Increasing the productivity of a plant for moisture evaporation from oil sludge by application of efficient method for technological parameters calculation

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Abstract. The paper presents the method of heat calculation of recovery stages for the plant of moisture evaporation from oil sludge. It enables to increase the plant power and reduce fuel consumption per one unit of evaporated moisture in heating boiler.

1 Introduction

At the modern stage of chemistry and petrochemistry development, the processes of management of waste, including oil and sludge, are under strict complex requirements. These include reducing energy and resource consumption, increasing their technical and economic efficiency, ensuring environmental safety according to the world standards [1,2]. The existing technologies for oil sludge disposal often do not respond to the stated requirements, and have a negative impact on the environment by their own waste, which have to be buried.

Over the past decades, various technological solutions for disposal of oil sludge have been proposed. However, despite the achieved results, these technologies need significant improvement due to annual enforcement of laws related to environmental protection and increasing requirements for their performance.

The issues of processing and using the resource potential of chemical, petrochemical, oil production waste and heavy oil residues (oil sludge) and assessing their environmental impact were considered in works of many Soviet and Russian scientists, such as: R.Kh. Fassakhov, M.Yu. Malikova, N.S. Yamanina, A.A. Desyatkin, T.A. Kulagina, A.F. Nadein, L.K. Altunina, L.I. Swarovskaya, A.Yu. Evdokimov, N.T. Elovshin, I.V. Efremov, A.G. Ishkov, V.M. Ferdman, A.B. Dmitrevsky, N.L. Guryleva, V.G. Maksimovich, V.A. Argunov, O.G. Fetisov, B.E. Prusenko, G.L. Handel, N.V. Lavrov, R.V. Surzhikova, M.S. Shpinkova, T.Sh. Aksanov, G.G. Gladyshev, N.M. Ismailov and others.

But despite the obvious urgency of the problem of oil sludge disposal, such productions are still not as widespread as required. This is explained by the fact that such plants, both Russian and international, have a high cost with low productivity and efficiency. In recent times oil sludge separation units (BRNSh) are the most promising in the field of oil-containing waste recovery

[3]. Such plants are based on evaporation of moisture from oil sludge waste, they also can be potentially improved and achieve higher energy efficiency.

In the present work, a method of thermal calculation of a plant for moisture evaporation from petroleum products is proposed. Using it, technological parameters are identified that significantly affect the performance and thermal efficiency of the BRNSh-3 unit (the number "3" means the volume of oil sludge (m³) loaded in plant) [4].

2 Technological scheme of BRNSh plant

To determine the potential for improving and increasing efficiency of the oil sludge separation unit (BRNSh) an efficient design scheme is proposed [3]. Using variable approaches the proposed calculation procedure allows one to introduce new technological modes and thereby increase the thermal efficiency and productivity of the considered plant.

Consider the technological scheme and operation principle of BRNSh.

Figure 1 shows the technological thermal scheme of plant for moisture evaporation from oil sludge with additional recovery heat exchangers.

The technological scheme of plant consists of the following stages: WHB is water heating boiler; ES is evaporation stage (main), heated by water from boiler; RS is recovery evaporation stage; OR is recovery heater of oil sludge; WP is vacuum water ring pump; S is separator; K is calorifer. The plant includes the following elements: circulation pump for water and oil sludge; lines of heating and cooling water, steam and condensate [5].

The plant has the following operation stages:

1. The preheated oil sludge in equal volumes is loaded into the main and recovery evaporation stages.

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Fig. 1. Thermal scheme of plant for moisture evaporation from oil sludge (BRNSh) with recovery heat exchangers.

Oil sludge is heated to reduce the time of water evaporation at the main stage.

2. After the plant gets into action, the process of evaporation of moisture from oil sludge starts. The primary steam directed to heat the recovery steam stage (RS) is condensed inside the heating pipes. In this case, the condensation heat is spent to moisture evaporation in RS and to cover the heat losses.

3. The secondary steam leaving RS is sent to heat the recovery heater OR, where the unheated oil sludge is located.

4. The condensate of heating steam, which goes out of recovery stage and heater, is discharged into a container, from which it is drained as necessary.

5. Non-condensed steam and non-condensing gases from the RS recovery stage are sent through the valve through the secondary steam line to the OR.

6. The steam from OR recovery stage is sent to the WP vacuum pump, where it condenses under the influence of cooling water.

7. The resulting mixture of water and gases is sent to separator C having a discharge into the environment.

8. After removing gases from separator, the remaining heated water from separator C is fed to the heater K, where it is cooled and then sent to a vacuum pump.

It is advisable to compose the heating surface RS from horizontally arranged pipes with a slight slope for condensate drainage. Inside the pipes, the heating steam condenses, and oil sludge is heated using free convection [6].

Further operation of the heat-recovery evaporation stage CP is considered in more detail (Fig. 2).

Fig. 2. Schematic diagram of the heat-recovery evaporation stage.

Heated oil sludge is fed into the CP tank. After evaporation process starts in the main evaporation stage, the primary steam leaving it with temperature t_1 and pressure p_1 enters the heating pipes of heat-recovery stage, where it condenses at about the same temperature and pressure. Some reduction in steam pressure due to hydraulic losses is not taken into account. After heating of recovery stage begins, the oil sludge is heated to the evaporation temperature t_2 , which is determined by pressure p_2 in the tank of recovery stage, after which the process of evaporation of moisture from the oil sludge begins.

Evaporation in the main and heat-recovery stages, connected in series along the steam flow, takes place under vacuum created by the vacuum ring water pump WP. The heated oil sludge is taken from the lower part of tank of evaporation stages by central circulation pumps and fed to evaporator shelves located in the upper part of tank, which serve to increase the mass transfer surface of oil sludge. With partial evaporation of moisture on the shelves of evaporator, the oil sludge is cooled by several degrees, and flows back to the lower part of the stage tanks [7].

3 Operation principle of the plant

To introduce the necessary parameters into the calculation model, it is necessary to consider the plant operating modes, when evaporation stages operate as evaporators.

Denote the absolute pressure at evaporator stages by p_1 and p_2 . The corresponding temperatures of steam formed in them are t_1 , and t_2 . The maximum temperature head between the heating steam and oil sludge in the recovery stage is $\Delta t_{\max}=t_1-t_2$ [8].

The average temperature head is $\Delta t=\zeta \cdot \Delta t_{\max}$. Here the coefficient $\zeta \leq 1$ depends on hydraulic losses during heating steam movement and on flow rate of oil sludge pumped by the circulation pump in the recovery stage and affecting the average oil sludge temperature in the tank [9].

The smaller the hydraulic losses are and the greater the oil sludge flow rate is, the closer is the coefficient ζ to unity. To minimize hydraulic losses, it is necessary to use a circuit with parallel steam motion inside the heating pipes.

Steam flow rates G_1 , G_2 (kg/s) are generated in evaporator stages in the set operation mode, and steam flow rate G_1 is pre-set according to the procedure [3]. Assume heat of condensation (evaporation) of water steam r_1 and r_2 at pressures p_1 and p_2 are in pressure range of 0.006÷0.06 MPa at condensation temperatures of 36.2÷85.9 °C. The plant condensation heat varies from 416 to 2293 kJ/kg.

Suppose $Q_1=G_1 \cdot r_1$ is the heat flux (W), which is released during the complete condensation of the primary steam with the flow rate G_1 inside the pipes of the recovery stage heater; $Q_2=G_2 \cdot r_2$ is the heat flux (W), which is spent for formation of secondary steam G_2 , and is released during its condensation:

The heat balance of the recovery stage is written in the form:

$$Q_2 = \eta \cdot Q_1, \quad (1)$$

where $\eta \leq 1$ is the thermal efficiency of recovery stage. Thermal insulation of the outer surface of the stage housing provides a heat balance with efficiency of $\eta \geq 0.99$.

If coefficients $\eta=1$ and $r=\text{const}$, then for the set mode the condition is fulfilled: $Q_1=Q_2$; $G_1=G_2$ and the total efficiency of plant is determined by the formula $G_2=2 \cdot G_1$. In this case the productivity will increase by about 2 times, the fuel consumption burned in boiler does not change, and the specific fuel consumption (per 1 kg of evaporated moisture) will decrease by 2 times.

The heat flux through the heater RS surface is equal to:

$$Q_1 = \frac{Q_2}{\eta} = k \cdot \Delta t \cdot F = k \cdot \zeta \cdot \Delta t_{\max} \cdot F \quad (2)$$

where k is the heat transfer coefficient from heating steam to oil sludge, (W/(m²·K));

Δt and $\Delta t_{\max}$ are the average and maximum temperature heads, (°C) ($\Delta t_{\max}=t_1-t_2$);

ζ is the coefficient which relates Δt and $\Delta t_{\max}$ ($\Delta t=\zeta \cdot \Delta t_{\max}$);

F is the surface area of heater determined from outer pipe diameter, (m²).

If we neglect the hydraulic resistance during the heating steam motion and the change in condensation temperature, then the coefficient ζ can be calculated by the expression:

$$\zeta = \left(1 + \frac{0.5 \cdot k \cdot F}{W} \right)^{-1},$$

where $W=c_o \cdot G_o$; c_o is the mass heat capacity of oil sludge, (J/(kg·K));

G_o is the mass flow rate of oil sludge pumped by circulation pump (kg/s).

The latter formula shows that with an infinite increase in W , the coefficient ζ tends to unity, which will require infinite energy expenditures for pumping oil sludge [10].

Figure 3 shows the relationship between coefficient ζ and $\omega=W/(k \cdot F)$.

Fig. 3. Relationship between coefficient ζ and $\omega=W/(k \cdot F)$.

Fig.3 shows that for $\omega=5$ ($W=5 \cdot k \cdot F$) the coefficient $\zeta \approx 0.9$. When ω is increased from 5 to 10, the coefficient ζ increases from 0.9 till 0.95, i.e. for only 5.5 %, while electricity consumption N for pumping oil sludge increases by about 2³=8 times (as $N \sim W^3$). When ω is decreased from 5 to 2 the coefficient ζ decreases from 0.9 to 0.8, i.e. by 12.5%, while electricity consumption for pumping oil sludge decreases by 15.6 times. Decreasing of ζ requires the corresponding increase in heater surface, i.e. its price. Optimal values of ω and ζ should be determined from technical and economic estimates. One can assume that reasonable value of ζ is in the range 0.8÷0.95, which corresponds to $\omega=2 \div 10$; and reasonable flow rate of oil sludge is determined using the formula $G_o=(2 \div 10) \cdot k \cdot F / c_o$ [11].

The heat transfer coefficient from heating steam to oil sludge k in the recovery stage RS is determined by expression, as for a flat wall [4]:

$$k = \frac{1}{\frac{1}{\alpha_1} + \frac{\delta_c}{\lambda_c} + \frac{1}{\alpha_2}}, \quad (3)$$

where α_1 is the heat exchange coefficient from condensing steam to the inner surface of pipes;

α_2 is the heat exchange coefficient from outer surface of pipes to oil sludge;

λ_{pw} is thermal conductivity coefficient of pipe wall;

δ_{pw} is thickness of pipe walls.

Note that the thermal resistance of heat exchange on the inner surface of pipe $1/\alpha_1$ and pipe wall δ_{pw}/λ_{pw} is many times less than the thermal resistance of heat exchange from the outer surface of pipe $1/\alpha_2$. Therefore, in a first approximation, we can take $k \approx \alpha_2$. In this case, the average temperatures on the outer and inner surfaces of pipes in the first approximation are equal to $t_{pw2} \approx t_{pw1} = t_1 - \delta t_w$, where t_1 is the temperature of condensation (saturation) of the primary steam; δt_w value is a fraction of a degree.

Since coefficient α_1 is approximately two orders of magnitude higher than coefficient α_2 and weakly affects the heat transfer coefficient k , so the minimal heat exchange coefficient α_1 can be determined by the Nusselt formula for calculating heat exchange during condensation of stationary steam inside horizontal pipes [12]:

$$\alpha_1 = 0.65 \cdot \left(\frac{\lambda_w^3 \cdot \rho_w^2 \cdot g \cdot r}{\mu_w \cdot \delta t_w \cdot d_{in}} \right)^{0.25}, \quad (4)$$

where thermo-physical parameters of condensate (water) λ_w , ρ_w , μ_w are chosen for the condensation temperature

t_1 (λ_w) is thermal conductivity coefficient;

ρ_w is density;

μ_w is dynamic coefficient of water viscosity;

r is heat of steam condensation at temperature t_s ;

$\delta t_w = t_1 - t_{pw1}$ is the difference between temperatures of steam condensation and the inner surface of heating pipe; d_{in} is the pipe inner diameter.

All values in (4) are presented in SI units.

The heat exchange coefficient to oil sludge α_2 can be calculated using the well-known formula for calculating heat exchange for free convection of liquid near horizontal pipes [13]:

$$\alpha_2 = 0.5 \cdot \lambda_o \left(\frac{g \cdot \beta_o \cdot \delta t_o}{\nu_o^2 \cdot d_{out}} \right)^{0.25} \cdot \left(\frac{Pr_o}{Pr_{c2}} \right)^{0.25} \quad (5)$$

where λ_o , β_o , ν_o are coefficients of thermal conductivity, thermal volumetric expansion, kinematic viscosity of oil sludge for its average temperature t_o ;

d_{out} is the outer pipe diameter;

Pr_o , Pr_{pw2} are the Prandtl numbers of oil sludge at temperatures t_o and t_{pw2} ;

$\delta t_o = t_{pw2} - t_o$ is the difference between temperatures of outer surface of pipes and average temperature of oil sludge.

The average temperature of oil sludge at the recovery stage is determined by the expression

$$t_o = t_2 + \Delta t_{\max} (1 - \zeta) = t_1 - \zeta \cdot (t_1 - t_2).$$

Temperature t_o is approximately $1 \div 2$ °C more than evaporation temperature t_2 .

The thermal conductivity and viscosity coefficients, as the main thermo-physical properties of oil sludge, affect the coefficient α_2 and k to a large extent. Thermo-physical properties of oil sludge, affecting heat exchange, are weakly dependent on moisture content, if it is less than 30%.

Coefficient α_2 is significantly affected by temperature difference δt_o . It is known that δt_o is equal to the average temperature head of the considered stage: $\delta t_o \approx \Delta t = t_1 - t_o$. Expression (5) at $k \approx \alpha_2 \sim \Delta t^{0.25}$ and density of heat flux from heating flux to $q = k \cdot \Delta t$ shows that q is proportional to $t^{1.25}$.

The values of k and q are determined as follows: assume $\delta t_o \approx \Delta t$, using expression (5) the coefficient α_2 is calculated in the first approximation, so the heat flux density is $q \approx \alpha_2 \cdot \Delta t$. Since $q = \alpha_1 \cdot \delta t_w$, the heat flux on the inner surface of pipe δt_w is found from equation (4):

$$\delta t_w = \left(\frac{q}{0.65} \right)^{\frac{4}{3}} \left(\frac{\mu_w \cdot d_{in}}{\lambda_w^3 \cdot \rho_w^2 \cdot g \cdot r} \right)^{\frac{1}{3}}. \quad (6)$$

From the known δt_w , the heat exchange coefficient α_1 on the inner surface of pipes is calculated from expression (4). Further, expression (3) is used to defined k more accurately and to determine heat flux density $q = k \cdot \Delta t$. The value δt_o is found from expression: $\delta t_o = \Delta t - q(1/\alpha_1 + \delta_{pw}/\lambda_{pw})$. Using formula (5) one can calculate coefficient α_2 , and determine $q = \alpha_2 \cdot \delta t_o$.

Expressions (6) and (4) are used to find α_1 ; expression (3) is used to calculate the heat transfer coefficient k .

4 Computation model

To perform the calculation, one should take into account the production characteristics of the plant:

- Temperature of the heating steam $t_1 = 75$ °C,
- Steam pressure 0.039 MPa.
- Average temperature of oil sludge $t_o = 55$ °C.
- Average temperature difference between steam and oil sludge $\Delta t = t_1 - t_o = 20$ °C.
- Heating pipes of heat-recovery stage are horizontal steel pipes Du-40 with outer diameter $d_{out} = 0.048$ m, and inner diameter $d_{in} = 0.040$ m,
- Thermal conductivity of pipes $\lambda_{pw} = 51.5$ W/(m·K).

Thermo-physical properties of oil sludge are taken according to [5] (transformer oil):

- Heat exchange coefficient α_2 on the outer surface of heating pipes calculated by (5) for $\delta t_o \approx 20$ °C, $\alpha_2=90.9$ W/(m²·K),
- Value $q \approx \alpha_2 \cdot \Delta t = 1818$ W/m². Value δt_w , calculated by (6), is $\delta t_w \approx 0.1$ °C,
- Heat exchange coefficient α_1 , calculated by (4), is $\alpha_1=27980$ W/(m²·K),
- Heat transfer coefficient, calculated by (4), is $k=90.1$ W/(m²·K),
- $k \approx \alpha_2$, and $\delta t_o \approx \Delta t$.

During design calculation inside the evaporator stages of recovery stage for the temperatures of the primary and secondary steam t_1 and t_2 , coefficient ζ , and flow rate of the primary steam G_1 from the main stage in evaporation mode, the pressures are taken as p_1 and p_2 .

Heat flux transmitted during condensation of primary steam is $Q_1=G_1 \cdot r_1$. Expressions (3-6) are used to calculate the heat transfer coefficient k , and formula (2) is used to determine the necessary area F of heater surface of the recovery stage [14].

The pipes surface area is $F=\pi \cdot d_{out} \cdot l \cdot n$, where l is length of one pipe; n is the amount of pipes.

If to assume $G_1=0.031$ kg/s, then for $r_1=2320$ kJ/kg the value Q_1 is equal to 72.7 kW.

For $\Delta t=20$ °C and $k=90.1$ W/(m²·K) the necessary area of heater surface of the recovery stage is $F=40.3$ m².

As heating pipes we choose horizontal pipes Du-40 of length $l=2.5$ m. For the outer pipe diameter $d_{out}=0.048$ m the design amount of pipes is $n \approx 112$.

Steam of temperature t_2 , re-entering from the recovery stage RS inflows for heating to OR, where it heats cold oil sludge of mass M of initial temperature $t_{cold} \approx 25$ °C. This heater is a tank facing out, in the bottom of which heating pipes are located. These pipes are immersed in oil sludge, where the secondary steam condenses, and part of it, non-condensed flash steam, is pumped out by a vacuum pump. During OR operation oil sludge is heated approximately to the condensation temperature of the secondary steam t_2 [15].

The condition for plant operation is $M=M_1 + M_2$, where M_1 and M_2 are the oil sludge masses loaded in the main and recovery evaporation stages. Masses M_1 and M_2 are selected from the condition that the evaporation process of the main and utilization stages ends simultaneously. The mass ratio of M_1 and M_2 can be determined from the heat balance equation:

$$M_1 \cdot \varphi \cdot r_1 \cdot \eta = M_2 \cdot \varphi \cdot r_2 \cdot \eta$$

It is seen that $M_2/M_1=\eta \cdot r_1/r_2$. At temperatures $t_1=75$ °C and $t_2=55$ °C evaporation heat is equal to: $r_1=2320$ kJ/kg; $r_2=2370$ kJ/kg. If assume $\eta=0.98$, then $M_2/M_1 \approx 0.96$.

Part of heat of the secondary steam from RS is spent on heating the oil sludge in recovery stage. For the temperature of cold oil sludge t_{cold} and the temperature of the heated oil sludge $t_o \approx t_2$, the amount of heat spent for its heating will be: $Q_o=c_o \cdot M \cdot (t_o - t_{cold})$. The amount of

heat released during condensation of the secondary steam $Q_s=M_2 \cdot \varphi \cdot r_2$, where φ is the initial moisture content of oil sludge.

Taking $M_2 \approx M_1$, $M \approx 2M_2$; $\varphi=0.2$; $c_o=2.5$ kJ/(kg·K); $r_2=2370$ kJ/kg; $t_{cold}=20$ °C; $t_o=55$ °C, the ratio of Q_o and Q_s is obtained:

$$Q_o / Q_s \approx 2c_o \cdot (t_o - t_{cold}) / (\varphi \cdot r_2) \approx 0.25$$

The calculation showed that only a small part of the secondary steam heat can be used to heat the oil sludge. To achieve higher efficiency of this process, it is necessary to calculate the heating surface area of the recovery heater in accordance with the area of the recovery stage [16].

5 Conclusions

This work describes a general thermal scheme and a method for thermal calculation of a plant for moisture evaporation from oil products. The authors proposed a thermal calculation for the existing oil sludge separation unit BRNSh-3. As a result of the performed analysis, the technological shortcomings were identified and recommendations were developed to improve thermal efficiency and productivity of the plant. The first recommendation is the need to increase the parameter of thermal power transmitted from the heating water to oil sludge up to the nominal heat output of water boiler. The second recommendation is to use the heat of steam generated during moisture evaporation from oil sludge using a recovery evaporation stage.

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