Evaluation of the possibility of using propane and hydrofluorolefin group refrigerants as an eco-friendly replacement for R134a in combined heat transformers

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Abstract. In connection with the gradual reduction in the use of refrigerants of HFC groups, regulated by the Paris Agreement, its amendments and additions, the question arises of finding environmentally friendly working fluids with high thermodynamic efficiency in the thermal transformer cycle. The article discusses the possibility of using refrigerants from the HFO and propane group as environmentally friendly substitutes for R134a for combined vapor compression thermal transformers. The evaluation of the thermodynamic efficiency of the machines for the joint production of heat and cold, produced on the basis of the entropy method of thermodynamic analysis, is carried out. The results of modeling a single-stage combined heat transformer showed the thermodynamic feasibility of using R290 as a substitute for R134a. The analysis of the results obtained showed the limited possibility of effective use of refrigerants of the HFO group as working bodies of combined heat transformers.

1. Introduction

Substances of the group of hydrofluorocarbons (HFC) and their mixtures are often used as working bodies of refrigeration machines and heat pumps. Due to the fact that a number of HFC refrigerants, in particular R134a, have a high global warming potential (GWP), their use is regulated in accordance with the Paris Agreement [1], its amendments and supplements. Every year, measures are being taken to reduce the use and production of refrigerants from the HFC group, and the leading countries in this area are the EU countries.

Due to the reduction in the use of refrigerants with high global warming potential [1-2], most of which are the working fluids of refrigeration machines and heat pumps, it is obvious that there is a need to search for alternative refrigerants with low GWP. At the same time, the substitute should not only be ozone-friendly and have a low global warming potential, but also have a greater or equal thermodynamic efficiency, in comparison with R134a, when used as a working substance of a thermal transformer.

Some of the most popular alternative refrigerants today are substances from the group of hydrofluoroolefins (HFO): R1234yf and R1234ze(E), positioned by manufacturers as substitutes for R134a [3]. Refrigerant R134a is widely used in climatic and refrigeration technology. In [4], an extensive analysis of the use of the refrigerant R1234yf in various heat and cold supply systems is carried out. According to [4], R290 is also considered an alternative to R1234yf as a substitute for R134a. The results of the studies presented in [4] and the opinions of their authors about the effective use of R1234yf are ambiguous. In [5], data on the combustion of R290 and R1234yf are presented.
when they leak from the thermal transformer circuit. According to the conclusions made by the authors [5], R1234yf can ignite only from an open flame.

A possible energy-saving measure for objects of the agro-industrial complex that have a need for heat and cold are the use of a combined heat and cold supply unit based on a vapor compression thermal transformer. In contrast to the separately used chiller and heat pump, the combined heat transformer allows you to obtain a beneficial effect for two or three temperature levels with less energy consumption, in comparison with separate options, at similar operating temperatures. In [6-7] the topic of partial utilization of the waste heat of condensation of a refrigerating machine is touched upon.

The purpose of this work is to analyze the thermodynamic efficiency of a combined vapor compression thermal transformer using refrigerants of the HFO and R290 groups in comparison with R134a under various operating modes.

2. Materials and methods

To assess the thermodynamic efficiency, mathematical modeling of the cycles of thermal transformers at various evaporating and condensing pressures was carried out. Cycles of one-stage compression were selected for the analysis, the description of which is given in [8].

The main methods today are the methods of thermodynamic analysis, among which the exergy method is most often used. The method for analyzing a thermal transformer using the exergy method is presented in [9-10]. However, in [11] the disadvantages of applying the exergy method for the analysis of low-temperature refrigeration systems are indicated and the use of the entropy method is proposed. In addition, the entropy method is simpler and more convenient than the exergy method. Ease of use is clearly shown in the calculation of the refrigeration machine [12]. Since the study of a system of combined heat and cold production involves considering a system with two temperature regimes, the entropy method was chosen to simulate combined heat transformers.

When constructing the model, the losses of the thermal transformer cycle processes were taken into account, as well as losses during the transformation of electrical energy supplied in the compressor into work supplied to the refrigerant using energy efficiency [13]. To take into account the polytropic nature of the compression process, the entropy of the discharge state was taken into account as 1.01 of the entropy of suction. The range of the compressor compression ratio was taken in the range from 0 to 30. The design ambient temperature was taken equal to 293.15K. When constructing the cycles of thermal transformers, the following initial parameters were taken: the boiling point range of the working fluid in the evaporator (hereinafter t0) was taken in the range -50 °C … + 20 °C, with a step of 10K; for condensation temperatures (hereinafter tk) the range of + 30 °C… + 60 °C was chosen, with a step of 10K; suction steam superheat was 10K; supercooling of the liquid after the condenser was 3K. The mass flow rate of the refrigerant for all considered cycles is assumed to be 1 kg / s.

For simulation, the following refrigerants were selected as the working fluid of the combined thermal transformer: R1234yf, R1234ze (E), R134a, R290. Data on the thermodynamic properties of working substances in various states are obtained from the programs: CoolPack and Danfoss Coolselector 2.

3. Results

The calculation results are presented as a dependence of the degree of thermodynamic perfection (hereinafter η) on the compressor compression ratio (hereinafter π) at different tk for the selected working bodies. For clarity, the extreme characteristics of the refrigerant from the condensing range selected above are presented (figure 1).
Figure 1. Characteristics of the change in $\eta$ cycles of combined thermal transformers at various $t_k$.

The change in the degree of thermodynamic perfection, depending on the temperature parameters of the cycle for the refrigerants under consideration, is shown in figure 2.

To assess the effectiveness of alternative working fluids as substitutes for R134a, figure 3 shows a graph of the change in the ratio $\eta$ of the analyzed refrigerants to $\eta$ R134a in the considered range of boiling temperatures, at different $t_k$.

4. Discussion

As can be seen from the graph in figure 1, all $\eta$ lines have a similar pattern of change, depending on $\pi$. At low $\pi$ values, the characteristics increase, approaching the extremum. When the extremum is reached, with a further increase in $\pi$, the characteristics tend to decrease, tending to zero. With increasing $t_k$, the value of $\eta$ decreases. The nature of the change in the lines $\eta$ for various refrigerants with increasing $t_k$ is preserved. The values of $\pi$ at which the lines reach the maximum $\eta$ differ for different working bodies. For the working bodies under consideration, the value of $\pi$, at which the extremum is reached in the simulated circuit of the thermal transformer, varies within 3.2 ... 5.5. The
lines shown in figure 1 have a common interval $t_0$. In comparison, the characteristics $\eta$ of refrigerants with a lower $\pi$ at the same $t_k$ and $t_0$. And a decrease in the boiling point change more slowly. Figure 2 shows the change in $\eta$ from $t_0$ for the considered working bodies. All lines shown on the chart, with a decrease in $t_0$ from $+20^\circ{\text C}$, first increase, approaching the extremum. Having reached the maximum value, $\eta$ of the working substances decreases nonlinearly with a decrease in the boiling point.

![Figure 3. Change in the ratio $\eta$ of alternative refrigerants to $\eta$ R134a at different $t_k$ and $t_0$.](image)

The characteristics of R290 at high $t_0$ have $\eta$ values close to those of R134a. But the $\eta$ R134a lines reach a minimum at lower $t_0$. With a further decrease in $t_0$, $\eta$ R290 turns out to be higher than $\eta$ R134a. With an increase in $t_k$, the tendency to change the characteristic $\eta$ R290 relative to $\eta$ R134a remains.

The $\eta$ R1234ze (E) lines at low $t_k$ have a similar character of variation with the $\eta$ R134a lines. With increasing $t_k$, the lines $\eta$ R1234ze (E) and R134a have similar values in the region of low $t_0$. With an increase in $t_0$ at high $t_k$, the difference between the values of $\eta$ R1234ze (E) and R134a increases. The characteristics $\eta$ of R1234yf at low $t_k$ and high $t_0$ have a significantly lower value of $\eta$ in comparison with R134a. After passing the minimum, the $\eta$ R1234yf line first approaches the $\eta$ R134a characteristic, and then passes above the line for $\eta$ R134a. With an increase in $t_k$, the difference between the values of $\eta$ R1234yf and R134a decreases, but the tendency of changes in characteristics remains the same. With increasing $t_k$, the lines $\eta$ R1234yf and R134a intersect at higher $t_0$.

The graph in figure 3 shows the ratio of $\eta$ alternative refrigerants to $\eta$ R134a. Lines R290, with $t_k$ in the range $+30^\circ{\text C}...+40^\circ{\text C}$ and $t_0$ on the segment $+20^\circ{\text C}...+10^\circ{\text C}$, have a value greater than 1. In the middle of the $t_0$ range, characteristics R290, with $t_k$ in the range $+30^\circ{\text C}...+40^\circ{\text C}$, take a value close to 1. With a further decrease in $t_0$, the line R290 - increases. With an increase in $t_0$, at $t_k$ in the range $+20^\circ{\text C}...+5^\circ{\text C}$, the R290 line acquires a value close to 1 with a subsequent increase with decreasing $t_0$. The change in characteristics for R1234yf has a similar character to the R290 lines. However, unlike the lines for R290, at $t_k$ in the range $+30^\circ{\text C}...+40^\circ{\text C}$ and $t_0$ in the interval $+20^\circ{\text C}...+5^\circ{\text C}$, the characteristics of R1234yf have values less than 1. With decreasing $t_0$, the values of $\eta$ R1234yf increase and become larger than for R134a. With an increase in $t_k$, the numerical value of the R1234yf characteristics increases, in comparison with similar lines at $t_k$ in the range of $+30^\circ{\text C}...+40^\circ{\text C}$. The lines of variation of R1234ze (E) at $t_k$ in the range $+30^\circ{\text C}...+35^\circ{\text C}$ and $t_0$ in the interval $+20^\circ{\text C}...+10^\circ{\text C}$ have values greater than 1. With decreasing $t_0$, the characteristics acquire a tendency of nonlinear decrease. With an increase in $t_k$, in the range $t_0+20^\circ{\text C}...+10^\circ{\text C}$, the R1234ze (E) lines have values less than 1. With an increase in $t_k$, the characteristics of R1234ze (E) increase, approaching the extremum, followed by a decrease at $t_0$ below $-15\,^\circ{\text C}$. As $t_k$ grows, the numerical values of the R1234ze (E) lines are less than 1 in the entire range of $t_0$. 


5. Conclusion

Based on the simulation, the following conclusions can be drawn:

- The use of refrigerants of the HFO group as substitutes for R134a in the circuit of a single-stage combined thermal transformer is thermodynamically effective in limited ranges of boiling and condensing temperatures;
- Refrigerant of the HFO group with the closest values of thermodynamic efficiency to R134a, in the considered range of evaporating temperatures and low condensing temperatures, is R1234ze (E);
- The use of R1234yf refrigerant instead of R134a is thermodynamically effective at high condensing temperatures and evaporating temperatures below - 20 °C;
- The use of propane as a substitute for R134a is thermodynamically more efficient in comparison with the use of refrigerants of the HFO group in the entire temperature range under consideration;
- Subject to compliance with industrial safety requirements, refrigerant R290 can be considered as an environmentally friendly substitute for R134a in combined heat transformers.

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