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Improving the performance of the vapor compression cycle using an internal heat exchanger

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Abstract. The main additional consumer of electrical energy in an electric bus is the climate system, which can consume up to 30% of electrical energy. This problem is especially relevant in Russia at low ambient temperatures. The optimal solution is to switch the vapor compression unit to heat pump mode. However, at low temperatures, its efficiency decreases and performance is insufficient. One way to improve efficiency is to use an internal heat exchanger. In this paper, we studied the effect of an internal heat exchanger on the performance of a vapor compression cycle using R290, R410a and R507a refrigerants. The influence of geometry on the performance of the internal heat exchanger is determined. The use of an internal heat exchanger makes it possible to increase coefficient of performance by 10-13%.

1 Introduction

The active introduction of electric vehicles and electric buses leads to the need to heat the interior of the vehicle in winter and cool it in summer. Heating due to direct electric heating greatly reduces the mileage of an electric vehicle, so their manufacturers are switching to vapor compression units, which allow them to cover the needs of both interior cooling and heating, by switching the vapor compression unit to the "heat pump" mode.

To reduce the consumption of electricity for the needs of the air conditioning system, it is necessary to increase its thermodynamic efficiency. The main direction is the use of liquid refrigerant subcoolers after the condenser [1], which can increase the coefficient of performance (COP) of the cycle up to 20%, but this option involves the use of a liquid cooler and is difficult to implement in electric transport. The second direction is the use of an internal heat exchanger (IHX) [2], where a study is presented in the Aspen software package and the increase in the conversion factor is 22-25%, which is an overestimated result, due to the fact that the geometry of the internal heat exchanger is not taken into account. Experimental studies show an increase in efficiency of about 10% when using an internal heat exchanger [3]. Therefore, for better prediction and obtaining reliable results in the calculation process, it is necessary to take into account the design of the heat exchanger, as well as the properties of refrigerants that change depending on temperature and pressure.

2 Method

In this paper, a study was made of the influence of the geometric dimensions of the IHX on the COP heating of the vapor-compression refrigeration cycle. As an object of study, the climatic vapor-compression unit of an electric bus was taken. The equipment of the installation is selected to provide a cooling power of 30 kW in air conditioning mode, the thermal power in heating mode is when using refrigerants R290 - 12 kW, R410a - 20.5 kW, R507a - 14.4 kW. A one-dimensional mathematical model was created in the Amesim software product, taking into account the geometric dimensions of the heat exchange equipment (Fig. 1). The model consists of a compressor, condenser, condensate collector, expansion valve, evaporator and heat exchanger-internal heat exchanger.

To calculate hydraulic losses, the equivalent length in the condenser is 760 mm, in the evaporator 1150 mm; the flow area in the condenser is 14900 mm^2, the evaporator is 4830 mm^2, the hydraulic diameter in the condenser-evaporator and condenser is 10 mm. The compressor has a working volume of 474 cm^3, a volumetric efficiency of 0.75, an isentropic efficiency of 0.85, and a mechanical efficiency of 0.95. Compressor capacity varies with compressor speed. The expansion valve, as in reality, consists of two components: a bulb and a diaphragm control valve. In the flask of the thermostatic valve, the dependence of the pressure and temperature of the refrigerant used on the saturation line is set. The diaphragm valve of the thermostatic expansion valve is set to a diaphragm area of 200 mm^2 and a spring constant of 5000 N/m.

The model is based on the balance thermal calculation. On the side of single-phase coolants, the heat flow is calculated by the product of mass flow, heat capacity and temperature difference at the inlet and outlet. In the evaporator and condenser, the calculation is based on the difference in enthalpies, because there are phase transitions. You can control what percentage of liquid and gaseous refrigerant that enters from the

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heat exchanger. The internal heat exchanger is implemented using tubes in a gaseous and liquid refrigerant circuit with convective heat exchange, in which phase transitions can occur. Also in the internal heat exchanger, the mass of the tube itself is taken into account.

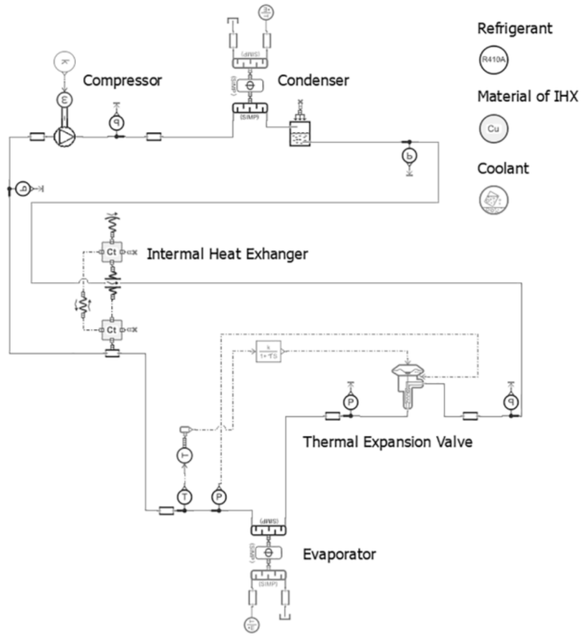

Fig. 1. Scheme of a vapor compression unit with an internal heat exchanger.

The following global variables have been created: pipe length and diameter, wall thickness, rib thickness and height, number of ribs. The main parameters of the heat exchanger-internal heat exchanger: cross-sectional area, convective heat exchange area and equivalent hydraulic diameter, volume and mass of the tube are entered as formulas from global variables and are recalculated depending on the parameters of the study.

The model without a recuperative heat exchanger was verified using experimental data when the experimental unit was operating in the heat pump mode [4], the modeling error was no more than 1.87% (Fig.2).

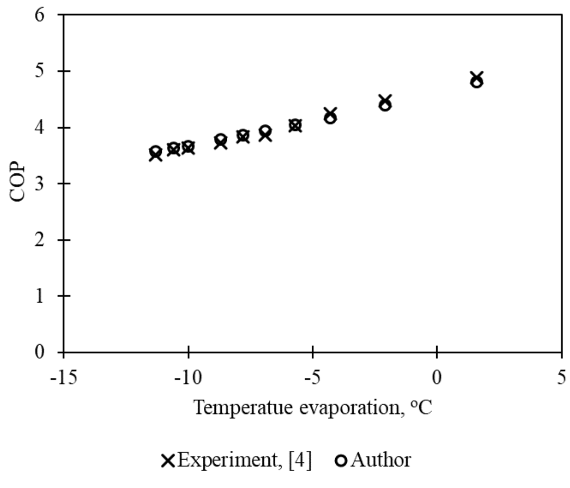

Fig. 2. Verification of a one-dimensional mathematical model.

This model makes it possible to analyze the efficiency of a vapor compression unit in both static and dynamic modes of operation. In this work, a simulation of operation is performed for 500 seconds to achieve a steady state.

3 Result

Design of the heat exchanger - the internal heat exchanger is a tube-in-pipe heat exchanger twisted into a spiral to save space. To ensure a low level of hydraulic losses, the gaseous refrigerant moves through the inner tube with a large flow area, and the liquid refrigerant between the tubes, with a small flow area (Fig. 3).

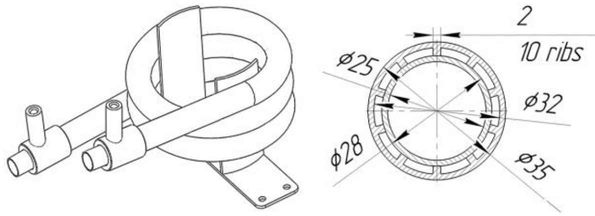

Fig. 3. Appearance and section of the tube of the internal heat exchanger.

A study was made of the influence of changes: the inner diameter, the height of the ribs and the length of the IHC, when the unit is operating in the heating mode, because This mode is the most energy-consuming when operating the air conditioning unit. The temperature in the evaporator was -25 ºC, and in the condenser +30 ºC.

To assess the effect of the internal heat exchanger on the heating COP of the vapor compression cycle, studies were carried out when the length of the internal heat exchanger tube was changed from 250 to 3000 mm with a step of 250 mm. Thermodynamic cycles were built when working with an internal heat exchanger of various lengths (for R410a refrigerant are shown in Fig. 4).

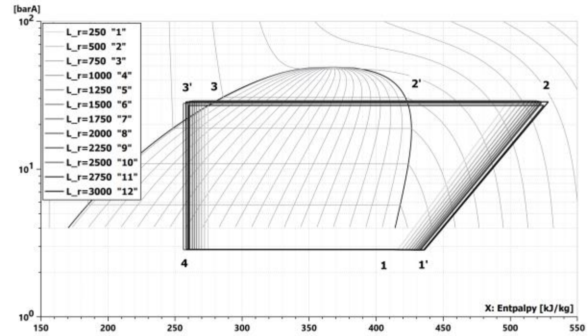

Fig. 4. Refrigeration cycle with internal heat exchanger using R410a refrigerant.

With an increase in the length of the internal heat exchanger, the areas of overheating of the gaseous refrigerant after the evaporator 1-1' and subcooling of the liquid refrigerant after the condenser 3-3' increase, which confirms the adequacy of the operation of the mathematical model of the vapor compression unit with an internal heat exchanger.

With an increase in the length of the internal heat exchanger, the increase in heat flow when using R290 refrigerant is from 240 W to 1314 W, for R410a refrigerant - from 336 W to 1922 W, for R507a refrigerant - from 318 W to 1870 W (Fig. 5). The conversion factor increases when using refrigerant

R410a from 2.59 to 2.74; refrigerant R290 from 2.63 to 2.86; refrigerant R507a from 2.64 to 2.93.

The absolute values of the heat flow of the internal heat exchanger for refrigerant R410a and R507a are very close, the difference is no more than 6%, in contrast to refrigerant R290, the heat flow of which is 28% lower than R410a.

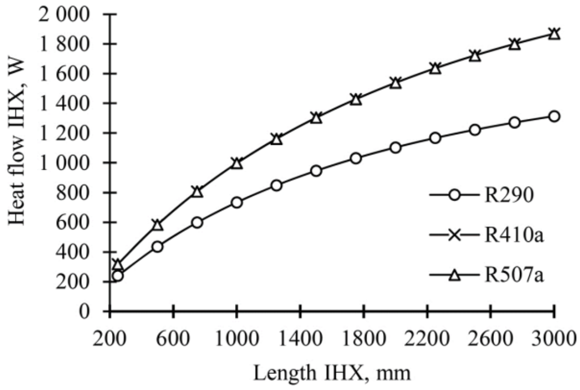

Fig. 5. Influence of the tube length of the internal heat exchanger on its heat flow.

From Fig. 5 it can be seen that the dependence of the increase in heat flow on the length of the internal heat exchanger is not linear.

In addition, studies have been carried out on the efficiency of the internal heat exchanger depending on the inner diameter of the tube where the gaseous refrigerant flows. The diameters of the inner tube are selected based on the range of copper pipes used in air conditioning 13, 16, 20, 26 and 33 mm. The length of the tube of the internal heat exchanger was 2000 mm.

The influence of the diameter of the inner tube of refrigerants R290, R410a and R507a is shown in Fig. 6 and shows the effect of the area of the passage section along the gaseous path.

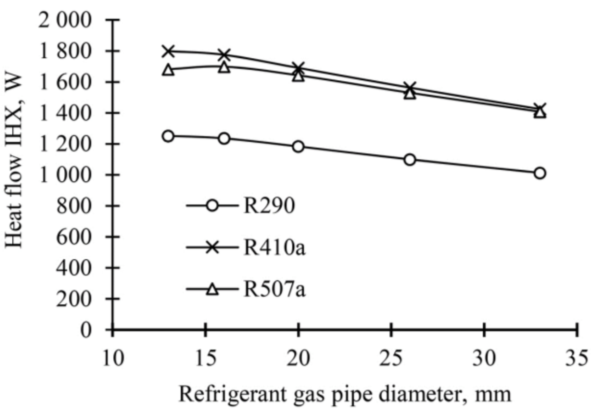

Fig. 6. Influence of the diameter of the inner tube of the internal heat exchanger on its heat flow.

With an increase in the inner diameter, the thermal power of the heat exchanger decreases, which is associated with a decrease in the speed of the gaseous refrigerant and, as a result, a decrease in the heat transfer coefficient. The absolute value of the heat flow when using refrigerant R290 is lower than the heat flow R410a by 28-30%.

An analysis of the effect on the diameter of the tube for gaseous refrigerant at the heating COP (Fig. 7) shows that at small diameters there is a decrease in the conversion coefficient, which is due to large hydraulic losses for refrigerant R290 - 11.8 kPa, for R410a - 11.4 kPa, for refrigerant R507a - 12 kPa, while with a tube diameter of 20 mm and a maximum conversion coefficient, the hydraulic losses are 1.7 kPa, respectively; 4.1 kPa and 4.4 kPa, resulting in a reduction in the mass flow rate of the refrigerant.

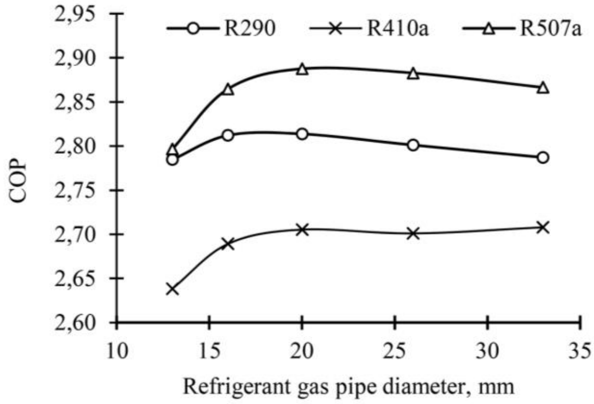

Fig. 7. Influence of the diameter of the inner tube of the internal heat exchanger on heating COP.

A study was made of the influence of the influence of the height of the rib, which characterizes the area of the passage section for the liquid refrigerant. Rib height in the study ranged from 0.5 mm to 3 mm in 0.25 mm increments. The results of the influence of the height of the fin of the internal heat exchanger on its heat flow are shown in Fig. 8.

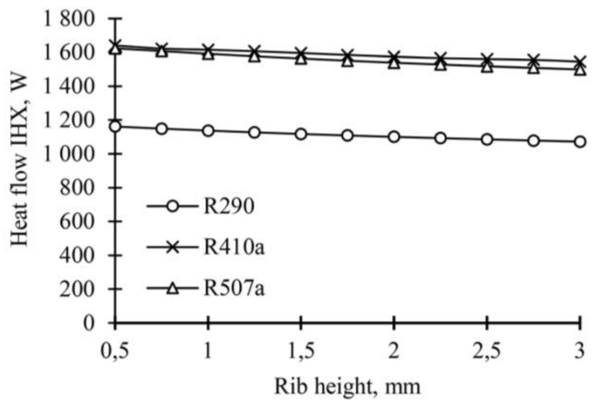

Fig. 8. Influence of the fin height of the internal heat exchanger on its heat flow.

With an increase in the height of the fin, the heat flow decreases slightly for all the refrigerants considered. The decrease is 5.8-7.7% between the maximum and minimum value. Hydraulic losses for liquid refrigerant are shown in Fig. 9. With a decrease in the height of the fin less than 1 mm, a sharp increase in the hydraulic resistance along the liquid path is seen. In absolute terms, the maximum value with R507a is 180 kPa, with R410a 150 kPa and with R290 51.3 kPa. Despite a significant increase in hydraulic resistance, the maximum value of the conversion coefficient with a minimum rib height of 0.5 mm when using refrigerant

R290 is 2.84, when using R410a - 2.71 and when using R507a - 2.9.

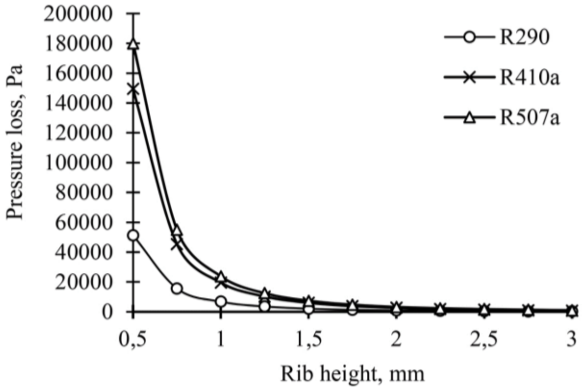

Fig. 9. Influence of the height of the fin of the internal heat exchanger on the hydraulic losses of liquid Refrigerant.

4 Conclusion

A decrease in the flow area along the liquid and gaseous circuits in both cases leads to an increase in hydraulic losses, but only a decrease along the gaseous path leads to a decrease of the COP refrigeration cycle, which is due to the location of the elements in the circuit of the vapor-compression refrigeration unit. The liquid circuit of the internal heat exchanger is in a high pressure area upstream of the expansion valve and an increase in hydraulic losses causes the expansion valve to open more and eventually the refrigerant mass flow remains constant. In the case of a gaseous refrigerant circuit, which is located after the expansion valve and before the compressor, an increase in hydraulic losses reduces the refrigerant mass flow, which leads to a decrease in the heating COP of the vapor compression cycle as a whole.

The application of the developed model makes it possible both to evaluate the characteristics of the heat exchangers of the vapor compression unit and to analyze their influence on the operation of the vapor compression unit as a whole, since the model includes the geometric characteristics of real equipment. Identify problem areas at the stage of design and selection of equipment.

A rational approach in the design of internal heat exchangers is the selection of the pipe diameter for gaseous refrigerant to limit hydraulic losses to 5 kPa, which corresponds to a speed of up to 25 m/s, the selection of the height of the liquid channel along the liquid circuit while limiting hydraulic losses to 10 kPa, which corresponds to the speed 1 m/s. The length of the heat exchanger-internal heat exchanger of this design must be more than 2000 mm.

The use of an internal heat exchanger makes it possible to raise the heating COP of the refrigeration cycle by 10-13%, depending on the working fluid. The increase in the heat flow of the vapor compression unit in heating mode when using refrigerant R290 is 10.8%, R410a - 6.62%, R507a - 14%. The low value of the percentage increase when using R410a refrigerant is due to the large heat flow of the vapor compression unit without the use of an internal heat exchanger, which is 70% more than that of R290 refrigerant and 42.3% more than R507a refrigerant.

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