Korean J. Chem. Eng., **31**(10), 1732-1735 (2014)
DOI: 10.1007/s11814-014-0223-z
pISSN: 0256-1115
eISSN: 1975-7220

RAPID COMMUNICATION

A novel working fluid for building air-conditioning and ocean thermal energy conversion

Ho-Saeng Lee*, Hyeon-Ju Kim*, and Dongsoo Jung,†**

*Seawater Utilization Plant Research Center, Korea Research Institute of Ships & Oceans Engineering, Goseong-gun, Gangwon-do 219-822, Korea
**Department of Mechanical Engineering, Inha University, Incheon 402-751, Korea
(*Received 13 May 2014 • accepted 4 August 2014*)

Abstract−An azeotropic mixture of R32/R290 is proposed for both building air-conditioning and ocean thermal energy conversion (OTEC) applications. R32/R290 is an environmentally safe working fluid mixture with no ozone depletion potential (ODP) and low global warming potential (GWP). This mixture can successfully replace R410A used in many residential air-conditioners and heat pumps since its GWP is quite low, about 25% of that of R410A. The same mixture also can be used in OTEC power plants to replace conventional working fluids of medium vapor pressure. Due to the increase in density, a significant reduction in equipment is expected, which consequently will result in an initial cost reduction.

Keywords: Alternative Working Fluid, Air-conditioning, R32/R290 Mixture, Ocean Thermal Energy Conversion

INTRODUCTION

Chlorofluorocarbons (CFCs) have been used as refrigerants for various refrigeration and air-conditioning equipment for more than a half century due to their excellent thermodynamic and chemical properties. But these useful fluids have been regulated and completely phased out by the Montreal protocol [1] due to a finding that chlorine atoms in them destroy the stratospheric ozone layer. In 1997, Kyoto protocol was proposed for the reduction of the green house warming, which calls for the energy efficiency improvement in all energy conversion devices including refrigeration and air-conditioning and power generation devices [2].

To comply with such global environmental issues effectively, conventional working fluids have to be changed to more environmentally friendly ones. At the same time, if possible, the size of the refrigeration and air-conditioning and power generation equipment has to be decreased for the reduction of possible emissions of working fluids to the atmosphere due to leaks. For this purpose, more research has to be carried out for the development of new alternative working fluids.

R22, a hydrochlorofluorocarbon (HCFC), has been used predominantly in residential and commercial air conditioners and heat pumps. Even though the Montreal protocol requires the complete phase out of R22 by 2020, all European countries have already stopped using R22 and from 2010 the United States has not used R22 in new equipment. Therefore, R22 has to be replaced by environmentally safe refrigerants. Unlike CFC11 and CFC12, however, no pure refrigerant has been identified to substitute for R22.

For the past decade, a refrigerant mixture of R410A (50%R32/50%R125) has been identified as a promising candidate for R22, and many products charged with this alternative fluid have been on the market. R410A is an near-azeotropic mixture whose gliding temperature difference (GTD) is less than 0.2 °C. Its vapor pressure is about 50% higher than that of R22 and hence its volumetric capacity is significantly increased. Due to the high pressure, compressors and heat exchangers are to be redesigned completely for the optimization necessary to accommodate the lower volumetric flow rate associated with the use of R410A. A simple thermodynamic cycle analysis shows that the thermodynamic efficiency of R410A is somewhat lower than that of R22. The actual energy efficiency of R410A, however, is found to be higher than that of R22 due to the improved compressor efficiency and reduced energy losses in some components of the refrigeration system [3].

Even though R410A is used quite extensively these days, there is a great concern for the high global warming potential (GWP) of R410A. The 100 year GWP of R410A is 2068 as compared to that of carbon dioxide (CO_2), which is even higher than that of R22 whose GWP is 1790. In fact, the Kyoto protocol has in itself a control measure for greenhouse gases including hydrofluorocarbons (HFCs). Consequently, HFC134a was identified as one of the controlled greenhouse gases. The global warming potential (GWP) of HFC134a, one of the major refrigerants used in refrigeration and air-conditioning field, is 1430 as compared to that of CO_2. In fact, the European Union's F-Gases regulation banned the use of HFC134a from 2011 in automobile air conditioners of newly manufactured vehicles for environmental protection [4]. The regulation specifically prohibits the use of fluorinated greenhouse gases whose GWP is greater than 150. In the light of this development for the ban of HFCs with high GWPs, the fate of R410A is not certain at this time since its GWP is even higher than that of R134a. Therefore, many people and organizations try to develop alternative refrigerants with low GWPs for R410A these days.

Recently, a large number of renewable energies have been used such as solar, wind, geothermal energy and various types of waste and unused heat. These are classified as low grade heat sources. The use of low grade heat sources in the form of renewable energy

†To whom correspondence should be addressed.
E-mail: dsjung@inha.ac.kr

is one of the ways of generating electricity for its potential in reducing the fossil fuel consumption and environmental damage [5].

Ocean thermal energy conversion (OTEC) is a power generation method converting low grade heat energy into electricity by using the temperature difference between the warm surface water and the cold deep water of the ocean. The OTEC concept was first conceived by D'Arsenoval in 1881 [6]. In 1979, an OTEC pilot plant was installed in Hawaii by the state of Hawaii and several US companies [7]. They made a small OTEC plant which produced a net output of up to 18 kW. They used ammonia (R717) as a working fluid in a simple closed loop Rankine cycle. Since then, much research has been done to improve the performance of the closed loop OTEC plant [8-10]. Even though many researchers performed a variety of research, the bottleneck for the use of OTEC plants is the high initial cost. The closed loop OTEC plant is basically composed of a turbine and large size heat exchangers for evaporator and condenser. To reduce the initial cost, those components comprising the OTEC plant should be minimized, and the best way to accomplish this object is to use a high vapor pressure working fluid providing high density.

The objective of this study was to present an environmentally friendly working fluid with no ozone depletion potential (ODP) and low GWP for building air conditioning and OTEC applications.

ANALYSIS: DEVELOPMENT OF A NEW WORKING FLUID

For the past few decades, refrigerant mixtures have been proposed as promising candidates for conventional pure refrigerants. Well designed mixtures are known to provide such good characteristics as thermodynamic property tuning and material compatibility [11]. Also, due to the limited number of environmentally safe pure refrigerants, many refrigerant mixtures such as R410A, R407C, and R404A have been proposed and many of them are being used in the market.

To achieve the objective of our study, HFCs of high vapor pressure with low GWP and natural fluids have to be used. Among the HFCs of high vapor pressure, R32, a hydrofluorocarbon with no ODP and low GWP of 716 is the only candidate left. The vapor pressure of R32 is roughly 50% higher than that of R22, and hence it is used as one of the components of R410A.

One of the best ways of solving energy and environmental problems in the refrigeration industry is the use of such natural refrigerants as hydrocarbons. Hydrocarbons have zero ODP and very low GWP, typically less than 5. 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 [12] 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%. Granryd [13] also performed thermodynamic cycle and heat transfer analysis for R290 and R22 and arrived at a similar conclusion as that of Purkayastha and Bansal [12]. Recently, Hwang et al. [14] 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.

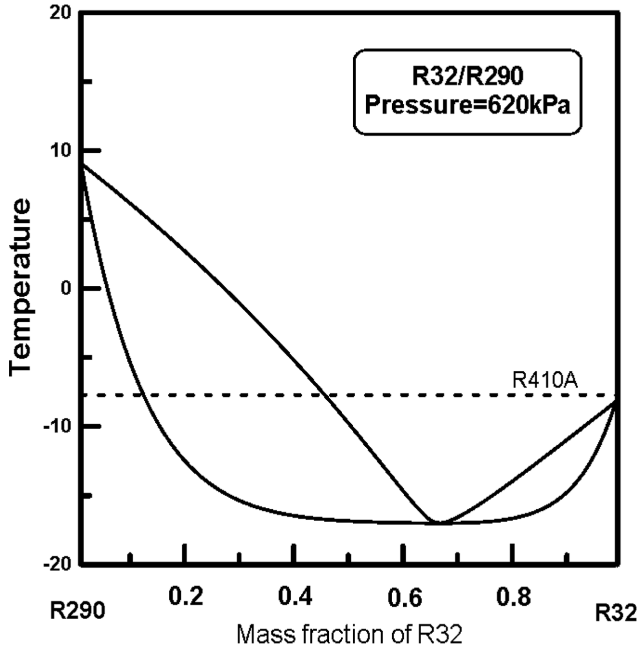

Fig. 1. Temperature-composition diagram of R32/R290 mixture.

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 [15].

Considering all these, therefore, a novel mixture of R32/R290 is proposed for both air-conditioning and OTEC applications in this study.

Fig. 1 shows the temperature-composition diagram of R32/R290 mixture. As shown in Fig. 1, the proposed mixture is an azeotrope at the composition of 67% R32. At this composition, the vapor pressure of R32/R290 mixture is about 14% higher than that of R410A. All thermodynamic properties are calculated by REFPROP routines developed by the US National Institute of Standards and Technology (NIST) [16].

DISCUSSION

1. Air Conditioning Application

To compare the theoretical performance of R32/R290 mixture with R410A, a Cycle-D program developed by the US NIST was used [17]. Table 1 lists the comparison results for R32/R290 mixture and R410A for a typical air-conditioning condition of evaporation and condensation temperatures of 7 and 45 °C, respectively.

As seen in Table 1, the coefficient of performance (COP) of an R32/R290 mixture is about 5% lower than that of R410A, while the discharge temperature of this mixture is similar to that of R410A. A slight decrease in COP can be overcome by the optimization of

Table 1. Thermodynamic cycle calculation results for air-conditioning application

Fluid	Composition (Mass %)		VC (kJ/m^3)	COP	T_{dis} (°C)	GTD (°C)	GWP
	R32	R290					
R410A			5630	3.70	79.1	0.1	2068
R290		100	3293	3.93	65.6	0	3
Example 1	60	40	6138	3.46	78.7	2.4	431
Example 2	65	35	6351	3.49	78.5	0.3	466
Example 3	70	30	6482	3.51	79.8	0.4	502
Example 4	75	25	6540	3.51	82.4	1.4	538
Example 5	80	20	6568	3.54	85.4	2.6	573

the compressor and actual reduction in energy losses in some component of the refrigeration system as with R410A [3]. The mixture, however, provides 13-15% high capacity, indicating a further reduction in equipment and production cost. On the other hand, the COP of R32/R290 mixture is 10.5% lower than that of R290 while the capacity of this mixture is 100% higher than that of R290.

Since the GWP of this mixture is about 25% of R410A, it is considered a good long term candidate to replace R410A in both residential and commercial air-conditioning applications. A similar observation was made for a typical heat pumping condition of evaporation and condensation temperatures of −7 and 41 °C, respectively.

2. OTEC Application

In an OTEC plant, the temperature of the surface water and deep sea water is about 22 to 30 °C and 4 to 5 °C, respectively, and the corresponding temperature difference is 17 to 26 °C. For this application, the organic Rankine cycle (ORC) is usually employed because of its excellent performance in converting the low grade heat to electricity. The temperatures of the heat source in ORC are lower than those in conventional fossil fuel power plants. In general, the ORC plants use refrigerants or hydrocarbons as the working fluids instead of water. The performance of the ORC is directly related to the thermodynamic properties of the working fluid [18]. Consequently, a good working fluid could generate a more efficient and cheaper plants. So far, ammonia (R717), propane (R290), propylene (R1270), and R22 have been proposed as working fluids in the ORC of OTEC plant. These are all medium vapor pressure fluids exhibiting similar vapor pressure.

Table 2 lists the theoretical efficiency of the ORC calculated under the typical evaporation and condensation temperatures of 28 and 7 °C for OTEC applications. For calculations, isentropic turbine efficiency, superheat at the evaporator, and subcooling at the condenser are assumed to be 0.7, 0 °C, and 0 °C, respectively. As seen in Table 2, theoretical efficiencies of the conventional fluids are very similar. The efficiency of 67%R32/33%R290 mixture is 5% lower than the average value of the conventional ones. The biggest advantage of the 67%R32/33%R290 mixture, however, lies in the high vapor pressure resulting in a significant reduction of turbine and heat exchangers. Due to the increase in density, about 50% reduction in the basic components is expected with the use of this mixture as compared to the case with the conventional fluids such as HCFC22. This, in turn, would lead to the direct reduction of the initial cost, which is very desirable from the view point of massive installations of OTEC plants in tropical oceans and in off shores in conjunction with the discharge warm water from the nuclear power plants. Of course, the evaporator pressure increases with the use of 67%R32/33%R290 mixture. This, however, can be easily managed. At present, the condensing pressure of R410A in a typical air-conditioner during summer is about 2,700 kPa while the evaporator pressure of 67%R32/33%R290 mixture in a typical OTEC plant during summer is about 2,200 kPa.

Table 2. Thermodynamic cycle calculation results for OTEC application

Fluid	Efficiency (%)	Pevap (kPa)	Pcond (kPa)
Ammonia (R717)	4.67	1099	554
R22	4.57	1131	622
R290	4.49	1027	584
R1270	4.48	1245	718
67%R32/33%R290	4.34	2208	1285

CONCLUSIONS

A novel azeotropic mixture of R32/R290 is proposed for both air-conditioning and OTEC applications. R32/R290 is an environmentally friendly working fluid with no ozone depletion potential and low global warming potential. This mixture is a long-term solution to replace R410A currently used in many residential and commercial air-conditioners and heat pumps since its GWP is much lower than that of R410A. The same mixture also can be used in OTEC power plants to replace conventional working fluids. Due to the increase in density, a significant reduction in the size of equipment is expected, which in turn will result in an initial cost reduction.

ACKNOWLEDGEMENT

This work was financially supported by the National R&D project of 'Development of Energy Utilization of Deep Ocean Water' supported by the Korean Ministry of Ocean and Fisheries.

NOMENCLATURE

CFC : chlorofluorocarbon
COP : coefficient of performance
GTD : gliding temperature difference [°C]
GWP : global warming potential
HFC : hydrofluorocarbon
HCFC : hydrochlorofluorocarbon
ODP : ozone depletion potential
P : pressure [kPa]
T : temperature [°C]
VC : volumetric capacity [kJ/m^3]

Subscript

dis : discharge
evap : evaporator
cond : condenser

REFERENCES

1. United Nations Environment Program, *Montreal protocol on substances that deplete the ozone layer* (1987).
2. Global Environmental Change Report, *A brief analysis of the Kyoto protocol*, **9**(24) (1997).
3. A. Cavallini, *Int. J. Refrigeration*, **19**, 485 (1996).
4. Directive 2006/40/EC of the European Parliament and of the Council, Official Journal of the European Union, 14.6 (2006).
5. W. H. Avery and C. Wu, *Renewable energy from the ocean-A guide to OTEC*, Oxford, Oxford University Press (1994).
6. A. d'Arsonval, *Revue Scientifique*, **17**, 370 (1881).
7. L. A. Vega, *Marine Technology Society Journal*, **6**(4), 25 (2002).
8. C. Wu and T. J. Burke, *Appl. Therm. Eng.*, **18**, 295 (1998).
9. P. Straatman, G. Wilfried and V. Sark, *Sol. Energy*, **82**, 520 (2008).
10. F. P. Moore and L. L. Martin, *Appl. Therm. Eng.*, **28**, 1015 (2008).
11. D. A. Didion and D. B. Bivens, *Int. J. Refrigeration*, **13**, 163 (1990).
12. B. Purkayastha and P. K. Bansal, *Int. J. Refrigeration*, **21**, 3 (1998).
13. E. Granryd, *Int. J. Refrigeration*, **24**, 15 (2001).
14. Y. Hwang, D. H. Jin and R. Radermacher, *Int. J. Refrigeration*, **30**, 633 (2007).
15. Designation and safety classification of refrigerants, ANSI/ASHRAE Addenda a, b, c, d, e, f, g, and h to ANSI/ASHRAE Standard Issue 34 (2007).
16. M. O. McLinden, S. A. Klein, E. W. Lemmon and A. P. Peskin, *NIST thermodynamic and transport properties of refrigerants and refrigerant mixtures* - REFPROP Version 9.0 (1998).
17. P. A. Domanski, D. A. Didion and J. Chi, *NIST vapor compression cycle design program*, CYCLE-D Version 4.0 (2003).
18. W. C. Andersen and T. J. Bruno, *Ind. Eng. Chem.*, **44**, 5560 (2005).