A multistage heat pump unit model for reducing energy consumption of space heating at low ambient temperatures

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Abstract. Air heat pump units (HPUs) for space heating are used more widely than geothermal ones, mainly due to lower installation costs. The main disadvantages of geothermal installations are their low productivity and coefficient of performance (COP). In this work, a multistage heat pump unit with an air source was modeled, which leads to a decrease in the energy consumption of the compressors in all of the HPU stages at an ambient temperature of -30°C and a heating temperature from 20°C to 65°C. Wherein, the COP of the modeled multistage HPU in all modes is 20% higher in comparison with a two-stage HPU considered in the literature review. In addition, the influence of the decrease in the ambient temperature on the increase in the energy consumption of the first stage of a multistage HPU was presented in this work.

1. Introduction

Currently, due to the simplicity and low cost of installation, air HPUs are mainly used for space heating. However, at negative ambient temperatures, the use of HPU is limited by a decrease in the COP. Three options to find a solution to this problem are reflected in the work [1]. The configurations for improving the HPU design were analyzed and the results showed an insignificant decrease in the COP gradient with decreasing ambient temperature. The configurations are as follows: a two-stage HPU with intermediate cooling, a HPU with an economizer and a multistage HPU of a cascade cycle. The two-stage HPI with intermediate cooling proved to reduce the energy consumption of the refrigerant at the compressor inlet of the high-pressure stage, which consequently lead to an increase in the COP, when compared to a single-stage HPU. Instead of an HPU with intermediate cooling, a two-stage HPU with a closed economizer can be implemented. The economizer feeds a predetermined amount of two-phase refrigerant to the mixing chamber in the suction line of the high-pressure compressor stage, where it mixes with the hot discharge gas of the low-pressure compressor stage. This leads to a decrease in the temperature of the refrigerant at the compressor inlet of the high-pressure stage, which slightly increases the COP. The difference between the multistage cascade HPU in comparison with the other two-stage HPUs, is that two different refrigerants can be used in these units, while each refrigerant operates in its optimal range of operating conditions. The main disadvantage of the multistage cascade HPU with an air evaporator is the sharp decrease in COP at low ambient temperatures, where at an ambient temperature of -30°C and a heated water temperature of 50 °C the COP = 2.3.

In the work [2], research was carried out on the use of refrigerant injection at several points of the HPU spiral compressor channel, which made it possible to reduce the energy consumption of the compressor. This configuration of the cycle ensures minimal overheating of the refrigerant in the HPU compressor. However, with an increase in the number of refrigerant injection points, only the first three points give an increase in COP to 1.33. While, at other points, an insignificant increase in COP does not pay off by complicating the configuration of the HPU.

In the work [3], in order to increase the COP, an option of replacing the throttle valve with a refrigerant ejector was considered. The potential energy of the refrigerant compression is converted into kinetic energy of
the flow in the throat of the nozzle, where the refrigerant is ejected at the outlet of the evaporator and further
in the mixing chamber which leads to an increase in the pressure of the refrigerant at the compressor inlet. This
configuration of the HPU allows to reduce the operation of the compressor, especially at negative ambient

temperatures, which will ultimately lead to an increase in COP by 14.5%.

In this work, a multistage HPU model was developed to reduce the total energy consumption of the
compressors due to the redistribution of the refrigerant flow between the sequentially installed compressors
[4]. The aim of this work is to develop an efficient multistage heat pump unit model to reduce energy
consumption of space heating at low ambient temperatures.

2. Methods and calculations

As already mentioned, the multistage HPU developed in this work was able to reduce the total energy
consumption of the compressors due to the redistribution of the refrigerant flow between the sequentially
installed compressors. The scheme of the multistage HPU developed is shown in Figure 1.

![Figure 1. The scheme of the multi-stage HPU model.](image)

The refrigerant from the evaporator 1, after being compressed in the first-stage compressor 2, sequentially
enters the condenser 3 and the separator 4 of the first stage, where the refrigerant is separated into liquid and
vapor phases. The liquid phase of the refrigerant through the subcooler 5 and the throttle 6, enters the
evaporator 1. The vapor phase of the refrigerant is compressed by the second-stage compressor 7. Then the
refrigerant sequentially enters the condenser 8 and the separator 9. The liquid phase of the refrigerant from the
separator 9 through the subcoolers 10, 5 and the throttle 11 enters the evaporator 1. The vapor phase of the
refrigerant is compressed in the third stage compressor 12 and then, sequentially passing the condenser 13, the
subcoolers 14, 10, 5 and throttle 15, enters the evaporator 1.
The thermodynamic cycle of the multistage HPU in the P-H diagram is shown in Figure 2. G1, G2 and G3 are the refrigerant flow, respectively, through throttles 6, 11, and 15. From the P-H diagram it can be deduced that each of the compressors 2, 7 and 12, pumps the refrigerant with a flow rate equal to (G1 + G2 + G3), (G2 + G3) and G3. Thus, the heat mainly obtained as a result of the phase transition from vapor to liquid of the refrigerant with the flow rate G1, G2 and G3, respectively, in condensers 3, 8 and 13 of each stage goes to the stepwise heating of the high potential heat source (HHS). Compared with the known schemes of multistage HPI, where the entire refrigerant flow is sequentially pumped to the condensation pressure in the last stage of the HPU developed, with the same heating power, the total energy consumption of the compressors decreased approximately by 30%.

![Figure 2. The P-H diagram of the multistage HPU](image)

Thermal calculation of single- two- and three-stage HPUs was carried out according to the method described in the patent [4]. A calculation example of a three-stage HPI is presented in this patent, where the calculation is based on the method of determining the proportion of the refrigerant consumption from the flow rate of one kg of the heated HHS, determined from the heat balance of each HPU stage.

\[
\alpha_x = \frac{G_{xx}}{G_{HHS}} = \frac{c_{pHHS}(t_{Hx} - t_{H(x-1)})}{(H_{2x} - H_{H(x-1)})\eta_{eff}}
\]

\[
\alpha_{x2} = \frac{G_{x2}}{G_{HHS}} = \frac{c_{pHHS}(t_{x1} - t_{x2}) - \alpha_{x1}(H_{2x2} - H_{x2}) - \alpha_{x2}(H_{kx2} - H_{kx1})}{(H_{2x2} - H_{kx1})\eta_{eff}}
\]

\[
\alpha_{x1} = \frac{G_{x1}}{G_{HHS}} = \frac{c_{pHHS}(t_{x1} - t_{x0}) - (\alpha_{x1} + \alpha_{x2})(H_{2x1} - H_{x1})}{(H_{2x1} - H_{kx1})\eta_{eff}} = \frac{(\alpha_{x1} + \alpha_{x2})(H_{kx1} - H_{kx0})}{(H_{2x1} - H_{kx0})\eta_{eff}}
\]

where \(G_{x1}, G_{x2},\) and \(G_{x3}\) are the refrigerant flow rate, respectively, of the first, second and third stages; \(c_{pHHS}\) is the isobaric heat capacity of the HHS working fluid; \(t_{x0}\) is the temperature of the working fluid of the HHS
before entering the three-stage HPU; \( t_{n_1}, t_{n_2} \) and \( t_{n_3} \) are the temperatures of the HHS working fluid at the outlet of condensers 3, 8 and 13, respectively, of the first, second and third stage of the HPU; \( H_{2x_1}, H_{2x_2}, \) and \( H_{2x_3} \) are the enthalpies of the refrigerant at the compressor outlets 2, 7 and 12, respectively, of the first, second and third stages of the HPU; \( H_{kx_1}, H_{kx_2}, \) and \( H_{kx_3} \) are the enthalpies of the refrigerant at the subcooler outlets 5, 10 and 14, respectively, of the first, second and third stage; \( H_{nx_1} \) and \( H_{nx_2} \) are the enthalpies of the refrigerant at the saturation line (\( x = 0 \) Steam Dryness Fraction) with a pressure equal to the pressure of the refrigerant after the compressors 2 and 7, respectively, of the first and second stages of the HPU; \( \eta_{eff} \) is the effective efficiency of the condensators 3, 8, and 13.

The energy consumption by the compressor of each stage is calculated by the following formulas:

\[
N_1 = G_{HHS}L_1(\alpha_{x1} + \alpha_{x2} + \alpha_{x3})
\]

\[
N_2 = G_{HHS}L_2(\alpha_{x2} + \alpha_{x3})
\]

\[
N_3 = G_{HHS}L_3(\alpha_{x3})
\]

where \( L_1, L_2 \) and \( L_3 \) is the work spent on compressing one kg of refrigerant by compressors 2, 7 and 13, respectively, of the first, second and third stages of the HPU. The COP value is calculated by the following formula:

\[
\text{COP} = \frac{G_{HHS}C_{PHHS}(t_{n_2} - t_{w_0})}{N_1 + N_2 + N_3}
\]

R401a was chosen as the refrigerant. The multistage HPU heats the HHS (water) from \( t_w = 20 \, ^\circ\text{C} \) to \( t_w = 65 \, ^\circ\text{C} \) in the range of the low-potential heat source (LHS) (ambient air) \( t_w \) from -30°C to +15°C. The results of the calculations of COP\(_1\), COP\(_2\) and COP\(_3\), respectively, of single- two- and three-stage HPUs are shown in Table 1. As an example, the distribution by stages and the total energy consumption of all stages of the compressors of a three-stage HPU is shown in Table 2.

**Table 1. The COP of single-, two- and three-stage HPU**

| \( t_w \), \(^\circ\text{C} \) | COP\(_1\) | COP\(_2\) | COP\(_3\) | \( \Delta\text{COP}_{2}\), % | \( \Delta\text{COP}_{3}\), % |
|---|---|---|---|---|---|
| -30 | 1.77 | 2.90 | 2.97 | 38.9 | 40.4 |
| -25 | 1.98 | 3.11 | 3.20 | 36.4 | 38.1 |
| -20 | 2.17 | 3.36 | 3.46 | 35.5 | 37.3 |
| -16 | 2.36 | 3.53 | 3.66 | 35.0 | 37.3 |
| -10 | 2.68 | 3.95 | 4.11 | 32.5 | 34.8 |
| -5 | 2.99 | 4.35 | 4.41 | 31.2 | 34.4 |
| 0 | 3.32 | 4.78 | 4.54 | 30.0 | 33.8 |
| 5 | 3.77 | 5.33 | 5.01 | 29.1 | 32.8 |
| 10 | 4.27 | 6.00 | 5.62 | 28.8 | 32.8 |
| 15 | 4.87 | 6.83 | 6.36 | 28.7 | 33.3 |

**Table 2. The total energy consumption of all stages of the compressors of a three-stage HPU**

| \( t_w \), \(^\circ\text{C} \) | \( N_1 \) | \( N_2 \) | \( N_3 \) | \( \Sigma N \) |
|---|---|---|---|---|
| -30 | 52.48 | 7.20 | 3.64 | 63.4 |
| -25 | 48.00 | 7.28 | 3.64 | 58.9 |
| -20 | 43.54 | 7.28 | 3.64 | 54.46 |
| -16 | 40.6 | 7.28 | 3.64 | 51.5 |
| -10 | 34.9 | 7.28 | 3.64 | 45.86 |
| -5 | 30.75 | 7.28 | 3.64 | 41.67 |
| 0 | 26.66 | 7.28 | 3.64 | 37.58 |
| 5 | 22.69 | 7.28 | 3.64 | 33.55 |
| 10 | 18.70 | 7.28 | 3.64 | 29.62 |
| 15 | 14.86 | 7.28 | 3.64 | 25.78 |

3. Results and discussion

The results in Table 1 shows that with a decrease in the ambient temperature +15°C to -30°C, \( \Delta\text{COP}_{2} \) increased from 28.7 % to 38.9 %, while \( \Delta\text{COP}_{1} \) increased from 33.3 % to 40.4 %, where \( \Delta\text{COP}_{2} = (\text{COP}_{2} - \text{COP}_{1})100%/\text{COP}_{2} \) and \( \Delta\text{COP}_{3} = (\text{COP}_{3} - \text{COP}_{1})100%/\text{COP}_{3} \). Therefore, when water is heated from 20°C to 65°C, comparing the energy consumption of a two-stage HPU and a three-stage HPU to a single-
stage HPU, with similar initial parameters, energy saving of a two-stage HPU is from 11.1 kW to 41.5 kW, while for a three-stage HPU energy saving is from 12.9 kW to 43 kW.

The results in Table 2 showed the energy consumption of the second and third stages compressors does not depend on the ambient air temperature, while the energy consumption of the first stage compressor is directly related to the ambient air temperature, for an ambient temperature of +15°C $N_1=14.86$ kW, while for -30°C $N_1=52.48$ kW.

4. Conclusions
In this work, a multistage air HPU model was presented. The main highlights and conclusions of this work are presented below:

1. The reduction of energy consumption for space heating at low ambient temperatures is achieved by the modeled multistage HPU in this work, in which the total energy consumption of the compressors is reduced by redistributing the refrigerant flow between the sequentially installed compressor, which lead to an increase in the COP by 20%;
2. Heating the HHS from $t_{h1}=$const to $t_{h3}=$const, lead to an increase in the energy consumption of first-stage compressor only with decreasing ambient temperature.

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