13th IEA Heat Pump Conference
April 26-29, 2021 Jeju, Korea

Analytical study on performance of R134a, R404A, and R744 refrigeration truck system

Yunchan Shin[a], Yeonghun Kim[a], Minjun Kim[b], Honghyun Cho[b,*]

[a]Graduate school of Chosun University, Gwangju, 501-759, Korea.
[b,*]Department of Mechanical Engineering, Chosun University, Gwangju, 501-759, Korea.

Abstract

An automotive air-conditioning system and refrigeration truck is normally used refrigeration R134a and R404A. The natural refrigerant R744 is one of alternative refrigerant for refrigeration truck. In this study, the theoretical study on the performance comparison between R744, R134a, and R404A for the refrigeration truck. The cooling capacity, compressor work, and COP of R744 refrigeration system were analyzed according to outdoor air temperature and compressor rotating speed. Also, those are compared with those of R404A and R134a system. As a result, the performance of all systems with the outdoor temperature was rapidly decreased. The performance decrement of R404A is relatively higher than that of other system. In the change of RPM, the increasing rate of cooling capacity and compressor work of the R404A, R134a, and R744 system reached the highest at 1500 RPM. The data of this study is to provide the basic performance data of refrigeration system of refrigeration truck.

Keywords: Compressor work; COP; R134a; R404A; R744; Refrigeration capapcity

1. Introduction

As parcels and distribution supply recently increased, energy consumption for the storage and transport of parcels is increasing. In particular, the energy consumption for delivery has increased even more as the demand for delivery has increased compared to the storage of items. In addition, as the delivery of products requiring freshness from among the delivered products increases, the demand for a refrigeration truck using a refrigeration system is increasing to keep the temperature of the product storage room constant at all times.

Refrigeration trucks consume more energy than general trucks by using a refrigeration unit to maintain a constant temperature in the product storeroom. Therefore, research on improving the performance of refrigeration truck is essential for energy saving. The Ozone Depletion Potential (ODP) of R404A and R134a refrigerants, which are widely used in the refrigeration industry, is currently 0, but the Global Warming Potential (GWP) is very high at 4,700 and 1300, respectively. Regarding refrigerants used in automotive air conditioning systems, the European Commission has decided to regulate the use of refrigerants more than GWP of 150 for new vehicles since 2022. R744 refrigeration system can miniaturize because R744 refrigerant has a smaller specific volume than R404A and R134a. In addition, it can be used even at low temperatures since the boiling point is low. Table 1 showed the properties of refrigerant used in this study.

In this study, R404A, R134a and R744 refrigerants were applied to the refrigeration system of refrigeration trucks, and the performance of refrigeration truck refrigeration system was compared under various operating conditions. The results of this study may provide basic data on the performance of refrigeration truck refrigeration system with alternative refrigerants.

* Corresponding author. Tel.: 82-62-230-7050; fax: 82-62-230-7055.
E-mail address: hhcho@chosun.ac.kr.

Table 1 Refrigerant properties

Refrigerant	**R134a**	**R404A**	**R744**
Molecular weight [kg/kmol]	102.03	97.6	44.01
Boiling point [K]	247.08	319.15	194.65
Critical temperature [K]	374.2	345.1	304.25
Critical pressure [MPa]	4.06	3.73	7.38
Latent heat of vaporization at 25℃ [kJ/kg]	177.8	140.3	119.9
Flammability	Inflammable	Inflammable	Inflammable
Ozone depletion potential	0	0	0
Global warming potential	1300	4700	1

2. Simulation modeling and analysis

The refrigeration truck refrigeration system used in this study was developed by selecting the refrigeration truck currently operating on the road as the main analysis model. And the developed system shown in Fig. 1 is consist of compressor, condenser, expansion valve and evaporator. This simulation is conducted using the EES program and the flow of performance analysis was carried out as shown in Fig. 2.

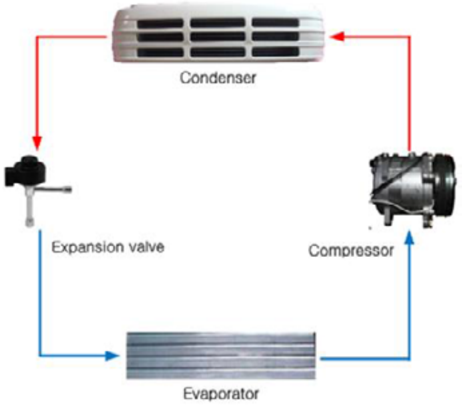

Fig. 1. Refrigeration cycle of refrigeration truck

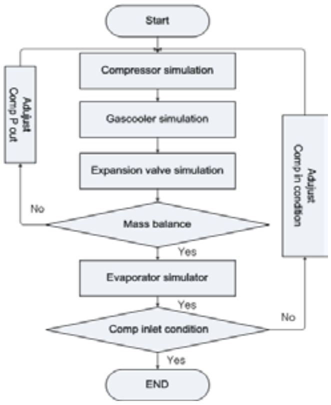

Fig. 1 Flow chart for the refrigerator cycle

2.1. Compressor modeling

The compressor of R404A, R134a and R744 used in the analysis of this study was selected due to its durability and widely used as swash plate compressor of automobile air conditioning systems. In the case of R744, as the rate of heat capacity is bigger than R404A and R134a, the stroke volume of the compressor is controlled to obtain the same refrigeration capacity from the system. The equation (1) was used to calculate the mass flow rate of R404A, R134a and R744. The volumetric and isentropic efficiency of R404A, R134a, and R744 in this study was used based on the experiment of previous study [1-3]. The volumetric and isentropic efficiency of the refrigeration system for R404A were used the equation (2) and (3) [1], respectively. In case of the refrigeration system with R134a, It was calculated by the equation (4) and (5) [2]. The volumetric and compression efficiency of refrigeration system for R744 was calculated by the equation (6) and (7) [3].

$$M_r = n\frac{\pi}{4}d_c^2 S_p N\frac{\eta_v}{v_s} \tag{1}$$

$$\eta_{v,R404A} = 0.3596 + 1.1072 \times S_p - 0.08132 \times \varepsilon + 0.0001175 \times N - 0.4025 \times S_p^2 - 2.449 \times 10^{-8} N^2 \tag{2}$$

$$\eta_{i,R404A} = 0.2402 + 1.4187 \times S_p - 0.09698 \times \varepsilon + 0.000123 \times N - 0.5852 \times S_p - 2.457 \times 10^{-8} N^2 \quad (3)$$

$$\eta_{v,R134a} = 0.8263 \left[1 - 0.09604 \left(\varepsilon^{\frac{1}{\gamma}} \right) - 1 \right] \quad (4)$$

$$\eta_{i,R134a} = 0.9343 - 0.04478 \times \varepsilon \quad (5)$$

$$\eta_{v,R744} = 1.149768 + 0.001025 \times P_{c,in} - 0.003592 \times P_{c,in} - 13.660815 \times V_s + 0.000059 \times N \quad (6)$$

$$\eta_{c,R744} = 0.781749 - 0.000956 \times P_{c,out} - 0.003812 \times SH_{c,s} - 0.003565 \times T_{c,s} + 0.000033 \times N \quad (7)$$

2.2. Heat exchanger modeling

The condenser consists of four rows and is divided into two tubes. And the evaporator is divided into six tubes and consists of eight rows each. Detailed specifications of the heat exchanger are shown in Table 2. In this study, the heat transfer and pressure drop correlation of single-phase and two-phase used for modeling of R404A, R134a and R744 system is shown Table 3. In addition, the heat transfer coefficient and pressure drop for the analysis of air side used the correlation of the Wang [14].

Table 2 Specification of heat exchanger

Specification	Condenser	Evaporator
Fin interval [mm]	2.1	4.56
Fin height [mm]	25.78	22.64
Fin width [mm]	24.83	26.13
Tube diameter [mm]	9.5	9.5
Tube thickness [mm]	0.5	0.5
Total size [mm]	760.2(L)×283.5(H)×99.3(W)	864.6(L)×135.8(H)×209(W)

Table 3 Heat transfer coefficient and pressure drop of R404A, R134a, R744 for heat exchanger modeling

	R404A		R134a		R744	
	Single- phase	Two- phase	Single-phase	Two-phase	Gascooler	Evaporator
Heat transfer coefficient	Wang[4]	Traviss[6]	Dittus and Boelter[8]	Gungor and Winterton[10]	Gnielinsk [11]	Yoon et al [13]
Pressure drop	Blasius[5]	Fridel[7]	Fanning and Pierre[9]	Fanning and Pierre[9]	Churchill [12]	Yoon et al[13]

2.3. The expansion device modeling

The expansion device used in the R404A, R134a, and R744 system used the electron expansion valve. The electron expansion valve is comprised of the orifice, needle and the drive stepping motor. The orifice diameter used to the modeling of R404A and R744 system was 1.6 mm. It used the equation of the Hwang and Kim [15]. The orifice diameter of the R134a system was 1.4 mm and it used the equation of the Chung et al [16].

2.4. The frost analysis

The frost growth in the evaporator has an bad effect on the system efficiency due to the decrease of heat transfer area in the heat exchanger. The thermal resistance and heat transfer coefficient of the frost layer was applied to the heat exchanger analysis of the R404A, R134a and R744. Thermal conductivity and density of the frost layer was calculated according to the equation proposed by Lee at al. [17] and those are calculated by the equations (8) and (9).

$$\mathrm{k_f} = \mathrm{k_{ice}} \times 0.26259(\mathrm{Re_d})^{0.49406}(\mathrm{Fo})^{0.18733}(\mathrm{w_a})^{-0.25087}(\mathrm{T_a^*})^{-7.20328}(\mathrm{T_c^*})^{5.5004} \quad (8)$$

$$\rho_\mathrm{f} = \rho_\mathrm{ice} \times 0.00008(\mathrm{Re_d})^{0.44785}(\mathrm{Fo})^{0.21083}(\mathrm{w_a})^{-0.53939}(\mathrm{T_a^*})^{23.90830}(\mathrm{T_c^*})^{5.69576} \quad (9)$$

3. Results and discussion

In this study, the performance characteristics of the system were investigated the performance for refrigeration cycle of the designed refrigeration truck refrigeration system using R134A, R404A, and R744 refrigerant. Fig. 3 showed the variation of COP, compressor work, and cooling capacity according to the change of outdoor air temperature. As the outdoor air temperature increased from 25℃ to 35℃, the compressor work of R404A, R134a, and R744 system increased by 19.1%, 13.1%, and 16.8%, respectively and the refrigeration capacity ratio decreased by 43.1%, 9.0%, and 41.5%, respectively.

Fig. 4 showed the variation of COP, compressor work, and cooling capacity according to the change of compressor rotating speed. As the compressor rotating speed increased from 1000 rpm to 3000 rpm, the ratio of compressor work and of refrigeration capacity rapidly increased at the system of R404A, R134a, and R744. Accordingly, the ratio of COP decreased because compressor work more increased than refrigeration capacity. The COP ratio of R404A and R744 system showed maximum value at the compressor rotating speed of 1500 rpm.

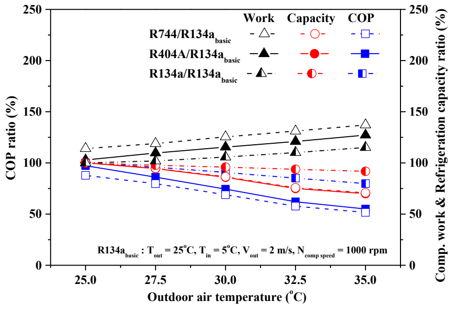

Fig. 3. Variations of compressor work, capacity, COP with outdoor air temperature

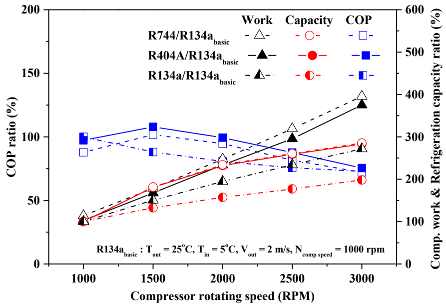

Fig. 4. Variations of compressor work, capacity, COP with compressor rotating speed

4. Conclusions

In this study, R404A, R134a and R744 refrigerants were applied to the refrigeration system of refrigeration trucks, and the performance of refrigeration truck refrigeration system was compared under various operating conditions. An automotive air-conditioning system and refrigeration truck is normally used refrigeration R134a and R404A. The natural refrigerant R744 is one of alternative refrigerant for refrigeration truck. In this study, the theoretical study on the performance comparison between R744, R134a, and R404A for the refrigeration truck. The cooling capacity, compressor work, and COP of R744 refrigeration system were analyzed according to outdoor air temperature and compressor rotating speed. Also, those are compared with those of R404A and R134a system. As a result, the performance of all systems with the outdoor temperature was rapidly decreased. The performance decrement of R404A is relatively higher than that of other system. In the change of RPM, the increasing rate of cooling capacity and compressor work of the R404A, R134a, R744 system reached the highest at 1500 RPM. The data of this study is to provide the basic performance data of refrigeration system of refrigeration truck.

Acknowledgements

This work was supported by “Human Resources Program in Energy Technology” of the Korea Institute of Energy Technology Evaluation and Planning (KETEP), granted financial resource from the Ministry of Trade, Industry & Energy, Republic of Korea (No. 20194030202410).

References

[1] Changqing, T., Yunfei, L., Xianting, Li., 2006. “A mathematical model of variable displacement swash plate compressor for automotive air conditioning system,” International Journal of Refriger

ation, Vol. 29, p. 270-280.
[2] Brown, J Steven., Yana-Motta, Samuel F., Domanski, Piotr A., 2002. "Comparative analysis of a n automotive air conditioning system operating with CO_2 and R134a," International of Refrigerat ion Vol. 25, Issue 1, p. 19-32.
[3] Sanchez, D., Torrella, E., Cabello, R., Liopis, R., 2010. "Influence of the Superheat Associated t o a Semihermetic Compressor of a Transcritical CO_2 Refrigeration Plant," Applied Thermal Engi neering, Vol. 30, Issue 4, p. 302-309.
[4] Wang C, C., 2001. "A Comparative Study of Compact Enhanced Fin-and-Tube Heat Exchangers," Heat and Mass Transfer, Vol. 44, p. 3565-3573.
[5] Blasius, H, Z., 1913. "Das Ahnlichkeitsgesetz bei Reibungsvorgangen in Flussigkeiten," Forschg. Arb. Ing. Wes., No.131, Berlin.
[6] Traviss D, P., Rohsenow W, M., Baron A, B., 1972. "Force convection condensation inside tube : a heat transfer equation for condenser design," ASHRAE Transactions, Vol. 79, p. 157-165.
[7] Friedel, L., 1979. "Improved friction pressure drop correlation for horizontal and vertical two-ph ase pipe flow," European two-phase flow group meeting, p. E2.
[8] Dittus F, W., Boelter L, M, K., 1930. "Heat Transfer in Automobile Radiators of the Tubular T ype," Publications in Engineering, University of California, Berkeley, Vol. 2, p. 443.
[9] Pierre, B., 1964, "Flow resistance with boiling refrigerants - part1," ASHRAE Journal, p. 58-65.
[10] Gungor, K, E., Winterton R, H, S., 1986. "A general correlation for boiling in tubes and annul i," International Journal of Heat Transfer, Vol. 19 p. 351-358.
[11] Gnielinski, V., 1976. "New Equation for Heat and Mass Transfer in Turbulent Pipe and Channel Flow," Int. J. Chemical Engineering, Vol. 16, p. 359-368.
[12] Churchill, S., 1997. "Friction Factor Equation Spans all Fluid Flow Regimes," Journal of Chemi cal Engineering, Vol. 7, Issue 24, p. 91-92.
[13] Yoon, S, H., Cho, E, S., Kim, M, S., 2004. "Characteristics of Evaporative Heat Transfer and P ressure Drop of Carbon Dioxide and Correlation Development Near the Critical Point," Proceedi ngs of the SAREK, Vol. 16, No. 6, p. 530-534.
[14] Wang C, C., Chi K, Y., Chang C, J., 2000. "Heat transfer and friction characteristics of plain fi n-and-tube heat exchanger, part II: Correlation," Vol. 43, p. 2693-2700.
[15] Hwang, Y, W., Kim, O, J., 2007. "Experimental Study on the CO_2 Flow through Electronic Exp ansion Valves," SAREK, p. 1237-1241.
[16] Choi, J, M., Chung, J, T., Kim, Y, C., 2004. "A generalized correlation for two-phase flow of a lternative refrigerants through short tube orifices," International Journal of Refrigeration, Vol. 27, p. 393-400.
[17] Lee, K, S., Kim, J, S., Yang, D, K., 2008. "Dimensionless correlations of frost properties on a cold cylinder surface," International Journal of Heat and Mass Transfer, Vol. 51, p. 3946-3952.