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USING HEAT FROM LOW-TEMPERATURE ENERGY SOURCES BY MEANS OF A HIGH-TEMPERATURE HEAT PUMP

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Abstract- In the paper '' Using Heat from Low-Temperature Energy Sources by means of a High-Temperature Heat Pump'' the authors have synthesized the results of their researches into exploiting heat from low-temperature energy sources (geothermal water, waste heat from process industry,...) They have presented method for obtain a clean energy for heating residential units using high-temperature heat pumps which use different refrigerants (working fluids) in their operation. These pumps developed with the development of an innovative idea in 2010 and they use heat from low-temperature secondary energy sources (45ºC) for district heating of residential units with the temperature of 90/70ºC. A series of refrigerants which can be used as working fluids in these pumps were analyzed. The paper presents a mathematical model for a single stage heat pump which the authors use for determining performance characteristics of the heat pump, together with a simulation of the operation of the pump using two different mixtures of working fluids. The authors show in detail the mutual dependences among the key performance characteristics of a high temperature heat pump and they determine the optimal type of a high temperature heat pump as well as of the refrigerant. They also present the working conditions of this pump (evaporation temperature, condensation temperature) at which its operation is financially justifiable.

Keywords - high temperature heat pump, heat transfer, mathematical model, refrigerating agents

1. INTRODUCTION

For a long time it has been recognized based on the predictions of scientists, climatologists and environmental experts that the temperature of the atmosphere has been rising rapidly since the mid twentieth century. People feel the consequences of global warming in every part of the world. It is the "greenhouse effect". Majority of studies have proved that global warming is mainly caused by human activities (industry, traffic, etc.) which destroy natural balance. The situation is alarming and people are trying to find the ways to avoid the pending catastrophes. The topic of numerous conferences and forums is research into the possible methods of reducing air (atmosphere) pollution. The most important solution would be improving energy efficiency by development of new technologies and technical systems and using endless sources of renewable energy. Moreover, we need to find new technological solutions in the field of process design and thermotechnics.

The consequences of intensive energy consumption and the notion of energy efficiency refer to the countries which are poor in energy sources and are the most endangered countries in Europe environmentally. Simpler and cheaper decisions referring to rationalization could lead to considerable saving of energy and reduce pollution. According to the Kyoto Protocol, the European Union committed itself to reduce the emission of greenhouse gases comparing the year 1990. Reaching particular goals which were set by the adopted documents involves the process of developing technologies for obtaining and exploiting cheap and environmentally friendly energy.

Studies usually show that weaknesses in energy transfer lie on the part of technological processes, which means that the problem is consumption of energy rather than its production. Almost regularly a dilemma emerges as to the ways to improve specific consumption of energy in technological processes, how to improve efficiency, how to convert energy more efficiently, how to use waste heat and replace combustion of traditional liquid and gaseous fuels with other sources of energy.

One of the possible methods of obtaining environmentally acceptable energy for heating residential units is the use of high temperature heat pumps which use different refrigerants in their operation and enable the transfer of energy from a lower to a higher level of temperature. These pumps use the heat of low temperature secondary energy sources (45°C) for the purpose of district heating at the temperature of 90/70°C. An innovative high temperature heat pump (HP) was developed and manufactured by a Japanese company named Mycom in 2010. That is the first example in the world which has a practical value and unprecedented possibilities of application in industry, which is confirmed by a series of European acknowledgements.

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Operation of high temperature heat pumps involves nowadays, primarily, the use of renewable sources such as geothermal energy, waste energy from process industry, etc. Globally, geothermal resources represent accumulated heat in the ground. The heat reaches the surface through younger magmatic intrusions. Geothermal energy is also produced in the decay of radioactive elements in different chemical processes which take place in the earth's crust. Temperature of the earth rises by 1°C to every 33 meters of its depth.

Hydrothermal energy, unlike petro-geothermal energy, is the energy of fluids (mainly liquid). The importance of hydro-geothermal energy is best described by the two natural properties: invariability and continuity of heat flow in geothermal water and inexhaustible heat present accumulated underground. We can, therefore, describe geothermal energy as a renewable energy source.
Traditionally, secondary, renewable sources of energy (geothermal energy as well, being such form of energy) fall into the following categories:

- high temperature sources with the temperature above 150°C which are used for electricity production, and
- low temperature sources with the temperature below 150°C which are used directly for heating .

Majority of flats in cities is older and with poor insulation so that the main system of heating is the high temperature system of heating at 90/70°C. Using a high temperature heat pump in the system of heating the energy of a low temperature heat source can be exploited additionally, even if its temperature drops below 42°C.

2. HIGH TEMPERATURE HEAT PUMP

A traditional heat pump is a process device which is used for transferring heat from the fluid of a lower temperature level to the fluid with a higher temperature level. Its working principle is based on the removal of "low temperature" energy of the surroundings, which is then given to fluid at a higher temperature level. Energy sources for the removal of heat are air, water or ground.

Heat pumps started developing rapidly at the time of the great oil crisis, with intensive researches into technological solutions for replacing fossil fuels with other sources of energy. Due to stricter environmental regulations, greater awareness of energy, environmental awareness of consumers and the increase of the cost of energy, heat pumps became more interesting since they were more productive energy wise and more environmentally friendly. With the development of new technologies, the methods of application, improved performances on one hand, and smaller dimensions and weight on the other, heat pumps are used more and more frequently. The latest types of high temperature heat pumps can be applied in high temperature systems of district heating. They use environmentally friendly refrigerants in their operation, and have a good ratio between electric power used and heat obtained. It amounts up to even 1:9.

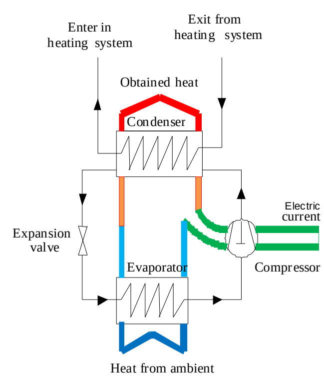
Scientists predict that heat pumps with different methods of implementation in the future will be a basic device in low temperature and high temperature heating systems. In the field of industry they represent an environmentally acceptable cooling method. A very important characteristic of heat pumps is the fact that they use much less primary energy compared with fossil fuels. If we use electric power from renewable sources for their operation, the emission of greenhouse gases becomes minimal, which will become, sooner or later, a standard for the operation of industrial plants [1, 2, 3].

A greater interest in the exploitation of renewable sources of energy for the purpose of district heating, the preparation of sanitary water and using heat pumps for electricity production have caused technical limitations due to relatively low temperatures of these renewable sources. This fact defined the direction in which the simple, or traditional heat pumps should be developed, namely the development of **high temperature heat pumps** in which sufficiently large difference in temperatures of evaporation and condensation is achieved.

Regarding the temperature of renewable sources of energy, the capacity of the heat pump and economic justifiability, the following types of high temperature heat pumps can be analyzed:

- A simple single stage high temperature heat pump,
- A two stage high temperature heat pump with a separator/splitter,
- A two stage high temperature heat pump with a heat exchanger.

A high temperature heat pump consists of an evaporator, condenser, compressor and expansion valve. The principle of operation is shown in Figure 1[4, 5].



Fg. 1. The principle of working of high temperature heat pump

In the evaporator, the refrigerant (working fluid) which is liquid, due to a lower pressure in the expansion valve, evaporates at a low temperature and a suitable pressure of saturation. By evaporation, the working fluid receives a certain amount of heat from the surroundings or from a renewable source of energy, ϕ_u. The working fluid vapor is then taken to the compressor where it is compressed to the pressure at which the condensation temperature of the working fluid is considerably higher than the temperature of the renewable source of energy. After compression, the vapour is condensed in the condenser. During this process, it gives a certain amount of heat ϕ_k to the system which is being heated, e.g. the system of district heating. The working fluid, now in liquid form, is again taken to the evaporator through the expansion valve [6]. Since the compressor is the main process unit of the heat pump it is necessary, when planning different implementations, to take into consideration the following: the ratio between pressures, maximum allowed pressure of the vapour, maximum allowed temperature, rotation speed, power/strength and volume flow of the compressor as well as other characteristics. [7]. The Mycom technical catalogue presents characteristics of the compressors which are used for high temperature heat pumps of this manufacturer.

3. REFRIGERANTS

Refrigerants are working fluids in heat pumps which absorb heat at a lower temperature level than renewable sources of energy and transfer it to the systems of a higher temperature level, e.g. a district heating system. The operation of heat pumps depends largely on the type of refrigerant (working fluid). The purpose of refrigerants is not only heat transfer, they also have to fulfill many conditions:

- They must have suitable physical and chemical properties, particularly when changing aggregate form,
- They must have a minimal effect on the environment, they must not be harmful to people or animals,
- They must mix with the substances which occur in nature,
- They must have acceptable price.

An ideal refrigerant has not been discovered yet and it probably will not ever be found. Majority of fluids used nowadays are halogenated hydrocarbons. However, they have a negative effect on the environment since they destroy the ozone layer. That is why new means are being developed that also have to possess good thermodynamic properties. The effect of refrigerants and other gases on the ozone layer is measured by ODP index (Ozone Depleting Potential), whereas their impact on the process of global changing of the environment is measured by GWP index (Global Warming Potential) [8].

The list of important refrigerants, their properties and ODP and GWP indexes are shown in Table 1.

Table 1. Refrigerating fluids

Refrig. fluid	Chemical formula	Molar mass g/mol	Temper. of boiling ºC	Temp. of crystall. ºC	Crit. temp. ºC	Crit. pressure kPa	Crit. vol. l/kg	ODP	GWP
R22	$CHClF_2$	86.48	-40.76	-160.0	96.0	4974	1.904	0.055	1500
R32	CH_2F_2	52.02	-51.80	-136.0	78.4	5830	2.326	0.0	550
R125	CHF_2CF_3	120.03	-48.57	-103.15	66.3	3630.6		0.0	3400
R134a	CH_3CH_2F	102.30	-26.16	-96.6	101.1	4067	1.81	0.0	1100
R143a	CF_3CH_3	84.00	-47.27	-111.81	72.71	3761	2.32	0.0	4300
R245fa	$CF_3CH_2CHF_2$	-	-	-	-	-	-	-	950
R290	$CH_3CH_2CH_3$	44.10	-42.09	-187.7	96.70	4248	4.53	0.0	
R407c	Mixture	86.20	-43.79		86.10	4635	1.98		1548.5
R600	$CH_3CH_2CH_2CH_3$	58.13	-0.5	-138.5	152.0	3794	4.383		
R717	NH3	17.03	-33.3	-77.7	1330.0	11417	4.245		
R718	H2O	18.02	100.0	0	373.99	22064	3.11		

Refrigerant R12 or difluorodichloromethane has ODP = 1 and indexes of other refrigerants are measured compared to it. With circular thermodynamic Carnot cycle it is possible to obtain good utilization if the latent evaporation heat of the refrigerant is high. Specific evaporation enthalpy (latent evaporation heat) affects the size of the heat exchanger as well as the dimensions of tubes and valves.

After analyzing refrigerants, considering their effect on the environment, when designing high temperature heat pumps, one needs to pay attention to the implementation of the following working fluids in them: R – 717, R – 600a, R – 290, R – 134a, R-245fa and R – 407c [13, 14].

4. MATHEMATICAL MODEL OF A SINGLE PHASE HIGH TEMPERATURE HEAT PUMP

Modeling the process of heat pumps, rather traditional than those high temperature, so far has been the subject of investigation of many researchers who have published their results in journals or at international congresses and symposia [15 - 22].

A single stage high temperature heat pump, basically, is a device which, using suitable refrigerants and a compressor, achieves a desired difference between condensation temperature (t_k) and evaporation temperature (t_v) from 35ºC to 50ºC. The operation of a single stage heat pump requires a heat source (renewable energy resource) with the temperature between 20ºC and 40ºC.

Creation of the mathematical model of a single stage high temperature heat pump which would be used for determining working characteristics of the pump, and the simulation of the two mixtures of working fluids was based on relevant physical, chemical and thermo-dynamical data. A linear or quadratic equation for calculating pressure, density and specific enthalpy depending on the desired working temperature was determined for each working fluid [14, 23]. The equation for calculating the pressure of vapour depending on temperature has the following form:

$$p = 10^{\left[A(\frac{1}{T})^2 + B(\frac{1}{T}) + C \right]}, \text{ Pa} \qquad (1)$$

where:

A, B, C – constants for calculating the pressure of vapour depending on temperature.

The equations for calculating the density of the liquid phase ρ_L and vapour ρ_g of the working fluid depending on temperature have the following form:

$$\rho_L = \left[a_L T^2 + b_L T + c_L \right], \quad \text{kg/m}^3 \qquad (2)$$

$$\rho_g = \left[a_g T^2 + b_g T + c_g \right], \quad \text{kg/m}^3 \qquad (3)$$

where:

a_L, b_L, c_L – constants for calculating the density of the liquid phase depending on temperature

a_g, b_g, c_g – constants for calculating the density of the vapour depending on temperature.

Calculation of the specific enthalpy of the liquid phase h_L and specific enthalpy of the vapour h_g of the working fluid is conducted according to the following equations:

$$h_L = \left[x_L T^2 + y_L T + z_L \right], \quad \text{J/kg} \qquad (4)$$

$$h_g = \left[x_g T^2 + y_g T + z_g \right], \quad \text{J/kg} \qquad (5)$$

where:

x_L, y_L, z_L – constants for calculating specific enthalpy of the liquid phase depending on temperature,

x_g, y_g, z_g – constants for calculating specific enthalpy of the vapour depending on temperature.

Based on the equations written in advance and using the program Mathcad, a program for calculating the working characteristics of a high temperature heat pump was designed and the calculation of the optimal ratio of the two working fluids in the mixture under desired conditions was simulated [11, 12, 24].

The heat flux of a single stage heat pump Φ_u and the heat flux obtained from the compressor Φ_k are calculated based on the equation:

$$\Phi_u = q_{m,T}(h_{g,2} - h_{L,3}), \text{ W} \qquad (6)$$

$$\Phi_k = q_{m,S}(h_{g,1} - h_{L,4}), \text{ W} \qquad (7)$$

where:

$h_{g,1}$ – specific enthalpy of the vapour of the working fluid at the place where it enters the compressor, J/(kg·K)

$h_{g,2}$ – specific enthalpy of the vapour of the working fluid at the head end on the compressor, J/(kg·K)

$h_{L,3}$ – specific enthalpy of the liquid working fluid in the condenser, J/(kg·K)

$h_{L,4}$ – specific enthalpy of the liquid working fluid at the entrance into the evaporator, J/(kg·K).

Coefficient of performance of the heat pump (COP – Coefficient of Performance):

$$COP_T = \frac{\Phi_u}{P_k} \qquad (8)$$

The COP for cooling of the cooling device:

$$COP_H = \frac{\Phi_k}{P_k} \qquad (9)$$

In order to determine the capacity of the heat pump or the cooling device correctly, it is necessary to calculate precisely the characteristics of the compressor. First, a compressor is chosen with its standard characteristics according to the calculated values and then a theoretical capacity of the heat pump or the cooling device is determined [7, 25].

The temperature of the working fluid on the head end of the compresor is as follows:

$$T_T = T_S \cdot r_k^{\frac{\chi - 1}{\chi}} \qquad (10)$$

The pressure ratio in the compressor is the following:

$$r_k = \frac{p_T}{p_S} \qquad (11)$$

Where:

T_s – temperature of the working fluid at the entrance side of the compressor, K,

χ – compressibility factor of the working fluid,

p_T – pressure of the working fluid vapour on the head end of the compressor, Pa,

p_S – pressure of the working fluid vapour on the intake side of the compressor, Pa.

The power P_k necessary for the operation of the compressor at adiabatic compression of the working fluid in a heat pump, or a cooling device, is calculated according to the following equation:

$$P_k = \frac{P_{ad}}{\eta_k} = \frac{\frac{\chi}{\chi-1} \cdot p_s \cdot V_s \left[r_k^{\frac{\chi-1}{\chi}} - 1 \right]}{\eta_k}, \text{ W} \quad (12)$$

where:

P_{ad} –Power of adiabatic compression of the working fluid, W,

η_k – coefficient of performance of the compressor.

The degree of fullness of the piston compressor λ is determined based on the following correlation:

$$\lambda = 1 - \varepsilon_\phi \left[r_k^{\frac{1}{\chi}} - 1 \right] \quad (13)$$

The real volume flow rate of the compressor:

$$q_{V_{k,s}} = q_{V_k} \cdot \lambda, \quad \text{m}^3/\text{s} \quad (14)$$

Volume flow rate of the working fluid in the compressort is:

$$q_H = q_{V_{k,s}} \cdot \frac{\rho_{g,s}}{\rho_{g,T}}, \quad \text{m}^3/\text{s} \quad (15)$$

Mass flow rate of the working fluid on the intake side of the compressor:

$$q_{m,S} = q_{V_{k,s}} \cdot \rho_{g,s}, \quad \text{kg/s} \quad (16)$$

Mass flow rate of the working fluid on the head end of the compressor:

$$q_{m,T} = q_H \cdot \rho_{g,T}, \quad \text{kg/s} \quad (17)$$

where:

q_{V_k} - volume flow rate of the vapour of the working fluid in the compressor, m^3/s,

$\rho_{g,s}$ – density of the working fluid vapour on the intake side of the compressor, kg/m^3,

$\rho_{g,T}$ – density of the working fluid vapour on the head end of the compressor, kg/m^3.

5. SIMULATION OF A SINGLE STAGE HIGH TEMPERATURE HEAT PUMP AND ITS RESULTS

"MathCad Professional" was used to determine characteristic properties of a single stage high temperature heat pump for the purpose of heating.

Taking into consideration physical and chemical, as well as thermo-dynamical properties of the working fluids, we have calculated their optimal ratio in the mixture. Based on the mathematical model, a program was written which enables calculation of characteristic properties of the pump and the compressor for different conditions. The results are shown in graphical form. The following boundary conditions were determined for an efficient calculation and simulation of the operation of a heat pump:

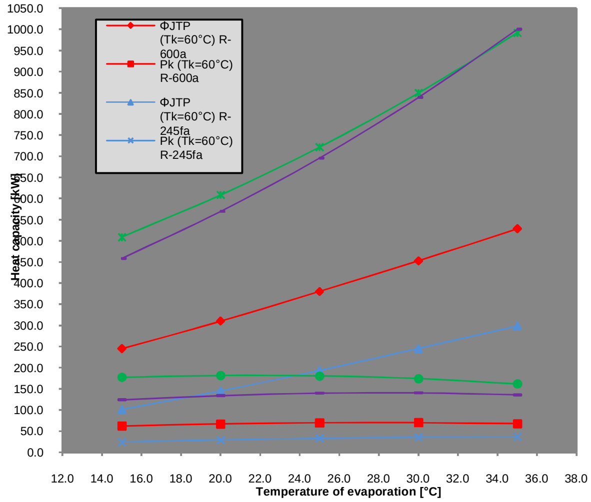
- Volume flow rate of the compressors is constant and amounts to q_{V_k} = 637 m^3/h,
- The upper limit of the power of Mycom type WBH compressor is P_k = 116 kW which represents 80% of maximum power of a compressor - 145 kW,
- The upper limit of the allowed pressure of the muxture of working fluids is 1.7133MPa which is 85.6% of maximum allowed pressure of the working fluid – 2.0MPa,
- The pressure ratio in the compressor is higher than 3.

Maximal degree of performance of the compressor at the number of revolutions of 1000min^{-1} was taken into consideration in the calculation. Considering the results of the calculation of the heat pump, the working fluid was also chosen based on the selected compressor.

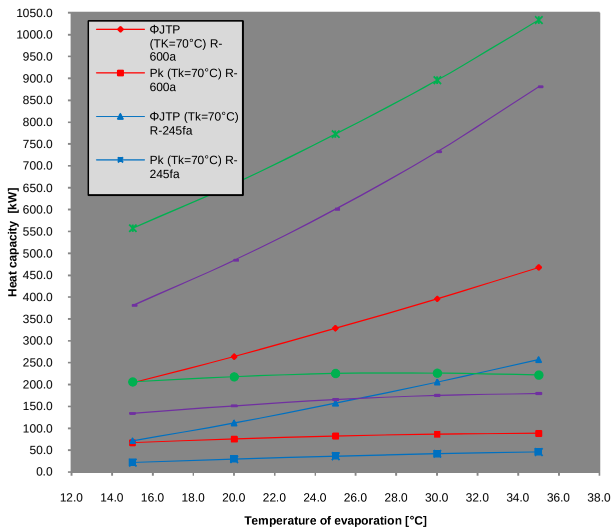
Calculation of a single stage high temperature heat pump was conducted for four different working fluids: R – 134a, R – 245fa, R – 290 and R – 600a and at the temperatures of evaporation t_u, 15, 20, 25, 30 and 35ºC. Condensation temperatures taken in this process were t_k – 60, 70 i 80ºC. The calculated values of the heat flow and energy consumption for the operation of the compressor are shown in graphs fg.2, fg.3 and fg.4. The heat pump contains a piston compressor with a volume capacity of 637 m^3/h. The diagram shows that the greatest heat flow is achieved with the refrigerants R – 290 and R – 134a , however more energy is consumed for the operation of the compressor. Refrigerant R-245fa gives low values of heat flow as well as the energy necessary for the operation of the compressor. The best results are obtained using refrigerant R-600a.

Values of the coefficient of performance of the heat pump, COP_T, were shown in diagram, fg.5, and they were calculated based on the equation (8). The results presented in fg. 5 show that the highest coefficient of performance is obtained for refrigerants R-245fa and R-600a. Refrigerants R – 134a and R – 290 achieve lower COPs. The pressure ratio is the ratio between the pressures on the head end and on the intake side of the compressor and it depends on temperature.

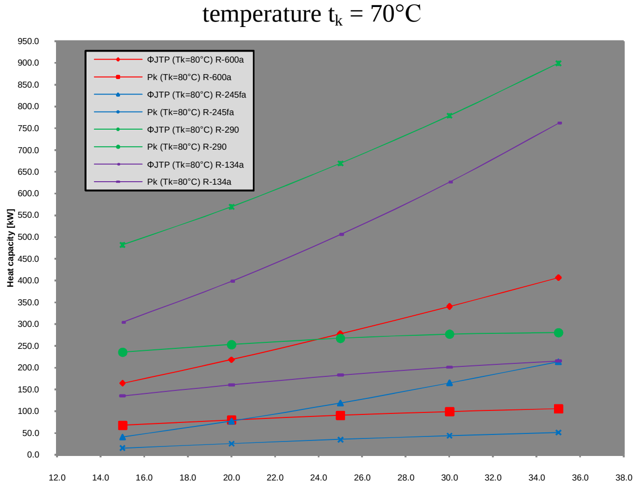
p



Fg. 2. Single stage heat pump at the condensation temperature t_k = 60°C

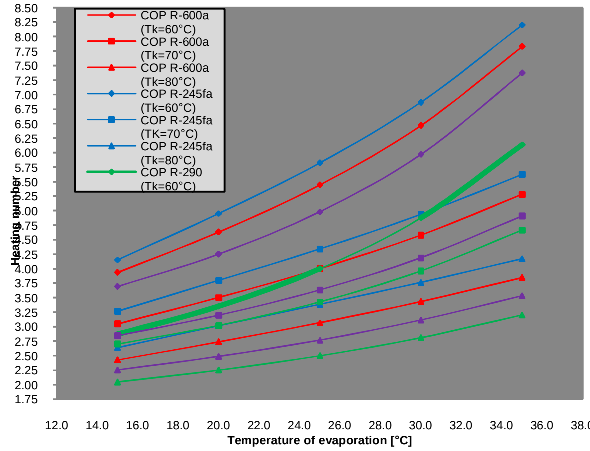


Fg.3. Single stage heat pump at the condensation temperature t_k = 70°C

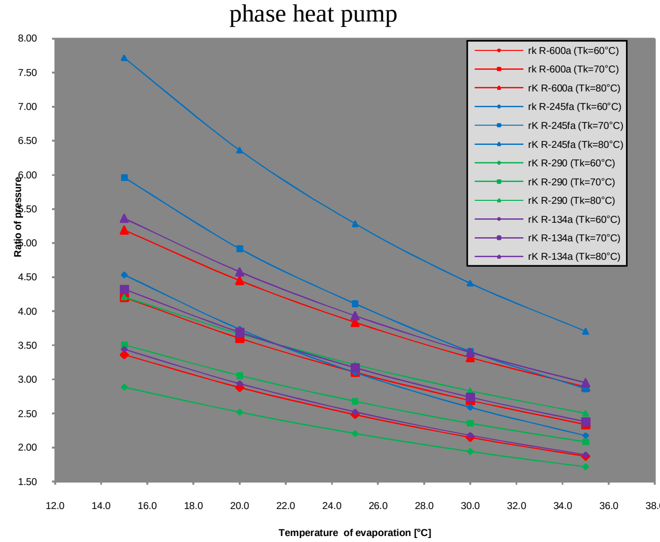


Fg. 4. Single stage heat pump at the condensation temperature t_k = 80°C

The pressure ratios are shown in diagram in Fg. 6 calculated according to correlation (10). Considering evaporation temperature, it is obvious that lower pressure ratios are obtained with refrigerant R – 290 and higher with R – 245fa. Pressure ratios for refrigerants R-600a and R -134a are very similar.



Fg. 5. Heating number (coefficient of performance) of single-phase heat pump



Fg. 6. The ratio of pressure at the exit and the entrance of the compressor in a single stage heat pump

Using refrigerant (working fluid) R-600a at evaporation temperature t_u = 25°C and condensation temperature t_k = 70°C, we obtain heat flow Φ_T = 357,9kW and power necessary for the operation of the compressor P_k = 82,0 kW. Coefficient of performance is COP_T = 4,365 and pressure ratio r_k = 3,105.

Based on the results of these researches it can be seen that refrigerant R-600a is suitable for Mycom WBH compressor. Other working fluids do not achieve optimal performance.

6. CONCLUSION

This paper investigates the possibility of using a high temperature heat pump for exploiting heat from a low temperature energy source.

It presents the process of selecting a suitable refrigerant (working fluid) for the operation of adiabatic circular process for different areas of application. The choice of refrigerant is based on reduction of negative effects on the environment as well as physical, chemical and thermic properties. It is also necessary to pay attention to the characteristics of the compressor as an important factor of adiabatic circular process of “raising heat”. The paper includes the representation of the selection of refrigerants for the operation of a high temperature heat pump which is used in the system of district heating.

Three different types of high temperature heat pumps are recommended for heating residential units:

- A single stage high temperature heat pump
- A two stage high temperature heat pump with a separator
- A two stage high temperature heat pump with a heat exchanger.

For each type of pump (though this paper only presents a single stage high temperature heat pump), a program was designed in MathCad Professional which enables calculation of characteristic properties of the heat pump and the compressor. The calculation was performed at different temperatures of evaporation and condensation. The results are shown in graphical form due to easier observation and evaluation of relevant characteristics of the pump, which enables easier choice of a suitable compressor. .

The main goal of simulation is to determine maximum heat flux and the degree of utilization of the compressor. All the restrictions that might occur in the operation were taken into account.

The researches presented in this paper suggest using refrigerant R-600[a] and Mycom WBH compressor with a single stage heat pump. Economic justifiability of the operation of this heat pump is possible at evaporation temperature t_u = 25°C and condensation temperature t_k = 70°C. The heat flow of a single stage heat pump in this example is 357.9 kW and energy consumption for compressor operation is 82.0 kW.

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