JJMIE

Volume 9 Number 4, August.2015
ISSN 1995-6665
Pages 289 - 296

Jordan Journal of Mechanical and Industrial Engineering

Thermodynamic Analysis of R152a and Dimethylether Refrigerant Mixtures in Refrigeration System

Ayyalusamy Baskaran[a] * and Koshy Mathews[b]

[a] Department of Mechanical Engineering, P. A. College of Engineering and Technology, Pollachi 642002, India
[b] Department of Mechanical Engineering, Kalaivani College of Technology, Coimbatore 641105, India

Received 17 Dec 2014 Accepted 6 Aug 2015

Abstract

R-134a is currently used as the refrigerant in refrigerator replacing the ozone depleting refrigerant R-12. Although R-134a has no Ozone Depletion Potential (ODP), it has a relatively larger Global Warming Potential (GWP) of 1300. In an effort to reduce greenhouse gas emissions, R-152a (difluoroethane) (GWP 130) and Hydrocarbons (GWP 20) are being considered as a replacement for R-134a. HC blend has a zero ODP and a negligible GWP. The only drawback of HC blend is the temperature glide. The drawbacks of using R-152a and HC blend with respect to GWP and temperature glide can be overcome by the refrigerant DME. The present paper presents the results of a thermodynamic study of new eco-friendly refrigerant blends of R-152a and DME. It was carried out for a single-stage vapor compression refrigeration system. These new refrigerants are generally azeotropic. Some of these new mixtures have better thermodynamic properties than those of pure R-152a. RefProp software has been used to determine the thermodynamic properties of the refrigerant blends. In this analysis, experimental validation of the new refrigerant mixture (60% DME + 40% R-152a) is carried out in domestic refrigerator. The results are better than those of R-152a and R-134a.

Keywords: *R152a, DME, Azeotropic Blends, Vapor Compression Refrigeration System, Coefficient of Performance*.

1. Introduction

For the past half century, chlorofluorocarbons (CFCs) have been extensively used in the field of refrigeration due to their favorable characteristics. In particular, CFC-12 has been predominantly used for small refrigeration units including domestic refrigerator/freezers. Since the advent of the Montreal Protocol, however, the refrigeration industry has been trying to find out the best substitutes for ozone depleting substances [1].

In 1997, the Kyoto protocol was agreed on by many nations calling for the reduction in the emissions of greenhouse gases including HFCs [2]. Since the GWP of HFC-134a is relatively high (GWP1300) and also expensive, the production and use of HFC-134a will be terminated in the near future.

B. O. Bolaji, M. A. Akintunde and T. O. Falade investigated experimentally the performance of three ozone friends HFC refrigerants (R-32, R-134a and R-152a) in a vapor compression refrigerator and compared the results obtained. The results show that the COP of R-152a was 2.5% higher than those of R-134a and 14.7% higher than that of R-32 [3].

Dimethylether (RE-170, DME) makes a better refrigerant than R-290 / R-600a blends as it has no temperature glide and does not separate during leakage. It has been extensively adopted by the aerosol industry as the most cost effective replacement for R-134a in propellant applications [4].

Valentine Apostol *et al.* [5] conducted a comparative thermodynamic study considering a single-stage Vapor-Compression Refrigeration System (VCRS) using, as working fluids, DME, R-717, R-12, R-134A, R-22 (pure substances) and R-404A , R-407C (zoetrope mixtures), respectively. The result of their study was that DME could be used as a refrigerant and that DME could be a good substitute for R-12 and R-134a.

A.Baskaran *et al*. [7] analyzed the performance of a vapor compression refrigeration system with various refrigerants mixture of HFC-152a, HC-290, HC-600a and RE-170 and their results were compared with R-134a as a possible alternative replacement. The results showed that the refrigerant blend RE-170 / R-152a (80/20 by wt %) was found to be a replacement for R-134a and also the COP of this blend is 5.7% higher than that of R-134a.

Choedaeseong, Dangsoo Jung [8] presented an experimental study on the application of R-435A (mixture

* Corresponding author. e-mail: boss120367@gmail.com.

of DME and R-152a) to replace HFC-134a in domestic water purifiers. Test results showed that the energy consumption and discharge temperature were 12.7% and 3.7°C lower than that of HFC-134a.

Jung, Dong-Soo *et al*. [9] examined, both numerically and experimentally, in an effort to replace HFC-134a used in the refrigeration system of domestic water purifiers. Test results showed that the system performance with R-435A was greatly influenced by the amount of the charge due to the small internal volume of the refrigeration system of the domestic water purifiers. With the optimum amount of charge of 21 to 22grams, about 50% of HFC-134a, the energy consumption of R-435A was 11.8% lower than that of HFC-134a. The compressor discharge temperature of R-435A is 8°C lower than that of HFC-134a at the optimum charge. Overall, R-435A, a new long-term environmentally safe refrigerant, is a good alternative for HFC-134a requiring a little change in the refrigeration system of the domestic water purifiers.

A. Baskaran and Koshy Mathews [10] conducted the thermal analysis of vapor compression refrigeration system with R-152a and its blends R-429A, R-430A, R-431A and R-435A. In their analysis, the effects of the main parameters of the performance was analyzed for various evaporating temperatures. The results showed that the refrigerant R435A consumed 1.098% less compressor power than that of R152a. The COP, refrigerating effect for R-435A was 1.229%, 32.198% higher than R-152a, respectively. The refrigerant mass flow decreased by 24.353% while using R-435A substitute to R-152a. Other results obtained from their analysis showed a positive indication of using R-435A as a refrigerant in vapor compression refrigeration system substitute to R-152a.

A. Baskaran *et al*. [13] analyzed the performance on a vapor compression refrigeration system with various eco-friendly refrigerants of HFC-152a, HFC-32, HC-290, HC-1270, HC-600a and RE170 and their results were compared with R-134a as a possible alternative replacement. The results showed that the refrigerants RE-170, R-152a and R-600a had a higher COP than R-134a and RE-170 was found to be a replacement for R-134a [13].

A. Baskaran *et al.* [14] studied the performance characteristics of domestic refrigerator over a wide range of evaporation temperatures (-30°C to 30°C) and condensation temperatures (30°C, 40°C, 50°C) for working fluids R134a and refrigerant mixtures RE-170/R-600a. Their study was carried out by comparing parameters such as pressure ratio, refrigerating effect, isentropic work, coefficient of performance, compressor power, volumetric cooling capacity discharge temperature and mass flow rate. Their results indicated a drop in replacement for R-134a with blend (RE-170/R-600a) with the mass fractions of 80%/20%.

The present study presents a method for reducing the refrigerant charge and for increasing the security by replacing R-152a with a blend of dimethylether (DME).

2. Dimethyl Ether as Refrigerant

The dimethylether (DME, C_2H_6O) possesses a range of desirable properties as a replacement for R-134a. These include better heat transfer characteristics than R-134a, a pressure/temperature relationship very close to R-134a, compatibility with mineral oils, compatibility with residual R-134a contamination, low cost and ready availability. It is also very environment-friendly. The ODP of DME is zero, and the GWP is 3 due to its very short atmospheric lifetime, only 6 days [6]. It is suitable for being used with ferrous metals, copper and copper-based alloys, and aluminum. The pressure-temperature relationship at saturation is very close to R-134a, as shown in Table 1. The basic physical properties of RE-170 and HFC refrigerants are shown in Table 2.

Table.1. Saturation pressure/temperature relationships of R-134a and DME

Temperature (°C)	Pressure(kPa) R-134a	Pressure (kPa) RE-170
-40	51.209	50.316
-20	132.73	124.24
0	292.80	265.18
20	571.71	505.99
40	1016.6	884.68
60	1681.8	1443.8

Table 2. Basic physical properties of eco-friendly refrigerants

Physical properties	**R-134a**	**R-152a**	**RE-170**
Molar Mass kg/kmole	102.03	66.051	46.07
Triple Temperature °C	-103.3	-118.59	-141.5
Boiling Point °C	-26.07	-24.023	-24.84
Critical Temperature °C	101.06	113.26	126.95
Critical Pressure , MPa	4.06	4.52	5.37
Critical Density kg/m^3	511.9	368	270.99
Assentric factor	0.327	0.2752	0.2007
Diapole at NBP	2.058	2.262	1.301
Miscibility with Oil	Nil	Good	Good

As a result of previously comparative studies, analyzing the advantages and disadvantages of using R-152a and DME in vapor compression refrigeration systems as well as their reciprocal compatibility, the idea, which is the ground of this thermodynamic study, emerges; i.e., to reduce the disadvantages of R-152a (relatively high density, low refrigerating capacity, high compressor discharge temperature, GWP) and those of DME (high saturation pressure, high mass specific mechanical work) through their reciprocal combination. Besides obtaining new competitive eco-refrigerants, this idea allows to extend the use of R-152a/DME blend from air conditioning (A/C) to refrigeration applications and reduction of R-152a mass charge. As a support for the new proposed eco-refrigerants, there is a mixture between R-152a and DME (20/80) % mass fraction which has been numbered and listed as a refrigerant mixture R-435A by ASHRAE recently.

3. Thermo Dynamic Study

In the present thermodynamic study, eleven refrigerants, R-152a/DME blends are taken into consideration, for which the DME mass fraction increases from 0%, (the blend referred to as A0 , i.e., pure R-152a) to 100% (the blend referred to as A10 , i.e., pure DME), with a mass fraction step of 10%. Consequently, R-435A is noted with the indicative A8. Figure 1 shows the variation of the saturation temperature with respect to R-152a mass fraction for various pressures (sat P = 1, 5, 10, 20 and 30 bar), both for the saturated liquid and dry saturated vapor. It also shows that the obtained blends are azeotropic. Figure 2 shows the significant increase of the latent heat of vaporization with the increase of DME mass fraction. Consequently, R-435A has approximately 30% higher latent heat of vaporization than pure R-152a.

In order to establish which of the suggested new refrigerants is most recommended and which is the most appropriate DME mass fraction, the present study compares the performances obtained when using all of these eleven refrigerants in a single-stage vapor compression refrigeration system working in the same conditions. The calculation of these performances was carried out by Vapor compression cycle design program [12] based on their thermodynamic properties given by RefProp software [11].

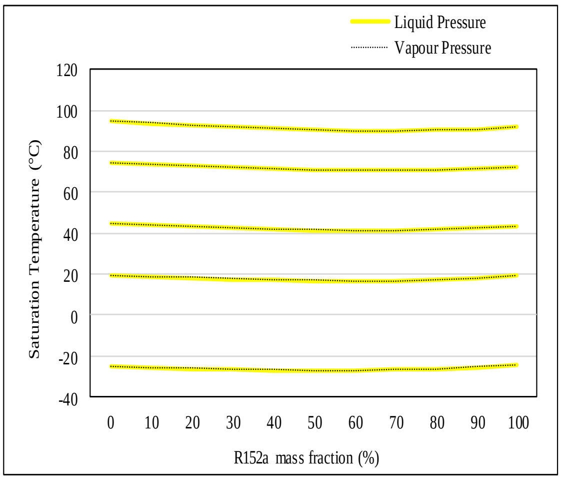

Figure 1. Saturation temperature depending on the pressure and R-152a mass fraction

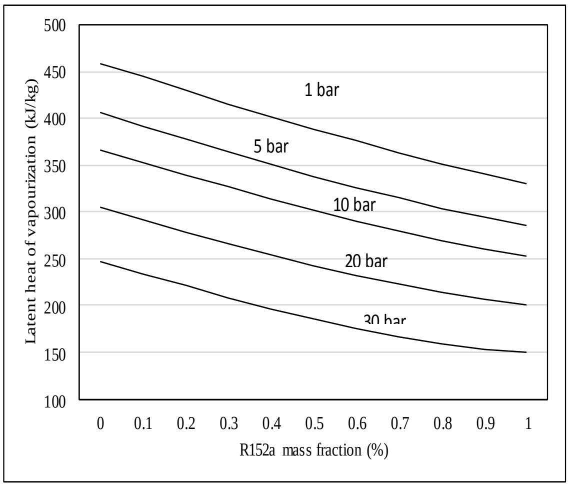

Figure 2. Latent heat of vaporization depending on the pressure and R-152a mass fraction

4. Calculation Methodology

In order to point out the optimum DME mass fraction and which of the eleven analyzed refrigerants is best suited for substituting R-152a, a comparative thermodynamic analysis was carried out, regarding the performances of a single-stage vapor compression refrigeration system. The schematic of sub critical cycle and thermodynamic cycle in p–h diagram, for an azeotropic refrigerant blend between R-152a and DME (A6), are presented in Figures 3a and 3b. The thermal calculation of the thermodynamic refrigeration cycle asserting the same cooling load (1kW), for all types of the analyzed refrigerant blends, based on R-152a and DME, has been performed by applying the following study parameters:

- evaporation temperature (T_e [$^{\circ}$C]);
- condensing temperature (T_c [$^{\circ}$C]);
- super heating degree (T_{sh} [$^{\circ}$C]);
- sub cooling degree (T_{sc} [$^{\circ}$C]);

Using the previously shown calculation methodology for a cooling load of 1kW and for the following values of the study parameters T_c=+40°C, T_{sc} =10°C, T_{sh}=20°C, calculations were made for different evaporation temperatures T_e = -30°C to +10°C, asserting a step of 5°C. The range chosen for the evaporation temperature refers to low temperature, refrigeration and A/C applications.

The performance parameters were determined by using calculation programs developed in CYCLE_D 4.0 software, for each of the eleven considered refrigerants.

  - Volume 9, Number 4 (ISSN 1995-6665)

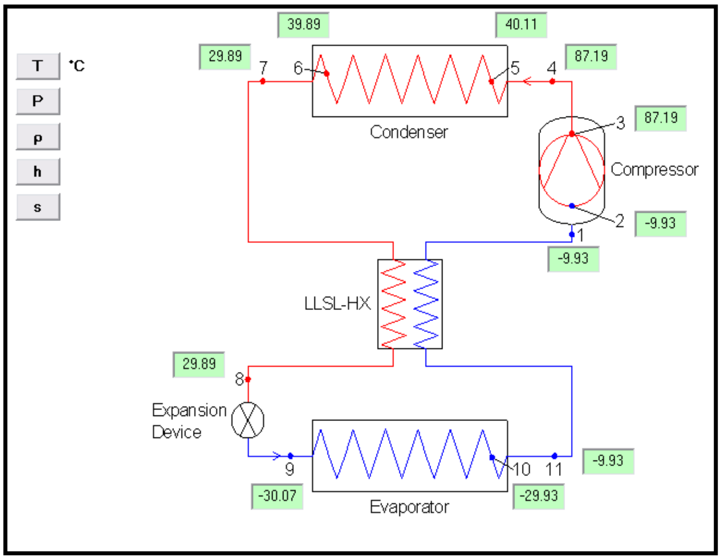

Figure 3. (a) Schematic of sub critical cycle for refrigerant blend A6

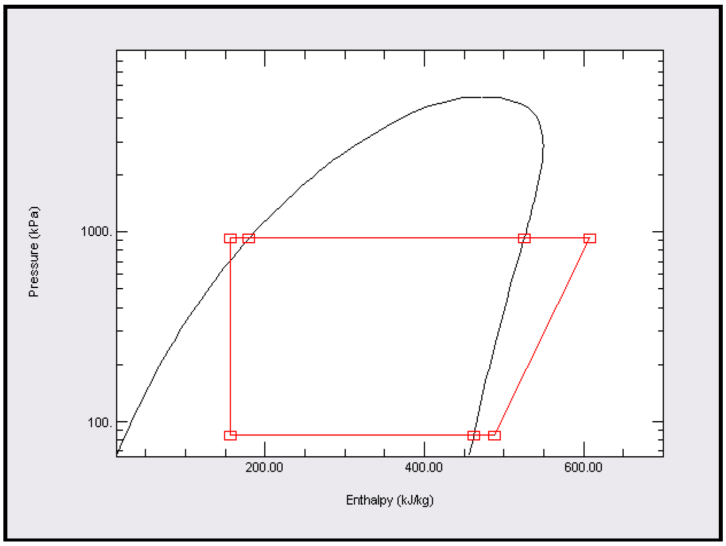

Figure 3. (b) Thermodynamic cycle in p - h diagram for azeotropic refrigerant blend A6

5. Materials and Methods

The test rig used for the experiment is a domestic refrigerator designed to work with R-134a. It consists of an evaporator, wire mesh air cooled condenser and hermitically sealed reciprocating compressor. Four pressure gauges were used and were respectively installed before and after each main component. All of these pressure gauges were fitted on a wooden panel to ensure that the gauge did not vibrate during testing. All of the ten points of the thermo couple wire were connected to the thermo couple scanner. Thermo couple scanner is a device to read the measured temperature. Among these points, 10 calibrated temperature sensors were installed at the evaporator inlet and outlet, compressor suction and discharge, compressor body, condenser outlet, dryer, freezer compartment and refrigerator cabin. In addition, the consumed voltage and current were recorded. The flow meter, which was connected to the pipe between condenser and filter dryer, was fixed to a wooden panel next to pressure gauges. The data were read through visualization and recorded every 15 minutes. Analyzing these data, the power consumption, working time, and ON time ratio of the compressor were calculated. To check the quality of condensed liquid a sight glass was provided. As per the manufacturer's specification the quantity of the charge was 80gms of R-134a. Since additional pipes were used to fix the measuring devices the charge was optimized for the setup. The power consumption was found to be minimum for the charge quantity of 140gms.

A power meter was connected with a compressor to measure the power and energy consumption. Service ports were installed at the inlet of the expansion device and compressor for charging and recovering the refrigerant. The evacuation of moisture in the system was also carried out through the service port initially; the system was flushed with nitrogen gas to eliminate impurities, moisture and other materials inside the system, which may affect the performance of the system. The system was charged with the help of charging system and evacuated with the help of a vacuum pump. The refrigeration system was charged with 140gms of R-134a and the baseline performance was studied. After completing the baseline test with R-134a, the refrigerant was recovered from the system and the experimental procedures were repeated with R-152a and refrigerant mixture A6. Figure 4 shows a schematic diagram of the measurement system used in the experimental setup. The most important specifications of the refrigerator are summarized in Table 3. Measured quantities with their range and uncertainties are listed in Table 4.

Figure 4. Schematic diagram of experimental setup

Table 3. Technical specifications of domestic refrigerator test unit

Cross Volume	180L
Storage Volume	169L
Current rating	1.1 max
Voltage	220-240V
Frequency	50Hz
No. of. Doors	1
Refrigerant type	R134a
Defrost System	Auto defrost
Refrigerant charged	0.140 kg
Capillary tube length	3.35m
Capillary tube inner diameter	0.00078m
Cooling capacity	182 W

Table 4. Measured quantities and their uncertainties

Quantity	Range	Uncertainty
Temperature	-40°C to 110°C	+1°C
Power consumption	0 to 1000W	0.001W
Voltage	0 to 240V	0.001V
Current	0 to 10A	0.001A
Pressure	0 to 300 PSI	+1PSI
Refrigerant flow meter	0 to 100 CC/Sec	0.1 CC/Sec

6. Experiments

As per the guide lines given by ASHRAE Hand book 2010, the energy consumption test and no load pull down test were conducted for the following conditions:

Freezer compartment : -18°C to -15°C
Food compartment : 3°C to 5°C
Steady ambient temperature : 25°C to 32°C

7. Results and Discussions

7.1. Thermodynamic Analysis

7.1.1. Variation of the Refrigerating Effect

In Figure 5, the variation of the Refrigerating Effect (RE) is presented as depending on the evaporation temperature (T_e) for each of the eleven types of refrigerants. For a certain type of blend (A0-A10), RE practically does not depend on T_e. In turn, RE increases with the increase of DME mass fraction. Thus, for R-435A refrigerant (A8 blend) RE increases by more than 30% in comparison with pure R-152a refrigerant (A0).

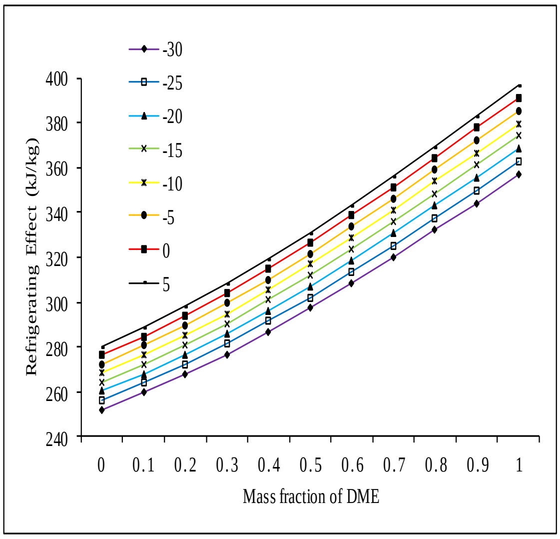

Figure 5. Variation of the Refrigerating effect depending on the evaporation temperature and the DME mass Fraction

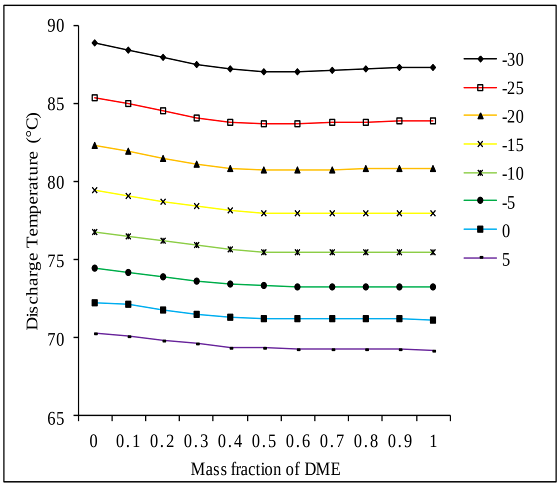

Figure 6. Variation of compressor discharge temperature depending on evaporating temperature and the DME mass Fraction

7.1.2. Variation of Compressor Discharge Temperature

Figure 6 highlights the advantage of reducing the discharge temperature by increasing the DME mass fraction, in case of replacing R-152a with R-152a/DME blends. Thus, it results that the R-435A refrigerant may be also used in good conditions in refrigeration application area (-15°C< T_e <0°C).

7.1.3. Variation of Saturation Pressure

Figure 7 shows that the saturation pressure increases with the increase of DME mass fraction, for the (0-55) % range. Therefore, at a certain constant evaporation temperature, the saturation pressure of R-152a/DME blends is higher than that of pure R-152a for the (20-80) % range.

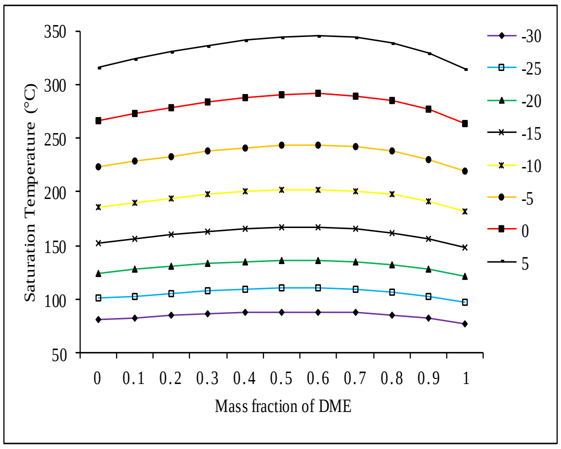

Figure 7. Variation of the saturation pressure depending on evaporating temperature and DME mass fraction

7.1.4. Variation of Coefficient of Performance

The COP variation, depending on the evaporation temperature and DME mass fraction, is shown in Figure 8. It results that for the same evaporation temperature, the COP of R-152a/DME blends is higher than that of pure R-152a. Thus, for R-435A refrigerant (A8 blend) COP increases by more than 30% in comparison with pure R-152a refrigerant (A0).

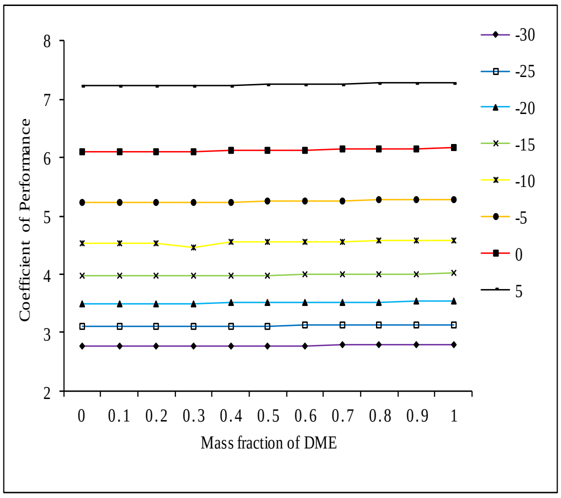

Figure 8. Variation of COP depending on evaporating temperature and DME mass fraction

7.1.5. Variation of Volumetric Refrigerating Capacity

Figure 9 displays the variation of the volumetric Refrigerating Capacity for R-152a/DME blend depending on the evaporation temperature and DME mass fraction. It results that for a certain evaporation temperature, within (0 - 40) % range the volumetric Refrigerating Capacity increases with the increase of DME mass fraction. This represents a very important advantage obtained when substituting R-152a with a blend having a DME mass fraction especially within (30-60) % range.

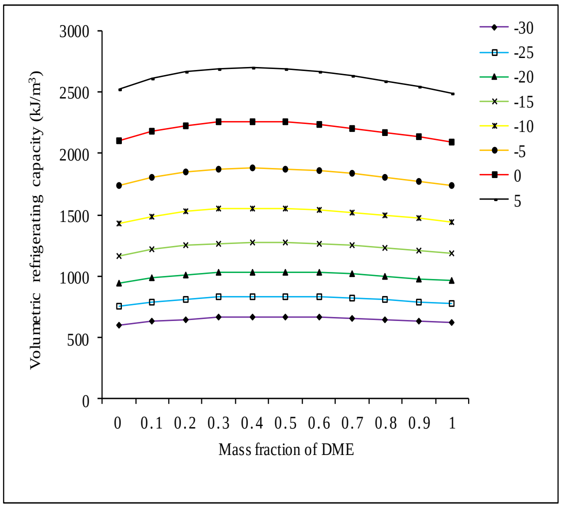

Figure 9. Variation of the volumetric Refrigerating Capacity depending on evaporating temperature and DME mass fraction

7.1.6. Variation of Refrigerant Volume Flow Rate

The variation of refrigerant volume flow rate at the compressor inlet depending on the evaporation temperature and DME mass fraction is shown in Figure 10. It results that with the increase of DME mass fraction within (10-90) % range, the refrigerant volume flow rate at the compressor inlet has lesser values than pure R-152a (A0). This represents another important advantage in the case of replacing R-152a, in an existing system, with the new proposed azeotropic blend containing (10-90))% DME mass fraction, which allows for the use of the same compressor.

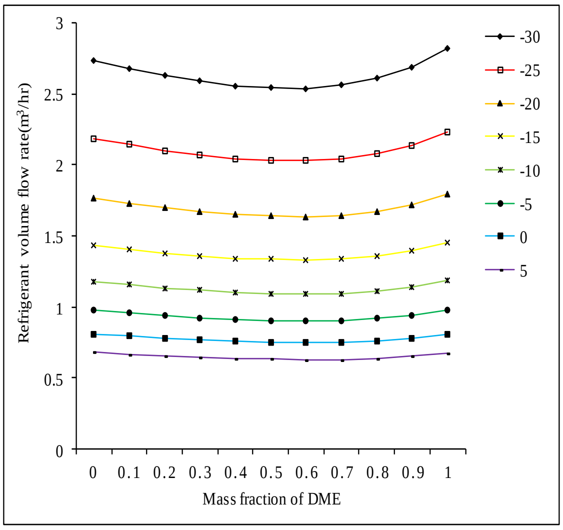

Figure 10. Variation of a refrigerant volume flow rate depending on evaporation temperature and DME mass fraction

7.1.7. Variation of Condenser Duty

The variation of condenser duty depending on the evaporation temperature and DME mass fraction is shown in Figure 11. It results that for a certain evaporation temperature, within the range the condenser duty increases with the increase of DME mass fraction.

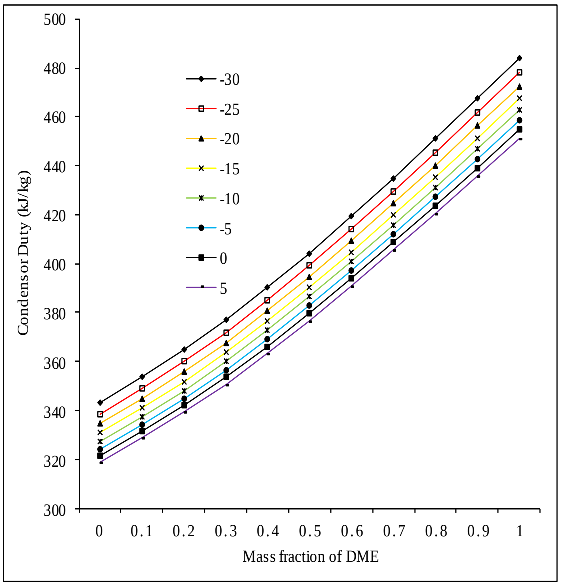

Figure 11. Variation of condenser duty depending on evaporation temperature and DME mass fraction

7.1.8. Variation of Compressor Power

The variation of compressor power depending on the evaporation temperature and DME mass fraction is shown in Figure 12. It highlights the advantage of reducing the compressor power by increasing the DME mass fraction, in the case of replacing R-152a with R-152a/DME blends.

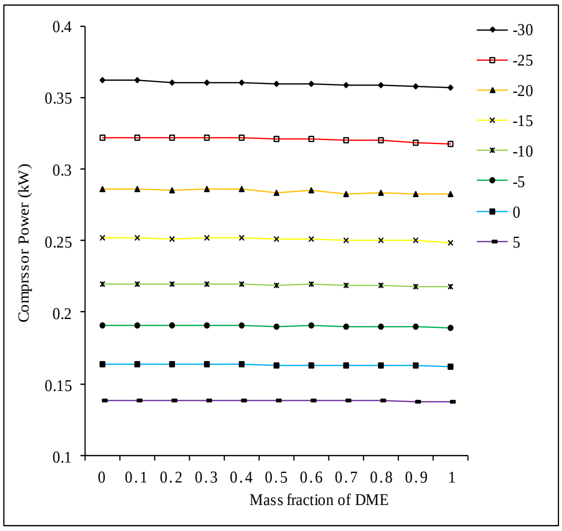

Figure 12. Variation of compressor power depending on evaporation temperature and DME mass fraction

7.2. Experimental Results

The average power consumption of the system is computed from the measurement system in the test rig. The coefficient of performance of the system for the refrigerants R-152a and new refrigerant mixture (A6) [DME 60% + R-152a 40%] are calculated and compared with base line refrigerant R-134a. The computational and experimental results are shown in Table 5.

Test conditions:

1. Evaporation Temperature (T_e) = -16°C
2. Condensation Temperature (T_c) = 55°C
3. Degree of sub cooling (T_{sc}) = 10°C
4. Degree of super heating (T_{sh}) = 20°C

Table 5. Validation of results

Sl.No.	Refrigerants	Computational Results		Experimental Results	
		COP	CP*	COP	CP*
1	R-134a	2.728	0.075	1.466	0.117
2	R-152a	2.830	0.072	1.520	0.107
3	A6 (DME 60% + R-152a 40%)	2.847	0.072	1.537	0.117

***Compressor Power (kW)**

From the above results, it is observed that the COP of the system with new refrigerant mixture (A6) is 4.88% and 1.15% higher than that of R-134a and R-152a, respectively. The average compressor power consumption of the refrigerant mixture is similar with R-134a and 9.35% higher than that of R-152a.

8. Conclusions

Thermodynamic analysis was performed for R-152a and various refrigerant blends of DME and R-152a. Based on this analysis, the performance of the refrigerant mixtures (A4, A5, and A6) in the vapor compression refrigeration system is good.

After having compared the thermodynamic performances of the considered refrigeration system operating in the same imposed conditions the following advantages emerged:

- Being azeotropic blends, they do not cause any problems neither in maintaining their initial composition during the charging process, nor in case of gas leaks on the high pressure side;
- Higher volume heat load for the lesser volume flow rate at the compressor inlet;
- Higher coefficient of performance;
- Increased compressor life due to lower compressor discharge temperature; and
- Reduced mass flow rate and the compressor power for the operation.

An experimental analysis, carried out in a domestic refrigerator in which R-134a, R-152a and refrigerant mixture (A6), is used for performance investigation. The experimental results are compared with computational results.

Based on the results, the refrigerant mixture [A6] is recommended as an alternative refrigerant and leads to a reduction in the GWP (less than 50). By considering all kinds of performance parameters the proposed refrigerant mixture enhances the performance of the refrigerator.

Acknowledgement

The present study was supported through the Department of Mechanical Engineering, P. A. College of Engineering and Technology, Pollachi-2.

References

[1] United Nation Environmental Programme, Montreal protocol on substances that deplete the ozone layer, Final Act, 1987.

[2] Global Environment Change Report, A brief analysis of the Kyoto protocol, Vol. IX, No.24, December, 1997.

[3] B. O. Bolaji , M. A. Akintunde, and T.O. Falade, "Comparative analysis of performance of three ozone-friends HFC refrigerants in a vapour Compression refrigerator", Journal of Sustainable Energy & Environment, Vol. 2, (2011) No.1, 61-64.

[4] Nicholas Cox, "Developments and opportunities using hydrocarbons refrigerant blends", Transforming Technologies Conference, Institute of Mechanical Engineers, London, 2010.

[5] Valentin Apostol, *et al*., "Thermodynamic Study Regarding the Use of Dimethylether as Eco Refrigerant"; Journal of Revista De Chime (Bucuresti), Vol. 60 (2009) No.7, 714-718.

[6] Adamson, B.M., "Di methyl Ether as an R-12 Replacement", IIR - Commissions B & E - Oslo, Norway, 1998,

[7] A. Baskaran, P. Koshy Mathews, "A Performance comparison of vapour compression refrigeration system using various alternative refrigerants", International Journal of Scientific & Engineering Research, Vol. 3 (2012) No.10, 1-6.

[8] Choedaeseong (Daeseongchoe) the world wide (yo-hanlee) Air (Dangsoo Jung), "Performance of R435A on refrigeration system of domestic water purifiers", International Journal SAREK, Vol.11 (2010) No.1, 366-371.

[9] Jung, Dong-Soo, et.al, "Performance Evaluation of R435A on Refrigeration System of Water Purifiers", Journal of the Korean Solar Energy Society, Vol. 33 (2013) No.1, 15-23.

[10] A. Baskaran, P. Koshy Mathews, "Thermal analysis of vapour compression refrigeration system with R152a and its blends R429A, R430A, R431A and R435A", International Journal of Scientific & Engineering Research, Vol. 3 (2012) No. 10, 1-8.

[11] Lemmon .EW, Huber .ML, McLinden. MO, NIST Reference Fluid Thermodynamic and Transport Properties – REFPROP. Version 9.0. National Institute of Standards and Technology, Boulder, USA 2010.

[12] Steven Brown. J, Piotr. A, Domanski, Eric W. Lemmon, CYCLE_D: NIST vapour compression cycle design program version 4.0 Gaithersburg (MD): National institute of standards and technology, Boulder, USA.2009.

[13] A. Baskaran, P. Koshy Mathews, "A Performance comparison of vapour compression refrigeration system using Eco friendly refrigerants of low global warming potential", International Journal of Scientific and Research Publication, Vol. 2 (2012) No. 9, 1-8.

[14] A. Baskaran, P. Koshy Mathews, "Investigation of New Eco Friendly Refrigerant Mixture Alternative to R134a in Domestic Refrigerator", Australian Journal of Basic and Applied Sciences, Vol. 9 (2015) No. 5, 297-306.