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Hydrodynamics and thermophysics of oil emulsions in petrochemical heat exchangers

Właściwości hydrodynamiczne i termofizyczne emulsji olejowych w petrochemicznych wymiennikach ciepła

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ABSTRACT: Heat exchangers are used in aviation and space technology, power engineering, chemical processing, oil refining, the food industry, refrigeration and cryogenic technology, heating and hot water supply systems, air conditioning, and various types of heat engines. With the growth of energy capacity and production volume, the mass and dimensions of the heat exchangers used are increasing. A large amount of alloyed and non-ferrous metals is spent on their production. Reducing the mass and dimensions of heat exchangers is therefore a pressing problem. The most promising way to solve this problem is heat exchange intensification. Experience in the creation and operation of various heat and mass transfer devices has shown that the heat exchange intensification methods developed to date provide a 1.5–2-fold or even greater reduction in the dimensions and metal content (mass) of these devices compared with similar serially produced devices with the same thermal power and power for pumping of heat carriers. Research into heat exchange intensification is being carried out in various countries, and at a noticeably increasing pace. To date, various methods of intensification of convective heat transfer have been proposed and studied. Recently, interest has arisen in the use of thermodynamic methods to assess the efficiency of heat exchangers and, in particular, heat transfer intensification. It is proposed to compare the total changes in entropy in heat exchangers when irreversible heat exchange processes occur in them and the flow overcomes hydraulic resistance. If the intensification is effective, the total entropy change will be lower than in a device with smooth surfaces. It should be noted that, when comparing different methods, assessments of heat transfer intensification efficiency give qualitatively identical results. The article shows the effect of sedimentation of solid particles (clay, sand and other solid impurities contained in crude oil) on the heat exchange surface, as well as the hydrodynamics and heat exchange in tubular heat exchanger systems with oil emulsions. The effect of sedimentation of solid particles in turbulent and transverse flow motion is shown. The presence of various forces causing the movement of particles (droplets) in the volume of the flow has a significant impact on the sedimentation of solid particles on the surface and on the fragmentation of droplets in the flow. A mathematical model of the heat exchange process for heating oil emulsion in series-connected heat exchangers of oil refining is developed and applied.

Keywords: heat exchange intensification; entropy change; thermodynamic methods; hydraulic resistance; sedimentation of solid particles.

STRESZCZENIE: Wymienniki ciepła znajdują zastosowanie w lotnictwie i kosmonautyce, energetyce, przemyśle chemicznym, rafineryjnym, spożywczym, w technologiach chłodniczych i kriogenicznych, w systemach ogrzewania i zaopatrzenia w ciepłą wodę, w klimatyzacji oraz w różnych typach silników cieplnych. Wraz ze wzrostem mocy instalacji oraz skali produkcji zwiększeniu ulega masa i gabaryty stosowanych wymienników ciepła, co wiąże się z dużym zużyciem stopów i metali nieżelaznych. Zmniejszenie masy i wymiarów wymienników jest zatem istotną kwestią. Najbardziej obiecującym sposobem zaadresowania tego problemu jest intensyfikacja wymiany ciepła. Dotychczasowe doświadczenia związane z projektowaniem i eksploatacją różnego rodzaju urządzeń do wymiany ciepła i masy wskazują, że metody intensyfikacji pozwalają zmniejszyć wymiary i metalochłonność urządzeń nawet 1,5–2-krotnie (i więcej) w porównaniu z urządzeniami produkowanymi seryjnie o tej samej mocy cieplnej i tym samym zapotrzebowaniu mocy na pompowanie czynnika roboczego. Badania nad intensyfikacją wymiany ciepła są prowadzone w różnych krajach, a ich tempo wyraźnie rośnie. Do tej pory zaproponowano i zbadano szereg różnych metod intensyfikacji konwekcyjnej wymiany ciepła. W ostatnich latach wzrosło także zainteresowanie metodami termodynamicznymi, które umożliwiają ocenę efektywności pracy wymienników ciepła oraz skuteczności zastosowanych rozwiązań intensyfikacyjnych. Proponuje się porównywanie całkowitych zmian entropii zachodzących w wymiennikach podczas nieodwracalnych procesów wymiany ciepła i pokonywania oporu hydraulicznego przez przepływ. Jeżeli intensyfikacja wymiany ciepła jest skuteczna, całkowita zmiana entropii będzie mniejsza niż w porównywalnym urządzeniu o gładkich powierzchniach. Warto zauważyć, że różne metody oceny efektywności intensyfikacji prowadzą do jakościowo zgodnych wyników.

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W artykule przedstawiono wpływ sedymentacji cząstek stałych (gliny, piasku i innych zanieczyszczeń naturalnie występujących w ropie naftowej) na powierzchnię wymiany ciepła oraz na hydrodynamikę i przebieg wymiany ciepła w rurowych systemach wymienników ciepła z emulsjami olejowymi. Omówiono sedymentację cząstek w warunkach przepływu turbulentnego i poprzecznego. Wykazano, że obecność sił powodujących ruch cząstek (kropelek) w objętości przepływu znacząco wpływa na ich osadzanie się na powierzchniach wymiennika ciepła oraz na rozdrabnianie kropelek w trakcie przepływu. Opracowano i zastosowano matematyczny model procesu wymiany ciepła podczas podgrzewania emulsji olejowej w szeregowo połączonych wymiennikach ciepła stosowanych w procesach rafineryjnych.

Słowa kluczowe: intensyfikacja wymiany ciepła; zmiana entropii; metody termodynamiczne; opór hydrauliczny; sedymentacja cząstek stałych.

Introduction

The flow of oil emulsions (OE) in heat exchanger pipe systems is accompanied by the simultaneous deposition of solid particles (clay, sand and other impurities contained in crude oil) on the heat exchange surface (Abbasov et al., 2006).

Deposits on the inner pipe surface deteriorate heat transfer performance (including for OE in particular) and significantly alter the hydrodynamics of the flow (flow regime, flow rate, pressure drop).

Precipitation of particles of different origins on the heat exchange surface is explained by many factors, among which the hydrodynamic and thermodynamic conditions, the rheological properties of the dispersed system, the adhesive compatibility of particles with the surface, physicochemical transformations in the boundary layer, and particle size and concentration should be highlighted (Mamedov and Abbasov, 2023).

At the same time, the deposited layer can have a negative effect on all types of flow transfer, as well as on the fragmentation of droplets in the oil emulsion.

Statement and solution of the problem

Analysis of the flow of oil emulsions in pipes showed that the deposition of a solid phase on their surface worsens heat exchange with the external environment due to a decrease in the heat transfer coefficient. A gradual increase in the particle layer in pipes leads to a decrease in the flow area and, accordingly, to an increase in pressure loss and flow rate (Zvonarev, 2019).

A decrease in the flow temperature over time at the outlet of the system has a negative effect on the separation of the oil emulsion in settling devices. The flow of dispersed particles in pipes is determined by the presence of various forces acting on the particles and generating turbulent and transverse migration rates, as well as gravitational velocity.

The transverse migration rate of particles based on the Magnus effect is defined as (Mamedov et al., 2023):

$$V_L = 0.03\mathrm{a}^{1/2}(VdV/dy)^{1/2}$$

Expressing the equations in dimensionless form yields:

$$V_L = R_M V + (dV_+/dy_+)^{1/2}$$

where:

$$R_M = 0.03 \cdot (aV_*^{\,3}/V)^{1/2}$$

$$y_+ = yV_*/V$$

$$V_+ = \nu/V_*$$

$$V_* = |\bar{r}|\rho$$

V_L – velocity of the liquid (or gas) at the wall or the local velocity in the boundary layer [m/s],

a – particle (droplets) size [m],

V – average or axial flow rate [m/s],

dV/dy – velocity gradient (the change in velocity along the normal to the surface (in the y direction)) [s^{-1}],

0.03 – empirical coefficient determined experimentally,

R_M – empirical coefficient (a parameter that takes into account the influence of molecular viscosity and flow regime) [dimensionless],

ν – kinematic viscosity of a liquid [m^2/s],

y – coordinate [m],

V_* – frictional (shear) velocity (characterizes the intensity of turbulent pulsations at the wall) [m/s],

y_+ – given coordinate (used in the laws of velocity distribution in a turbulent boundary layer. It shows the distance from the wall in "viscous units") [dimensionless],

V_+ – reduced (normalized) velocity (the ratio of kinematic viscosity to frictional velocity) [dimensionless],

ρ – liquid density [kg/m^3].

Assuming the distribution of the carrier-phase velocity in the form:

$$y_+ \le 21.5 \qquad V_L = A^{3/2} y^{7/4e^{-0.075\,y_+\cdot(1.5-0.05\,y)^{1/2}}} \cdot R_M$$

$$y_+ \ge 21.5 \qquad V_L = \frac{y_+ \cdot \left[14-(0.53/R_+)\cdot y_+^2\right]^{1/2} \cdot R_M}{\left[(0.53/R_+)\cdot y_+^2 + 0.85y_+ + 14\right]^2}$$

where: $A \approx 0{,}02$; coefficient 21.5 – from the universal Spalding profile representing the inflection point: ≤ 21.5 – viscous (laminar) sublayer zone at the wall (molecular viscosity dominates → exponential profile); ≥ 21.5 – transitional/turbulent zone (turbulent transport → logarithmic behavior begins to prevail); coefficients 0.075, 1.5, 0.05 – empirical approximation of an exponential profile in a viscous domain; coefficients 14, 0.85, 0.53 – fitting to Nikuradse's turbulent friction data (Nikuradse, 1933).

Based on the condition $\partial V_L / \partial y_+ = 0$, the maximum value of upward migration is determined at $y_+ = 18.68$:

$$V_{L\max} / R_M = 0.67$$

Thus, the velocity of the upward migration of particles increases in the viscous layer, reaches its maximum in the transition zone, and decreases in the region of developed turbulence (Umanov, 2012; Zaliznyak and Zolotov, 2023). The value of upward migration velocity at the wall can be determined from the formula, considering $y_+ = a_+ = aV_*/v$.

The rate of turbulent migration of particles has a similar character:

$$V_T = 1/2 \, \frac{M_p^2 r_p}{v} V_*^3 V_+^2 \frac{dV_+}{dy_+} \tag{1}$$

where:

$M_p{}^2$ – degree of particle enlargement by the medium,
r_p – relaxation time,
v – viscosity.

It is assumed that the particle rotates on the surface due to differences in the velocities of the carrier phase at the wall ($v = 0$) and at a distance from the wall equal to a.

The accuracy of $y_{+\max}$ is determined by the degree of adequacy of the velocity profile V_+ in the transition zone, the peak of which occurs at $y_+ = 12.7$ (Mamedov et al., 2023).

Comparing the maximum turbulent and lifting migration velocities, we obtain:

$$\frac{V_{T_{\max}}}{V_{L_{\max}}} \approx 0.75 M_p^2 \frac{\Delta p}{\rho} \left[\frac{a}{V} \right]^{3/2} \cdot V_*^{3/2} \tag{2}$$

Numerical calculations using formula (2) for particles in an oil emulsion: ($T = 50°\text{C}$; $v_o = 0.223 \cdot 10^{-4}$ m²/s; $\rho_o = 850$ kg/m³; $\Delta\rho = 500$ kg/m³) and in air: ($v_H = 0.15 \cdot 10^{-4}$ m²/s; $\rho_H = 1.29$ kg/m³) showed that at a dynamic velocity $V^* = 1.0$ m/s, the turbulent migration velocity V_T for air exceeds the upward migration velocity for particles of size $a = 5$–50 µm by 50–1500 times, whereas the opposite is observed for oil (Figures 1 and 2).

In this case the range of V_T/V_L ratio should be:

$$V_T / V_L = 0.015 - 0.5.$$

This difference is amplified when heavy oils flow at low temperatures ($N_o = 150 \cdot 10^{-6}$ m²/s at $T = 10°\text{C}$). For liquid-solid systems, this is explained by the significantly shorter relaxation time in liquids compared with gases (Kuznetsov et al., 2013).

Thus, the presence of various types of particle migration can significantly affect particle (droplet) movement only within the boundary layer, whereas in the flow core the gravitational component is more significant. Various forces acting on particles (droplets) within the flow volume greatly influence the deposition of solid particles on the surface and the fragmentation of drops in the flow (Mamedov and Abbasov, 2023).

In oil refining, heating of the oil emulsion is carried out in a system of tubular heat exchangers. The calculation of the heat exchanger system for predicting the temperature at the inlet to the settling apparatus over time is based on the heat transfer equations:

$$\begin{cases} \dfrac{\partial T_1}{\partial \theta} + V_1 \dfrac{\partial T_1}{\partial \chi} = q_{11}\left(T_2 - T_1\right); \\ \dfrac{\partial T_2}{\partial \theta} + V_2 \dfrac{\partial T_2}{\partial \chi} = q_{22}\left(T_1 - T_2\right); \\ T_1(\theta,\chi)|_{\theta=0} = T_1(\chi), T_1(\theta,\chi)|_{\chi=0} = T_{10}; \\ T_2(\theta,\chi)|_{\theta=0} = T_2(\chi), T_2(\theta,\chi)|_{\chi=0} = T_{20}, \end{cases} \tag{3}$$

where:

T_1, T_2 – temperatures of the oil emulsion and the heating agent,
V_1, V_2 – flow rates in the pipe and inter-pipe spaces:

$$q_{11} = \frac{KF_1L}{\left(\rho_1 c_1 V_1 v_1\right)}; \quad q_{22} = \frac{KF_2L}{\left(\rho_2 c_2 V_2 v_2\right)}$$

where:

K – heat transfer coefficient,
F_1, F_2 – internal and external pipe surfaces,
ρ_i, c_i – flow density and heat capacity,
L – pipe length,
v_1 – kinematic viscosity of a liquid (Alder, 2001; Allaire and Craig, 2007).

System (3) is solved by the grid method taking into account boundary conditions and the deposition of various particles on the heat exchange surface. The proposed calculation algorithm makes it possible to consider the mutual influence of temperature and flow velocity on deposits and, conversely, the influence of deposited layer thickness distribution over the heat exchangers on heat and momentum transfer, as well as the hydrodynamic and thermal parameters in each device, considering variable thermophysical flow properties in pipe and inter-pipe spaces (Shen, 2017).

Figure 1 shows the changes in the deposit thickness ($\beta = 1 - \delta / R$), (δ – deposit thickness, R – pipe radius) along ten series-connected heat exchangers of the primary oil refining unit over one year of operation.

Figure 2 shows the curve of temperature change at the outlet to the settling device and its comparison with industrial data. As follows from the figure, after one year of operation, the temperature at the inlet to the settling tanks decreases by 15–20°C as contaminants accumulate on the surface. The largest particle deposition is observed in heat exchangers 7–10, where the temperature of the oil emulsion is high.

Dependence of the coefficient of turbulent exchange β on the parameter N, which characterizes the intensity of turbulent mixing in the boundary layer.

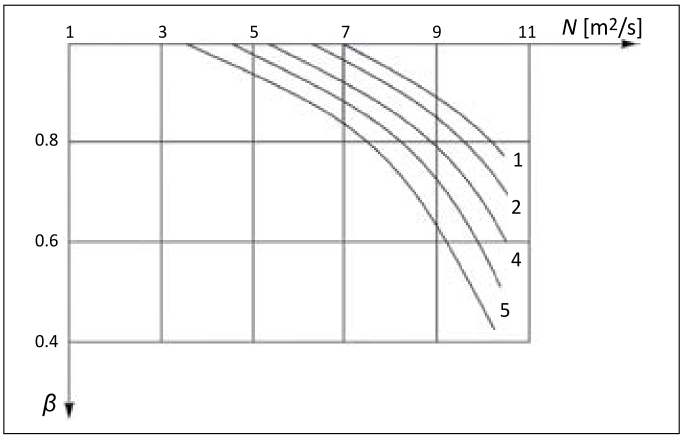

Figure 1. Change in the characteristic thickness of deposits on the heat exchange surface over time *t* equal to: 1 – 0.0016 h; 2 – 0.0032 h; 3 – 0.0048 h; 4 – 0.0065 h; 5 – 0.0080 h

Rysunek 1. Zmiana charakterystycznej grubości osadów na powierzchni wymiany ciepła w czasie *t* równym: 1 – 0.0016 h; 2 – 0.0032 h; 3 – 0.0048 h; 4 – 0.0065 h; 5 – 0.0080 h

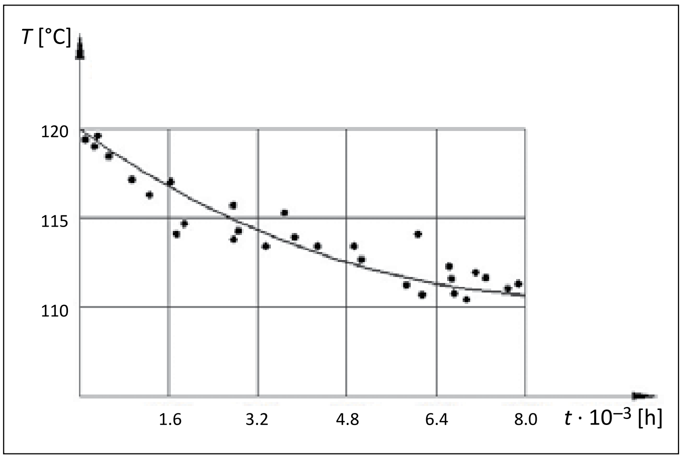

Figure 2. Decrease in the outlet temperature of crude oil over time (marked points are industrial data)

Rysunek 2. Spadek temperatury wyjściowej ropy naftowej w czasie (punkty zaznaczone to dane przemysłowe)

The graph shows curves for various values of the relative radial or geometric flow parameter (curves 1–5), which reflect the conditions of hydrodynamic interaction between the phases. The parameter is plotted along the abscissa axis N [m^2/s], associated with the turbulent diffusion of the pulse in the wall zone. The ordinate axis shows the change in the coefficient of turbulent exchange β, which characterizes the efficiency of the momentum (or heat/mass) transfer in the transverse direction.

The curves show a decrease in the coefficient β with an increase in the parameter N, which corresponds to a weakening of the influence of the wall region and a gradual transition to a more uniform velocity distribution across the section. The numbering of the curves (1–5) corresponds to increasing values of the determining parameter of the flow regime (for example, the radial coordinate or the Reynolds number in local form).

In the first heat exchangers, due to the low temperature, the thickness of the deposits is insignificant compared with the latter. A decrease in the temperature at the outlet to the settling tanks clearly worsens the separation of the oil emulsion due to an increase in its viscosity.

It should be noted that the narrowing of the channel in the heat exchanger pipes leads to flow turbulence ($Re = Reo\beta^{-1}$ – Reynolds number) and, consequently, to an increase in the probability of droplet collisions and their coalescence. Such flow turbulence is especially noticeable in heat exchangers 7–10.

Consequently, with particle deposition, along with the negative consequences of deteriorating heat exchange in the heat exchanger pipes, certain conditions are also created for increasing the intensity of pipe demulsification of the oil emulsion (Habibov et al., 2022).

The graph shows the dependence of temperature (T, °C) on time ($t \cdot 10^{-3}$, h) during the cooling process. The vertical axis shows the temperature in degrees Celsius, and the horizontal axis shows the time expressed in thousandths of an hour.

The initial experimental data are presented as separate dots (marked with black dots) located with some variation around the smoothed approximating curve. The curve has a decreasing character, which corresponds to the gradual decrease in the temperature of the object or medium under study over time.

At the initial moment, the temperature is about 120°C; then, as time increases to a approximately $8 \cdot 10^{-3}$ hours, the temperature gradually decreases and reaches values of about 110–112°C.

The graph is constructed against the background of a coordinate grid, which provides a convenient visual analysis of temperature changes at each stage of experimental observation.

Thus, the graph illustrates experimental data and a mathematical model of the cooling of a substance or system, in which the rate of temperature decrease diminishes over time, which may indicate a transition to a slower stage of heat exchange with the environment.

Conclusion

A model of the heat exchange process for heating an oil emulsion in series-connected heat exchangers of an oil refining plant is proposed and solved using the example of a primary oil refining unit.

Oil emulsions are among the most complex multiphase systems encountered in petrochemical production. Their hydrodynamic behavior and thermophysical characteristics significantly influence heat exchange efficiency in industrial equipment, particularly in heat exchangers operating under conditions of high viscosity, phase heterogeneity, and variable interfacial properties. Traditional methods of thermal calculation (based primarily on single-phase fluid theory) do not adequately describe the heat transfer processes occurring in emulsified media due to pronounced non-Newtonian rheology, unstable droplet structures, and interfacial interaction effects.

The complexity of the flow structure in pipelines and apparatus with emulsions leads to modifications in friction resistance, turbulence levels, and boundary layer behavior. The presence of dispersed water droplets in crude oil affects both the effective thermal conductivity and the heat capacity of the system, while coalescence and phase inversion phenomena introduce additional temporal variability into the heat exchange process. These factors may cause non-linear deviations of heat transfer coefficients from classical correlations, requiring alternative models that incorporate particle distribution, droplet deformation, and interfacial heat transfer mechanisms.

Although advances in experimental research and computational fluid dynamics have enabled deeper analysis of temperature fields, flow regimes, and emulsion stability under heat load, practical engineering approaches still rely heavily on empirical coefficients, limiting the reliability and predictive quality of thermal performance assessments in petrochemical heat exchange equipment.

Therefore, the development of scientifically grounded methodologies for evaluating hydrodynamic resistance and heat transfer in oil emulsions remains an urgent task. Improved theoretical models and experimental validation will contribute to the optimization of refinery and petrochemical processes by reducing energy consumption, enhancing operational safety, and increasing equipment service life.

This work has investigated the fundamental hydrodynamic and thermophysical properties of oil emulsions under typical operational conditions of heat exchange apparatus, establishing correlations that account for phase distribution, flow stability, and emulsion structure evolution during heating. The results support the creation of more accurate design frameworks for industrial heat exchangers handling emulsified oil systems.

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