M. N. Chepyrniy, Cand. Sc. (Eng.), Assist. Prof.; N. V. Rezydent, Cand. Sc. (Eng.)

APPLICATION OF STEAM COMPRESSION THERMAL PUMPING PLANTS FOR UTILIZATION OF THE DISCHARGED HEAT OF STEAM TURBINES CONDENSERS

Energy efficiency of the combined plants on the basis of condensing turbines and steam compression thermal pumping plants has been analyzed.

Key words: *steam generator, steam-power plant, evaporator, compressor, condenser, thermal-pumping plant.*

Introduction

In recent years, as a result of organic fuel cost rise, much attention is paid to the utilization of discharging low temperature sources of energy in thermal pumping plants [1 – 4]. The analysis of application and trends of development of thermal pumping technologies are considered in [1], where it was noted that the usage of conventional low-temperature sources of heat in the form of atmospheric air, surface, soil and sewage is rather limited in natural-climatic conditions of Ukraine and requires considerable capital costs. In these conditions the search of other sources of low temperature heat becomes an urgent problem. Usage of the heat of discharged products of fuel burning is considered in [2]. Another low temperature source of heat can be heat released in the environment with cooling water from the condenser of steam turbines [3]. Condensing steam-power plants (SPP) have comparatively small efficiency (η_{SPP} < 43%), stipulated by considerable (50% and more) losses of heat in condensers. The temperature of cooling water at the output of turbines condensers is within the range of 24 – 30 ^{o}C. It is expedient to use this released heat in thermal pumping plants (TPP) for heating and hot water supply.

Proceeding from the above-mentioned the task to analyze the efficiency of combined installation on the base of condensing STP and HPS was put forward.

Main results

Schematic diagram of thermal pumping plant connection with the condenser of steam turbine is shown in Fig. 1, the diagram contains the following designations: consumptions – G, temperatures – t, pressures – P, enthalpies h in characteristic points of the diagram. Calculation Calculation techniques of thermal circuits of steam power plants are suggested in [4], and thermal-pumping plants - in [5]. Operation efficiency indices of certain steam-power plant, namely efficiency – η_{SPP} can always be determined, by certificate data, results of the tests or thermal circuit calculation.

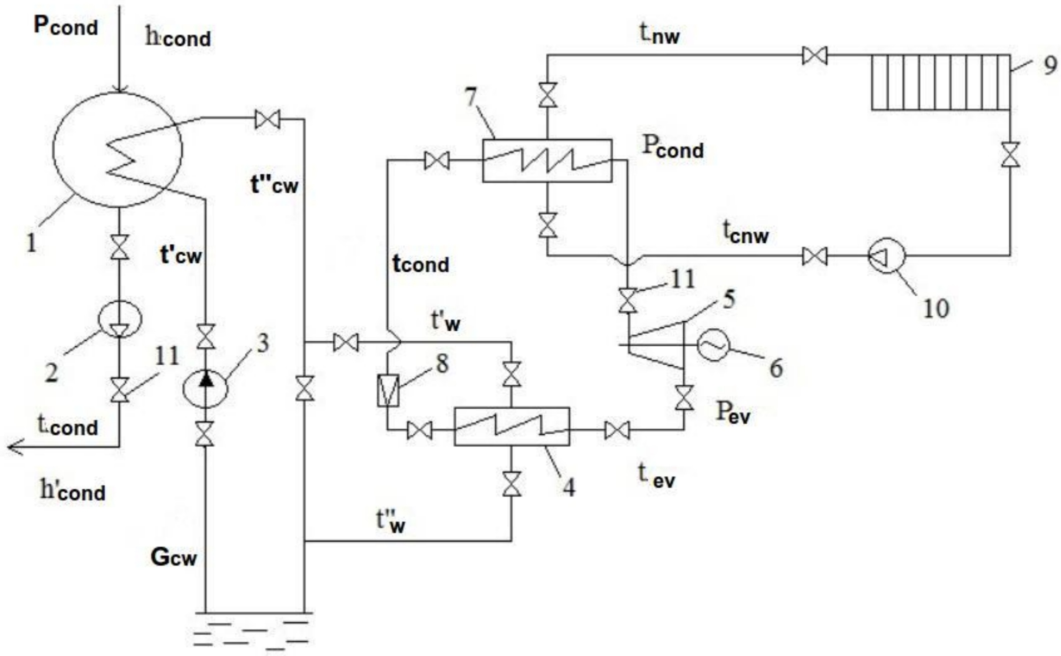

Fig. 1. Diagram of heat pumping station, powered from the condenser of steam turbine: : 1 – condenser of steam turbine; 2 – condensate pump; 3 – circulating pump; 4 – HPS evaporator; 5 – compressor; 6 – electric drive of HPS compressor; 7 – HPS condenser; 8 – throttle valve; 9 – heat load; 10 – networking pump; 11 – shut off valve

For condensing turbines thermal capacity, brought from steam generator to turbine plant, equals

$$Q_{SG} = Q_{TU} = N_E / \eta_{STP}, \tag{1}$$

where N_E – is power of STS electric generator.

Thermal capacity of turbine condenser is

$$Q_{cond} = Q - N_E = N_E (1 - \eta_{STP}) / \eta_{STP} = N_E \cdot \Psi. \tag{2}$$

For simplification of the calculations values of Ψ are given in Fig.2

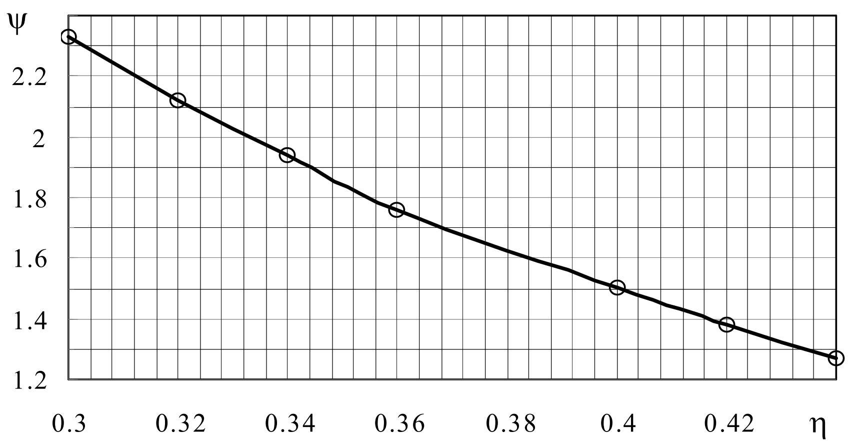

Fig. 2. Dependence of Ψ on the efficiency of steam turbine plants

Equivalent fuel rate at STP

$$B_{eq} = Q_{SG} / \left(\eta_{SG} \cdot Q_{lc}^{w}\right) = N_E / \left(\eta_{STP} \cdot \eta_{SG} \cdot Q_{lc}^{w}\right) / \eta_{STP}, \tag{3}$$

where η_{SG} – is the efficiency of steam generator; Q^{w}_{lc} = 29.3 MJ/kg – is heat of equivalent fuel combustion.

Fuel rate, kg/GJ

$$b_{eq} = B_{eq} \cdot 10^3 / N_E = 10^3 / \left(\eta_{STP} \cdot \eta_{SG} \cdot Q^{w}_{lc}\right), \quad (4)$$

Utilization factor of fuel heat

$$K_{UFN} = N_E / \left(B_{eq} \cdot Q^{w}_{lc}\right) = 10^3 / \left(b_{eq} \cdot Q^{w}_{lc}\right) = 34.13 / b_{eq} . \quad (5)$$

If we assume that cooling water from the condenser of the turbine in full volume arrives in the evaporator of TPP, then maximum power of the evaporator will be equal

$$Q^{max}_{ev} = Q_{cond}\left(\Delta t_{ev} / \Delta t_{cw}\right) = N_E \cdot \Psi \cdot \Theta , \quad (6)$$

where $\Delta t_{ev} = t'_{w} - t''_{w}$ – is water temperatures difference in the evaporator; $\Delta t_{cw} = t''_{cw} - t'_{cw}$ – the difference of cooling water temperatures in the turbine condenser; $\Theta = \Delta t_{ev} / \Delta t_{cw}$.

The analysis of thermal pumping plant operation is convenient to perform for single-unit power of HPS evaporator, i. e., Q_{ev} = 1 MW. The efficiency of HPS operation, as it is known, depends on the temperature of coolant evaporation in the evaporator t_{ev}, temperature of its condensation in condenser t_{cd} and efficiency of the compressor, i. e. on the value of heating coefficient φ, that characterizes the ratio of condenser power Q_{cd} to the compressor power N_{cm}. Value of φ can be determined directly in the process of HPS cycle construction on P-h diagram, or by dependences in [2]. Table 1 contains the results of calculations of main indices of TPP operation for conditions: Q_{ev} = 1 MW; compressor efficiency – η_{cm} = 0.84; t'_{w} = 29 °C; t''_{w} = 19°C; t_{ev} = 15 °C; working medium of HPS – R717 (ammonia).

Table 1

Main indices of heat pumping station operation

Indices	Condensation temperature in HPS, °C					
	50	60	70	80	90	100
Coolant consumption, *кg/c*	0.96	1	1.07	1.13	1.23	1.31
Power of compressor drive, KW	174.8	231.6	317.1	361.2	479.1	565.4
Condenser power, KW	1164	1220	1300	1336	1452	1538
Heating factor	6.66	5.27	4.1	3.7	3	2.72
Heating water temperature, *°C*	45	55	65	75	85	95
Return heating water temperature, *°C*	20	25	30	35	40	50
Power of the heating pump, KW	12	10.5	9.6	8.7	8.4	8
Aggregate electric power of the auxiliaries, KW	186.8	242.1	326.7	369.9	487.5	573.4

It is seen from Table 1, that with the increase of the condensation temperature of coolant vapour of thermal pumping plant (with the enhancement of the quality of thermal energy, supplied to the consumers) the efficiency of HPS operation decreases and electric power of auxiliaries grows. The character of φ and N_{aux} values change is shown in Fig. 3.

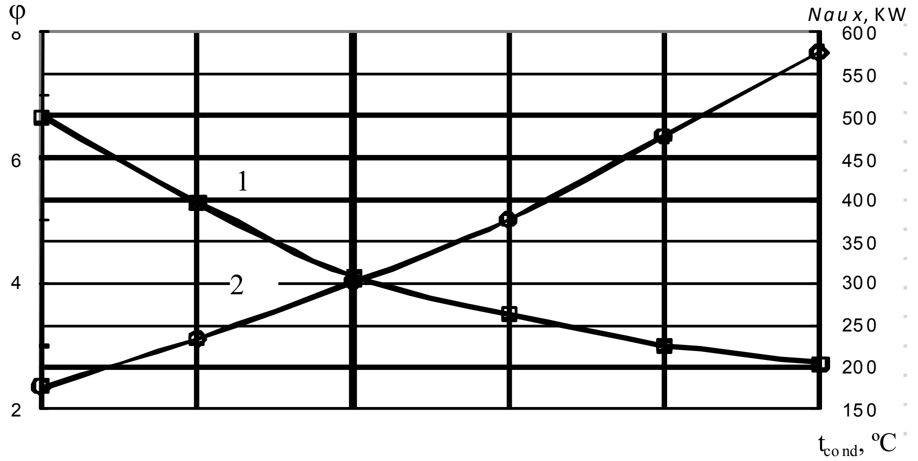

Fig. 3. Current values of the heating factor φ (line 1) and electric power of the auxiliaries – N_{aux} (line 2)

It should be noted that in the predetermined interval condensation temperature t_{cd} changes power of HPU condenser increases 1.32 time and power of the auxiliaries – 3 times.

Determined operation mode of steam-turbine unit is characterized by the conditions: N_E = const and B_{eq} = const. Total power released from combined installation, consrtructed on the basis of STP and HPU, will be

$$Q^{comb} = N_E - N_{com} + Q_{cond} = N_E \cdot (1 - \alpha_N + \alpha_N \cdot \varphi) = N_E \cdot \beta \,, \tag{7}$$

where $\alpha_N = N_{com} / N_E$ – is the share of electric power of STP, spent on the drive of TPP compressor; β – is the coefficient, characterizing the ratio of combined installation power to electric power of STP (Q_{com} / N_E) .

It seen, that if $\alpha_N = 0$, HPU does not function and only electric energy power N_E is supplied to the consumers and if $\alpha_N = 1$, only thermal energy of Q_{cd} power is supplied to consumers. On the base of (3), (4), (5) and (7), main indices of combined installation operation efficiency will be determined by the relations:

$$\left.\begin{aligned} b_{eq}^{comb} &= 10^3 / \left(\eta_{STP} \cdot \eta_{SG} \cdot Q_{lc}^{w} \cdot \beta\right) = b_{eq} / \beta \\ K_{UFH}^{comb} &= 10^3 / \left(b_{eq}^{comb} \cdot Q_{lc}^{w}\right) \cdot \beta = K_{UFH} \cdot \beta \end{aligned}\right\} \tag{8, 9}$$

It follows from the formulas, that specific flow rate of conventional fuel in the combined installation decreases, and utilization factor of fuel heat increases, since if $\alpha_N > 0$ $\beta > 1$.

Let us introduce designations

$$N^{comb} / N_E = \left(N_E - N_{comp}\right) / N_E = a \,,$$

$$Q_{cond} = Q_T ; \quad Q_T / N_E = b \,. \tag{10}$$

Taking into account (7) it is easy to determine that

$$b = \beta - a \,. \tag{11}$$

Let us evaluate profit-making component of the combined installation efficiency relatively basic efficiency (STP). Revenues of the energy, supplied during time unit (τ = 1) from STP and combined installation will be:

$$S_{STP} = N_{E\sup} \cdot P_E \cdot 1 = N_E \cdot P_E \,, \tag{12}$$

$$S^{comb} = N^{comb} \cdot P_E \cdot 1 + Q_T \cdot P_T \cdot 1 = \left[\left(N_{E\sup} - N_{comp}\right) \cdot P_E + Q_T \cdot P_T\right] \cdot 1 \,, \tag{13}$$

where N_{Esup} – is electric power, supplied from STP; P_T and P_E – are tariffs for thermal and electric energy, correspondingly.

If $\Delta S = S^{comb} - S_{STP}$ we refer to S_{STP}, then, taking into account (10) and (11) we obtain

$$J = \Delta S / S_{STP} = a + b(P_T - P_E) - 1 = a + b \cdot \mathrm{P}^* - 1. \quad (14)$$

Value J, like [6], is the indicator of profitable efficiency of the installation. If $J = 0$, then the combined installation does not have any advantage over the basic one; if $J < 1$ the combined installation is less profitable than the basic one, and $J > 1$, the combined installation is more profitable than the basic one. Values of J greatly depend on the ratio of tariffs for thermal and electrical energy. It is easy to note, that if $P_T = P_E$ $J = \beta - 1$.

Let us evaluate the operation indices of combined installation on the specific example. We will select STP with the condensing turbine К-12-35, manufactured by Kaluga Turbine Plant with the characteristics [7, 8] as the basic installation: rated electric power – $N_E = 12$ MW; pressure and steam temperature before the turbine – $P_o = 3.43$ MPa, t=435^0 C; parameters of steam after the turbine $P_{cond} = 4.9$ kPa, t_{cond}= 32.5^{0}C; number of non regulated steam release – 3; temperature of supplied water – $t_{sw} = 150$ ^{0}C; steam consumption at rated power and rated steam consumption – $D_o = 53.2$ t/h.

As a result of calculation of STP thermal circuit with the efficiency factor of steam generator $\eta_{SG} = 0.92$ it is determined: steam consumption in turbine condenser – 43.92 t/h; STP condenser capacity – $Q_{cond} = 26.71$ MW; capacity of steam turbine unit – 38.71 MW; equivalent fuel consumption – $\eta_{STU} = 0.31$; equivalent fuel consumption – $B_{eq} = 1.436$ kg/s; specific consumption of equivalent fuel – $b_{eq} = 123.79$ kg/GJ; energy consumption for proper needs of STU – $N_{PN}^{STU} = 0.41$ MW; fuel heat usage coefficient – $K_{UFN} = 0.275$.

Let thermal power, supplied to the consumers from TPP condenser is – $Q_{cd} = Q_T = 25$ MW. For the chosen value of Q_T, electric power of auxiliaries and other conditions indicated before the Table 1 main indices of TPP and combined installation operation were calculated, the obtained results are presented in Table. 2. This Table also contains calculated consumption of equivalent fuel in case of distributed scheme of energy supply: electric energy from the grid and heat from the hot-water boiler, the efficiency of the boiler equals the efficiency of the steam generator.

Table 2

Main indices of the combined plant operation

Indices	Condensation temperature in TPP, °C					
	50	60	70	80	90	100
Heating factor	6.66	5.27	4.1	3.7	3	2.72
Power of HPU evaporator, MW	21.247	20.256	18.902	18.244	16.667	15.810
Power of HPU compressor, MW	3.753	4.744	6.10	6.756	8.333	9.19
Delivered electric power, MW	7.592	6.643	5.318	4.685	3.13	2.284
Specific equivalent fuel consumption, kg/*GJ*	44.06	45.39	47.37	48.37	51.04	52.63
Utilization factor of fuel heat	0.77	0.752	0.72	0.705	0.668	0.648
Equivalent fuel consumption in case of distributed scheme of energy supply, kg/*s*	1.835	1.720	1.563	1.487	1.301	1.203
Saving of equivalent fuel at combined plant, kg/*hr*	1.436	1.022	0.457	0.183	-0.486	-0.838

It is seen from Table 2, that the power of TPT compressor increases considerably with the increase of condensation temperature in TPP condenser (with the growth of heat quality, supplied to the consumers). As a result, the supply of electric energy decreases and the combined installation approaches to the installation, that supplies only heat. The above-mentioned results in excessive consumption of fuel and decrease of the efficiency of combined installation operation.

For the preset conditions the most efficient are operation modes of combined installation when heating coefficient $\varphi \geq 4$, that corresponds to working medium condensation temperatures in TPP –

$t_{cd} \leq 70\ ^0$C. It is possible to enhance the efficiency of operation at less values of φ at the expence of increase of working medium evaporation in the evaporator of TPP, i. e., at the increase of cooling water temperature at the outlet of turbine condenser, but it is rather complicated for condensing turbines, designed for generation of electric energy. Another way of enhancement of the efficiency of combined installation operation of such type is the application of up-to-date heating devices, that operate with comparatively low temperatures of water (t_{NW} = 50 – 60 ºC) [9].

Regularity of combined installation efficiency profit component change at different relations of tariffs for heat and electric energy are shown in Fig. 4.

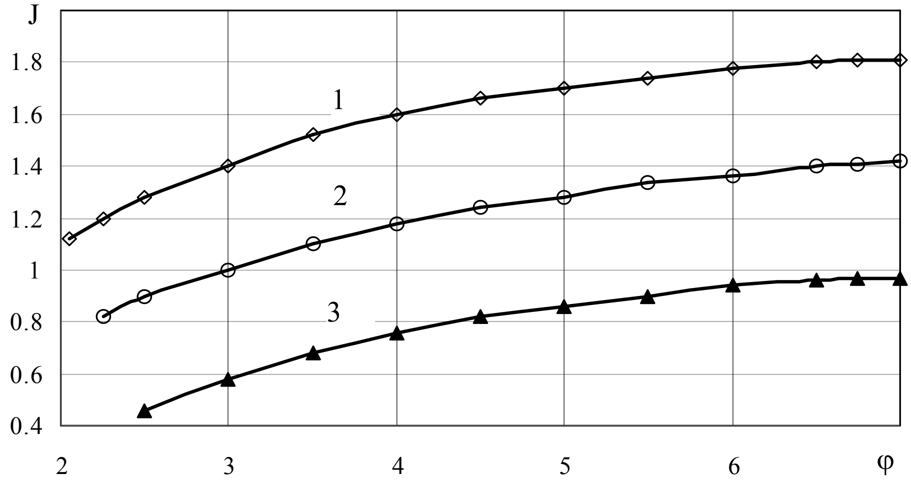

Fig. 4. Current values of efficiency profit component indicator
1 – P_T/ P_E = 1; 2 – 0.8; 3 – 0.6

Profitability of STP and TPP based combined istallation greatly depends on the ratio of tariffs for thermal and electrical energy. The greater this relation is the higher is the profitability of the combined installation. On condition of the same price for thermal and electric energy ($P_T = P_E$) profitable efficiency of the combined installation is 1.2 – 1.8 time higher, than of STP in the range of heating coefficients variation. With the decrease of the relation (P_T / P_E < 1) profit indicator of combined installation usage is shifted to greater values of φ. For the case of P_T / P_E = 0.6 in our example the application of the combined installation is not expedient.

Taking into account that maximum power of modern TPP does not exceed, as a rule, 5 – 6 MW, thermal pumping plant for the considered example must consist minimum of three TPP. This circumstance greatly increases both capital investment and the term of recoupment of capital investment. Besides, comparing the efficiency indices of the given combined installation operation with thermal power installations operating on the base of counter-pressure with steam extraction turbines [10] with, we can make a conclusion that the efficiency of the latter is higher then the efficiency of the combined installations on the basis of condensing STP and TPP and requires for less capital investmentд.

The expediency of application of this or that power installation for co-generation and supply of thermal and electric energy must be solved after detailed economic calculations, taking into account the tariffs for these rinds of energy.

Conclusions

1. Usage of exhaust heat from steam turbines condensers in thermal pumping plants is characterized by the reduction of electric energy supply from basic installation.

2. As a result of low temperature potential of exhaust heat the most efficient operation of thermal pumping plant is observed at rather low temperatures (50 – 70 ºC) of supplied heat.

3. The efficiency of the combined installation on the basis of condensing STP and TPP is the higher the greater is ratio of tariffs for heat and electric energy.

4. The efficiency of operation of the above-mentioned combined installation is lower than the efficiency of the installations on the base of counter-pressure turbine with steam extraction.

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

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

Vinnytsia National Technical University.