The influence of internal heat exchanger on energy efficiency and environmental effects of the Heat Pump using Low-GWP Refrigerants as substitutes

Zhao Yuqing, DaiYun, Gaoyan, Xie Lanyi, Hou Xiangyang, Gao Jianling
School of Civil Engineering, North China University of Technology.
Correspondence: No.5, at Jinyuanzhuang Road, Shijingshan District, Beijing, 100144, Email: zyq@ncut.edu.cn

Abstract: This paper presents an experimental analysis of the influence of heat exchanger on the performance of a heat pump system using Low-GWP refrigerants as replacements for R22. In this work, we compare the energy performance of a monitored heat pump system using NC01 (composed of R32, R1234ze(E), and R134a at a mass percentage of 50%:17%:33%), R32 and R1234ze(E) with and without the presence of an internal heat exchanger. From the experimental results, COP reductions of R1234ze(E), NC01 and R32 was 12%, 4% and 1.9% respectively, although the presence of an IHX can help to lessen these reductions between 2 and 6%. The results indicated lower TEWI amounts as a result of using NC01 as an alternative to R22 with the presence of IHT (internal heat exchanger).

1. Introduction
According to the Copenhagen amendment, the use of R22 will be banned by the end of 2030. At present, this HCFC represents 97.2% of the HCFC substances used in the refrigeration sector [1]. China is the world's largest country in terms of the amount of production and application of HCFC22. It is an imminent task to develop suitable replacements for R22.

R32 and R1234ze(E) have good thermal and environmental properties and are considered the most promising refrigerants by many scholars. The ODP of HFO-1234ze(E) and R32 is 0 for both, and the GWP is 6 and 675, respectively. Many theoretical and experimental studies [2] are focused on R32, and R1234ze(E) and its mixers used as alternatives of high GWP refrigerant due to its low GWP.

This work extends previous studies about possible R22 drop-in alternatives. Using the complementary advantage in volume heat and exhaust temperature of R32 and R1234ze(E), a new refrigerant (NC01) is formed with the third refrigerant R134a, which is nonflammable and azeotropic. The new refrigerant NC01 is a mixture of R32, R1234ze(E), and R134a at a mass percentage of 50%:17%:33%, respectively, which was determined through software REFPROP 9.0, and developed to replace R22 in the water-source heat pump. Main characteristics of R22 and its alternatives are shown in table 1.

| molar mass (kg/kmol) | specific latent heat (°C·kJ/kg) | Standard boiling point (°C) | critical temperature (°C) | critical pressure (MPa) | Critical density (kg/m³) | ODP | GWP |
|----------------------|-------------------------------|-----------------------------|--------------------------|------------------------|-------------------------|-----|-----|

Table 1. Main characteristics of R22 and its alternatives.
To clarify and compare the performance of each individual refrigerant, the drop-in experiments of the single refrigerant R32 and R1234ze(E) were also carried out. There are some investigations in which energy parameters were improved using an internal heat exchanger[3] [4] [5] [6]. Piotr A. Domanskia[7] presented that $C_p^0$ (Heat capacity in the limit of zero pressure) should be low for the simple vapor compression cycle or higher for a cycle with liquid line/suction line heat exchange. The comparative parameters include exhaust temperature, exhaust pressure, specific volume heat, energy consumption, and COP. The COP is presented in Eq. (1).

$$\text{COP}_{th} = \frac{h_1 - h_2}{h_2 - h_1}$$  \hspace{1cm} (1)

To clarify and compare the performance of each individual refrigerant, the drop-in experiments of the single refrigerant R32 and R1234ze(E) were also carried out. There are some investigations in which energy parameters were improved using an internal heat exchanger[3] [4] [5] [6]. Piotr A. Domanskia[7] presented that $C_p^0$ (Heat capacity in the limit of zero pressure) should be low for the simple vapor compression cycle or higher for a cycle with liquid line/suction line heat exchange. The comparative parameters include exhaust temperature, exhaust pressure, specific volume heat, energy consumption, and COP. The COP is presented in Eq. (1).

2. Test methodology and experimental setup
This subsection describes the test methodology used to evaluate the substitute refrigerants as well as the experimental setup and uncertainties of the measurement system.

2.1 Test methodology
The substitute refrigerants were evaluated in a water-source heat-pump system with a compressor input power of 6.54 kW. With the water temperature at condenser outlet kept at 45°C, and the water temperature at the evaporator inlet kept at 13°C, 18°C, and 23°C, which represent the water source temperature in winter, transition seasons, and summer, respectively, 24 tests were developed for the conditions of with and without the internal heat exchanger (IHX). These tests considered stable operation of the system during 10 min, and then the average was taken of the rate of 4 sets of test data for analysis.

2.2 Experimental plant
The experimental plant used for the evaluation of the substitute refrigerants was detailed in reference [8]. The experimental apparatus consists of a refrigerant loop, heat-sink water loop, and heat-source water loop. The refrigerant circulation system consists of a compressor with POE lubricating oil, condenser (braided heat exchanger), evaporator (braided heat exchanger), and electronic expansion valve. The source-water circulation subsystem is composed of a water-circulation pump, water tank, and evaporator. The hot-water circulation subsystem includes the water-circulation pump, water tank,
and condenser. The IHX is installed at the discharge line of the condenser and evaporator with two bypasses that allow it to be connected or disconnected from the refrigeration facility.

3. Results and discussion

This section presents and analyzes the experimental results obtained in the test carried out with R22, R32, R1234ze(E), and NC01 as the working fluid. The parameters analyzed are the heating capacity, COP, power consumption, and exhaust temperature.

3.1. Comparison of heating capacity, power consumption and COP

The heating capacity is obtained from the hot water side with the water volume and temperature difference, as shown in Eq. (2).

\[ Q_h = m_{\text{w,CON}} C_w (T_{\text{w,CON, out}} - T_{\text{w,CON, in}}) \]  

The COP of the heating mode is presented in Equation (3). It is obtained from the measured input power \( P_{\text{com}} \) and the heating capacity \( Q_h \).

\[ \text{COP} = \frac{Q_h}{P_{\text{com}}} \]  

Figure 2 (a) shows the variation in the heating capacity at different inlet source water temperatures when IHX is deactivated. It can be concluded that under the same working conditions, the heating capacity using R32 is up to 56% higher than that using R22. This important increment means that the displacement of the compressor for R22 is too high for R32 in a direct drop-in. Consequently, if R32 is used to replace R22, the size adjustment should be performed. In contrast, R1234ze(E) yields a reduction of about 50% heating capacity compared to R22. This behavior indicates that it could not be used as a directed drop-in in a heat pump designed for R22. To achieve a similar heating capacity, the use of larger compressors should be considered. Finally, the results showed that NC01 has a similar heating capacity to R22, and the increasing range is from 1.5% to 6.0%. It may be suitable as a drop-in alternative to replace R22 from the perspective of heating capacity.

The results when IHX is active are shown in figure 2 (b). The heating capacity difference between the baseline and R1234ze(E) is decreasing. At \( T_{\text{w, in}} \) (the temperature of the inlet water source) of 13 °C, the values of R1234ze(E) are increased by about 2%, and at \( T_{\text{w, in}} \) of 18 °C and 23 °C, by about 1.2% and 1.6%, respectively, than when IHX is deactivated. For NC01, the values increased by about 6.3%, 2.5%, and 0.1% at \( T_{\text{w, in}} \) of 13 °C, 18 °C, and 23 °C, respectively. The influence of IHX on the heating capacity is readily apparent for R1234ze(E) and NC01.

Figure 3(a, b) show the variation in compressor power consumption for all the tested refrigerants. R32 has the highest value of power consumption, followed by NC01, R22, and R1234ze(E). At different inlet water temperatures, the power consumption of the same refrigerant maintains the same energy cost because the compressor frequency is fixed.

Figure 4 (a) present the COP values resulting from the test without IHX. The COP obtained with R32 was slightly lower than that with R22 by about 3.5% at \( T_{\text{w, in}} \) of 13°C and 1.1% at \( T_{\text{w, in}} \) of 18°C. A
higher value of 4.1% was obtained at $T_{w,in}$ of 23°C. For R1234ze(E), the value of COP is decreased by 8.6–16.7%. Finally, the results showed that the COP of NC01 was decreased by about 14.2% at $T_{w,in}$ of 13°C, 5% at $T_{w,in}$ of 18°C compared with that of R22. The temperature of the inlet water source was higher and the COP difference was lower between R22 and drop-ins R32, R1234ze(E) and NC01.

When the IHX was used as shown in figure 4 (b), the COP difference between R22 and the drop-ins slightly decreased with respect to the increase in water temperature; at $T_{w,in}$ of 23 °C, the difference is increased from negative to positive for R32 and NC01.

For R22, R32 and NC01, the effect of IHX on COP is negative when $T_{w,in}$ is 13 °C and 18 °C, whereas R1234ze(E) is positive (about 1% increase). When $T_{w,in}$ is 23 °C, for R32, NC01, R22 and R1234ze(E), the effect of IHX on COP increased by 2.7%, 4.85%, 5.7% and 9.0%, respectively. IHX has different effects on COP for the four refrigerants. For R1234ze(E) the impact of IHX is advantageous, but for R22, R32, and NC01, it is not obvious. This is consistent with Piotr A. Domanski's research. Because the $C_p^0$ value of R1234ze(E) is the largest (101 J·mol⁻¹K⁻¹) among the four refrigerants, the other three refrigerants (R22, R32, and NC01) have a relatively small $C_p^0$ value of 56.43, and 59 J·mol⁻¹K⁻¹ (at temperature of 300K), respectively. Therefore, the effect of IHX is not obvious. Other factors, such as the transport performance, on COP also require further analysis.
3.2. Comparison of exhaust temperature

Figure 5 (a) shows the variation in compressor discharge temperature for all the tested refrigerants. As depicted in figure 5 (a), the minimum discharge temperature is reached by R1234ze(E) with a maximum decrease of -10.3 °C at a 13 °C inlet water source. NC01 and R32 maintain their increased discharge temperatures compared to R22, but R32 showed a higher increase than NC01. For R32, the minimum increase is 9.7 °C, whereas that for NC01 is 2.3 °C with respect to R22 at a 23 °C inlet water source.

When the IHX is used, as shown in figure 5 (b), the discharge temperature difference between R22 and its replacements had a large increase; at a $T_{w,in}$ of 23 °C, the differences for R32, NC01, and R1234ze(E) are 10.1 °C, 4.8 °C, and -7.3 °C, respectively. The higher discharge temperature is unfavorable for safe operation of the compressor. Hence, if NC01 and R32 are used as drop-in refrigerants to replace R22, the IHX is unfavorable to the heating system because it increases the discharge temperature while the COP remains unchanged.

![Figure 5](image)

**Figure 5. Relation between discharge temperature and source water temperature**

3.3. CO$_2$-equivalent emissions comparison

In this subsection, a TEWI analysis is presented to assess the CO$_2$-equivalent emissions saved by replacing R22 with alternative refrigerants. The TEWI analysis provides a good understanding of the phenomenon because it takes into account both direct (due to leakages) and indirect (electricity consumption) emissions. The TEWI value of the alternative refrigerant was calculated at the same rate of heating capacity and leakage (2%) \cite{9}. The TEWI analysis results are presented in table 2, and these results prove that the use of the NC01 and R32 refrigerants in this refrigeration system has a relevant environmental benefit, as the total CO$_2$-equivalent emissions of the system are reduced.

| DE [kgCO$_2$-eq.] | IE [kg CO$_2$-eq.] | TEWI [kgCO$_2$-eq.] |
|-------------------|---------------------|----------------------|
| R22 3801.00       | 169548.39           | 173349.39            |
| R32 850.50        | 165978.95           | 166829.45            |
| R1234ze(E) 16.63  | 183348.84           | 183365.47            |
| NC01 1268.40      | 171391.30           | 172659.70            |

4. Conclusions

An experimental analysis was carried out considering different low-GWP alternatives for R22 on the same refrigerating test bench equipped with a scroll compressor. The tested refrigerants were R32, R1234ze(E), and the mixture NC01 (R1234ze(E)/R134a/R32, 17%:33%:50%). A total of 24 tests were carried out in a vapor-compression system. The test condition involved different temperatures of inlet...
source water, at 13 °C, 18 °C, and 23 °C, while the temperature of the outlet heat sink water was kept constant at 45°C and using or not the IHX. A comparison in terms of heating capacity, COP, and discharge temperature is made from an experimental point of view, taking R22 as the baseline. The following conclusions were drawn for each refrigerant:

1) Focusing on the benefit of using the IHX, it can be concluded that this component produces a positive effect on the COP of R1234ze(E). For R32 and NC01, the influence of IHX on the heating capacity and COP is weaker. The discharge temperature differences between R22 and the drop-ins show a large increase when IHX is used. If NC01 and R32 are used as drop-in refrigerants to replace R22, the IHX is unfavorable to the heating system because it increases the discharge temperature, and the COP remains unchanged. For R1234ze(E), the discharge temperature remains in a safe range.

2) Compared with R22, the COP of the NC01 system is reduced by 0–6.4% on average. When the temperature of source water reaches to 23 °C, the COP of the NC01 grows to the same of R22. The heating capacity of NC01 is about 6.7% higher than that of R22. With respect to R22, the discharge temperature of NC01 increases by 0.5 °C to 1 °C when the IHX is not used. Taking the heating capacity into account, the COP and discharge temperature of NC01 have good properties to replace R22 as a drop-in refrigerant.

3) Regarding the similarity in operation and comparable energy performance observed through this study, it can be concluded that the utilization of NC01 can provide environmental and energy benefits. Therefore, NC01 could be considered a lower-GWP alternative to R22 in water-source heat-pump systems, in which a decrease in heating capacity is acceptable.

ACKNOWLEDGEMENTS
This work was funded by the Beijing Municipal Education Commission and North China University of Technology under the project of Research on the Performance of Water Source Heat Pump Units with Environmental Refrigerant, Project 16021 and 18XN150.

References
[1] X.C.Wang, 2003, Historic status of HCFC refrigerants in development of China’s refrigerating and air conditioning industry, HV&AC, Vol.33, No. 6, 23-25.
[2] M.S.Zhu, L.Shi, 2009, Exploration of using R32 to substitute for R22 in household/commercial air-conditioning, Refrigeration and air conditioning, Vol.9, NO.6, 31-34.
[3] Atilla G. Devecioğlu, VedatOruç, 2017, The influence of plate-type heat exchanger on energy efficiency and environmental effects of the air-conditioners using R453A as a substitute for R22, Applied Thermal Engineering, Vol.112, 1364–72.
[4] A. Mota-Babiloni, J. etc, Drop-in energy performance evaluation of R1234yf and R1234ze(E) in a vapor compression system as R134a replacements, Appl. Therm. Eng. 71 (2014) 259–265.
[5] A. Mota-Babiloni, etc, 2015, Drop-in analysis of an internal heat exchanger in a vapour compression system using R1234ze(E) and R450A as alternatives for R134a, Energy, Vol. 90, 1636–44.
[6] J. Navarro-Esbrí, R. Cabello, E. Torrella, 2005, Experimental evaluation of the internal heat exchanger influence on a vapour compression plant energy efficiency working with R22, R134a and R407C, Energy vol.30 621–36.
[7] Piotr A. Domanski, J. Steven Brown etc, 2014, A thermodynamic analysis of refrigerants: Performance limits of the vapor compression cycle, international journal of refrigeration vol. 38 71-79
[8] ZHAO Yuqing, LÜ Bing Experimental Research on a mixed refrigerant replacing R22, Chemical Industry and Engineering Progress, 2017, vol.36 (8) : 2866-74.
[9] Pavel Makhnatcha, etc, 2017, Retrofit of lower GWP alternative R449A into an existing R404A indirect supermarket refrigeration system, international journal of refrigeration, vol. 76 184-92
[10] Shi wenxin etc., 2017 Air conditioning refrigeration technology. China construction industry press.