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Study on the cost effectiveness of a combined evaporation unit

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Abstract. In a thermal power plant, water treatment plants are used to perform body losses in the main steam cycle using one of the following methods of water preparation: chemical, thermal, membrane or combination of them. One of the main advantages of thermal desalination is the low impact on environmental pollution. In the light of the ever-increasing environmental demands on energy processing systems, thermal desalination is becoming an increasingly preferred method of water treatment, since it allows wastewater to be used as feed water for evaporators. In our country, multi-stage evaporation units are quite widespread. They are used as operating units in industrial heating plants and as backup for condensation plants. These units have high thermal costs and are characterized by an excess of secondary vapour of the last evaporation step, which needs to be continuously removed from the plant to avoid loss of productivity. The main objective of this work is to minimize the total and thermal costs of the production of additive water in the main steam turbine cycle of the thermal power plant and the treatment of wastewater in evaporation complexes, as well as to determine the technical economic effectiveness of applying some technical solutions for the recovery of excess steam in multi-stage evaporation units.

1. Introduction

For the preparation of additive water in the main steam turbine cycle, the thermal power plant (TPP), as well as the treatment of wastewater, use one of the following methods: chemical, membrane, thermal or a combination of all. However, regardless of the method used in preparing to recharge the cycle of the steam turbine plant, electricity and, practically always, heat are necessary. The consumption of electricity and heat is the fuel or heat component of the production cost of additional water.

This component, along with capital costs, occupies one of the most important places in the cost structure of the production of additional water at the TPP. Despite the fact that the problem of choosing the method of water treatment is given considerable attention in our literature, the structure of the production cost of distillate is best reflected in [1] where it is shown that the cost of thermal and electrical energy accounts for about 40% of the total cost of distillate production (excluding the heating of the additive water to the temperature in the deaerator of the turbo unit). In fact, the fuel component of the production cost of the additive water, taking into account its heating to temperature in the deaerator, can range from 30% to 70% for various water treatment methods.

Water treatment plants (WTP) usually use specific heat consumption and underproduction of electricity as criteria for thermal efficiency, as well as heat consumption per 1 m 3 of additional water. From the authors' point of view [3] when comparing the evaporative units of different types or installations operating under different schemes, the specific heat consumption sufficiently characterizes the thermal economy of each of them, if, in all cases considered, the heating steam is brought to the installation from the same turbine selection.

Specific heat consumption $d_{h.c.}$ $\left(\frac{J}{kg}\right)$ is calculated by the formula [3]:

$$d_{h.c.} = \frac{Q_{t.c.}}{D_{w.c.}}, \qquad (1)$$

Where $Q_{t.c.}$ – total heat consumption for additive water production; $D_{w.c.}$ – additive water consumption.

The specific heat flow criterion is suitable for comparing (comparing) the thermal economy of the various schemes and types of evaporation units (EU) included in the same selection and having little connection with the main operating

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environment of the unit, Otherwise, along with the heat flow rate on the EU, it is necessary to take into account changes in the generated electric power of the turbocharger, solve the problem of finding an integral value characterizing the thermal economy.

In the same paper, the following formula is proposed for the calculation of total heat consumption:

$$Q_{t.c.} = D_{pri} \cdot (h_{pri} - h'_{pri}) - Q_{rem}, \quad (2)$$

where D_{pri} – consumption of heating (primary) steam $\left(\frac{kg}{s}\right)$; h_{pri} и h'_{pri} – respectively, enthalpy of vapour and condensate at saturation temperature $\left(\frac{J}{kg}\right)$; $Q_{отв}$ – heat removed from installation in other lines or heat exchangers of an electrical station (W).

However, this formula does not take into account the values of heat of steam flows. When comparing different schemes and types of IS, the equality of unit heat costs in the variants does not mean the same underproduction, for example, in the case of inclusion in different selections, the use of secondary steam heat in the heat exchangers of steam turbine plants (TPP). In this case, in order to account for the under-generation of electricity in [3] it is proposed to calculate the heat consumption by the formula:

$$Q_{t.c.} = (D_{pri} - \sum D_{sel}) \cdot (h_{pri} - h'_{pri}), \quad (3)$$

$\sum D_{sel}$ – total reduction of steam flow from turbine selection to the heat exchangers of the power plant due to the use of heat of steam and water flows away from EU.

Even for simplest installations, one of the fuel components is the consumption of electricity by EU itself. Thus, a full description of the fuel component requires a criterion that takes into account both heat and electricity consumption.

The authors [3] did not set the task of estimating the total fuel component of the cost of production, and in the reduced costs took into account the consumption of electricity and heat by simple coefficients of the unit cost of heat and electricity. However, if the determination of the cost of electricity is not a problem, the cost of steam heat causes significant difficulties. In addition, the specific heat flow criterion can only be used as a general indicator to determine which of the circuits or installations is more economical from the thermal point of view, but the actual value of this indicator, or the difference between the values of the indicator for the different options, does not give a direct idea of the fuel component. Such a view can only be given by a criterion that is easily converted into monetary or fuel form.

When considering distillation plants in general, the specific flow criterion for the evaluation of thermal economy is not possible even within the EU class multi-stage evaporation units - instantaneous evaporators - horizontal pipe layer evaporators excluding under-generation. If, however, a specific heat flow indicator is used, it is more appropriate to recalculate it for the specific heat consumption of fuel. The application of the specific heat flow criterion is justified for UPU serving for desalination of salt water, and there is a widespread use [4, 5]. However, it is not entirely justified for the UPU intended for the production of additive water for boilers at the thermal power plant.

In [6] a comparison of different methods of analysis of real thermal TPP circuits was made. According to the author of this work, the following methods are preferable:

- Power coefficient change method;
- Heat coefficient method;
- Power increment factor method.

In fact, when the ERP is activated, the power generated by the power plant is reduced, so the operation of these plants is associated with underproduction of electrical energy.

In this regard, the use of the under-generation criterion is more appropriate for determining the fuel component of an ERP producing additional water in the main steam cycle of a power plant. This indicator is useful for assessing the thermal economy of water treatment plants that consume heat from turbine selections. It does not matter what heat flow rate is brought or discharged from the TPD. It is only important how this affects the thermal efficiency of the turbine, that is, the generation of electricity and heat supply by the consumer.

The thermal component can be assessed in two ways:

– the fuel component is the difference between the generation of electricity by a turbine without the operation of a water treatment unit (WTU) and the generation of electricity by a turbine during the operation of a (WTU), that is, the generation of electricity is a variable value, and the heat flow to the turbine system constant ($N_э = var$ in $Q_o = const$);

– fuel component is associated with additional fuel consumption for production of additional hot steam consumption compensating heat consumption of water treatment plant ($N_o = var$ при $Q_э = const$).

However, the use of each of these assessment options has limitations. On the one hand, the calculation of underproduction has a physical flaw: all power units generate the specified mode load independent of the WTU, that is, the actual operation of the water treatment unit is associated with additional fuel consumption. On the other hand, the manufacturer provides the characteristics of turbine modes, and for the nominal operation mode, taking into account the additional fuel consumption, the steam consumption in the turbine «head» may exceed the maximum value.

It can be said that in the case of neglect of changes in pressure and enthalpy in the flow part of the turbine, the fuel component calculated through underproduction of electricity is equal to the fuel component calculated through additional consumption of fuel. By the way, this assumption allows not to take into account changes in the heat consumption of consumers when turning on the water treatment plant. In this case, the underproduction of electricity can be calculated by the power coefficient method. This method is used by many authors [2, 7-15] when investigating the fuel component of EU.

In the simplest case, the specific underproduction of electricity in distillate production is calculated using the formula [2]:

$$w = \frac{\eta_{em} \cdot Q_{am} \cdot e}{3{,}6 \cdot D_{w.c.}} \left(\frac{kW \cdot h}{t}\right), \tag{4}$$

Q_{am} – the amount of heat for the water treatment plant (kW); e – coefficient of variation of the extraction power of heat; $D_{w.c.}$ – additive water consumption $\left(\frac{kg}{s}\right)$; η_{em} – Electromechanical efficiency of the turbine.

In the heating mode of the turbine plant operation, the fuel component of the production cost of the additional water is connected to the specific fuel consumption calculated by the power increment factor method [2]:

$$b = \frac{Q_{h.c.}}{D_{w.c.}} \cdot \left(\frac{1+\varepsilon}{Q_h^f \cdot \eta_b \cdot \eta_l^h \cdot 10^3} - \frac{b_{rep} \cdot \eta_{em} \cdot \varepsilon}{3{,}6}\right) \left(\frac{kg\ (heat)}{t\ (add\ water)}\right), \tag{5}$$

$Q_{h.c.}$ – heat consumption with steam from the selection of the turbine (kW); $D_{w.c.}$ – additive water consumption $\left(\frac{kg}{s}\right)$; ε – coefficient of increment of the separation power from which heat is supplied; Q_f^h – fuel specific heat $\left(\frac{kJ}{kg}\right)$; η_b – boiler efficiency; η_l^h – takes into account the loss of heat during its transmission from the boiler to the turbo system, in shares; b_{rep} – specific fuel consumption for electricity generation at the replacement power plant $\left(\frac{kg}{kW \cdot h}\right)$.

Thus, the mode of operation of the turbocharger predetermines the use as an indicator of the fuel component of either specific underproduction of electricity or specific fuel consumption.

However, the operation of some water treatment plants may not be related to the undergeneration of electricity by the turbine system, for the simple reason that it is not connected to the turbine system. These include distillation plants that directly use the combustion heat of fuel for the production of additive water, and electrodistillers, and installations with a mechanical steam compressor that consumes electricity. Even the simple consumption of electricity by auxiliary equipment of a water treatment plant is not an underproduction. In fact, in all these cases, the fuel component of the plants can be expressed through under-generation of electricity, but in doing so we will make a methodological mistake, since no underproduction actually occurs.

Thus, none of the current thermal economy indicators of a water treatment plant fully reflects the physical nature of energy consumption in the process of additive water production at all water treatment plants installations and operating modes of equipment.

Assuming that any thermal process at a TPP costs fuel combustion heat consumption, it can be proposed to apply the primary energy consumption factor for the production of additive water as a criterion for the assessment of the fuel component [14]. In essence, the primary energy consumption coefficient shows the ratio of the combustion heat consumption of the fuel to the production of additive water and the heat consumption of the secondary steam, and is the fuel analogue of the heat value coefficient of the selected steam turbine system. According to this, the calculation formula for the primary energy coefficient is:

$$K_{pri.en.} = \frac{Q_f}{Q_{ad.w.}}, \tag{6}$$

where Q_f and $Q_{ad.w.}$ – Heat consumption of fuel and secondary steam (additive water).

In order to compare a water treatment plant using different water treatment methods with a $K_{\text{РПЭ}}$, coefficient, it is necessary to ensure the same heat flow rate of the secondary steam. There can be conditionally accepted:

$$Q_{ad.w.} = D_{w.c.} \cdot \bar{r}, \tag{7}$$

where $\bar{r}$ – average heat of vapour formation in the range of possible operating pressures evaporator unit, adopted equal 2250 $\frac{kJ}{kg}$ (at atmospheric pressure).

The value of the primary energy consumption factor for distillate production is its simplicity, the dimensionless appearance makes it convenient to compare the water treatment plant with each other. It should be noted, however, that it gives indicative values and has the disadvantages of the heat coefficient method. A more precise value of the fuel component for a specific variant of the thermal scheme of a water treatment plant, which is easy to obtain in monetary terms, still gives a criterion of under-generation of electricity during the production of additional water.

There are two ways to find a specific under-supply of electricity by a water treatment plant. The direct calculation is the same as (4) and through the primary energy consumption ratio as follows:

$$w = \frac{K_{pri.en.} \cdot \bar{r} \cdot \eta_{HPP}^{en}}{3,6} \left(\frac{kW \cdot hour}{ton}\right). \quad (8)$$

In formula (1-7) composition $K_{\text{РПЭ}} \cdot \bar{r}$ gives the value of fuel combustion heat consumption for production 1 $\frac{kg}{s}$ distillant, and multiplication by η_{HPP}^{en} allows to obtain electricity that is underproduced due to the water preparation process. Coefficiency 3,6 takes into account expense exchange from $\frac{kg}{s}$ to $\frac{t}{h}$.

For the heating mode of the turbine installation, the primary energy consumption coefficient can be found through (1-6):

$$K_{pri.en.} = \frac{b \cdot Q_h^f}{\bar{r}}. \quad (9)$$

The maximum economic effect of the combined unit is achieved with an optimum ratio of capacities of the evaporation unit and the horizontal-cut layer evaporator, and the evaporating unit, and horizontally cut layer evaporators should be optimized. The evaporation unit is optimized by using the maximum possible disposable temperature pressure and precisely the heat exchange surface necessary to obtain the specified output. Theoretically, any number of steps can provide the required performance, so the analysis involved options for an evaporation unit with different number of steps.

The evaporator unit is calculated using the following model. It is based on basic modes with a certain number of steps. For each number of steps, the evaporation unit is provided with the required capacity by the respective heat exchange surface, wherein the temperature distribution of the shells does not change, and the geometry of the housings change in proportion to their performance, so that the heat transfer coefficients remain constant and the maximum load of the last shell is not reached. The result is a linear relationship between the heat exchange surface area and the output. And there is no need for detailed thermal-hydraulic calculation of the evaporation unit depending on the performance. With this assumption it can be shown that the unit costs of the heating and excess steam will be constant for each number of steps. So, having the basic options and knowing the required performance, it is easy to estimate the area of the heat exchange surface of the housings evaporation unit steam flow rate per evaporator, and therefore, the capital and fuel cost component of the evaporation unit.

Horizontally cut layer evaporators can also use a different number of steps to determine the ratio of capital and fuel costs. In international practice, it is customary to use the following relationship between capital investments, depending on the cost of the device, and fuel costs, directly proportional to the heating steam consumption per installation [17, 18 19]:

$$\left(\frac{D_{h.vap.}^{base}}{D_{h.vap.}^{des}}\right)^{0,6} = \frac{K_{h.vap.}^{des.}}{K_{h.vap.}^{base}}, \quad (10)$$

where $D_{h.vap.}^{base}$ and $D_{h.vap.}^{des}$ – heating vapour costs for horizontal cut layer evaporators in the basic and design variants, respectively; $K_{h.vap.}^{des.}$ and $K_{h.vap.}^{des.}$ – cost of horizontal layer evaporators in base and design variant, respectively.

In the basic variant, the horizontal-cut layer evaporators, the specific heat consumption, is equal to 290 $\frac{kJ}{kg}$ distillant. Knowing the calculated heat flow rate on the horizontal-cut layer evaporators and the cost at the base heat flow rate, the (10) is the estimated cost of the horizontal-cut layer evaporators. The ratio (10) also makes it possible to find the optimal flow of heating steam on the horizontal-cut layer evaporators.

When an excess vapour is used, the evaporator unit can be used as a heater for horizontal cut layer evaporators in two cases:

1. The consumption of excess steam at the design capacity of the evaporator unit exceeds the optimal heating steam flow to the horizontal-cut layer evaporators at the design (specified) capacity of this evaporator. Then the use of the entire excess steam consumption as heating for horizontal cut layer evaporators will reduce the capital investment in the apparatus.
2. The consumption of excess vapour at design capacity of the evaporator unit is less than the optimal flow rate of the heating steam to the horizontal cut layer evaporators at the calculated capacity of this evaporator, and to obtain optimal parameters of the horizontal-cut layer evaporators, it is necessary to fill this difference with steam from the collector 0.8-1.3 MPa.

The capital investment in the evaporation unit is determined by the heat exchange surface and the number of stages, wherein the exponential dependence is the most reliable. The same type of relationship is also used to calculate the base values of horizontal laminated evaporators by capacity. Fuel costs are determined by the underpower generation of the turbo plant due to the inclusion of the evaporative unit-horizontal laminated evaporators in the circuit of the power unit (using power change factors). In fact, the thermal costs depend on the mode of operation of the unit and the calculation should be made taking into account the duration of the load during the year [8]. In order to simplify the design model, assume that the turbocharger system operates throughout the year in nominal mode with a fully open rotatable aperture.

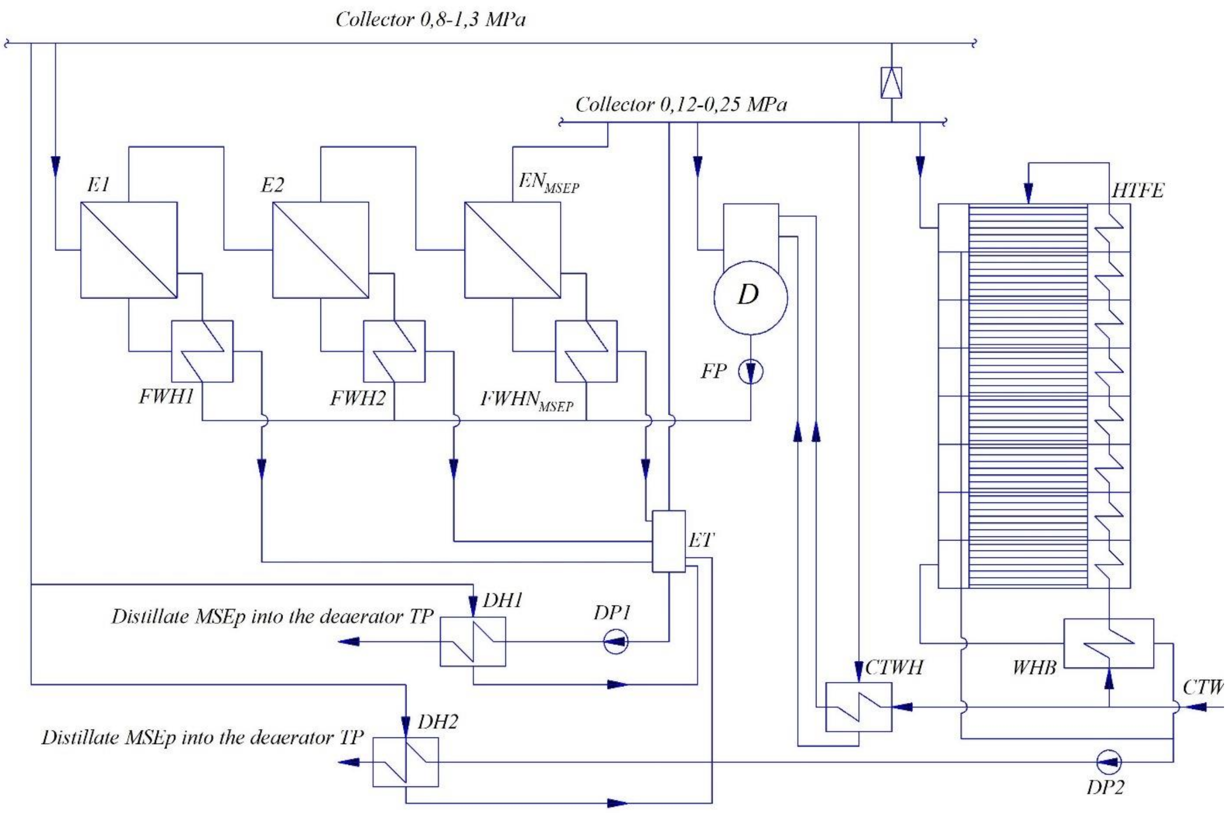


Fig. 1. Principal thermal scheme of the combined evaporation unit: evaporation unit - horizontal cut layer evaporators with the introduction of the distillate into the deaerator of the turbo plant: DH1, DH2 – preheater distillate evaporator unit and horizontal cut layer evaporators; DP1, DP2 – distillate pump; HR – Heat Recovery Steam Generator; XOB – chemically refined water; TP – turbo unit; FP – feedwater pump; D – deaerator; FWH1 – feed water heater; E – vaporizer

2. Methods

It is convenient to use equivalent annual costs (EAC) [8] calculated by formula as a criterion against which the effect and effectiveness of the combined plant will be assessed:

$$\mathrm{EAC} = E \cdot C + O, \qquad (11)$$

where E – discount rate; C – capital investment; O – total operating costs.

Total operating costs include capital and fuel components. The change in other costs at different productivity ratios evaporation unit and horizontal cut layer evaporators can be neglected.

Equivalent annual costs are calculated using formulas suggested by the author [20], mln. soums:

1. Temperature of distillate evaporator and horizontal cut layer evaporators equal to 40°C.

a) evaporation unit excess steam consumption less than optimal heating steam flow to horizontal layer evaporators $\left(b \cdot D_{vap.ins.} < D_{h.vap.}^{op}\right)$

$$EAC_1^{\text{a}} = \left(\alpha_{\text{ам}} + \beta_{\text{рем}} + \gamma_o + E\right) \cdot M \cdot \left(1 + \varphi_{a.c.} + \lambda_{an.eq.}\right) \cdot n_{vap.ins.} \cdot k_F \cdot \left[\frac{D_{vap.ins.} \cdot r_{av}}{\sum_{i=1}^{n_{vap.ins.}} K_i \cdot \Delta t_i}\right]^{k_F^{deg.}} + 10^{-6} \cdot D_{vap.ins.} \cdot \tau_{ins.} \cdot c_{e.t.} \cdot e_{out} \cdot a \cdot (h_{\text{out}} - h'_d) + \left(\alpha_{d.r.} + \beta_{m.r.} + \gamma_{exp} + E\right) \cdot M \cdot \left(1 + \varphi_{a.c.} + \lambda_{an.eq.}\right) \cdot K_{h.vap.}^{base} \cdot \left[\frac{D_{h.vap.}^{base}}{D_{h.vap.}^{opt.}}\right]^{0,6} + 10^{-6} \cdot \left(D_{h.vap.}^{\text{opt.}} - b \cdot D_{vap.ins.}\right) \cdot \tau_{ins.\text{уст}} \cdot c_{e.t.} \cdot L \cdot e_{out} \cdot (h_{out} - h'_d); \qquad (12)$$

b) the evaporation unit's excess steam consumption exceeds the optimal heating steam flow to the horizontal layer evaporators $\left(b \cdot D_{vap.ins.} > D_{h.vap.}^{\text{opt.}}\right)$

$$EAC_1^b = \left(\alpha_{d.r.} + \beta_{m.r.} + \gamma_{exp} + E\right) \cdot M \cdot \left(1 + \varphi_{a.c.} + \lambda_{an.eq.}\right) \cdot n_{vap.ins.} \cdot k_F \cdot \left[\frac{D_{vap.ins.} \cdot r_{av}}{\sum_{i=1}^{n_{vap.ins.}} K_i \cdot \Delta t_i}\right]^{k_F^{deg}} + 10^{-6} \cdot D_{vap.ins.} \cdot \tau_{ins} \cdot c_{e.t.} \cdot e_{out} \cdot a \cdot (h_{out} - h'_d) + \left(\alpha_{d.r.} + \beta_{m.r.} + \gamma_{exp} + E\right) \cdot M \cdot (1 + \varphi_{a.c..} + \lambda_{m.r.}) \cdot K_{h.vap.}^{base} \cdot \left[\frac{D_{h.vap.}^{base}}{b \cdot D_{vap.ins.}}\right]^{0,6}; \quad (13)$$

2. Temperature distillate evaporation unit and horizontal cut layer evaporators equal to the temperature in deaerator turbocharger (pic. 1).

a) Evaporation unit excess steam consumption less than optimal heating steam flow to horizontal layer evaporators $\left(b \cdot D_{vap.ins.} < D_{h.vap.}^{opt.}\right)$

$$EAC_2^a = \left(\alpha_{d.r.} + \beta_{m.r.} + \gamma_{exp} + E\right) \cdot M \cdot \left(1 + \varphi_{a.c.} + \lambda_{an.eq.}\right) \cdot n_{vap.ins.} \cdot k_F \cdot \left[\frac{D_{vap.ins.} \cdot r_{av}}{\sum_{i=1}^{n_{vap.ins}} K_i \cdot \Delta t_i}\right]^{k_F^{deg}} + 10^{-6} \cdot D_{vap.ins} \cdot \tau_{уст} \cdot c_{ээ} \cdot e_{отб} \cdot \left[(1 + a - b) \cdot \left(h'_d - h_{dis}^{vap.ins}\right) + a \cdot (h_{out} - h'_d)\right] + \left(\alpha_{d.r.} + \beta_{m.r.} + \gamma_{exp} + E\right) \cdot M \cdot \left(1 + \varphi_{a.c.} + \lambda_{an.eq.}\right) \cdot K_{h.vap.}^{base} \cdot \left[\frac{D_{h.vap.}^{base}}{D_{h.vap.}^{opt}}\right]^{0,6} + 10^{-6} \cdot \left(D_{h.vap.}^{opt} - b \cdot D_{vap.ins}\right) \cdot \tau_{ins} \cdot c_{e.t.} \cdot L \cdot e_{opt} \cdot \left(h_{opt} - h'_{dis}\right) + \left[D_{vap.ins} - D_{vap.ins} + b \cdot D_{vap.ins} + \left(D_{h.vap.}^{opt} - b \cdot D_{vap.ins}\right) \cdot L\right] \cdot e_{out} \cdot \left(h'_d - h_{dis}^{h.vap}\right); \quad (14)$$

b) the evaporation unit's excess steam consumption exceeds the optimal heating steam flow to the horizontal layer evaporators $\left(b \cdot D_{vap.ins} > D_{h.vap.}^{opt}\right)$

$$Eqv.\,anual\,income_2^b = \left(\alpha_{ам} + \beta_{рем} + \gamma_o + E\right) \cdot M \cdot (1 + \varphi_{К.А.} + \lambda_{В.О.}) \cdot n_{vap.ins} \cdot k_F \cdot \left[\frac{D_{vap.ins} \cdot r_{av}}{\sum_{i=1}^{n_{vap.ins}} K_i \cdot \Delta t_i}\right]^{k_F^{степ}} + 10^{-6} \cdot D_{vap.ins} \cdot \tau_{ins} \cdot c_{e.t.} \cdot e_{out} \cdot \left[(1 + a - b) \cdot \left(h'_d - h_{dis}^{vap.ins}\right) + a \cdot (h_{out} - h'_d)\right] + \left(\alpha_{d.r.} + \beta_{m.r.} + \gamma_{exp} + E\right) \cdot M \cdot \left(1 + \varphi_{a.c.} + \lambda_{an.eq.}\right) \cdot K_{h.vap.}^{base} \cdot \left[\frac{D_{h.vap.}^{base}}{b \cdot D_{vap.ins}}\right]^{0,6} + 10^{-6} \cdot \left(D_{vap.ins} + b \cdot D_{vap.ins}\right) \cdot \tau_{ins} \cdot c_{e.t.} \cdot (h_{out} - h'_{dis}) \cdot e_{out}; \quad (15)$$

Where $\alpha_{d.r.}$ – depreciation rate; $\beta_{m.r.} = 0{,}18 \cdot \alpha_{ам}$ – maintenance rate; $\gamma_{exp} = 0{,}25 \cdot (\alpha_{d.r.} + \beta_{m.r.})$ – common expenditure share; M – factor for installation costs; $\varphi_{a.c.}$ – coefficient for automation costs and instrumentation; $\lambda_{an.eq.}$ – coefficiency for ancillary equipment costs; r_{av} – average heat of vaporizing of evaporating unit $\left(\frac{kJ}{kg}\right)$; $(K_i \cdot \Delta t_i)$ – product of heat transfer coefficient and temperature pressure i-th corpse of evaporating unit $\left(\frac{кВт}{м^2}\right)$; k_F – multiplier of the function value of the evaporator's corpse (mln. soums); k_F^{deg} – multiplier of the degree function value of the evaporator's corpse; $n_{vap.ins}$ – number of steps of evaporating unit; $D_{vap.ins}$ – expected capacity of evaporating unit $\left(\frac{kg}{s}\right)$; τ_{ins} – number of operating hours of evaporator unit with installed capacity per year $\left(\frac{hour}{year}\right)$; $c_{e.t.}$ – grid electricity tariff $\left(\frac{soum}{kW \cdot hour}\right)$; a – percentage of evaporator evaporator vapour flow per evaporator unit; e_{out} – coefficient of change in the output of the turbine supplying the steam collector 0,8-1,3 MPa; h_{out} – enthalpy steam from the manifold $\left(\frac{kJ}{kg}\right)$; h'_d, $h_{dis}^{h.vap}$, $h_{dis}^{vap.ins}$ – enthalpy of feed water after deaerator, enthalpy of distillate of horizontal-pipe layer evaporator and evaporator unit; $D_{h.vap.}^{opt}$ – optimum heating steam consumption on horizontal-pipe layer evaporators at the design capacity of horizontal-pipe layer evaporator $\left(\frac{kg}{s}\right)$; L – conversion factor to account for the difference between the enthalpy vapour from the collector and the excess vapour of the evaporation unit.

The following values are assumed: $E = 0{,}12$; $\alpha_{d.r.} = 0{,}037$; $M = 1{,}85$; $\varphi_{a.c.} = 0{,}3$; $\lambda_{an.eq.} = 0{,}15$; $\tau_{ins} = 6000$; $c_{e.t.} = 0{,}41$; $e_{out} = 0{,}257$ (a value for ПТ-80-130); $h_{out} = 3020$. In formulae (12÷15), the first term takes into account the capital cost of the evaporation unit, the second - the fuel component of the evaporation unit, the third and fourth - the same for horizontal-pipe layer evaporators. In the submitted formulae, the variable value is the capacity of the evaporating unit $\left(D_{vap.ins}\right)$. It varies from 0, with the performance of horizontal-pipe layer evaporators $D_{h.vap.} = D_{vap.ins}$, to the required capacity of the evaporating unit $D_{vap.ins} = D_{vap.ins}$ $\left(D_{h.vap.} = 0\right)$. The remaining values are expressed through the capacity of the evaporation unit. Thus, formulae 12÷15 are functions of a single variable. In addition, this model needs to be supplemented by another limitation. In the area of low performance, the horizontal-pipe evaporators of the heating steam to this unit may not exceed its calculated capacity.

The formula (11) is obtained by converting the initial formula for calculating the discounted (integral) costs for the entire life of the installation:

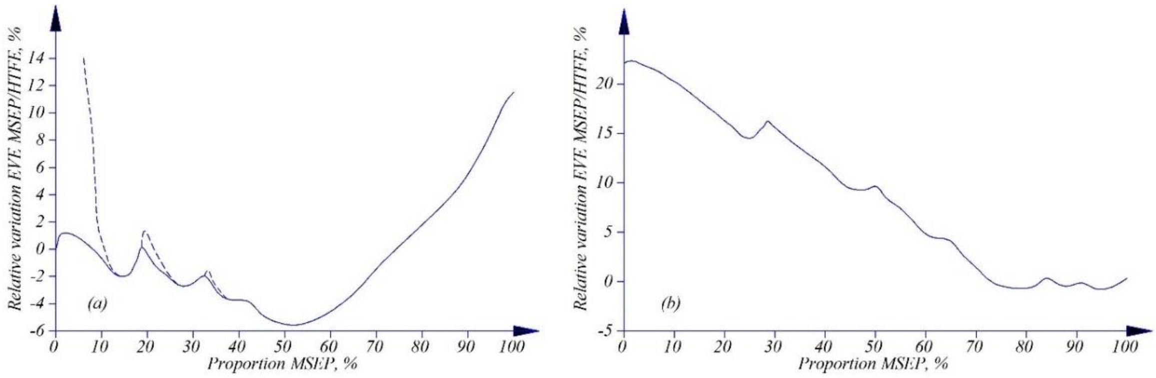
$$DC = \sum_{\tau=0}^{\tau_p} \left(O'_\tau + К_\tau - К_{liq.\tau}\right) \cdot (1 + \mathrm{E})^{-\tau}, \tag{16}$$

where O'_τ – total operating costs without depreciation; $К_{liq.\tau}$ – Liquid (non-smortified) fixed assets; $К_\tau$ – investments per annum τ; τ_p – expected period of operating or longevity, in years.

The difference between the maximum economic efficiency values of the evaporating horizontal-tube layer evaporators of the two variants is 0.2%, and the difference between the optimal load fraction of the evaporating apparatus is not more than 5%. It can be seen that there is little difference between the two calculations. The difference is entirely due to the fact that in the formulae (12÷15) presented above, the input is normal rather than discounted depreciation [20]. For example, increasing the discount rate of E in (16) from 0.12 to 0.14 or reducing the calculation period from 30 to 15 years could achieve a near-perfect match. In addition, since further studies of the influence of various factors on the efficiency of the evaporative installation-horizontal-pipe layer evaporators are carried out, the results of the calculation for (12÷15) can be considered reliable.

3. Results

The calculation is carried out according to formulas (12÷15) for each number of steps n_(evaporation unit)=1 7, so there are 14 curves. Results of the calculation of the relative change in discounted costs of the evaporative installation-horizontal-tube layer evaporators, compared with the corresponding indicator of separate horizontal-pipe. Tubular layer evaporators for the distillate temperature up to 40 are shown in Picture 2. This dependency is based on a minimum value equivalent to the annual costs calculated for (12) and (13). The wavelength of the line is due to the discreteness of the number of apparatuses (evaporation stages) involved in the analysis.



a) *b)*

Fig. 2. Relative change in equivalent annual costs of evaporation unit-horizontal-tube layer evaporators compared to equivalent annual costs of separate horizontal-tube layer evaporators at capacity of evaporator unit 100 $\frac{ton}{hour}$ $((a)\ t_{dis} = 40°\text{C})$ and $((b)\ \ t_{dis} = t_{dear})$

In the event that the temperature of the distillate is brought to the temperature of the turbocharger deaerator, the results of the formulae (14) and (15) will be as shown in Figure 2-b. The minimum value of the equivalent annual cost is around 50% of the evaporation unit, with a saving of 5.5% compared to the equivalent annual costs of the individual horizontal-pipe layer evaporators and 17% compared to the equivalent annual costs of a separate evaporation unit (fig. 2-a). When a low-load evaporator unit is connected to a horizontally-pipe layer evaporator, the equivalent annual costs are initially increased due to a substantial initial increase in the capital cost of the evaporation unit. The same effect occurs in the area of small horizontal-pipe layer evaporators, however, it manifests much less, because the large consumption of excess steam evaporation unit gives the opportunity to significantly reduce the capital investment in the horizontal-pipe layer evaporators.

The dotted line shows the equivalent annual expenses of the evaporation unit-the horizontal-pipe layer evaporator without the use of vapour throttling from the collector 0.8-1.3 MPa on the horizontal-pipe layer evaporator, that is, the case when the heating steam horizontal-pipe layer evaporator is only excess vapour evaporation unit. It can be seen that in the case of small fractions of the evaporation unit the costs of the combined unit are overstated. When the temperature of the distillate is brought to the temperature of the medium in the deaerator of the turbocharger (fig. 2-b), the costs of a separate horizontal-pipe layer evaporator exceed the costs of an individual evaporation unit. In addition, the consumption of the excess vapour of the evaporation unit in this case becomes significantly less, so that the value of the optimal ratio of the plant performance is shifted to the evaporation unit, and the efficiency of the combined plant is significantly reduced (savings ~1%). As mentioned above, the total costs (equivalent annual costs) shown in Figure 2-a and 2-b include capital and fuel components. Very typical is the change in the share of fuel costs in the total cost structure shown in Figure 3 and 3-b, respectively, for options to bring the distillate temperature to 40 and to the ambient temperature in the deaerator of the turbocharger.

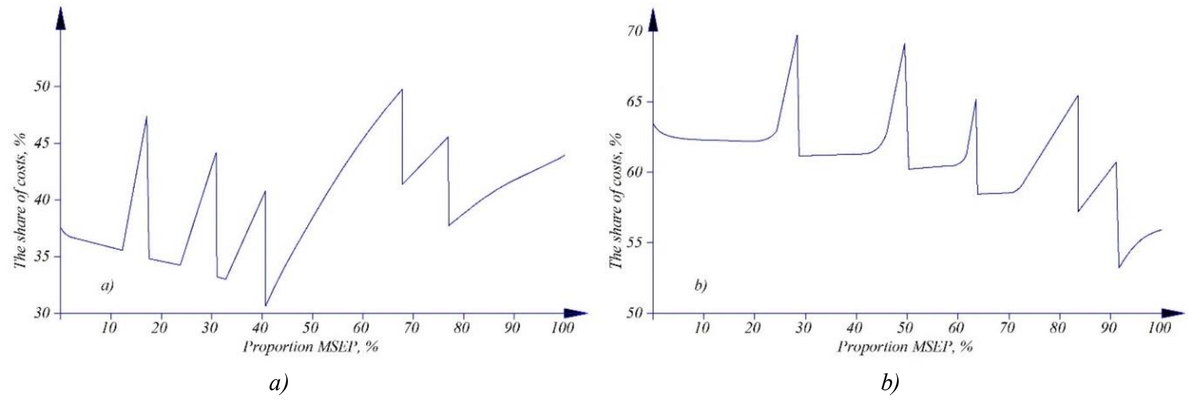


Fig. 3. Share of fuel costs in the structure equivalent annual evaporation unit costs of horizontal-pipe layer evaporators at capacity 100 $\frac{ton}{hour}$ $((a)\ t_{dis} = 40°C)$ и $((b)\ t_{dis} = t_{dear})$

At the beginning (in the range of 0 12% of the evaporation unit share) there is a decrease in the consumption of heating steam on the horizontal-pipe layer evaporator from the collector 0.8-1.3 MPa, since the calculation of the consumption of excess vapour evaporation unit. As a result, the fuel component is reduced (Fig. 3a). When the heating steam horizontal-pipe film evaporators becomes only the excess vapour of the evaporation unit, the share of fuel cost reaches the minimum value. A further increase in the evaporation unit load is associated with an increase in the fuel component and total costs. This continues until the option of two steps of the evaporation unit is available at a lower cost. The values of the capital and fuel constituents are rearranged intermittently. The same goes for the number of steps of the evaporation unit of 3, 4 and so on. The same reasoning is valid for another option (Fig. 3-b). Here, the smoother changes in dependency are due to the influence of the thermal costs associated with heating the distillate to the ambient temperature in the deaerator of the turbocharger.

4. Conclusion

The method of calculation and optimization of parameters of the combined evaporation unit, which include evaporation units and vacuum evaporators, having optimal technical characteristics for the specified distillate performance, has been developed. Influence of change of external parameters on economic efficiency of combined evaporative installation has been investigated. It is obtained that the maximum economic efficiency of the use of combined evaporation unit can be 12% and 7%, respectively, when the distillate is introduced into the capacitor and the deaerator of the turbocharger, the optimum percentage of the evaporation unit load in the composition of the plant is 55% and 70%, respectively.

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