Journal of Fundamental and Applied Research **Vol. 3**, Issue 3 (2023) **20230016**

Received: 22 July 2023 / Accepted: 13 September 2023
Published online: 15 September 2023
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EFFECT OF FLOW RECIRCULATION ON HEAT TRANSFER INTENSITY IN A TWO-TUBE HEAT EXCHANGER

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Abstract. The results of computational and experimental studies of the heating process of an oil and gas condensate mixture of 70%Gascondensate+30%Oil with recirculation of part of the flow in an experimental two-tube heat exchanger are presented. According to the results of the experiments, it was determined that in the case of organizing the heating process with recirculation of 10-30% of the volume of the mixture, the flow rate in the pipe of the experimental apparatus increases from 0.291 to 0.345 m/s, the temperature of the heated mixture at its outlet increases from 69 to 83 ℃, the temperature difference of the heated mixture increases accordingly from 3 to 14 ℃ compared to the control experience. It was found that when recirculating 25% of the flow volume, the temperature of the heated mixture increases by 1.2 times, its viscosity decreases to 1.17 times, the flow rate increases by 1.2 times, and the thickness of the viscous sublayer in the pipe decreases by 1.25 times. At the same time, the improvement of the hydrodynamic conditions of the process contributes to an increase in the heat transfer coefficient in the apparatus by 1.14 times, an increase in the transferred amount of heat by 1.4 times and a sharp decrease in the rate of scale formation in the heat exchange pipe. It is shown that when organizing a process with recirculation of a part of the flow, it becomes possible to achieve an improvement in the hydrodynamic conditions of the process, an additional rise in the temperature of the heated raw materials and an increase in the heat transfer coefficient in tubular apparatuses up to 15%.

Keywords: oil and gas condensate mixture, viscosity, viscous sublayer, flow rate, Reynolds criterion, Darcy coefficient, flow recirculation, heat exchange, scale

I. INTRODUCTION

At oil refineries, the thermal preparation of liquid hydrocarbon raw materials for primary distillation is carried out in tubular apparatuses due to the removal of heat from hot technological flows departing from the column of atmospheric distillation of oil - distillates of fuel fractions, fuel oil and circulation irrigation [1, 2]. To date, various methods have been proposed and investigated for the intensification of convective heat exchange in tubular heat exchangers, which can be combined into the following three main groups [3]: - methods of artificial turbulence of the flow in the wall zone of heat exchange devices (Kalinin E.K., Dreitzer G.A., Yarkho S.A. and Zakirov S.G.), based on the periodic creation of small vortex zones near the wall, which are a source of additional turbulence of the flow; - methods of twisting the flow inside twisted oval pipes (Ievlev V.M., Vilemas Yu.V. and Dzyubenko B.V.) with longitudinal and transverse flow around tightly packed bundles of twisted pipes; - methods of controlled separation of the boundary layer (Zhukauskas A.A. and Schlanciauskas A.A.) during the transverse flow of pipe bundles by installing turbulators on their surface. One of the practical and little-studied ways to increase the intensity of heat transfer in tubular heat exchangers of oil refining is the organization of recirculation of a part of the flow of heated hydrocarbon raw materials [4]. However, the effective volume of recirculation of the flow in this case should be established by technical and economic calculations, taking into account the temperature changes in the properties of raw materials and their effect on the duration of the process and the energy costs of pumping it through the heat exchanger. Based on this, we investigated the effect of the degree of recirculation of the flow of liquid hydrocarbon raw materials (oil and gas condensate mixture) on the intensity of heat exchange in an experimental horizontal two-tube heat exchanger (Fig. 1) under various hydrodynamic conditions. At the same time, the main attention is paid to the temperature change of the heated mixture at the outlet of the apparatus [5, 6].

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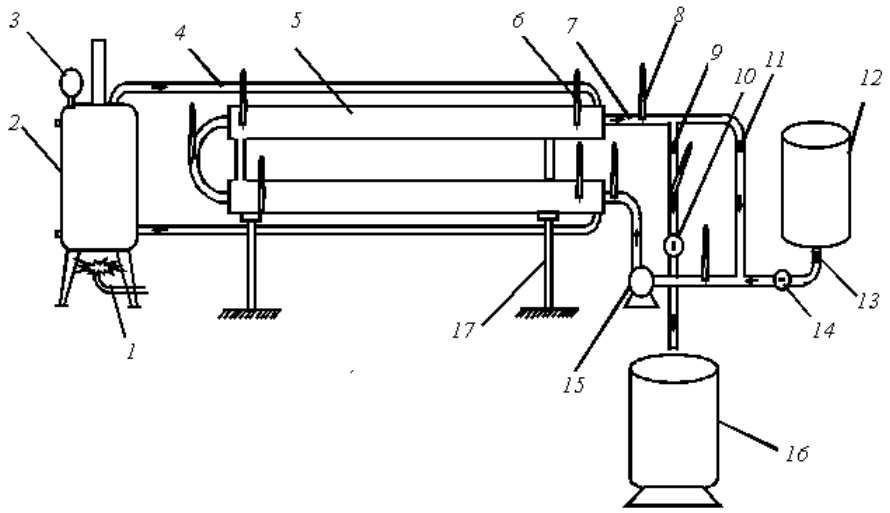


FIG. 1. 1- gas burner; 2 - steam generator; 3 - pressure gauge; 4 - steam supply pipe; 5 - outer tube (casing) of the heat exchanger; 6 - thermometers for heating agent; 7 - inner tube of the heat exchanger; 8 - thermometers for heating raw materials; 9 - valve for regulating the flow of liquid; 10 and 14 - meters for measuring the flow rate; 11 - valve for regulating the recirculation of a part of the raw material; 12 - flow tank for oil; 13 - valve for adjusting the feed of raw materials; 15 - centrifugal pump for pumping oil; 16 - dimensional tank; 17 - support rack. Diagram of a model installation for studying the effect of flow recirculation on the efficiency of heat exchange

II. METHODS AND MATERIALS

Figure 1 shows an experimental horizontal two-tube heat exchanger.

The essence of the experiments is as follows. A part of the working mixture heated in the heat exchanger, in the amount of 10-30% of its total volume, is selected and added to the flow entering the cold mixture apparatus. An increase in the volume flow rate of the mixture supplied by the pump V contributes to an increase in the flow rate in the inner tube of the apparatus, as a result of which the value of the number *Re* increases. With an increase in *Re*, the intensity of convective heat exchange increases, as a result of which the temperature of the mixture at the outlet of the heat exchanger increases. The planned range of changes in the consumption of hydrocarbon raw materials ensures the establishment of various hydrodynamic modes of its movement in the apparatus. During the experiments, the volumetric flow rate of the mixture in the apparatus varied within $V = 2.0 \div 2.6 \times 10^{-5}\ \mathrm{m}^3/\mathrm{s}$, and the speed of its movement in the pipe increased from 0.063 to 0.83 m/s. During the experiments, the oil and gas condensate mixture was heated within the temperature range from 20-31 to 69-83 ºC. The planned range of changes in the volume flow of the mixture $V = 8.3 \div 10.8 \times 10^{-5}\ \mathrm{m}^3/\mathrm{s}$ ensures the establishment of various hydrodynamic modes of its movement in the experimental apparatus.

A. Results and discussions

The results of studies to determine the effect of recirculation of part of the flow on the increase in the temperature of the mixture at the outlet of the experimental heat exchanger are summarized and presented in the following table 1.

№ experiments	Volume fraction of flow recirculation $\Delta V, \%$	Volumetric flow rate of the mixture $V, 10^5\ \mathrm{m}^3/\mathrm{s}$	Flow rate υ, m/s	Mixture temperature, °C	Δt,°C	t_n-t_k
1*	-	8.33	0.265	20	69	-
2	10	9.16	0.291	22	72	3
3	15	9.58	0.305	24	74	5
4	20	10.0	0.318	27	77	8
5	25	10.4	0.331	29	81	12
6	30	10.8	0.345	31	83	14

TABLE I. Change in the temperature rise of the heated mixture in an experimental two-tube heat exchanger due to recirculation of part of the flow

Note: 1* - a control experiment without recirculation of the flow; Δt is the difference in temperatures of the heated mixture during experiments with recirculation of part of the flow compared to the control experiment.

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As can be seen from the data in Table 1, in a control experiment conducted without recirculation of the flow in the apparatus, at a mixture velocity of 0.265 m/s in the pipe, it heats up from 20 to 69 ºC. In subsequent experiments, the process of heating the oil and gas condensate mixture was carried out with recirculation of the flow. At the same time, the share of recirculation of the flow is from 10 to 30% of the total volume of the mixture. The results of calculations performed according to experimental data show that in the case of organizing the heating process with recirculation of part of the volume of the mixture, the flow rate in the experimental apparatus increases from 0.291 to 0.345 m/s, the temperature of the heated mixture at the outlet increases from 69 to 83 ° C. The temperature of the heated mixture increases accordingly from 3 to 14 ° C compared to the control experiment. Further, we have established the influence of the volume of the recirculated mixture on the hydrodynamic parameters of the heating process in the horizontal pipe of the experimental heat exchanger by calculating the values of the number *Re*, the thickness of the viscous sublayer of the mixture δ_b and the heat transfer coefficient *K* in the apparatus. The value of the criterion *Re*, which determines the mode of movement of the oil and gas condensate mixture in the horizontal pipe of the experimental apparatus, is determined by the well-known formula [8]:

$$\mathrm{Re}_\ell = \frac{v \cdot d}{\nu} \tag{1}$$

where v - the flow velocity of the mixture in the inner tube of the apparatus, m/s; d - the inner diameter of the pipe, m; ν - the kinematic viscosity coefficient of the oil and gas condensate mixture, mm^2/s. According to a two-layer model of the structure of a turbulent fluid flow in a pipe [7], a very thin viscous layer with a thickness δ [8, 9] is formed near the inner surface of the wall of the heat transfer pipe, in which the shear shear stress τ, determined by Newton's law of viscous friction, has a predominant influence [8]. Within a thin viscous sublayer, the flow regime is laminar, and the flow velocity increases linearly from zero on the pipe wall to some averaged value of the longitudinal component of the velocity of the iw at the outer boundary of the sublayer. At the same time, there is no pulsation in the layer (laminar film). However, it was later established [3] that the pulsation of velocity, pressure and tangential stress are also transmitted to the viscous sublayer. The intensity of the longitudinal velocity pulsations in the viscous sublayer can reach up to 0.3 (max), and the rest of the pipe cross-section will be occupied by a turbulent flow core with intense pulsations of velocity and mixing of its particles. Since the thickness of the viscous sublayer is very small, the velocity gradient along the normal to the direction of movement in it can be taken equal to $dv/d\delta = v_w/\delta_w$. Then, the tangential stress ta on the pipe wall will be equal to

$$\tau_o = \mu\left(\frac{dv_x}{dy}\right) = \mu\left(\frac{v}{\delta_w}\right) = \rho\nu\left(\frac{v}{\delta_w}\right) \tag{2}$$

where μ and ν - are the dynamic and kinematic viscosity coefficients of the liquid. After a series of transformations (2), the following expression is obtained for determining the thickness of a viscous sublayer δ_w:

$$\frac{\delta_w}{d} = \frac{N \cdot 8^{0.5}}{\mathrm{Re}\lambda^{0.5}} \tag{3}$$

where N - a dimensionless complex similar in structure to the number *Re* : $\frac{v}{v_{\text{din}}} = \frac{v_{\text{din}} \cdot \delta_w}{\nu} = N = \text{const}$; λ is the Darcy coefficient (coefficient of hydraulic friction). Based on experiments on the study of the flow structure near the pipe wall, it was found [7] that the thickness of the viscous sublayer δ_w is a pulsating value that can vary in time from $\frac{6.5d}{\mathrm{Re}\lambda^{0.5}}$ to $\frac{51d}{\mathrm{Re}\lambda^{0.5}}$.

For practical purposes, it is recommended to take $N \approx 11.6$. With this in mind, the thickness of the viscous sublayer of the liquid δ_w is calculated by the formula derived from (3):

$$\delta_w \approx \frac{30d}{\mathrm{Re}\sqrt{\lambda}} \tag{4}$$

It follows from (4) that an increase in the values of the number *Re* and the coefficient λ leads to a decrease in the thickness of the viscous sublayer δ_w in. The value of the coefficient λ in the laminar flow mode was determined by the formula [8, 10]:

$$\lambda = \frac{64}{\mathrm{Re}} \tag{5}$$

and for the turbulent flow regime, taking into account the roughness of the pipe wall, the formula of A. Altshul was used [8, 10]:

$$\lambda = 0.11\left(\frac{\Delta}{d} + \frac{68}{\mathrm{Re}}\right)^{0.25} \tag{6}$$

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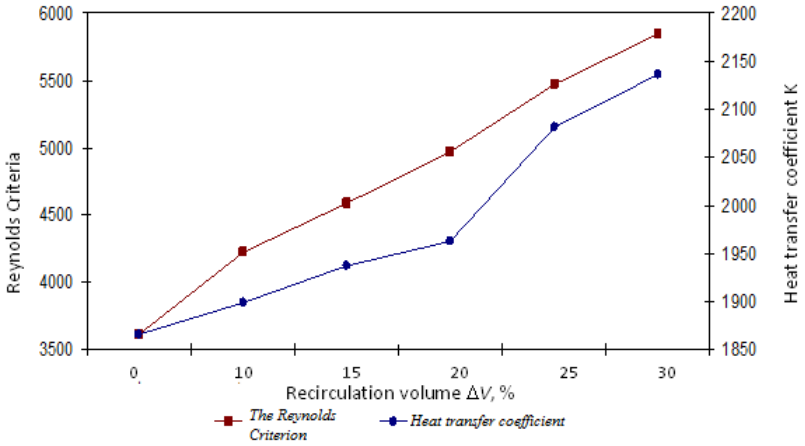


FIG. 2. Changes in the number of Re and the heat transfer coefficient K in the apparatus from the volume of recirculation of the flow of the oil and gas condensate mixture 70% GC+30%O

The amount of heat transferred from the hot coolant (gas condensate vapors) to the heated mixture is determined from the basic heat transfer equation [8, 9]:

$$Q = KF \cdot \Delta t_m \tag{7}$$

where Δt_m is the average temperature pressure, °C; *F* is the pipe surface, m^2. The value of the heat transfer coefficient *K* in the experimental heat exchanger is calculated according to the equation [8, 12]:

$$K = \frac{1}{\frac{1}{\alpha_1 r_e} + \frac{1}{\alpha_2 r_i} + \frac{1}{\lambda} \cdot 2.3 \cdot \log \frac{r_e}{r_i} + \frac{1}{r_{ce}} + \frac{1}{r_{ci}}} \tag{8}$$

where r_e and r_i are the outer and inner radius of the inner tube of the experimental apparatus, m; r_{ce} and r_{ci} are the thermal conductivity of the contamination layer on the outer and inner surfaces of the pipe, $W/(m^2 \cdot K)$. Calculation results for determining the number of Re, the thickness of the viscous sublayer δ_w in (mm) and heat transfer coefficients *K* $W/(m^2 \cdot K)$ at different recirculation volumes ΔV (in%) of a mixture of 70%GC+30%O are presented in Table 2.

ΔV, %	ν, mm^2/c	Re	λ	$\delta_v \times 10^3$, mm	K, Vt/($m^2 \cdot$ K)
-	1,42	3605	0,0410	4,0	1865
10	1,38	4217	0,0393	3,6	1899
15	1,33	4586	0,0382	3,4	1937
20	1,28	4968	0,0376	3,2	1963
25	1,21	5471	0,0366	3,0	2081
30	1,18	5847	0,0360	2,8	2136

TABLE II. The effect of recirculation of the oil and gas condensate mixture flow on the thickness of the viscous sublayer and the heat transfer coefficient in the experimental heat exchanger

The data in Table 2 indicate that with an increase in the value of the Re number, the intensity of convective heat exchange in the apparatus increases and the amount of heat transferred from the hot coolant to the cold flow of the heated mixture increases. At the same time, the thermal efficiency of the proposed method of organizing the process is characterized by an increase in the temperature of the mixture at the outlet of the apparatus. As you can see, with an increase in the volume of the recirculated mixture from 10 to 30%, the Re value increases from 3605 to 5471, the coefficient of friction of the flow against the walls of the heat transfer pipe decreases from 0.041 to 0.036, the thickness of the viscous sublayer in the pipe decreases from 4.0 to 3.0 10-3 mm, and the heat transfer coefficient in the experimental apparatus increases from 1865 to 2136 $W/(m^2 \cdot K)$. The following Figure 2 shows the curve of change in the values of the number Re and the heat transfer coefficient *K* $(W/m^2 \cdot K)$ in an experimental heat exchanger from an increase in the volume of recirculation of the oil and gas condensate mixture of 70% GC + 30%O in the range from 10 to 30%.

As can be seen from Fig.2, in the studied limit, changes in the volume of recirculation of a part of the flow of an oil and gas condensate mixture in an amount from 10 to 30% leads to an improvement in the hydrodynamics of the flow in the heat transfer

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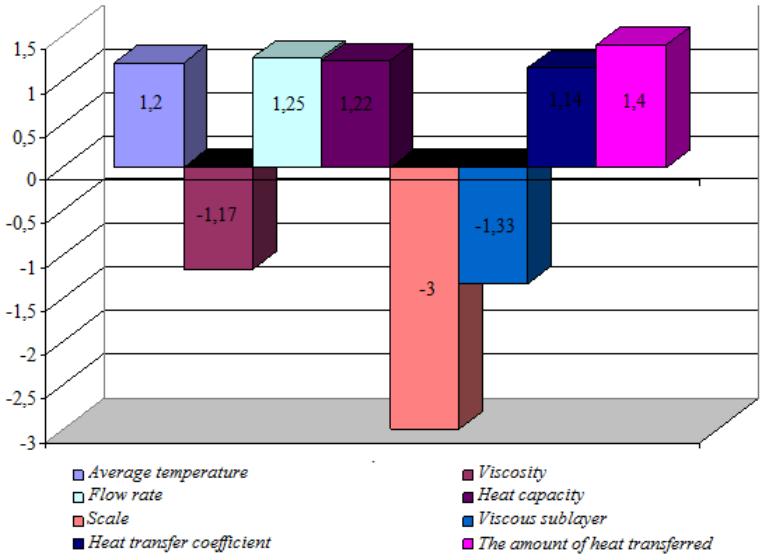


FIG. 3. Changes in the physical and thermophysical properties of the oil and gas condensate mixture during its heating with recirculation of part of the flow by 25 %

pipe, which is characterized by an intensive increase in the *Re* value (upper curve) and contributes to a significant increase in the heat transfer coefficient *K* in the experimental heat exchanger (lower curve). When recirculating part of the flow, along with an increase in the volume flow rate of the mixture and its velocity, the hydraulic resistance of the heat exchange pipe simultaneously increases. As is known, the pressure of the heated mixture (Pa) is consumed to overcome the internal friction forces ΔP_{fr} arising when moving the oil and gas condensate mixture along the length of the pipe and overcoming local resistances ΔP_{lr} [13–16]:

$$\Delta P = \Delta P_{\text{fr}} + \Delta P_{\text{lr}} = \lambda \left(\frac{\omega^2 \rho}{2} \right) \left(\frac{L}{d_{\text{in}}} \right) + \sum_{i=1}^{n} \xi_i \frac{\rho \omega^2}{2} \tag{9}$$

where λ - coefficient of internal friction; ω - average flow rate of the mixture, m/s; ρ - density of the mixture, kg/m^3; L - total length of the heat exchange pipe; d_{in} - equivalent (internal) pipe diameter; ξ_i - coefficients of local resistances, the numerical values of which are equal to: at the entrance to the pipe with sharp edges - ξ_1 = 0,5; at the outlet of the pipe with sharp edges - ξ_2=1,0; for rough pipe with minor corrosion - ξ_3 = 0,2. Analysis of the calculated and experimental data given in Tables 1 and 2 shows that an additional increase in the temperature of the oil and gas condensate mixture during its heating, organized according to the method with recirculation of part of the flow, also has a positive effect on changes in the physical and thermophysical properties of raw materials (Fig. 3).

III. CONCLUSIONS

Thus, according to the results of the conducted studies, it can be concluded that the organization of the heating process with the recirculation of part of the flow is a practical way to increase the efficiency of tubular heat exchangers for the thermal preparation of oil and gas condensate mixtures for primary distillation. In particular, when recirculating 25% of the volume of the oil and gas condensate flow, the final temperature of the heated mixture increases by an average of 1.2 times, which leads to a decrease in its viscosity to 1.17 times and an increase in the flow rate by 1.2 times. Due to the change in the flow mode, intense pulsations of the flow velocity occur, which helps to reduce the thickness of the viscous sublayer of the mixture on the wall of the heat exchange pipe by 1.25 times. At the same time, an additional increase in the temperature of the mixture leads to an increase in its heat capacity by 1.22 times, contributes to an increase in the heat transfer coefficient in the apparatus by 1.14 times and an increase in the transferred amount of heat by 1.4 times. In addition, in the experiments, a decrease in the rate of scale formation in the wall of the heat exchange pipe was also observed, which may be a probable consequence of the intensive movement of the flow of the oil and gas condensate mixture in the pipe.

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