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ENERGY EFFICIENCY OF HEAT PUMP HEAT SUPPLY SYSTEM WITH HEAT UTILIZATION OF TECHNOGENIC AIR EMISSIONS

Abstract: *In this article, the aim is to analyze the conditions of efficient use of heat obtained from the utilization of technogenic air sources, and to find the optimal values of the heat usage parameters in the heat pump heating system. This will allow using the thermal potential, which was previously wasted. It is necessary to determine the optimal degree of cooling of the lower heat source in the evaporator of the heat pump (optimal depth of use of the lower energy source), because with decreasing coolant temperature at the evaporator outlet and increasing the useful effect – proportionally increases the cost of HP compressor.*

Keywords*: efficient use of heat, optimal the heat usage, heat pump, heating system*

Introduction

Industrial units and systems, where the high-temperature heat-technological process is realized, create the technical base of main productions of the national economy, namely ferrous and non-ferrous metallurgy, production of building materials, food industry and mechanical engineering. They consume almost 75-80% of high-potential thermal energy, but the use of thermal energy in these economy productions is characterized by a relatively low fuel heat utilization rate – up to 30%. As a result of technological processes at industrial enterprises there is a large amount of low-temperature thermal energy which is not used in the technological cycle. Depending on specific conditions, the spent thermal energy can be used in heat pumps as a lower heat source for heat supply of workshops, production areas, warehouses of industrial enterprises [1-3].

Thus, through the introduction of heat pumps in enterprises with high–temperature processes and units, it is possible to create a combined energy technology system that naturally connects energy and heat technology systems to ensure the highest economic efficiency of energy production and technological products realization [3].

Almost all scientific or research developments related to the introduction of heat pump technology for technogenic air heat sources recovery are at the stage of individual design solutions and applications. In the available literature there are only isolated studies without comprehension and full analysis of results and attempts to apply them to other systems. Thus, the analysis of research in the field of HP applications in heat supply systems showed that this issue is open and necessary to address [1, 4].

Based on the method of balance equations, a theoretical model of the heat pump system (HPS) for heat supply (Fig. 1), as well as a method of thermodynamic analysis of its work was developed. Using the numerical calculation method, data were obtained that allow to evaluate the efficiency of technogenic sources from the condition of obtaining the maximum useful effect in the heat pump heating system, and determine the optimal depth of technogenic air emissions as a lower energy source.

Description of the basic heat pump heating system working at the expense of utilization of technogenic air sources

Figure 1 shows a HPS heat supply system that works by utilization of technogenic air heat sources.

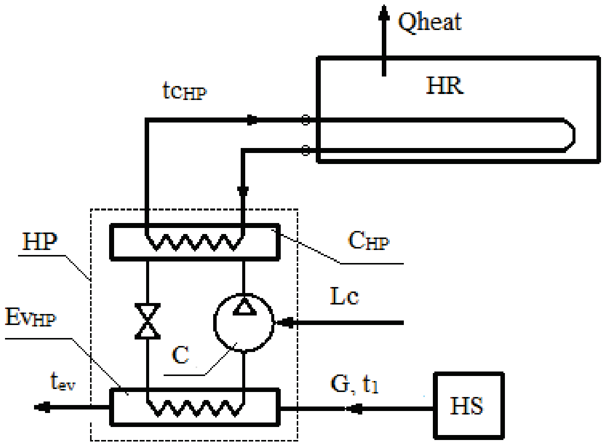


FIGURE 1. *HPS heat supply system that works by utilization of technogenic air heat sources: HR – heated room, HS – heat source, HP – heat pump, C_{HP} – HP condenser, Ev_{HP} – HP evaporator, C – compressor*

The operation principle is a follows: low-temperature heat source, i.e. exhausted air with temperature t_1 (varies in range 20...60°C) and mass flow G_a is fed into the HP evaporator. Here the coolant is cooled and its outlet temperature is t_{ev}. The heated room has heat loss to the environment Q_h. For their compensation the flow extracted from the HP condenser Q_{heat} is used with the temperature of the heating coolant $t_{\text{C}_{\text{HP}}}$ at the entrance to the heating system.

The temperature of the coolant at the outlet of the heat pump evaporator t_{ev} should be determined from the condition of obtaining the maximum useful effect, because the amount of heat taken from the lower source energy depends on the temperature difference at the inlet and outlet of the HP evaporator, and the consumption of coolant. In this case, the thermal capacity of the HP and the temperature of the coolant in the heating system are known values, which are determined by the characteristics and needs of the object in thermal energy to reach the goals of heat supply.

Thermodynamic analysis of the use of heat from man-made air emissions in the heat pump system for low-temperature heating

The condition of further analysis is the conditions of use of technogenic heat source, which correspond to the maximum useful effect, taking into account energy expenses for the HP compressor drive.

$$Q = Q_{ut} - \frac{L_c}{\eta_{\text{CPP}}\eta_{\text{EPL}}} \tag{1}$$

where:

Q_{ut} – heat flow utilized while cooling of technogenic air emissions, kW;
L_c – energy costs for the drive of the HP compressor, kW;
η_{CPP} – energy efficiency of a condensing power plant, it is taken equal to 0.38;
η_{EPL} – efficiency of power lines, it is taken equal to 0.95 [2].

The heat flux Q_{ut}, that is utilized during the cooling of the exhaust gases is defined as

$$Q_{ut} = Q_{ev} = G_a c_p (t_1 - t_{ev}) \tag{2}$$

where:

Q_{ev} – heat flow in the heat pump evaporator, kW;

G_a – mass flow of technogenic air source, kg/sec;

c_p – specific heat of air, respectively, kJ/(kg°C);

t_1, t_{ev} – the temperature of the technogenic air source at the inlet and outlet of the HP evaporator, respectively, °C.

The energy consumption of the HP compressor L_c is determined by the expression

$$L_\kappa = Q_{ev} / (\varphi - 1) \tag{3}$$

where φ is the actual HP transformation coefficient.

The theoretical heat transformation coefficient of an ideal Carnot cycle can be written as

$$\varphi_{th} = \left[1 - \frac{T_{ev}^{\text{HP}}}{T_c^{\text{HP}}} \right]^{-1} \tag{4}$$

where:

T_{ev}^{HP} – the absolute temperature of evaporation of the refrigerant in the HP evaporator, K;

T_c^{HP} – the absolute condensation temperature of the refrigerant in the HP condenser, K.

The absolute temperature of evaporation of the refrigerant in the HP evaporator is determined as

$$T_{ev}^{\text{HP}} = 273 + t_{ev} - \Delta t_{ev} \tag{5}$$

where Δt_{ev} is the difference in temperature of the coolant and the working fluid of the HP at the outlet of the evaporator HP, °C.

The absolute condensation temperature of the refrigerant in the HP condenser is defined as

$$T_c^{\text{HP}} = 273 + t_c + \Delta t_c \tag{6}$$

where:

t_c – the water temperature at the outlet of the HP condenser, °C;

Δt_c – the temperature difference between the working fluid of the HP and the water at the outlet of the HP condenser, °C.

Substituting (5), (6) into (4), we obtain the expression for determining the Carnot cycle transformation coefficient taking into account thermal irreversibility

$$\varphi_T = \left[1 - \frac{273 + t_{ev} - \Delta t_{ev}}{273 + t_c + \Delta t_c} \right]^{-1} \tag{7}$$

According to the recommendations, we can assume that Δt_{ev} = 10°C for air, respectively, and Δt_c = 5°C for low–temperature water heating system.

However, equation (7) does not take into account the nature of the actual cycle in the heat pump. To take into account various types of irreversibility and the nature of the cycle during the operation of the real HP in (7) is introduced a correction factor, which is the efficiency of HP. Thus, equation (7) for the real cycle of the heat pump unit can be rewritten as

$$\varphi = \eta_{\mathrm{HP}}\left[1-\frac{273+t_{ev}-\Delta t_{ev}}{273+t_c+\Delta t_c}\right]^{-1} \tag{8}$$

where η_{HP} is the efficiency of the heat pump that can be taken 0.6.

To determine the temperature of the coolant supplied from the HP condenser to the low–temperature water heating system, has the force of the equation, which is derived based on the analysis of heat transfer processes in the system heating water – indoor air – atmospheric air

$$t_c = t_r + \left(t_c^{\mathrm{est}} - t_r\right)\left[\left(t_r - t_0\right)/\left(t_n - t_0^{\mathrm{est}}\right)\right]^{\frac{1}{(1+n)}} \tag{9}$$

where:

t_r – room temperature, °C;

t_0 – ambient temperature, °C;

t_0^{est} – the estimated temperature of the coolant in the heating system, in case of designed ambient temperature t_0^{est} (t_0^{est} = –20°C);

n – coefficient that characterizes the selected heating system (for low–temperature heating systems n = 0).

Taking into account the above formulas (2)-(9), the initial equation (1) can be written as

$$Q = G_a c_p (t_1 - t_{ev})\left[1-\frac{1}{(\varphi-1)\eta_{\mathrm{CPP}}\eta_{\mathrm{EPL}}}\right] \tag{10}$$

Therefore, the specific beneficial effect that can be obtained by utilizing the heat of technogenic air sources using a heat pump, taking into account the energy costs for the drive of the compressor of the heat pump, attributed to 1 kg of air heat source, is determined by the ratio

$$q = \frac{Q}{G_a} = c_p (t_1 - t_{ev})\left[1-\frac{1}{(\varphi-1)\eta_{\mathrm{CPP}}\eta_{\mathrm{EPL}}}\right] \tag{11}$$

The algorithm for obtaining the specific useful effect from the use of technogenic air emissions allows us to investigate the calculation method of the conditions for achieving the maximum value of this useful effect, ie the optimal values of cooling temperature of air emissions at the outlet of the HP evaporator or the optimal degree of heat.

Estimated analysis of the optimal parameters of heat use of technogenic air emissions in the low–temperature heating system

The purpose of the calculation analysis is to implement a numerical calculation according to the above method to determine the optimal conditions for heat utilization of technogenic emissions, namely the optimal cooling temperature t_{ev}^{opt} and its dependence on the parameters of the problem, ie the temperature of technogenic air emissions t_1, estimated temperature of the coolant in the heating system t_c^{est} and ambient temperature t_0.

According to this idea, Figure 2 shows the calculated dependences of the specific useful effect due to the utilization of heat of technogenic air emissions from the emission temperature at the outlet of the HP evaporator for different values of the source temperature (t_1 = 20°C; 30°C; 40°C; 50°C; 60°C), at different values of the calculated temperature of the coolant in the heating system (t_c^{est} = 40°C; 50°C; 60°C) and the estimated ambient temperature (t_0 = –20°C).

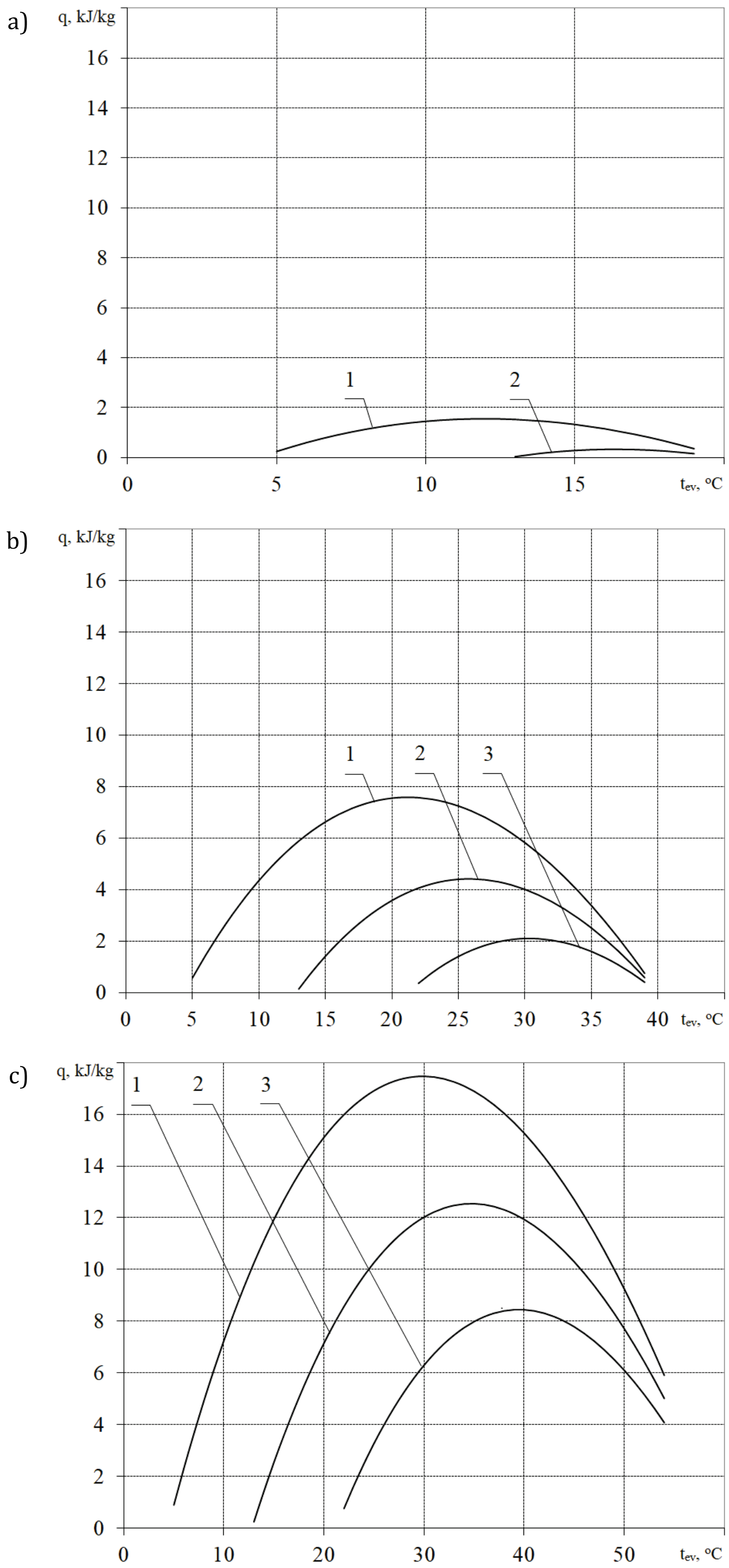


FIGURE 2. *Specific useful effect received as a result of technogenic air heat sources utilization by a HP depending on the temperature at the outlet of the HP evaporator: a), b), c) temperature of technogenic air emissions at the inlet of the HP evaporator* t_1 *= 20 °C; 30 °C; 40 °C; 50 °C; 60 °C respectively: 1-3 – at the design temperature of the heating coolant in the heating system* t_c^{est} *= 40 °C; 50 °C; 60 °C*

As can be seen from the graphs, these dependences are extreme in nature with the maximum useful effect, which corresponds to the optimal values of the exhaust air temperature at the outlet of the HP evaporator. The maximum useful effect increases with increasing temperature of technogenic emissions and with decreasing design temperature of the coolant in the heating system, i.e. under conditions that improve the operating conditions of the heat pump.

The obtained dependences also allow to determine the conditions for achieving the maximum of the useful effect, i.e. the optimal values of the system parameters. Figure 3 shows the dependences of the optimal air temperatures at the outlet of the HP evaporator and the corresponding dependences of the difference in air temperatures at the inlet and outlet of the HP evaporator, which characterize the degree of heat use of technogenic emissions. It is seen that the degree of utilization of heat of air emissions increases (as well as the maximum useful effect) with increasing emission temperature t_1 and with a decrease in the design temperature of the coolant in the heating system t_c^{est}. This is due to the fact that with increasing efficiency of HP conditions improve for deeper utilization of the lower heat source, i.e. the heat of air emissions.

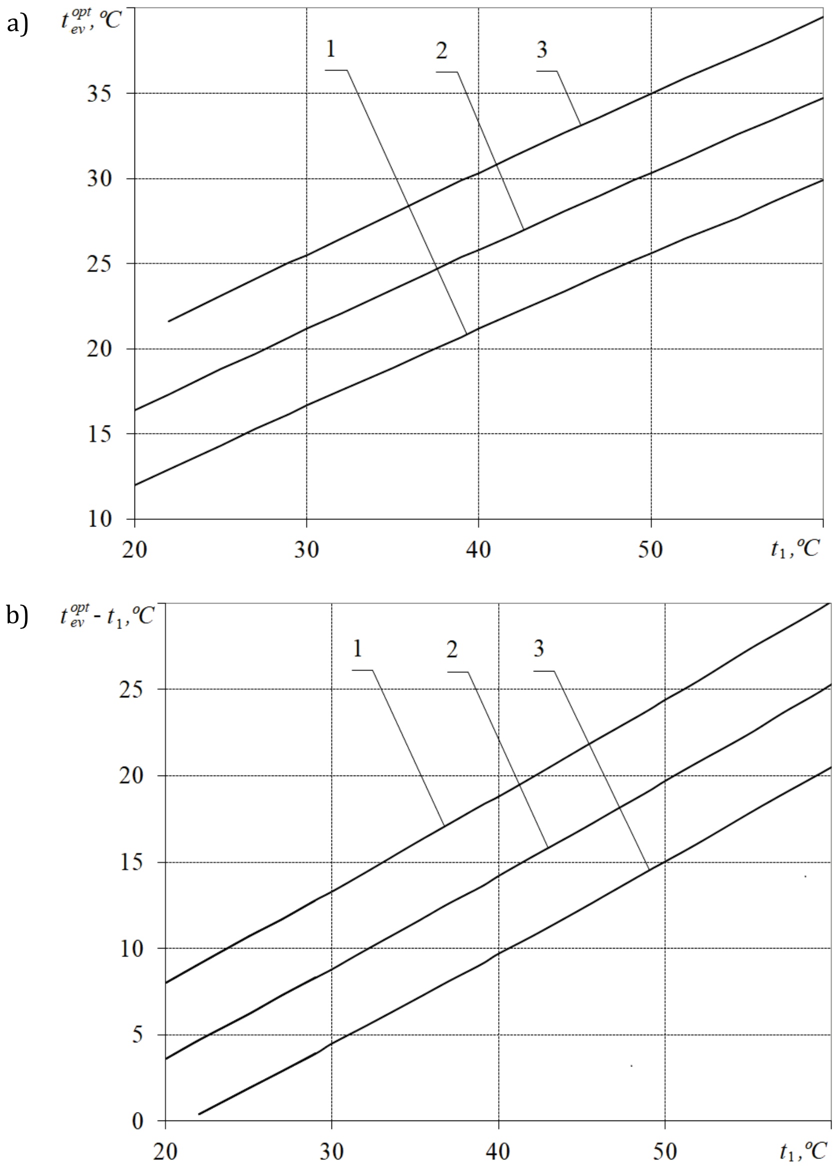


FIGURE 3. *Dependence of: a) the optimum temperature of the technogenic air source at the outlet of the HP evaporator from the temperature of technogenic air emissions, b) the degree of use of technogenic air source from the temperature of technogenic air emissions, respectively 1-3 – design temperature of heating coolant in the heating system* t_c^{est} *= 40 °C; 50 °C; 60 °C*

By further numerical analysis, it was found that with changes in ambient temperature, the values of the optimal temperatures of the technogenic air source at the outlet of the HP evaporator, and the corresponding maximum beneficial effects, also change. The results of this analysis for the optimal air temperature at the outlet of the HP evaporator are presented in Figure 4.

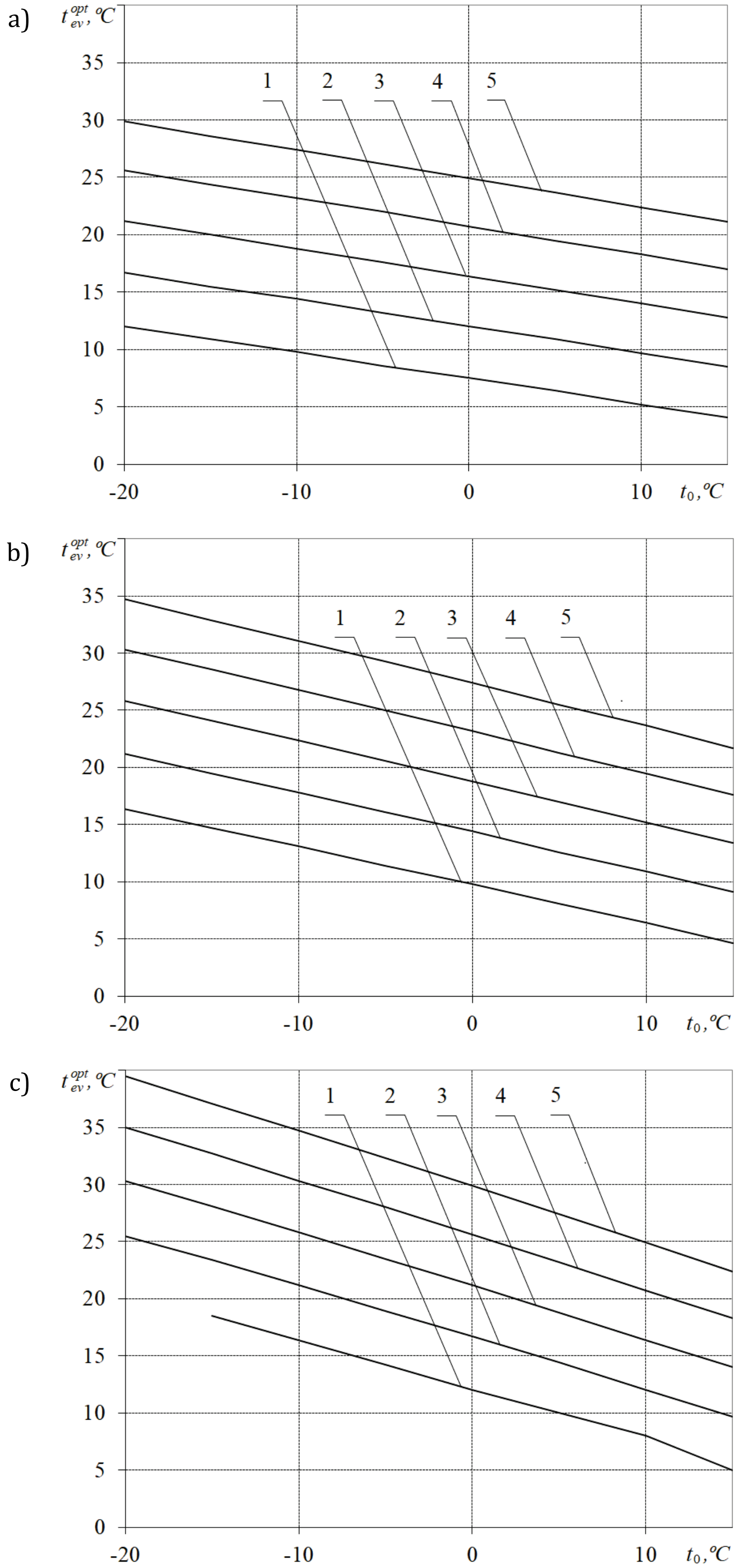


FIGURE 4. *Dependence of the optimum temperature of the technogenic air source at the outlet of the HP evaporator on the outside air temperature: a), b), c) the calculated temperature of the heating coolant in the heating system* t_c^{est} *= 40 °C; 50 °C; 60 °C, respectively 1-5 – at the temperature of technogenic air emissions* t_1 *= 20 °C; 30 °C; 40 °C; 50 °C; 60 °C*

Based on these dependences, the dependences of the optimal degree of heat utilization of air emissions (optimal temperature difference $t_1 - t_{ev}^{\text{opt}} = \Delta t_{ev}^{\text{opt}}$) were obtained, which are presented in Figure 5.

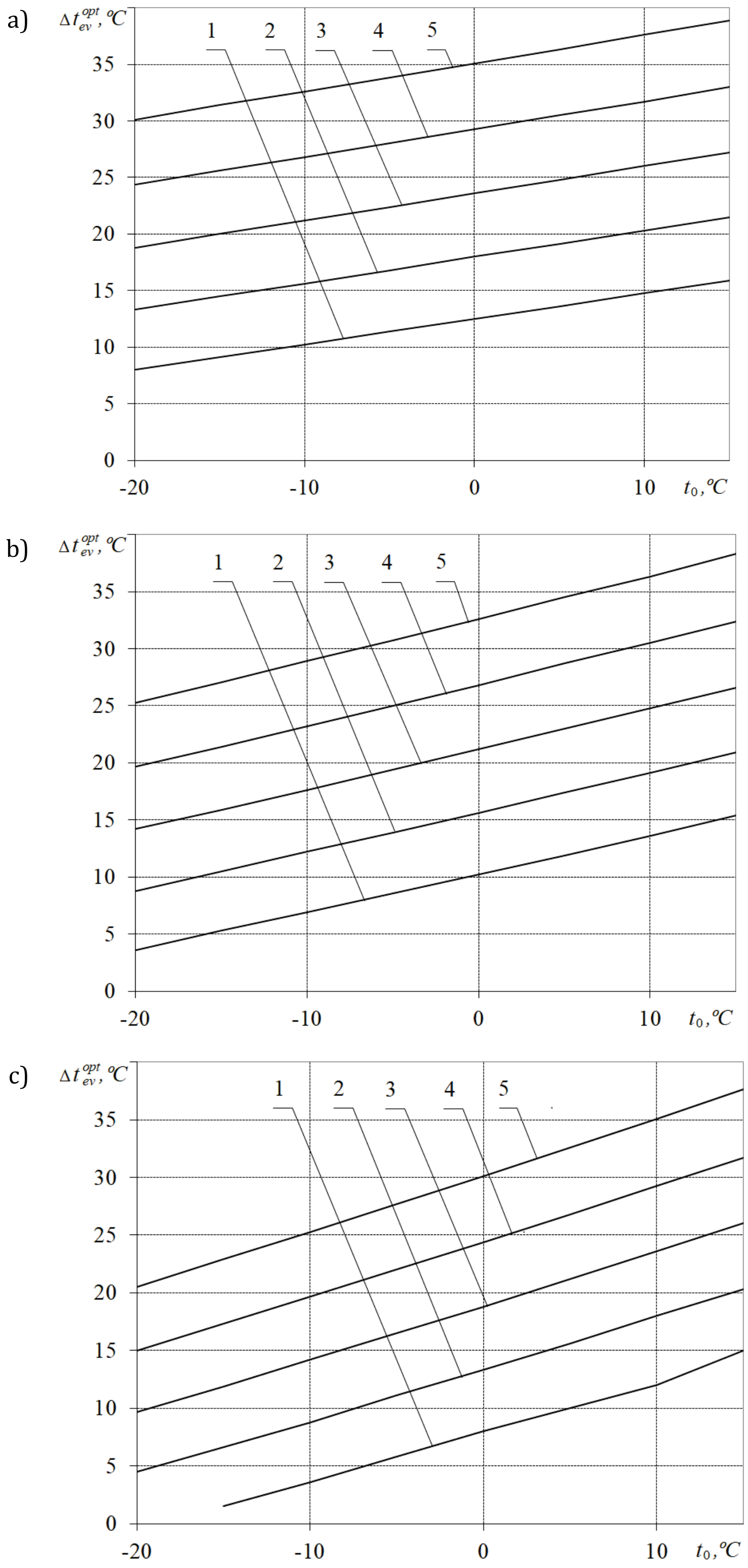
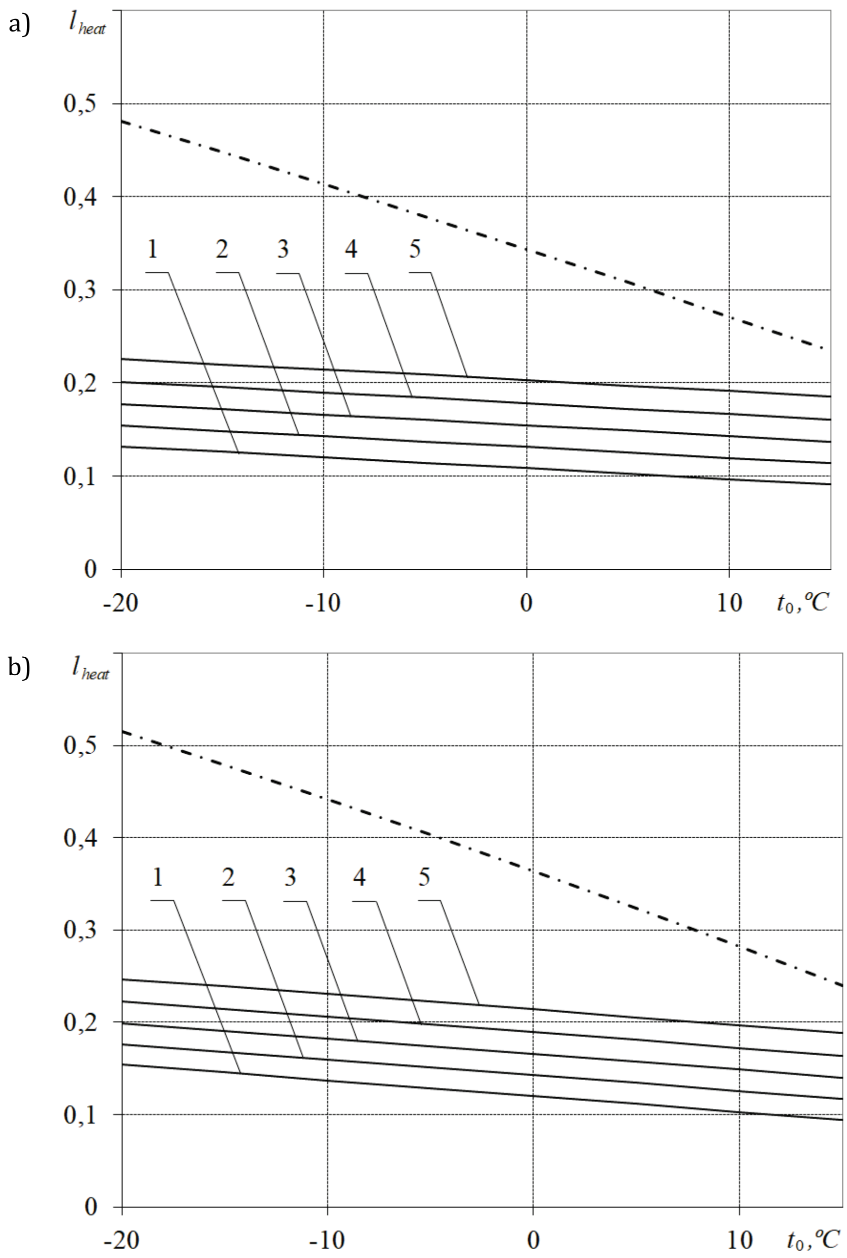


FIGURE 5. *Dependence of the degree of use of technogenic air source on the outside air temperature: a), b), c) the calculated temperature of the heating coolant in the heating system* t_c^{est} *= 40 °C; 50 °C; 60 °C, respectively 1-5 – at the temperature of technogenic air emissions* t_1 *= 20 °C; 30 °C; 40 °C; 50 °C; 60 °C*

The graphs show that the decrease in ambient temperature for all other parameters of the system (t_1 and t_c^{est}) leads to a decrease in the optimal temperature difference Δt_{opt} which corresponds to the maximum of useful effect as at the same time working conditions of the heat pump owing to the increase in temperature of the heat carrier worsen in heating system. It should be noted that with lowering the temperature of ventilation emissions below t_1 = 20°C for heat pump heating system with a design temperature t_c^{est} = 60°C at ambient temperature t_0 = −20°C the value of the optimal temperature difference Δt_{opt} decreases to negative values, which means no useful effect from utilization of air emissions and for their further utilization in the heating system an additional lower heat source is required with additional consumption of external energy to increase its potential.

To compare the energy efficiency of heat pump heating systems using the heat of technogenic air emissions and the heat of atmospheric air, specific costs of external energy for the heat pump heating system on the ambient temperature are plotted. The corresponding dependences are presented in Figure 6.



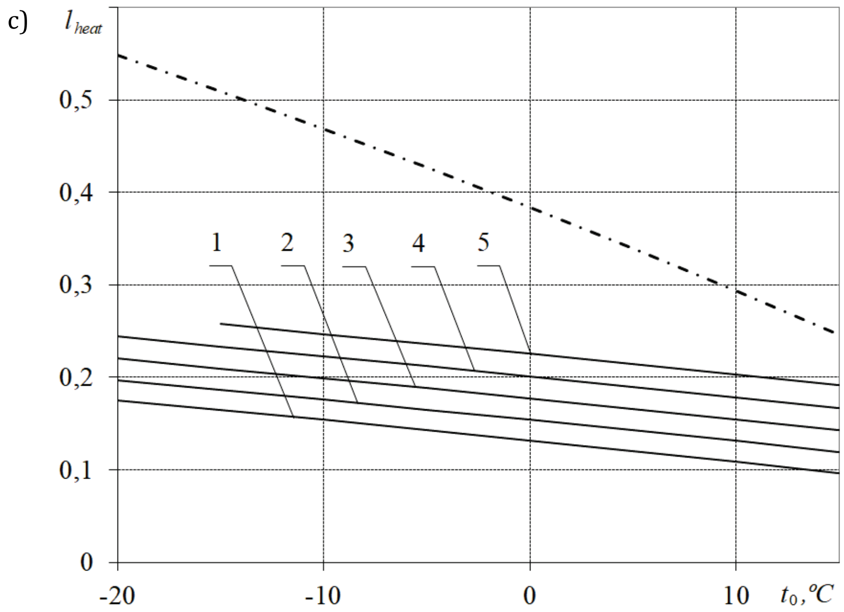


FIGURE 6. *Dependence of specific costs of external energy for the heat pump heating system on the ambient temperature: a), b), c) the calculated temperature of the heating coolant in the heating system* t_c^{est} *= 40°C; 50°C; 60°C, respectively: 1-5 – at the temperature of technogenic air emissions* t_1 *= 20°C; 30°C; 40°C; 50°C; 60°C*

As it can be seen from the graphs, the use of heat from techogenic air emissions is characterized by much lower specific energy consumption. The energy effect increases with decreasing ambient temperature due to the independence of the lower source temperature from the ambient temperature.

Conclusions

Analysis of the results of the study presented in this section allows us to draw the following conclusions.

1. The use of heat of technogenic air emissions in low–temperature heat pump heating systems allows to obtain a useful energy effect in the form of the difference between the utilized heat and the heat consumption of the primary fuel to drive the heat pump.
2. The maximum value of the beneficial effect is achieved under conditions of optimal use of heat of air emissions in the heat pump, ie under conditions of achieving the optimal value of the temperature difference between the inlet and outlet of the heat pump evaporator.
3. The optimal degree of heat use of air emissions in the heat pump (and, accordingly, the beneficial effect) increases with increasing temperature of technogenic emissions and with decreasing design temperature of the heating coolant in the heating system and decreases with decreasing ambient temperature.
4. When the emission temperature is reduced below 20°C and the outside air temperature to –20°C, the useful energy effect of air emissions disappears, ie to provide a heating system there is a need to use an additional lower heat source with additional external energy consumption for the heat pump.
5. The specific costs of external energy in the heat pump system using technogenic air emissions are weakly dependent on the ambient temperature and at its design temperature t_0 = –20°C can be reduced compared to the system using the heat of ambient air by about 3 times.

Conflicts of Interest: The author declares no conflict of interest.

References

[1] European Heat Pump Association (EHPA) [Electronic resource]. Access mode – http://www.ehpa.org/.

[2] Bezrodny M.K., Prytula N.O., *Thermodynamic and energy efficiency of heat pump schemes of heat supply:* Monograph. K.: NTUU "KPI" Publishing House "Polytechnic", 2016, 272p.

[3] Tkachenko O.O., *High–temperature processes and installations*: Textbook. K.: A.C.K., 2005, 480 p.

[4] Zhang J., Wang R.Z., Wu J.Y., *System optimization and experimental research on air source heat pump water heater*. Applied Thermal Engineering 27 (5, 6) (2007), pp. 1029-1035.