) can be achieved in heat exchangers due to their temperature gliding effect during phase change [12]. Jung et al. [13] conducted a series of tests with 14 refrigerant mixtures to replace R22 for air-conditioning applications and found that the performance of some zeotropic mixtures was better than that of R22.

For the alleviation of greenhouse warming in the future, applying zeotropic refrigerant mixtures to air-conditioning and refrigeration equipment needs to be considered at this time. In the literature, however, few studies are found dealing with zeotropic refrigerant mixtures composed of hydrocarbons applied to heat pumps and air-conditioners. One of the best hydrocarbons for replacing R22 in residential air-conditioners and heat pumps is R290. Even though the energy efficiency of R290 is higher than that of R22, the capacity of R290 is 10–15% lower than that of R22 as shown by other works [3–5,7]. One way of increasing the capacity is to add a higher vapor pressure refrigerant [12]. In this study, small amount of ethane (R170) was added to R290 to increase the capacity. Since there has been no information in the open literature on the performance of hydrocarbon mixture composed of ethane (R170) and propane (R290), cooling and heating performance of R170/R290 mixture was measured in this study under typical summer and winter conditions in a heat pump bench tester and the results were compared with those of R22.

2. Experiments

2.1. Experimental apparatus

To achieve the goal of this paper, a breadboard type heat pump bench tester was designed and built in our laboratory. Fig. 1 shows the schematic of the experimental heat pump whose nominal capacity is roughly 1 ton of refrigeration (3.5 kW).

The evaporator and condenser of the heat pump were manufactured by connecting eight pieces of pre-manufactured double tube commercial pipes (E-stick) in series. Each pipe stick is 740 mm long and inner and outer diameters are 19.0 mm and 25.4 mm, respectively. Fig. 2 shows the detailed connection of the pipe sticks. The total length and heat transfer area based on the inner diameter of the evaporator and condenser are 5.92 m and 0.3536 m^2, respectively. Both evaporator and condenser were designed to be counter-current and the secondary heat transfer fluid passed through the inner tube while the refrigerant flowed through the annulus. Throughout the tests, water was used as the secondary fluid for both evaporator and condenser and precision water/ethylene glycol chiller and heating bath of 0.1 °C accuracy were used to control the temperatures of the water/ethylene glycol entering into the condenser and evaporator, respectively.

The bench tester was equipped with a hermetic rotary compressor developed for R22. A fine metering needle valve was used as an expansion device to control the refrigerant mass flow rate. Even though a suction line heat exchanger (SLHX) was installed initially to examine the effect of SLHX, it has not been used during this study.

A liquid eye was installed at the exit of the condenser to see the state of the refrigerant coming out of the condenser. A filter drier was installed before the expansion valve to remove contaminants. Charging ports were made at the inlet of the evaporator for liquid and at the inlet of the compressor for vapor. Finally, to reduce the heat transfer to and from the surroundings condenser and evaporator were heavily insulated with polyurethane foams and fiberglass insulation.

2.2. Measurements

More than 40 copper–constantan thermocouples were installed along the evaporator and condenser to measure the refrigerant and water temperatures. Also the compressor dome and discharge pipe temperatures were measured for comparison. All thermocouples were calibrated before their use against a precise RTD thermometer of 0.01 °C accuracy. Pressures were measured at the inlets and outlets of the evaporator and condenser using calibrated pressure transducers. Power input to the compressor was measured by a digital power meter of 0.5% accuracy. Finally, mass flow rates of the secondary heat transfer fluid were measured by precision coriolis force mass flow meters.

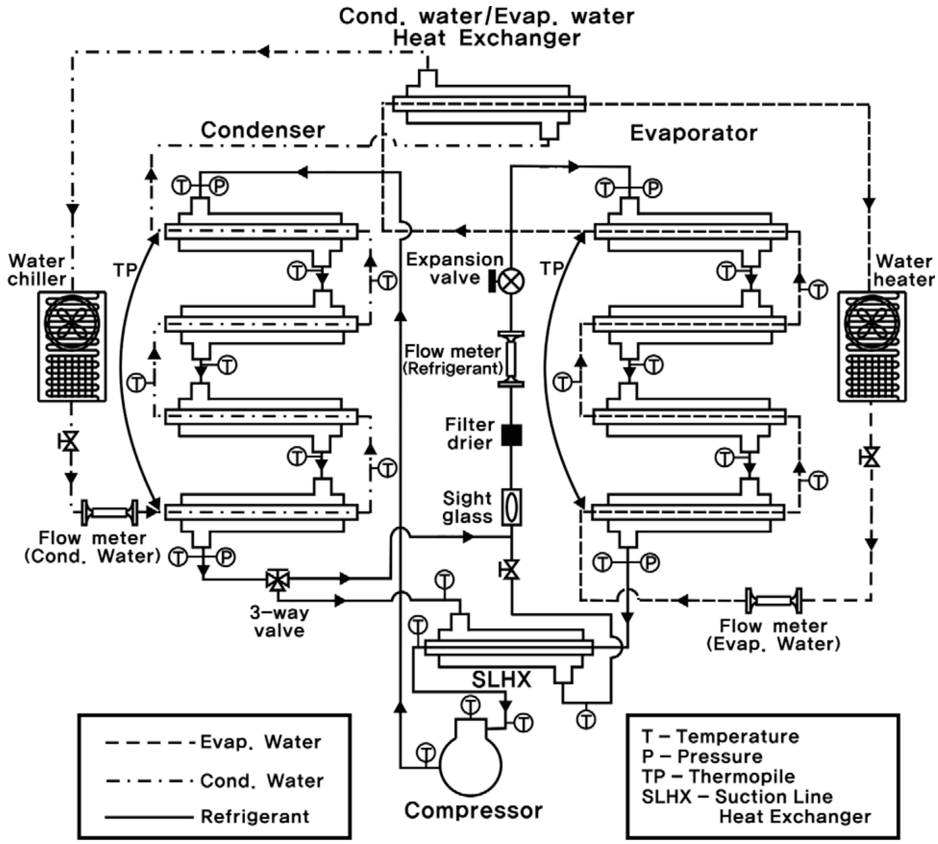

Fig. 1. Schematic of the heat pump bench tester.

Cooling and heating capacities were determined by measuring the mass flow rate and temperature difference of water in the evaporator and condenser sides. This temperature difference of water was measured by a thermopile composed of six copper–constantan thermocouples whose performance was calibrated by a set of RTDs of 0.01 °C accuracy. A typical accuracy of the thermopile is less than 0.1. Table 1 lists the uncertainties of some experimental parameters in this study. All data were taken under steady state by a computerized data logging system and stored for later analysis.

2.3. Test condition

To properly compare the performance of various refrigerants, a fair test condition should be employed. For this purpose, all tests were conducted with the external HTF (water in this study) temperatures fixed. In this study, tests were performed under two sets of different evaporator/condenser saturation temperatures for R22: 7 °C/45 °C, −7 °C/41 °C. The first condition reflects normal air-conditioning condition during summer. On the other hand, the second condition reflects normal heat pumping conditions during winter. For a given condition, first of all, tests were carried out for R22 with the adjusted external HTF temperatures to provide the required saturation temperatures in the evaporator and condenser. Table 2 shows the HTF temperatures and mass flow rate under two conditions. And then subsequent tests were performed under the same external conditions for R290 and R170/R290 mixture at five compositions. For a given external condition, actual saturation temperatures of the various refrigerants in the evaporator and condenser varied a little due to the difference in heat transfer characteristics of these fluids.

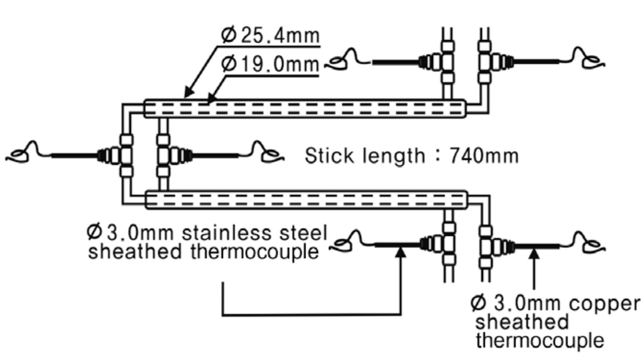

Fig. 2. Details of evaporator connection.

2.4. Test procedures

Test procedure for a given condition is as follows:

(1) The system was evacuated for 2–3 h before charging.
(2) Temperatures in the chiller and heating bath were set and the secondary HTF was pumped into the evaporator and condenser, and the system was charged with a specific

Table 1
Uncertainties of experimental parameters.

Parameters	Uncertainty
Temp. (RTD)	±0.01 °C
Temp. (thermocouple)	±0.1 °C
Pressure	±3.4 kPa
Mass flow rate	±0.2%
Work (wattmeter)	±0.5%

Table 2
Some variables to set test conditions.

Test condition	$T_{e,w}$ (°C)	$T_{c,w}$ (°C)	$\dot{m}_{e,w}$ (g/s)	$\dot{m}_{c,w}$ (g/s)
A (summer cooling)	27	29	94	115
B (winter heating)	9	31	94	115

Table 3
Refrigerants tested in this study.

Ref. no.	Refrigerant (mass fraction)	GTD (°C)
1	R22	0
2	R290	0
3	2%R170/98%R290	2.5
4	4%R170/96%R290	4.7
5	6%R170/94%R290	6.6
6	8%R170/92%R290	8.4
7	10%R170/90%R290	10.0

refrigerant. For all pure fluids tested in this study, the system was charged with a vapor refrigerant at the compressor inlet. For the mixture, the system was charged with a lower vapor pressure refrigerant at the compressor inlet, which was followed by a higher vapor pressure fluid. A digital scale of 0.1 g accuracy was employed to measure the amount of charge.

(3) The expansion valve was controlled, and simultaneously the amount of charge was adjusted to maintain the constant superheat and subcooling, usually 5 °C each, at the exits of evaporator and condenser.

(4) When the system reached steady state for more than 1 h, data were taken every 30 s for more than 30 min.

2.5. Refrigerants and lubricants

In this study, thermal performance of R22, R290 and R170/R290 mixture at five compositions was measured. Table 3 lists all refrigerant tested and their gliding temperature difference (GTD). For a given mixture, GTD is the temperature difference between the beginning and ending temperatures during evaporation. GTD, of course, varies with mixtures and their compositions.

ODP and GWP of R22, the reference fluid, are 0.05 and 1700, respectively. On the other hand, ODPs and GWPs of R170 and R290 are zero and less than three, respectively. Therefore, R170 and R290 and their mixture are environmentally friendly and can be good long term alternatives in residential air-conditioners and heat pumps.

Lubricant is also important in refrigeration system because it is circulated with the refrigerant inside the refrigeration circuit. Since a drop-in replacement is the focus of the present study, conventional mineral oil used with R22 is used for all refrigerants. In fact, one of the advantages of hydrocarbons and their mixtures is that they are completely miscible with the mineral oil [14,15].

3. Results and discussion

In this study, thermodynamic performance of R22, R290 and R170/R290 mixture at five compositions was measured in a heat pump tester equipped with a commercial hermetic rotary compressor under typical air-conditioning and heat pumping conditions. Table 4 lists various measured system parameters such as COP, capacity, discharge temperature, and amount of charge for all refrigerants tested under both cooling and heating conditions. The measurement uncertainties were estimated by the method suggested by Kline and McClintock [16] and the uncertainties of the compressor work, capacity, and COP were 0.5%, 2.1%, and 2.2%, respectively. The heat balances between the refrigerant and water sides on the evaporator and condenser were within 3%. For each refrigerant, tests were performed at least two times and COPs agreed within 1% repeatability.

3.1. Coefficient of performance

In order to alleviate greenhouse warming, the energy efficiency of energy conversion devices should be improved. In air-conditioning and heat pumping, the COP is a measure of energy efficiency for a given device charged with a specific refrigerant. Hence, it is important to examine, first of all, COPs of tested refrigerants against the reference fluid, R22, in selecting alternative fluids. In this study, the COP was defined as the measured capacity divided by the electricity input to the compressor. As described earlier, cooling and heating capacities were determined by measuring the mass flow rate and temperature difference of water in the evaporator and condenser sides.

Fig. 3 shows the COP of R22, R290 and R170/R290 mixture at various compositions under both conditions. As seen in Fig. 3, the COP of R290 is 6.8–15.4% higher than that of R22 under both conditions. This result agrees well with previous results by other studies [3,4]. As for the mixture of R170/R290, the COP decreased at a constant rate as R170 was added to R290 with an interval of 2%. In fact, the COP is a strong function of the critical temperature of the refrigerant. Ethane (R170), the very high vapor pressure refrigerant, has very low critical temperature and hence its COP is inherently low. Thus, adding R170–R290 produced an unfavorable result in terms of energy efficiency. The COP of R170/R290 mixture, however, was higher than that of R22 in the composition range of up to 6% R170 under both conditions.

3.2. Capacity

Refrigeration capacity is as important as COP in refrigeration. If the capacity of an alternative refrigerant deviates too much from that of the reference fluid, the compressor must be redesigned

Table 4
Summary of test results for various refrigerants.

Ref. No.	Refrigerants	Condition A (summer cooling)						Condition B (winter heating)					
		COP	Diff. (%)	Q_e (W)	Diff. (%)	$T_{dis.}$ (°C)	Charge (g)	COP	Diff. (%)	Q_c (W)	Diff. (%)	$T_{dis.}$ (°C)	Charge (g)
1	R22	3.48		3830		86.7	1300	3.51		3325		97.1	1350
2	R290	4.01	15.4	3543	−7.5	61.7	550	3.75	6.8	3139	−5.6	67.3	550
3	2%R170/98%R290	3.83	10.0	3624	−5.4	65.1	550	3.70	5.4	3273	−1.6	68.9	550
4	4%R170/96%R290	3.73	7.1	3685	−3.8	66.0	550	3.59	2.3	3358	1.0	70.6	550
5	6%R170/94%R290	3.60	3.4	3737	−2.4	67.2	550	3.53	0.6	3430	3.2	72.3	550
6	8%R170/92%R290	3.48	0.0	3808	−0.6	68.9	550	3.39	−3.4	3473	4.5	74.2	550
7	10%R170/90%R290	3.37	−3.2	3852	0.6	70.1	550	3.33	−5.1	3504	5.4	74.7	550

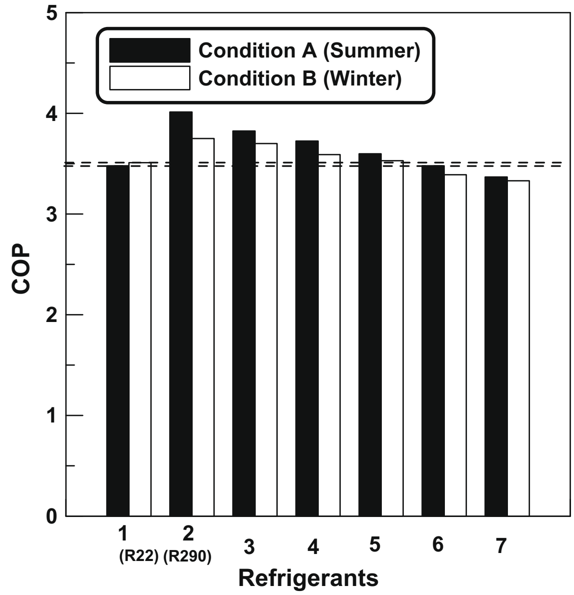

Fig. 3. Measured COP of R170/R290 mixture.

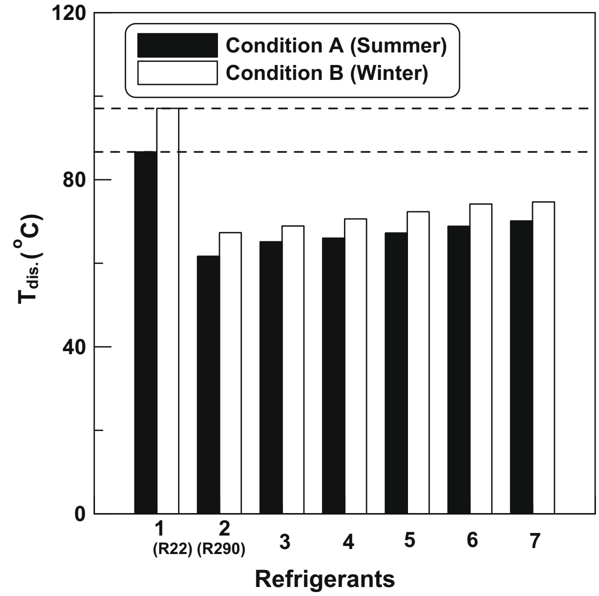

Fig. 5. Measured discharge temperature of R170/R290 mixture.

completely which would be quite costly. Therefore, it would be good for the alternative refrigerants to provide a similar capacity to that of the reference fluid.

Fig. 4 shows the refrigeration and heat pumping capacities, Q_e and Q_c in Table 4, of R22, R290, and R170/R290 mixture under both conditions. As seen in Fig. 4, the capacities of R290 were 5.6–7.5% lower than those of R22 under both conditions. Therefore, for R290 the compressor displacement volume needs to be increased to maintain the same capacity as that of R22.

As for the mixture of R170/R290, both refrigeration and heating pumping capacities increased as the amount of R170 increased because of the large capacity of R170. Especially, the capacities of the mixture were similar to those of R22 in the composition range of 4–6% R170. At these compositions, drop-in replacement of R22 was possible with this mixture. This is a good feature since a major compressor overhaul is not necessary.

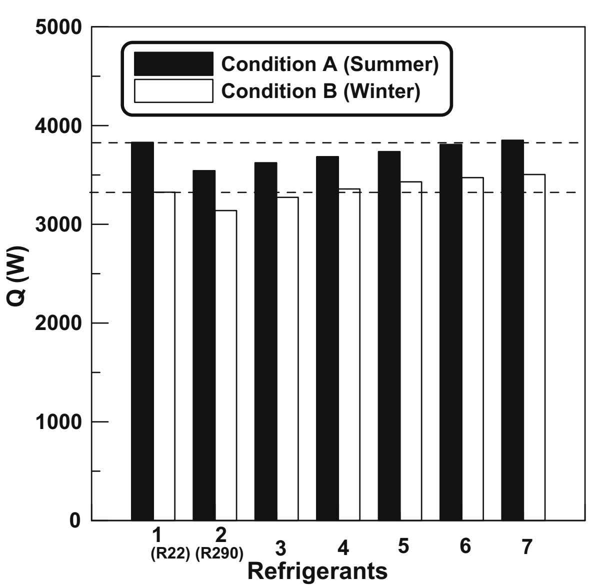

Fig. 4. Measured capacity of R170/R290 mixture.

3.3. Compressor discharge temperatures

In applying alternative refrigerants, the lifetime and reliability of the system as well as the stability of the refrigerant and lubricant should be considered. These characteristics can be examined indirectly by measuring the compressor discharge temperature (T_{dis}). In this study, a thermocouple was attached to the compressor discharge line with 3 mm insulation around the sensors and hence the temperature deviation due to the change in surrounding was very small.

As seen in Fig. 5, the compressor discharge temperatures of R290 and R170/R290 mixture were 16.6–28.2 °C lower than that of R22 under both conditions. This is a good characteristic and will be very beneficial to the manufacturers since it will lead to an improvement in system reliability and lifetime. From this observation, it can be safely concluded that the proposed mixture would be appropriate from the viewpoint of system reliability and fluid stability.

As for the mixture of R170/R290, the compressor discharge temperature increased as the amount of R170 increased.

3.4. Refrigerant charge

In this study, the optimum amount of charge was determined when the actual subcooling at the exit of condenser was 4–7 °C. For mixtures, the uncertainty in the amount of charge was 10 g due to the complicated charging procedure involved. Most of the hydrocarbons have smaller liquid densities than those of most of the halocarbons and hence the amount of charge decreases significantly with hydrocarbons [17]. As seen in Table 4, the amount of charge for all hydrocarbon refrigerants tested decreased up to 58% as compared to R22. This will help alleviate further the direct emission of refrigerant which is responsible for the greenhouse warming.

4. Conclusions

In this study, thermodynamic performance of two pure refrigerants of R22 and R290 and R170/R290 mixture at five compositions was measured in a breadboard type heat pump tester equipped with a commercial hermetic rotary compressor under air-conditioning and heat pumping conditions. For the mixture, the composition varied from 2% to 10% of R170 with an interval of 2%. Various performance parameters were measured and following conclusions were drawn from the results.

(1) The COP of R170/R290 mixture decreased at a constant rate as R170 was added to R290. The COP of R170/R290 mixture was higher than that of R22 in the composition range of up to 6% R170 under both conditions.
(2) The refrigeration and heating pumping capacities of R170/R290 mixture increased as the amount of R170 increased. Especially, the capacities of the mixture were similar to those of R22 in the composition range of 4–6% R170. At these compositions, drop-in replacement of R22 is possible with this mixture.
(3) R170/R290 mixture had 16.6–28.2 °C lower compressor discharge temperatures as compared to R22. This is a good feature for long term system reliability.
(4) The amount of charge of R170/R290 mixture decreased up to 58% as compared to R22 due to its low liquid density.
(5) R170/R290 mixture in the composition range of 4–6% R170 is a good long term 'drop-in' replacement refrigerant for R22 for both air-conditioning and heat pumping applications from the view point of energy efficiency and greenhouse warming. In this study, however, the flammability and safety issues were not studied and also not the criteria for comparison.

Acknowledgement

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