M. M. Chepurniy, Cand. Sc. (Eng.), Assist. Prof.; S. J. Tkachenko, Dc. Sc. (Eng.), Prof.; N. V. Resydent, Cand. Sc. (Eng.)

PECULIARITIES OF APPLICATION OF STEAM COMPRESSING HEAT PUMP PLANTS

Energy efficiency of heat supply from hot-water boiler houses and steam compressing heat pumping plants is analyzed. The expediency conditions of heat pumping plants application are determined.

Key words*: *heat pumping plant, evaporator, compressor, condenser, gas-turbine plant, waste-heat boiler.

Introduction

In conditions of prices increase for organic fuel much attention is paid to the usage of low temperature heat sources in heat pumping plants (HPP), used for heating, hot water supply, drying etc. However, multipurposeness of HPP is an important factor, they can be simultaneously be used both as heaters and coolers. By their nature, heat pumping plants (HPP) are means for transporting low-temperature heat from the environment or other source to higher temperature level. Steam-compressor heat pump plants, consisting of evaporator, compressor, condenser and throttling valve are most widely used installations. Low temperature heat Q_{ev} is supplied in the evaporator to working medium of heat pumping plant (HPP). In the compressor, mechanical energy N is supplied to working medium, as a result, energy $Q_{cond} = Q_{ev} + N$ with higher temperature level is removed from the condenser. The efficiency of HPP operation is evaluated by means of so-called thermal (heating) coefficient, presenting the relation:

$$\varphi = Q_{cond} / N = (Q_{ev} + N)/ N. \qquad (1)$$

Coefficient φ is a part of all other indices, characterizing the efficiency off HPP operation. It depends on the temperature of the working medium in the evaporator T_{ev}, in condenser T_{cond} and efficiency factor of the compressor η_{comp}. As it is known [1, 2], losses of energy in the drive of the compressor, are not part of thermal performance of HPP but dissipate in the environment.

Heat supply from heat pumping plants (HPP) is considered to be alternative to hot-water boiler heat supply. In every case there exists certain value of φ, at which energy efficiency of heat supply provided by HPP exceeds the efficiency of heat supply provided by hot-water boilers. Definition of real (operating) values of φ gives the possibility to choose the capacity of HPP compressor N for the preset power of heat supply Q_{cond} or evaluate power of heat supply Q_{cond} for the given capacity of low-temperature heat source Q_{ev}, i. e.

$$N = Q_{cond} / \varphi; Q_{cond} = \varphi \cdot Q_{ev} /(\varphi - 1). \qquad (2)$$

Taking into account the above-mentioned, we put forward the task to obtain the convenient engineering relations for φ definition and ways of evaluation of energy efficiency of HPP operation as compared with the operation of hot water boiler houses.

Basic results

Experimental data, given in [4, 5] in the form of $\varphi = f(T_{ev}, T_{cond}, \eta_{comp})$ with $\eta_{comp} = 0.82$, for example, are shown in Fig. 1.

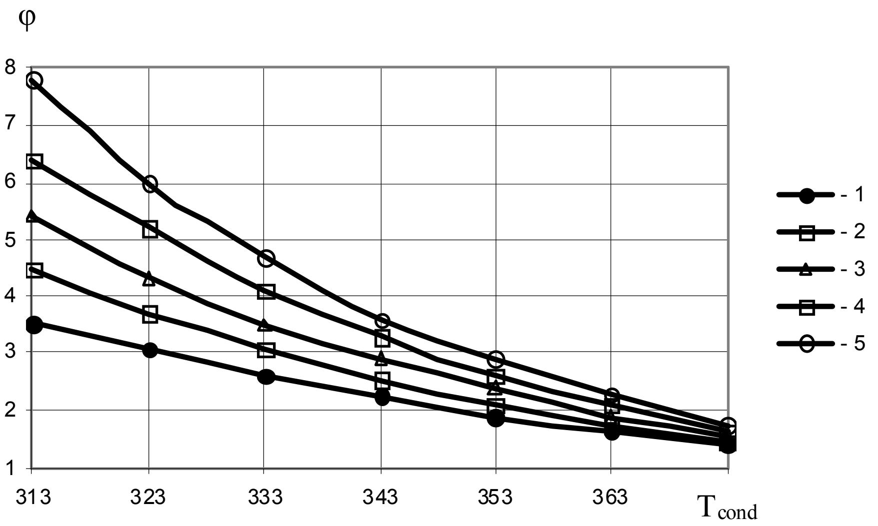

Fig. 1. Character of heating factor change :
1 – T_{ev} = 263 K; 2 – 273; 3 – 283; 4 – 293; 5 – 303

Calculation formula for φ coefficients determination is obtained on the basis of data, shown in Fig. 1:

$$\varphi = \exp\left(a - x \cdot T_{cond}\right) \cdot C, \tag{3}$$

where values a and x are given in Fig. 2, $C = 0.4\ \eta_{comp} + 0.678$.

Relation (3) with the accuracy ± 4.17 % agrees with the experimental data.

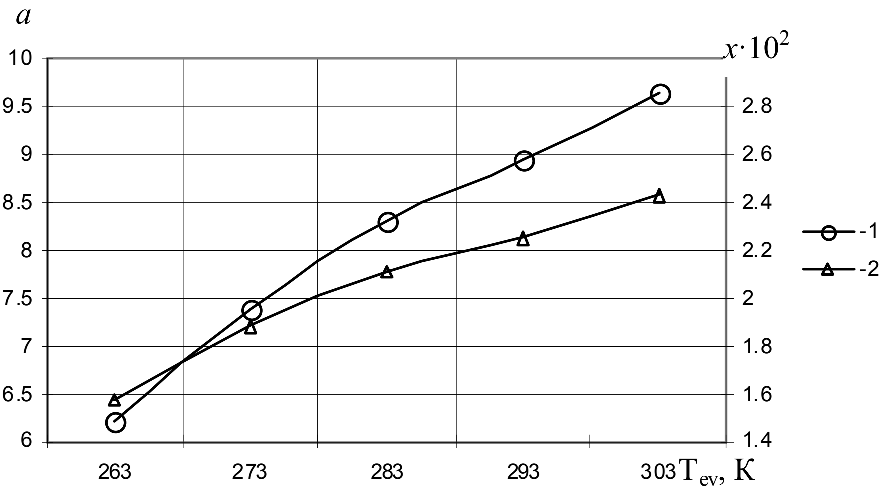

Fig. 2. Values of a (curve 1) and x (curve 2) in the formula (3)

It is seen from the Fig, that higher values of φ correspond to higher values of T_{ev} and lower values of T_{cond}. In other words, values of φ grow with the decrease of temperatures difference $\Delta T = T_{cond} - T_{ev}$, that agrees with [2, 3].

Comparison of energy efficiency of heat supply, provided from hot-water boiler and HPP is carried out at identical generated thermal capacity Q_{cond}, and on condition that, heat supply is performed in one and the same heating network. Equivalent fuel consumption per hot-water boiler, that supplies thermal power Q_{cond}, is determined by the formula, кg/s

$$B_{b0} = Q_{cond} / \left(Q_{ef} \cdot \eta_{b0}\right), \tag{4}$$

where $Q_{ef} = 29.3$ MJ /kg – is heat of combustion of equivalent fuel; η_{b0} – is efficiency of the boiler.

If the fan for air supply into boiler furnace and smoke exhauster for removal of fuel combustion products from the boiler, are available total capacity N_{du} of fan and smoke exhauster drives (total capacity of forced draft units) is taken from supply network. Equivalent consumption of conventional fuel at electric stations of energy system, that equals kg/sec corresponds to this capacity

$$E_{du} = N_{du} / (Q_{ec} \cdot \eta_{es} \cdot \eta_{en}), \tag{5}$$

where η_{es}, η_{en} – are average values of electric station and electric network efficiency, correspondingly.

It is clear, that total equivalent fuel consumption in boiler houses is, kg/sec

$$C_{bh} = C_{boil0} + C_{du}. \tag{6}$$

Calculations of C_{du} showed, that equivalent consumption of fuel per drive of forced draft units does not exceed 1.15% of fuel consumption per boiler on condition that $\eta_{es} = 0.34$ and $\eta_{en} = 0.9$. The latter values are defined by the data, taken from «Statistical yearbook of Ukraine-2011». Increase of fuel consumption by C_{du} stipulates the decrease of boilers efficiency by the same per cent, i. e., $\eta_{cond} = \eta_{b0} - 0.015$. This enables to determine the consumption of equivalent fuel directly by (4), if $\eta_{b0} = \eta_{cond}$.

In HPP with electric drive electric power N in taken from electric network. Equivalent consumption of conventional fuel at electric power station corresponds to this power, kg/sec

$$E_{pc} = N / (Q_c \cdot \eta_{es} \cdot \eta_{en}) = Q_b / (Q_c \cdot \varphi \cdot \eta_{es} \cdot \eta_{en}). \tag{7}$$

Economy or over expenditure of conventional fuel at HPP as compared with boiler house equals, t/h

$$\Delta E = 3.6 (E_{bh} - B_{es}) = \frac{3.6 \cdot Q_b}{Q_c} \left(\frac{1}{\eta_b} - \frac{1}{\varphi \cdot \eta_{es} \cdot \eta_{en}} \right). \tag{8}$$

It is clear that the economy of conventional fuel can be obtained on condition that $1/\eta_b > 1/(\varphi \cdot \eta_{es} \cdot \eta_{en})$ which corresponds to inequality

$$\varphi > \eta_b / (\eta_{es} \cdot \eta_{en}). \tag{9}$$

The expression (9) agrees with [3], where this result has been obtained in another way. Fig. 3 shows the dependences of the value of conventional fuel economy on condition: $Q_b = 1$ MW; $\eta_{es} = 0.34$ and $\eta_{en} = 0.9$.

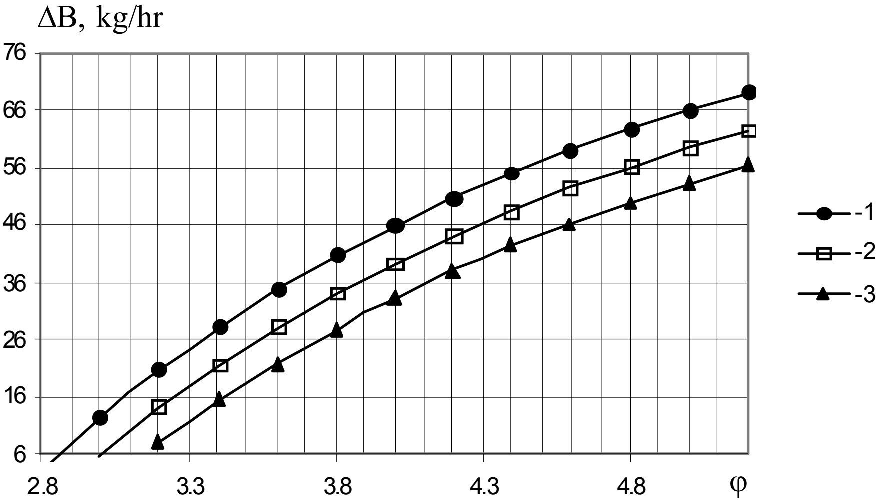

Fig. 3. Dependences $\Delta B = f(\varphi, \eta_к)$: $1 - \eta_к = 0{,}84$; 2 – 0,88; 3 – 0,92

From Fig. 3 it is seen that the value of φ exercises the greatest impact on the value of fuel economy. Under certain conditions the economy of fuel at HPP can reach 60 kg/hr.

It is known [6], that it is expedient to evaluate energy efficiency of thermal units operation by means of specific consumptions of conventional fuel, which represent the relations of conventional fuel consumptions to the volume of generated energy (in our case, to the value Q_b). Proceeding from (4) and (7), it is easy to define, kg/MJ

$$b_b = B_{bh} / Q_b = 1/(Q_c \cdot \eta_b), \qquad (10)$$

$$b_{es} = b_{HTT} = E_{ps} / Q_b = 1/(Q_c \cdot \varphi \cdot \eta_{es} \cdot \eta_{en}). \qquad (11)$$

Relative value of specific consumption of the fuel, expressed in per cent, must characterize energy efficiency or inefficiency of HTT operation, as compared with boiler house, i. e.

$$b_* = \frac{b_b - b_{HTT}}{b_b} \cdot 100 = \left(1 - \frac{\eta_b}{\varphi \cdot \eta_{es} \cdot \eta_{en}}\right) \cdot 100. \qquad (12)$$

If $b_* = 0$, then the consumption of conventional fuel in boiler house equals the equivalent consumption of the fuel in energy system for electric drive of HTT compressor. Positive values of b_* characterize percentage economy of the fuel at HPP, and negative values – over expenditure. To simplify the calculations, nomograph, shown in Fig. 4, is constructed.

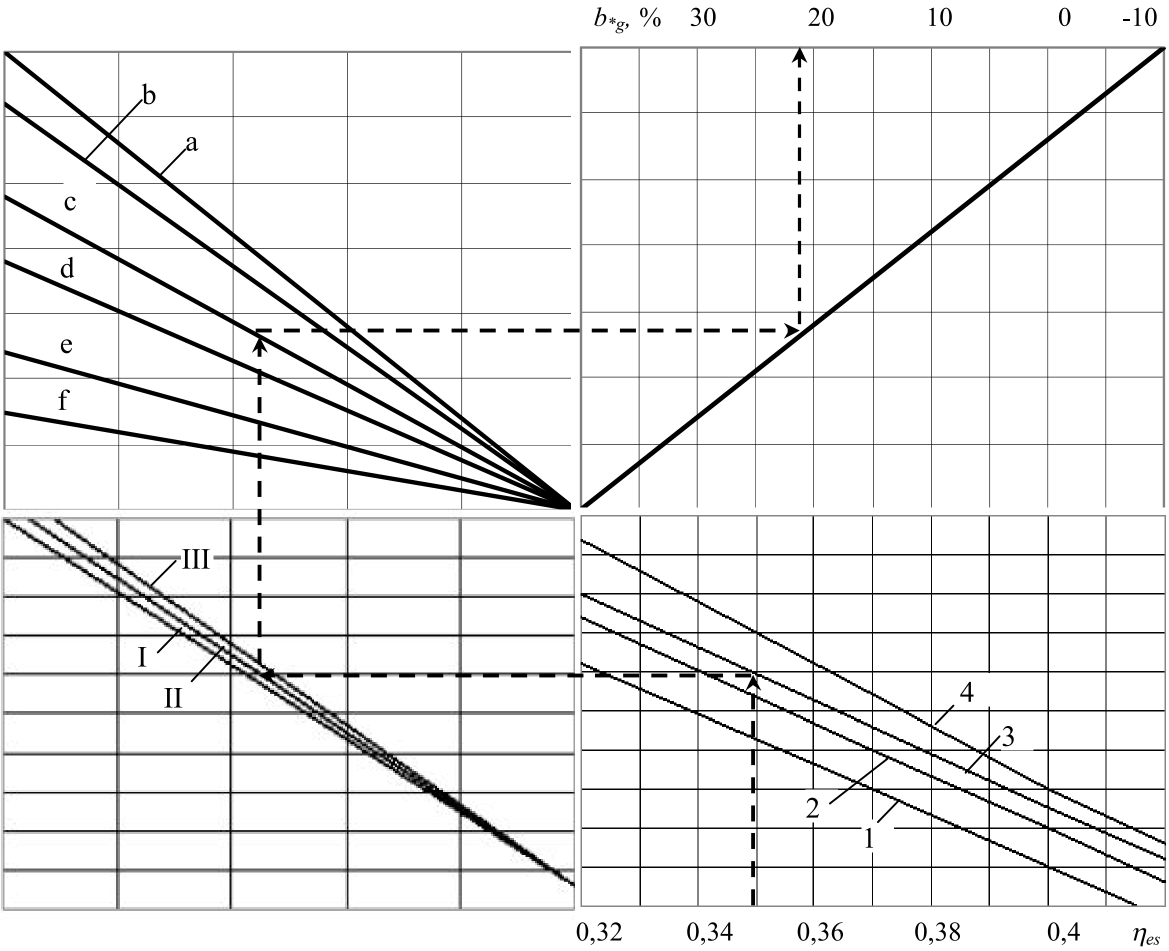

Fig. 4. Nomograph for determination of b_* : $1-\eta_b=0{,}84$; 2 – 0,88; 3 – 0,9; 4 – 0,94; I $-\eta_{en}=0{,}88$; II – 0,9; III – 0,94; $a-\varphi=2{,}6$; $b\ -3$; $c\ -3{,}5$; $d\ -4$; $e\ -5$; $f\ -6$

It is seen from Fig. 4, that values of φ and η_{es} exercise the greatest impact on the value of b_*.

Now let us consider economic aspect of HTT application instead of hot water boiler house.

Conventional fuel consumption in boiler house, t/hr

$$E_{bh}=\frac{3.6\cdot Q_b}{Q_c\cdot\eta_b}=\frac{3.6\cdot Q_b}{29.3\cdot\eta_b}=0.123\frac{Q_b}{\eta_b}. \tag{13}$$

Hour cost of the fuel, burnt in boiler house, hrs.

$$Z_b=E_b\cdot C_f\cdot\tau=0.123\cdot Q_b\cdot C_p\cdot 1/\eta_b, \tag{14}$$

where C_f – is the cost of conventional fuel, hrs/t.

Hour cost of electric energy, consumed by HPP compressor, hrs.

$$Z_{HTT}=N\cdot C_e\cdot\tau=Q_b\cdot C_e\cdot 1/\varphi, \tag{15}$$

where C_e – is the cost of electric energy, hr/(MW·h).

Relative hour cost of sources of power, %

$$W=\left(\frac{Z_b}{Z_{HTT}}-1\right)\cdot 100=\left(\frac{0{,}123\varphi S}{\eta_b}-1\right)\cdot 100=(H-1)\cdot 100, \tag{16}$$

where $S=C_f/C_e$.

If $W=0$, then financial expenditures for fuel sources in boiler house and HPP are the same. Positive values of W characterize percentage over expenditure of resources in boiler house, negative values – in HPP. It is seen from (16), that main indices, influencing the value of W, are φ and S. The character of the influence of these values on H complex in (16) for $\eta_b = 0.9$, is shown in Fig. 5.

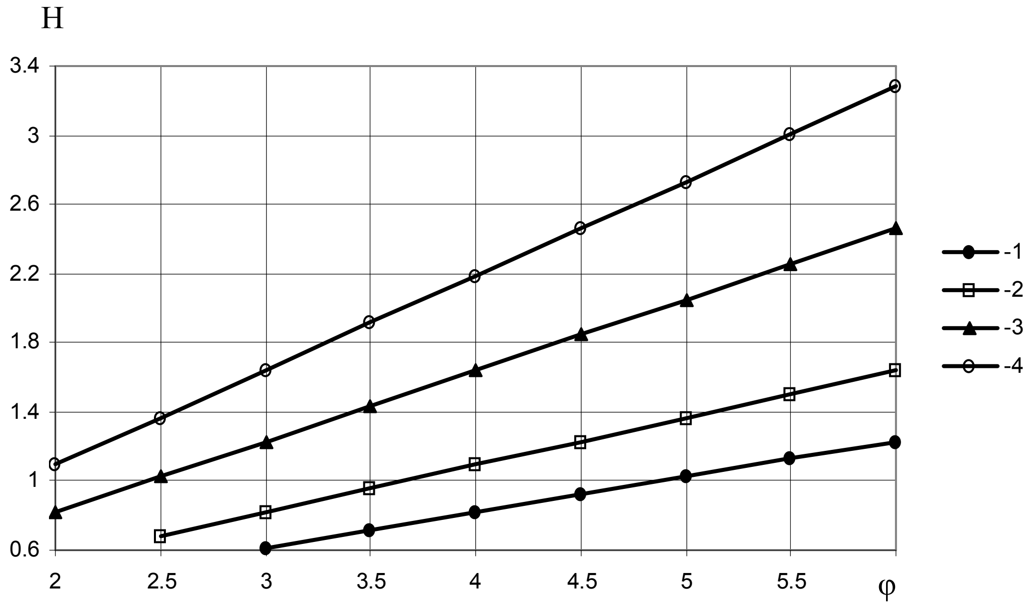

Fig. 5. Dependences $H = f(\varphi, S)$: $1 - S = 1{,}5$; 2 – 2; 3 – 3; 4 – 4

Economic efficiency of resources usage for energy sources in HPP increases, when φ and fuel prices increase. It should be noted that the price for electric energy grows at a slower rate, than the price for fuel. This circumstance must promote wider introduction of HPP But in case of low fuel prices limiting values of $\varphi_{\lim}$, when $H > 1$ and $W > 0$, increase. It is seen from Fig. 4, that if $S = 1.5$, then $\varphi_{\lim} > 5$. It should be noted, that the value of W is an indicator of economic component of HPP application, as it characterizes only expenditures for energy resources. It is a necessary supplement (12). For instance, it is seen from Fig. 5, that economic component of HPP application efficiency for $S = 2$ will be in case $\varphi > 3.6$, and energy component, by (12) – if $\varphi = 3$. That is why, we would like to draw your attention to the fact, that the increase of HPP energy efficiency cannot always be the guarantee of its economic efficiency.

One of the methods, aimed at the increase of energy efficiency of HPP operation is the application of gas engines as compressor drive [7]. Now we will compare the efficiency of heat supply from hot water boiler house and HPP with compressor drive from gas turbine. For certain gas-turbine installation (GTI) its certificate data are always known: net power– N_g, efficiency factor – η_g, temperature of gases exhausted in GTI – t_{eg}. Due to high values of t_{eg} GTI are equipped with waste-heat boiler, where at the expense of exhaust gases cooling to the temperature of $t_{w.b.}$ return heating water of heat supply system is heated.

The efficiency of heat supply of boiler house and HPP with gas-turbine drive of the compressor can be compared either on the condition of the same thermal power Q_b, or on condition, that useful power of GTI equals necessary power of the drive of HPP compressor. The comparison according to the first variant is connected with the difficulties of GTI choice, as the ratio between thermal powers of HPP condenser and waste-heat boiler is not known. Taking into account this fact, we choose GTI, useful capacity of which will be equal to the capacity of the compressor, i. e. $N_g = N$.

Consumption of the fuel at GTI, kg/s

$$B_g = N_g / (Q_e \cdot \eta_g). \tag{17}$$

Power of exhaust gas of GTU

$$Q_{e.g} = (1-\eta_g) N_g / \eta_g. \tag{18}$$

Coefficient of heat utilization of exhaust gases in waste-heat boiler [7]

$$\psi = \frac{t_{e.g.} - t_{w.b.}}{t_{e.g.} - t_{en}}, \tag{19}$$

where t_{en} – is the temperature of the environment, that, according to International norms, equals $15\,^\circ\mathrm{C}$.

Thermal capacity of waste-heat boiler

$$Q_{w.b.} = Q_{e.g.} \cdot \psi = (1-\eta_g) \cdot N_g \cdot \psi / \eta_g = \gamma \cdot N_g. \tag{20}$$

Thermal capacity of TPP condenser with certain value of heating coefficient

$$Q_c = \varphi \cdot N_g. \tag{21}$$

Total thermal capacity of TPP with gas turbine drive of the condenser

$$Q_t = Q_{w.b.} + Q_c = N_g \cdot (\gamma + \varphi). \tag{22}$$

Similarly (8), the formula for economy or over expenditure of equivalent fuel will be

$$\Delta B_g = 3{,}6 \cdot Q_c / Q_e \cdot \left[1/\eta_{b.h.} - 1/(\eta_g \cdot \varphi)\right]. \tag{23}$$

It is clear that the economy of equivalent fuel on TPP is achieved on condition $\eta_{b.h.} < \eta_g \cdot \varphi$. It increase of $\eta_{b.h.}$. and at increase of η_g and φ. The character of dependences $\Delta B_g = f\left[(\eta_g \cdot \varphi), \eta_{b.h.}\right]$ is similar to dependences show Fig. 3.

Fuel rate of equivalent fuel for heat generation, kg/MJ

$$b_g = B_g / Q_t = 1/\eta_g \cdot (\gamma + \varphi) Q_e. \tag{24}$$

Fuel rate of equivalent fuel in boiler house is determined by (10). Relative value of fuel rate of equivalent fuel equals, %

$$b_{*g} = \frac{b_{b.h.} - b_g}{b_{b.h.}} \cdot 100 = \left[1 - \frac{\eta_{b.h}}{\eta_g \cdot (\gamma + \varphi)}\right] \cdot 100. \tag{25}$$

Here, as in (12), positive values of b_{*g} characterize over expenditure of equivalent fuel in boiler house. For convenience of b_{*g} determination nomograph, shown in Fig. 6 is constructed.

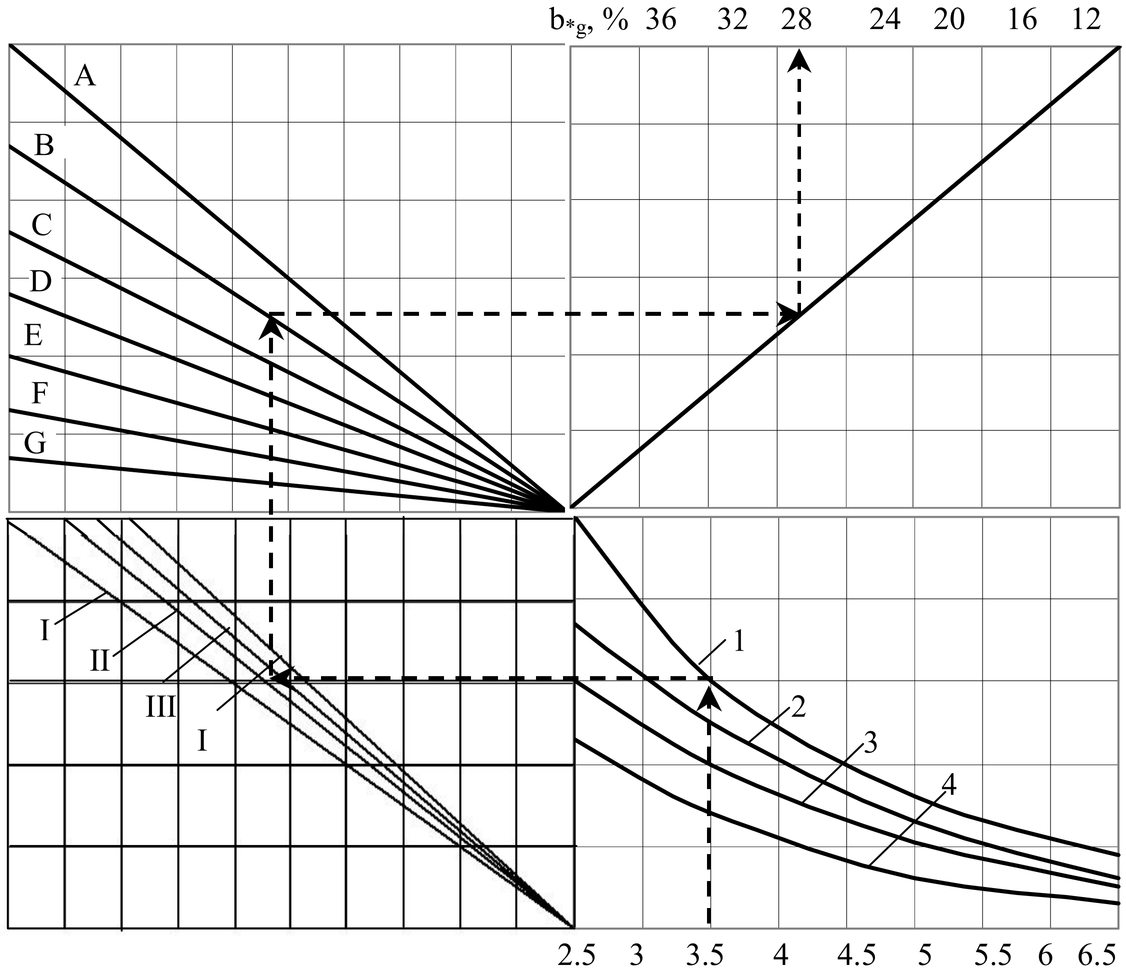

Fig. 6. Nomograph for determination of relative fuel rate of equivalent fuel on TPP with gas-turbine drive of the compressor: 1 – γ = 1,0; 2 – 1,4; 3 – 2; 4 – 2,6; I – $\eta_{b.h.}$ = 0,94; II – 0,9; III – 0,85; IV – 0,8; A – η_g = 0,3; B – 0,32; C – 0,34; D – 0,36; F – 0,4; G – 0,42

It is seen from the nomograph that the greatest impact on b_{*g} value is exercised by heating coefficient of HPP and efficiency factor of gas turbine unit. With the increase of these values the efficiency of using of HPP with gas turbine drive of the compressor increases. Comparing (12) and (25), we see that at equal values of $\eta_{b.h.}$ and φ on condition that $\eta_{es} \approx \eta_g$ energy efficiency of HPP with gas turbine drive of the compressor is higher than the efficiency of HPP with electric drive of the compressor, since $\eta_{en} < 1$ and $\gamma \geq 1$. It is easily seen. It is set: $\eta_{b.h.} < 0.9$; $\varphi = 3{,}2$; $\eta_{es} = 0.34$; $\eta_{en} = 0{,}9$; $\eta_g = 0.32 < \eta_{es}$; $\gamma = 1$. Then calculations of b_* by (12) and b_{*g} by (25) give: $b_* = 8{,}09\%$, $b_{*g} = 33\%$.

When TPP with gas turbine drive operates, both GTU and boiler house burn equivalent fuel at the same price. Taking into account (13), (14), (16) and (17), we obtain the expression for determination of hour relative consumption of equivalent fuel, %

$$W_g = \left(\frac{Z_{b.h.}}{Z_{HPP}} - 1 \right) \cdot 100 = \left(\frac{\eta_g \varphi}{\eta_{b.h.}} - 1 \right) \cdot 100. \qquad (26)$$

Comparing (25) and (26) we can see, that in this case the index of energy efficiency exceeds the value of the indicator of economic usage of energy resources. Over expenditure of the fuel in boiler house is greater, when η_c is less and the values of η_g and φ are greater, it is proved by (23). If, for instance, $\eta_g = 0.34$, and $\eta_{b.h.} = 0.9$, then limiting value of heating coefficient, at which the reduction of expenses for fuel takes place, equals $\varphi_{\lim} = 2.8$.

We draw your attention to the fact, that the decision, regarding the expedience of HPP usage in each given case should be taken, proceeding from detailed technical economic calculations, as it is known, that the specific cost of HPP and especially GTU, considerably exceeds the cost of boiler equipment. Besides, unit power of HPP is limited and does not exceed 5 – 6 MW.

Conclusions

1. Peculiarities of operation of thermal pumping plants with electric and gas turbine drive of the compressor are analyzed.

2. Convenient formulas have been obtained, nomographs for determination of HPP operation efficiency as compared with the operation of heating boiler houses have been constructed.

3. Conditions and limits of HPP basic characteristics measurement, as well as the impact of the relations of energy resources prices , at which the increase of HPP efficiency and fuel economy by 20% and more is achieved, have been determined.

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Chepurnyi Mark **–** Cand. Sc. (Eng.), Assist. Professor, Professor with the Department of Heat and Power Engineering.

Tkachenko Stanislav – Dc. Sc (Eng.); Professor, Head of the Chair of Heat and Power Engineering.

Rezident Nataliia **–** Cand. Sc. (Eng.), Senior lecturer with the Department for Heat and Power Engineering.

Vinnytsia National Technical University.