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Influence of Condensing Temperature on Heat Pump Efficiency

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Abstract: The thermodynamic aspect of a compression type heat pump (HP) is briefly described and special attention is given to investigation of condensing temperature influence on heat pump efficiency in heating mode, expressed by its coefficient of performance (COP). Heat pumps are usually applied for the purposes of heating and cooling of energy efficient buildings where they have advantages in low-temperature systems, as it is well documented in the paper. The comparison of real thermodynamic processes with thermodynamically most favorable Carnot's process is made. The results in the paper show that COP is diminishing with increasing of condensing temperature and also depends on real properties of working fluids. The impact of compressor efficiency for two real working media is also analyzed in the paper. There is significant diminishing of COP with diminishing of compressor efficiency. The intension of the paper is to help better understanding of this very effective and prosperous technology, and to encourage its development, production, and efficient application.

Key words: Heat pump, condensing temperature, coefficient of performance, real working fluid, compressor efficiency.

1. Introduction

Heat pump (HP) is a device that allows the transmission ("boot") of heat from lower temperature level into the system of higher temperature level. In accordance with the second law of thermodynamics this is only possible with some compensation, i.e. expenditure of mechanical work, and in reality can be done by means of suitable active substances (working fluids) in a circular process [1]. HP enables the exploitation of energy sources at relatively low temperatures (e.g. ambient air, surface water from rivers, lakes or the sea, groundwater, soil layers below the Earth's surface, waste heat from various processes, etc.). Since most of these sources are renewable the HPs have been usually considered in the framework of renewable energy technologies. They are used in heating, cooling, air conditioning or ventilating systems in buildings and for warming of sanitary water, but also for various other thermal energy requirements.

The paper discusses the thermodynamic fundamentals of commonly used compression HP. For that type of HPs detailed analyses of some individual parameters impact on energy characteristics have been carried out. One of the main characteristics for heating regime is coefficient of performance (COP). The temperature of warm source has significant influence on COP and that can be analyzed through the condensing temperature of working fluid.

2. The Thermodynamic Fundamentals of Compression Type HP

2.1 Theoretical Process

The performance of compression type HP is based on a counter-clock-wise circular process. It is a process

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where working fluid is going from initial state, then passes through many different successive thermodynamic states and at the end is returned to initial state again. The process can be repeated cyclically, enabling continuous operation of the device. The cycle shown the thermodynamic diagrams (*p-v*, *T-s*, *h-s*, etc.) gives a closed curve with a counter-clock-wise round.

Thermodynamically the best process is counter-clock-wise reversible Carnot's process which consists of 4 reversible successive changes of states of working fluid: (1) adiabatic compression, (2) isothermal compression, (3) adiabatic expansion and (4) isothermal expansion. Carnot's process with one-component working fluid in wet region theoretically can be implemented as it is shown in *T-s* diagram of Fig. 1. The processes of heat supplying and conveying can be carrying out at constant temperature and at constant pressure at the same time (evaporation or condensation of working fluid) but the adiabatic processes of expansion and compression technically can not be realized, because of enormous changes in working fluid volumes and possible hazardous hydraulic ram.

Although Carnot's process can not be realised, it can still serve as theoretically the best comparative assessment for all other real processes.

2.2 Real Process

The process shown in Fig. 1 must be modified to become really feasible. Instead of adiabatic expansion the choking (throttle) expansion valve is used, and the compression is moved from the wet region to dry (overheated) area as it is shown in Fig. 2. The evaporation process of working fluid is completely done at constant temperature T_i, and the condensation of working fluid is also completed at constant temperature T_c. For even better control of the process in real circumstances, a little under cooling of condensate ($T_3 < T_c$) and a little superheating of dry vapour ($T_1 > T_i$) can be proposed.

A real compression type HP consists of a compressor, a condenser, an expansion valve, and an evaporator. All these parts are usually placed in the same casing and represent a unique device (Fig. 3).

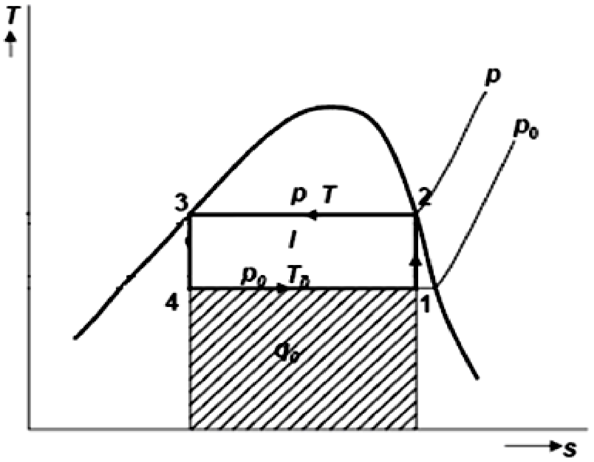
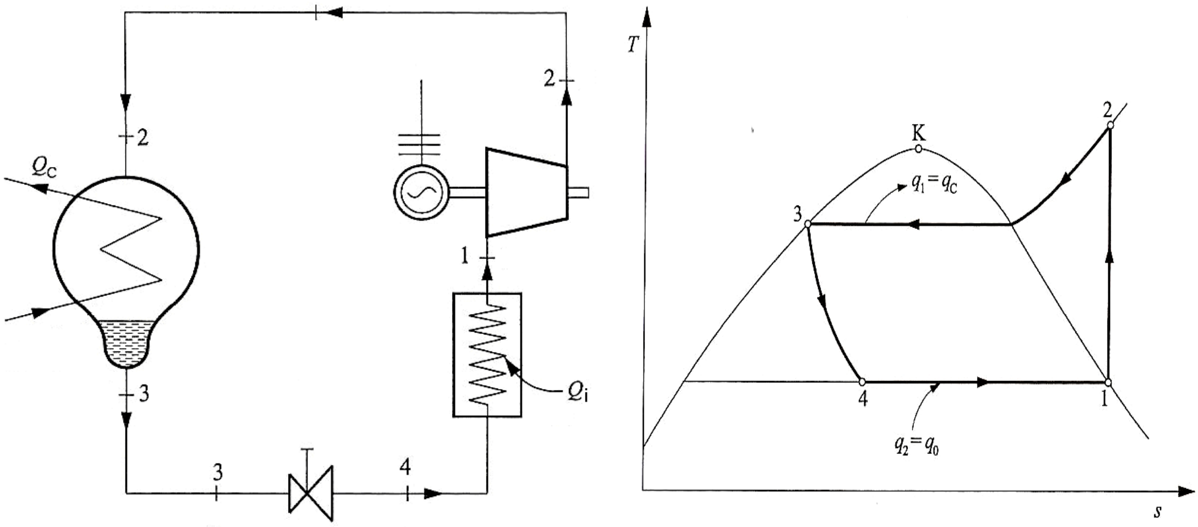


Fig. 1 Carnot's process with one-component working fluid [2].

The only active part of the device is compressor, driven usually by an electric motor. Supplied mechanical energy is used for increasing the energy potential of primary working fluid (increasing its pressure and temperature from state 1 to state 2 in Fig. 2). Heat supplied to primary working fluid in evaporator is given by a secondary working fluid (i.e. brine) from low temperature heat source, and in condenser heat is conveyed from primary working fluid at higher temperature to another secondary working fluid (i.e. heating water) as it is shown in Fig. 3. Each secondary cycle needs a pump, and there are also piping, fittings, heat exchangers and automatic regulation. While secondary fluids are used only for heat transfer between HP and heat sources at lower and higher temperatures, primary working fluid is taking part in compression, condensation, throttling and evaporation processes with different thermodynamic changes of states. Therefore a specific process in HP can be realised only with a working fluid that enables operation in defined temperature ranges. Besides good thermodynamic and physical properties, some other requirements on primary working fluids have to be fulfilled (such as: compatibility with system and chemical stability, good economical properties and small impact to the environment).



(a) (b)

Fig. 2 The modified real process: (a) an outline, and (b) *T-s* diagram [1].

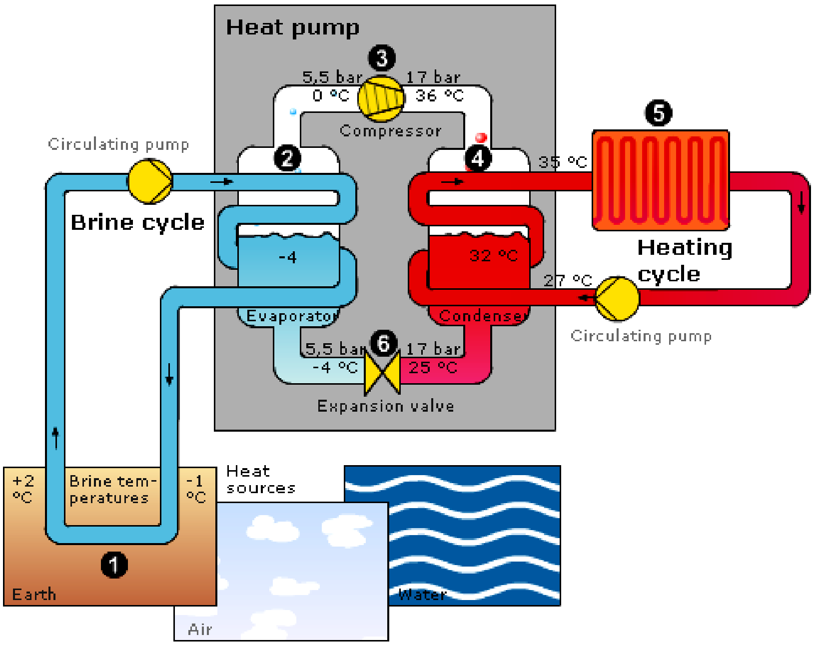


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Fig. 3 Schematic view (outline) and operation of compression type HP [3].

There are many fluids that can be applied as a primary working fluid in HP, for example inorganic media as H_2O (R718), NH_3 (R717), CO_2 (R744), air (R729), SO_2 (R764) or halogenated hydrocarbons as R11, R12, R13, R22, etc. [2]. Each working fluid has its specific properties and therefore is most suitable for a particular application and a particular temperature range. The real properties influence the working characteristics of HP as it is shown in continuation in the paper where two different media (R717 and R12) are used and analysed.

2.3 HP Efficiency Definitions

The efficiency of a real process in HP can be described by some coefficients that are briefly defined below.

For heating mode of operation the COP (ε_{DT}) is defined as a ratio of heat energy given to the heated space or media Q_{dov} to electric energy used for driving the compressor E_{pog}, or as the ratio of heating power Φ_{DT} to compressor electric motor power P_{el}:

$$\mathrm{COP} = \varepsilon_{DT} = \frac{Q_{dov}}{E_{pog}} = \frac{\Phi_{DT}}{P_{el}} \tag{1}$$

For cooling mode of operation the Energy Efficiency Ratio (EER) (ε_{RU}) is defined as a ratio of cooling energy (energy conveyed from cooled space or media) Q_{odv} to electric energy used for driving the compressor E_{pog}, or as the ratio of cooling power Φ_{RU} to compressor electric motor power P_{el}:

$$\mathrm{EER} = \varepsilon_{RU} = \frac{Q_{odv}}{E_{pog}} = \frac{\Phi_{RU}}{P_{el}} = \varepsilon_{DT} - 1 \tag{2}$$

In continuation the influences of some impact parameters on HP efficiency are analyzed only through COP, because EER is also defined as "COP-1" according to Eq. 2.

3. Condensing Temperature Influence on COP

3.1 Influence Parameters Levels

The temperature of HP evaporator is fixed here at 10 ℃ (T_i = 283 K) like in an earlier paper [4] where the influence of some impact parameters on a geothermal heat pump COP is preliminary analyzed. The higher temperature source, to which the heat from HP is conveyed, is modelled through the condensing temperature of primary working fluid. The condensing temperature, as the first impact parameter here is changed in a wide range from 30 ℃ to 80 ℃ (Tc = 303 K to Tc = 353 K) with a pitch of 5 K. This main impact parameter is researched in combination with two other parameters. The second parameter is compressor efficiency (η_K) which is searched at three levels: adiabatic ideal process ($\eta_K = 1$) is compared to two real irreversible processes with $\eta_K = 0.8$ and $\eta_K = 0.6$. The impact of real properties of primary working fluid is analyzed at two levels through applying two different media: R717 and R12. Their real properties are taken from Ref. [1].

3.2 Thermodynamic Calculation Procedure

The process shown in *T-s* diagram on Fig. 2 is taken as the basis for thermodynamic calculation. Using real properties of working fluids (pressures p, enthalpies h, and temperatures t) the following is calculated particularly for each level of every impact parameter:

(1) specific heat energy supplied to HP working fluid in evaporator at T_i = const:

$$q_{odv} = h_1 - h_4 \tag{3}$$

(2) specific mechanical work supplied to HP compressor:

$$e_{pog,\eta} = (h_2 - h_1)/\eta_K \tag{4}$$

(3) specific enthalpy of working fluid at the end of irreversible compression:

$$h_{2,\eta} = h_1 + e_{pog,\eta} \tag{5}$$

(4) specific heat energy conveyed from HP (and supplied to heated space or heated media) in condenser at T_c = const:

$$q_{dov,\eta} = h_{2,\eta} - h_3 \tag{6}$$

(5) COP for irreversible process in real circumstances:

$$COP_\eta = q_{dov,\eta}/e_{pog,\eta} \tag{7}$$

(6) COP of reversible theoretical Carnot's process (Fig. 1) between temperatures T_i and T_c:

$$COP_C = T_c/(T_c - T_i) = 1/(1 - T_i/T_c) \tag{8}$$

The impact parameters and their levels are taken only for impact analysis in this paper. For a particular detailed thermodynamic calculation all temperatures of primary and secondary working media in each heat exchanger have to be known and taken into account.

3.3 Results and Discussions

Thermodynamic calculations are carried out for process according to Fig. 2 using ammonia (R717) and freon (R12) as primary working fluids in defined range of condensing temperature T_c (30 ℃ to 80 ℃). Results are given in Fig. 4 as a function of COP depending on condensing temperature (T_c) and real properties of working fluids. For comparison on the same diagram there is shown COP for theoretical Carnot's process. It can be seen significant diminishing of HP efficiency

(COP) with increasing of temperature T_c. Generally the conclusion is that HP is more efficient at lower temperatures T_c and smaller temperature difference (T_c-T_i) or temperature ratio (T_c/T_i). Therefore HP can be proposed for using in low temperature systems of heating and cooling (surface systems with floor, wall or ceiling heat exchangers) rather then in higher temperature radiator's or convector's systems.

There can also be observed in Fig. 4 that the HP efficiency is significantly dependable on real properties of applied working fluid. COP for HP with R717 is about 20% better than for HP using R12. In comparison to ideal Carnot's process diminishing of COP for real working fluids is between 20% and 30% for R717, or between 35% and 50% for R12. On the other hand R12 needs lower pressure rise and therefore maximal pressures in process with R12 are lower than in process with R717.

Calculation results for temperatures higher than 60 ℃ (T_c > 333 K) have to be taken with some uncertainty because in reality the compression process could be provided in two stages with intercooling which is not taken into account.

Real circumstances of compression process are taken into account with compressor efficiency. Results of thermodynamic calculations for $\eta_K = 1$, $\eta_K = 0.8$ and $\eta_K = 0.6$ for ammonia (R717) as working fluid are shown on Fig. 5 and for freon (R12) are shown in Fig. 6. It can be seen significant diminishing of COP with diminishing of compressor efficiency.

The final (maximum) temperature in the process is also an important process parameter. Results of calculation show that these temperatures are growing up with diminishing of compressor efficiency. The final temperatures are lower in processes with R12.

4. Conclusions

Thermodynamic aspects of commonly used compression type heat pumps (HP) are briefly described. The coefficient of performance (COP), as a factor that defines HP efficiency in heating mode, is introduced. Special attention is given to the investigation of condensing temperature influence on COP. That influence is researched together with the

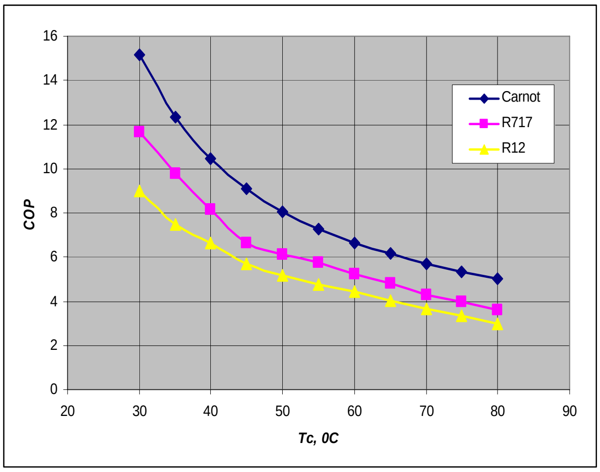

Fig. 4 Influence of real working media and condensing temperature T_c on COP of HP.

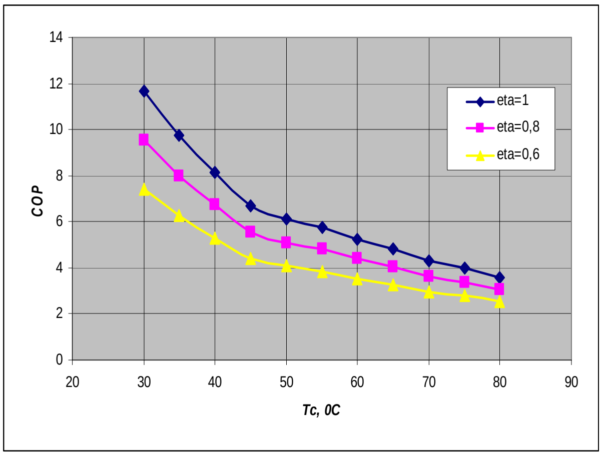

Fig. 5 Influence of compressor efficiency and condensing temperature T_c on COP of HP working with R717.

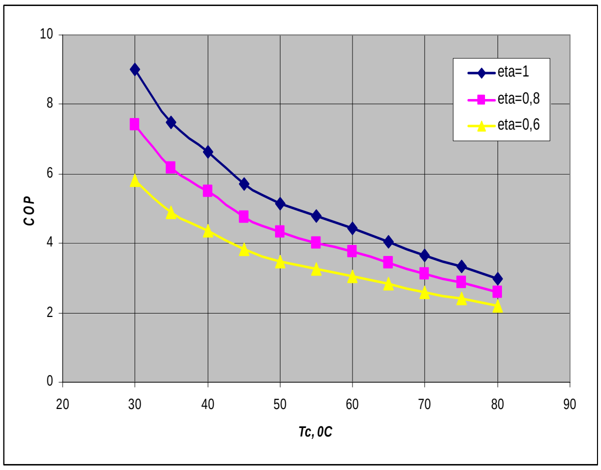

Fig. 6 Influence of compressor efficiency and condensing temperature T_c on COP of HP working with R12.

influence of real working media properties and the irreversibility of compression process expressed by compressor efficiency. The thermodynamic calculations are carried out for wide range of condensing temperatures (30 ℃ to 80 ℃) and for 3 levels of compressor efficiency ($\eta_K = 1$, $\eta_K = 0.8$ and $\eta_K = 0.6$). The real properties of primary working fluid are taken into account at two levels through applying two different media: ammonia (R717) and freon (R12). The results of extensive thermodynamic calculations are presented in comparative diagrams.

The results show that COP is diminishing with increasing of condensing temperature T_c, and also depends on real properties of working fluid. In comparison to Carnot's ideal process, diminishing of COP for real working fluids are about 25% for R717, and about 35% for R12. There is also significant diminishing of COP with diminishing of compressor efficiency.

The results of calculations confirm better prosperity of using HP technology in low temperature systems of heating and cooling (surface systems with floor, wall or ceiling heat exchangers) in comparison to higher temperature radiator's or convector's systems.

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