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