NRM30 as a possible substitute for R22 in marine vapour compression refrigeration systems

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Abstract. The purpose of this paper is to investigate the possibility of using NRM30 in order to replace R22, in existing plants on board the ships. NRM30 is a refrigerant mixture of R134a/R1270/RE170 (55/37.5/7.5 by mass percentage). This approach is based on the better environmental behaviour of NRM30. The comparison between R22 and NMR30 has been developed on the basis of Coefficient of Performance (COP), temperature at compressor exit, power consumption per ton of refrigeration and volumetric refrigeration capacity variations, when evaporation temperature and condensation temperature increase. The above mentioned are calculated when the evaporation temperature varies in the range (-2, +10)°C and the condensation temperature varies in the range (40, 50)°C. The results reveal that COP increases with the increase of the evaporation temperature and the decrease of the condensation temperature- for both refrigerants. Although the ecological refrigerant (NRM30) shows an average COP value lower than the one of R22 (about 30% lower), NRM30 ensures an ecological operation of the plant and lower temperatures at compressor exit- which it is benefic for the long life of this machine. For the considered temperature ranges, the plant operates in efficient conditions for the higher value of the evaporation temperature (+10°C) and for the lowest value of the condensation temperature (40°C). For this conditions, it is seen that the vapours temperatures at the compressor exit are lowest, being ensured also the safe operation of the compressor.

1. Introduction
Refrigeration on board of ships is a vital technology when the aim is the maintenance of food, drinks, cargo and garbage in proper conditions during the voyage. Other application is air conditioning, essential for the transported goods and crew or passengers thermal comfort.

According to the International Maritime Organisation (IMO), in 2014, about 70% of the world merchant fleet used the Freon R22 on board the ships [1]. This, R22 was met on board of fishing vessels, passenger ships and cargo ships.

The frequent use of R22 it is based on its very favourable thermodynamic behaviour and low energy consumption, but actual systems have to use refrigerants able to reply to environmental requirements as well [2].

R22 or Chlorodifluoromethane, is responsible, together with other chemicals, for the ozone layer depletion; it also contributes to the global warming rise.

This refrigerant belongs to Hydrochlorofluorocarbon (HCFC) refrigerants, which have been prohibited according the Montreal Protocol [3]. This type of refrigerants contain elements as: carbon, chlorine, fluorine and hydrogen and are seen as transitional refrigerants.
The Conference held in Copenhagen (1992) imposed the production stop of HCFC starting with 31 December 2014, so that substitutes will accomplish null Ozone Depletion Potential (ODP) low Global Warming Potential (GWP) and Total Equivalent Warming Impact (TEWI – assessing the real effect of refrigerants on global warming) [4,5].

In the framework of the Regulation (EC) No 2037/2000 – that deals with ODS (Ozone Depleting Substances), starting with 1st January 2010, the import, production, selling or using the virgin R22 is banned; still R22 might be used in existing facilities till 2015, the following major challenge being the finding of the proper substitute [6].

The refrigerant considered in this paper, as a possible substitute of R22, is NRM30 a mixture of R134a/R1270/RE170 given by the following mass percentage: 55/37.5/7.5. This choice is motivated by the better environmental behaviour of NRM30, compared with the one of R22. In table 1 are given some thermodynamic features of the unwanted refrigerant and the ones met in the components of NRM30, safety data and environmental information as well [7,8].

| Properties                      | Refrigerant | R22 | R134a | R1270 | RE170 |
|---------------------------------|-------------|-----|-------|-------|-------|
| Molecular weight (g/mol)        |             | 86.47 | 102.0 | 42.08 | 46.07 |
| Critical temperature (°C)       |             | 96.2  | 101.1 | 92.4  | 128.8 |
| Critical pressure (MPa)         |             | 4.99  | 4.06  | 4.67  | 5.32  |
| Normal boiling point (°C)       |             | −40.8 | −26.1 | −47.7 | −24.8 |
| Safety group                    |             | A1   | A1    | A3    | A3    |
| ODP (R11=1)                     |             | 0.04  | 0.0   | 0.0   | 0.0   |
| GWP (100 yr)                    |             | 1790  | 1370  | 20    | 1     |

The following pylons are mentioned: the molecular weight has to be low, in the case of vapour compression systems, since the marine refrigeration compressor sizes should be limited, the critical temperature should be very high, in order to be obtained a good refrigeration effect with the plant, the critical pressure should be low and the normal boiling point as well – to be ensured low values of temperatures.

Consequently, within this paper it is developed a theoretical thermodynamic comparative performance assessment of a single stage vapour compression refrigeration cycle working with R22 and NRM30.

The proposed comparison is based on the assessment of the Coefficient of Performance, temperature at compressor exit, power consumption per ton of refrigerant and volumetric capacity variations – when evaporation and condensation temperatures increase. The results will show that NRM30 is an acceptable substitute for R22.

2. Methods and materials

The absolute temperature – entropy diagram of the considered system is given in figure 1 and the mathematical formulation of the analysis is as follows [9].

Specific heat addition in the evaporator:

\[ q_0 = h_1 - h_4 \]  \hspace{1cm} (1)

Specific compressor work:

\[ w_c = h_2 - h_1 \]  \hspace{1cm} (2)
Coefficient of Performance:

\[ \text{COP} = \frac{q_s}{w_c} \]  

(3)

Power consumption per ton of refrigerant:

\[ P_{PR} = 3.5167/COP \]  

(4)

Volumetric cooling capacity:

\[ VRC = q_1 \cdot q_0 \]  

(5)

where: \( h \) – specific enthalpy and \( q \) – density.

3. Results and discussions

In this paper, the results are obtained when the evaporation temperature varies in the range \((-2\text{ to }10)\)°C for the given condensation temperature of 54°C and when the condensation temperature varies in the range \((40\text{ to }50)\)°C – for a given evaporation temperature of 10°C; the superheating and sub cooling degrees are of 5°C.

Figures 2 – 7 show the variations of the specific heat addition in the evaporation, specific compressor work, Coefficient of Performance, temperature at the compressor exit, power consumption per ton of refrigerant and volumetric cooling capacity, with the increase of the evaporation temperature \((t_0)\), for both refrigerants.

Figure 2. Effect of evaporation temperature on the specific heat addition for a condensation temperature of 54°C.
Figure 3. Effect of evaporation temperature on the specific compressor work for a condensation temperature of 54°C.

Figure 4. Effect of evaporation temperature on the Coefficient of Performance for a condensation temperature of 54°C.

Figure 5. Effect of evaporation temperature on the discharge temperature of the compressor for a condensation temperature of 54°C.
Figure 6. Effect of evaporation temperature on the power consumption per ton of refrigeration for a condensing temperature of 54°C.

Figure 7. Effect of evaporation temperature on the volumetric cooling capacity for a condensation temperature of 54°C.

Figures 2 – 7 shows the same trend for the both refrigerants: the increase in the evaporation temperature lead to the increase in the values of specific heat addition in the evaporator, Coefficient of Performance and volumetric cooling capacity and to the decrease of specific work consumption, temperature at compressor exit and power consumption per ton of refrigerator.

This is due to the fact that the increment of the evaporation temperature is met in the increment in latent heat of evaporation and in the temperature difference between the system and the environment, with positive effects on COP values and discharge temperature of the compressor.

The volumetric cooling capacity depends on the density of the refrigerants (as seen in the given formulae). The rise of the cooling capacity per unit volume of refrigerant at evaporator exit with the evaporation temperature is due to the rise of the vapour density.

Figures 8 – 11 show the variations of the Coefficient of Performance, temperature at the compressor exit, power consumption per ton of refrigerant and volumetric cooling capacity with the increase of the condensation temperature, for both refrigerants.

Figure 8. Effect of condensation temperature on the Coefficient of Performance for an evaporation temperature of 10°C.
Figure 9. Effect of condensation temperature on the discharge temperature of the compressor for an evaporation temperature of 10°C.

Figure 10. Effect of condensation temperature on the power consumption per ton of refrigeration for an evaporation temperature of 10°C.

Figure 11. Effect of condensation temperature on the volumetric cooling capacity for an evaporation temperature of 10°C.

Figures 8 – 11 also show the same trend for the both refrigerants: the increase in the condensation temperature determines the increase of the temperature at the compressor exit and of the power consumption per ton of refrigerant.

Since a high value of COP indicates a high efficiency of the cycle, results that the considered system should operate at high evaporation temperatures and at low condensation temperatures.
The results reveal the fact that for $t_0 = 10^\circ$C and $t_c = 54^\circ$C, NRM30 provides an improved COP with 6.99%, while for $t_c = 40^\circ$C and $t_0 = 10^\circ$C, when using NRM30, COP is 30% lower compared with the one of R22.

When selecting a substitute for a refrigerant, it is important to check values of vapours temperatures leaving the compressor and values of volumetric cooling capacities. High temperatures after the vapours compression will damage the compressor oil and will shorten the operation life of this machine.

On the other hand, volumetric cooling capacity will impose the sizes of the chosen compressor. It is seen that NRM30 offers lower $t_2$ temperatures, as observed from Figures 4 and 9 (for example, for $t_0 = 10^\circ$C and $t_c = 54^\circ$C, $t_2$- when using NRM30, is 15.79% lower, while for $t_c = 40^\circ$C and $t_0 = 10^\circ$C, $t_2$- when using NRM30, is 16.28% lower).

For the considered example, VRC provided with NRM30 is lower than the one of R22 with 16%, and 28%, respectively.

4. Conclusions
A comparative theoretical thermodynamic analysis is presented in order to assess the performance of a single vapour compression refrigeration cycle working with R22 and NRM30. It was found that the Coefficient of Performance increases together with evaporation temperature increase (when keeping the condensation temperature constant), and decrease together the condensation increase (when keeping the evaporation temperature constant); in the first situation, the efficiency of the cycle results to be improved in the range (5.13 to 6.99)% when using NRM30 in the cycle. Also, the discharge temperature of the compressor decrease with increase of the evaporation temperature and with the decrease of the condensation temperature; the best values are obtained for the substitute (NRM30). When keeping constant the condensation temperature, NRM30 ensures lower discharge temperatures in the range (15.79 to 22.09)%, while when maintaining the evaporation temperature constant, NRM30 shows lower discharge temperatures in the range (16.28 to 18.22).

It was also found that the volumetric cooling capacity increases with the increase of the evaporation temperature and with the decrease of condensation temperature; these values are lower when using NRM30 in the cycle, the smallest gap (of 12%) being seen for the following operation conditions: $t_0 = 10^\circ$C and $t_c = 54^\circ$C.

Taking into consideration the reality given by the fact that there is no perfect refrigerant, NRM30 can be seen as a substitute of R22 due to its better environmental behaviour, improved COP or ensuring of a longer live of the compressor.

5. References
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