BULETINUL Universităţii Petrol – Gaze din Ploieşti	Vol. LX No. 4B/2008	49 -58	Seria Tehnică

Experimental Study Regarding Heat Transfer through Direct Contact between Immiscible Liquids

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Abstract

The subject of the present paper is the experimental study of heat transfer through direct contact between three warm liquid petroleum fractions, warm toluene, and cold water. Contact between two immiscible liquids has been made by dispersing drops of either warm liquid petroleum fraction, toluene, in the cold water that represented the continue phase.

Access and exit measurements have been made for each of the liquids brought in direct contact, their flow capacities, the frequency of the formed drops and the amount of time necessary for a drop to reach the contact layer.

The measurements made were necessary for calculating the changed thermal fluxes at the level of each system formed of two immiscible liquids, of toluene or petroleum fraction drop diameter that goes through the layer of water, of heat transfer area between the drops of warm petroleum fraction or toluene and cold water and of global heat transfer coefficient between the drops of warm petroleum fraction or toluene and cold water. These results were correlated while taking into account the influence of physic features of the two immiscible liquids put in direct contact and four criteria relations that shape the heat transfer between the immiscible liquids were obtained.

Keywords*: heat transfer, immiscible liquid, coefficient of global heat transfer, flow rate, the continue phase.*

1. Introduction

The processing technologies of oil and petroleum fractions suppose the heating of technologic flows up to high temperatures imposed by the respective technological processes (chemical reactions, fractioning, etc.). Technological flow cooling resulted at high temperatures can be obtained by heat regeneration, through heat recuperation and through using same cooling agents as air and recycled water [1, 2]. In most cases of technological heating and cooling systems from chemical and petrochemical plants are obtained by separation of heat from cold flows with the help of a metallic wall, built according to cylinder or plane geometry.

The technological development of heat changes diversified the constructive variants already existing, for the purpose of economic and technologic optimization of the installation. The theoretical and applied studies regarding heat transfer through direct contact between immiscible liquids are very little developed in comparison with the traditional method of heat transfer between fluids that are separated by a wall.

Because, in some cases the direct heat transfer between immiscible liquids would be a more efficient solution in comparison with the heat transfer made with the help of wall method, the present study has the purpose of contributing to obtaining theoretical information belonging strictly to this kind of systems. In the case of direct heat transfer between immiscible liquids with different temperatures, the heat transfer mechanism is influenced by the physical features of the two liquids and by the manner in which the two come in direct contact. The most simple dispersed systems are made of two immiscible liquids, one of which, forms a continue phase and the second is dispersed in drops in the continue phase.

The heat transfer mechanism that is produced at the crossing between displacing drops in the stationary or moving continue phase, cannot be associated with the pure heat transfer mechanism made by convection, or with the heat transfer mechanism made by conduction through this interface. This heat transfer mechanism must be introduced in the category of convection heat transfer, but a special type of convection in which the displacements that imply heat transfer are immiscible liquids moving one from another. Of all the numerous possible variants for the study of heat transfer, there has been chosen the case in which the liquid with the higher density is the cold liquid that forms the continue phase. The liquid with the lowest density and with the highest temperature disperses in drops at the inferior level of the continue phase. These drops will have an ascendant way through the continue phase, phase that can be either stationary or descending (flowing in counter stream between the phases), or in an ascending way (flowing in uniflow between the phases), as compared to the dispersed phase [1,2].

2. Experimental part

The immiscible liquids used in the experiment have been water as the continue phase and petroleum fractions: diesel, motor oil, generator oil, and a pure toluene hydrocarbon, as disperse phases.

The circulation, in counter stream and in uniflow, has been performed of immiscible liquids in direct contact. The installation used in the experiment (fig.1) has been used for toluene and petroleum fractions heated drops and heat transfer study, they have constituted disperse phases and cold water as the continue phase.

The laboratory installation was a vacuous space shell column, so that the heat loss through the walls would be very low, negligible, in comparison with the thermal flow changed between the phases [3,4].

The glass column had a height of H = 70 cm, and the interior diameter Di = 30 mm. The contact height in the column between the drops of dispersed liquid and the continue phase was height contact 50 cm. Only one drops distribution nozzle was used, a glass nozzle with the interior diameter Di = 4,5 mm.

The experimental installation, presented in fig. 1 assures a great deal of flexibility regarding the study of work parameters influence (flow temperature, physical features) regarding the translation of the drops in dispersed phase, in the stationary continue phase or in ascending displacement.

The work mode supposes basically following the next stages: 1.stabilization the continue phase (constant flow capacity and temperature); 2.starting the dispersal phase on the recirculation circuit; 3.stabilization flow capacity, temperature and pressure at the entrance in the distributor for the dispersal phase; 4.establishing flow capacity and dispersal phase exit temperature; 5.establishing the exit temperature of the continue phase; 6.measuring the frequency of the distributed drops in the continue phase; 7. measuring the time of distance transit between two points established on the wall of the dispersal column.

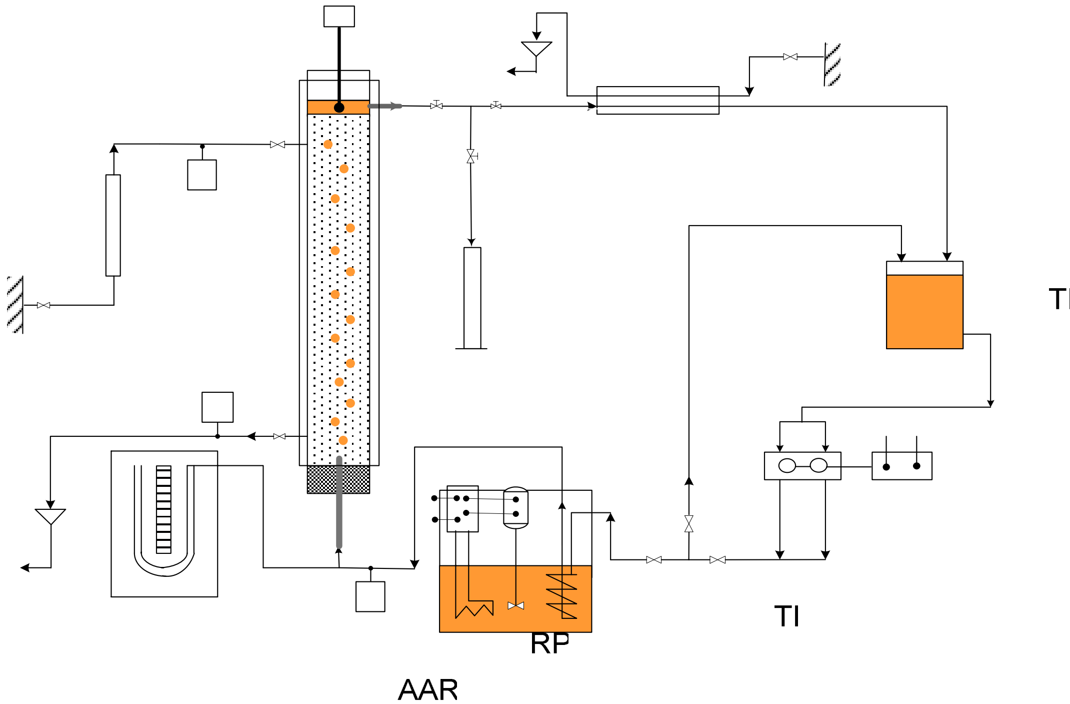


Fig 1. Experimental installation regarding heat transfer between the disperse petroleum fraction and the continue phase. CDV- vacuous space cell tower; VA- input tank; PPD- duplex peristaltic pomp; DP- drops distributor; RA-water cooler; C-sewerage; AAR-water pipeline; CG- graded cylinder; TI- temperature indicator; MD- differential pressure gauge; T-thermostat; RP- rotometer.

Because the measurements from point 4 and 5 can be affected by subjective errors, for each one repeated measurement (in most cases 5-th times) the result being used in the data processing being the arithmetic average of those measurements [5, 6].

3. Results and discussions

Spherical drops have been considered and the value of the average diameter has been determined, starting from the amount of product and number of drops formed in the respective time period. The transit time of a drop in the contacting layer was situated between 5-12 s.

For the flow circulation in counter stream entry petroleum fraction temperatures were situated around 70-80^{o}C, and at the exit, petroleum fraction temperatures were situated around 30^{o}C. Water had the initial temperature of 25^{o}C and the exit temperature was around 30^{o}C. For the flow circulation in uniflow entry petroleum fraction temperatures were situated around 70-80^{o}C, and at the exit petroleum fraction temperatures were situated around 30^{o}C, water had the initial temperature of 25^{o}C and the exit temperature was around 36-40^{o}C. When toluene was used as dispersal phase, it exit temperature was situated around 27^{o}C.

For the counter stream and uniflow circulation, calculating method is the same and it will be presented in the following [5].

The displacement ascending speed of drop petroleum fraction in the continue phase was calculated from the experimental data: $w_{p,exp} = \frac{H_{contact}}{\tau_{depl.drop}}$ (1)

where: $w_{p,exp}$ – the drops ascending displacement, m/s; $H_{contact}$ – contact height/level between the 2 liquids, m; τ_{drop} – drop displacement time on contact level, s.

The balance of heat between the thermal flow of warm and cold liquid: $Q_{released} = Q_{received}$ (2)

$$Q_{released} = Q_{fp} = m_{fp} \cdot \bar{c}_{p\,fp} \cdot (t_{fpi} - t_{fpe}) \quad (3)$$

$$Q_{received} = Q_{water} = m_{water} \cdot \bar{c}_{p\,water} \cdot (t_{we} - t_{wi}) \quad (4)$$

where: $Q_{released}$ – the thermal flow released by the warm petroleum fraction, W; $Q_{received}$ – the thermal flow received by water, W; m_{fp} – the warm petroleum fraction flow capacity, kg/s; $m_{apă}$ – the water flow capacity, kg/s;

t_{fpi}, t_{fpe} – temperatures of the warm petroleum fractions at entering and exiting the column, ^oC; t_{wi}, t_{we} – temperatures of the old liquid, water, at entering and exiting the tower/column, ^oC; $\bar{c}_{p\,fp}, \bar{c}_{p\,water}$ – average levels of heat for the warm petroleum fractions and water, at average entry and exit column temperatures, J/kg^oC.

The flow capacity for the two liquids have been determined by knowing the volumetric liquid flows and densities of average entrance–exit temperatures from the contacting tower/column.

The measurements determined the volume and diameter of the drop.

$$V_{drop} = \frac{V_{fp}}{f_{drops}} \quad (5)$$

where: V_{drop} – volume of a drop ml/drop, ml/drop; V_{fp} – petroleum fraction flow dispersed in drops, ml/min; f_{drops} – frequency of the drops when exiting the nozzle, drops/min.

By knowing the volume of a drop, its diameter was calculated and the number of drops from the contacting layer was determined knowing the frequency transit time of a drop in the layer:

$$d_{drop} = \sqrt[3]{\frac{6 \cdot V_{drop}}{\pi}} \quad (6)$$

$$n_{drops/layer} = f_{drops} \cdot \tau_{depl.drop} \quad (7)$$

where: d_{drop} – diameter of drop, m; $n_{drop/}$ – number of drops in the contacting layer;

The heat transfer surface of drops from the layer was determined knowing the surface from one drop and the drops number on the layer:

$$A_e = \pi d_{drop}^2 \cdot n_{drops/lazer} \quad (8)$$

The global heat transfer coefficient of drops from the layer was determined from Newton's law with the help of the relation: $Q = k \cdot A_e \cdot \Delta t_{med}$ .... (9)

where: $Q = Q_{released}$ - thermal flow released by the drops, W; A_e – heat transfer surface between the two immiscible liquids, m^2; Δt_{med} - the average logarithmical temperature difference between the 2 liquids that came in direct contact, ^oC; k - global heat transfer coefficient, $W/m^{2o}C$.

The average temperature difference between the two immiscible liquids was calculated as temperature difference log average. When the liquid flows circulate in counter stream or uniflow the average temperature difference is determined as the average logarithmical temperature, by the temperature difference at the warm nozzle and the temperature difference at the cold nozzle:

:
$$\Delta t_{m\log} = \frac{\Delta t_{wn} - \Delta t_{cn}}{\ln \frac{\Delta t_{wn}}{\Delta t_{cn}}} \qquad \text{......} \qquad (10)$$

where: Δt_{wn} - the temperature difference at the warm extremity, $\Delta t_{wn} = t_{fpi} - t_{we}$, ^oC;

Δt_{cn} - the temperature difference at the cold extremity, $\Delta t_{cn} = t_{fpe} - t_{wi}$, ^oC.

Analyzing the values of the calculated measures we can make the following interpretations:

In the case of counter stream liquid flow, the petroleum fraction debits have varied between 240-1500 cm3/h, the water flow varied between 2400-6000 cm3/h, drop frequency varied between 2280-7800 drops per hour, the ascending displacement speed of the drops in the layer varies between 4,2-10,0 cm/s.

In the case of uniflow liquid debits ,the petroleum fraction flows varied between 330-2040 cm3/h,the water flow varied between 2400-7200 cm3/h, the drop frequency varied between 2400-8100 drops per hour, the ascending displacement speed of the drop in the layer varies between 4,2-10 cm/s. In tables 1 and 2 are presented the values obtained for drops diameter and heat transfer coefficients the petroleum fractions warm drops and cold water.

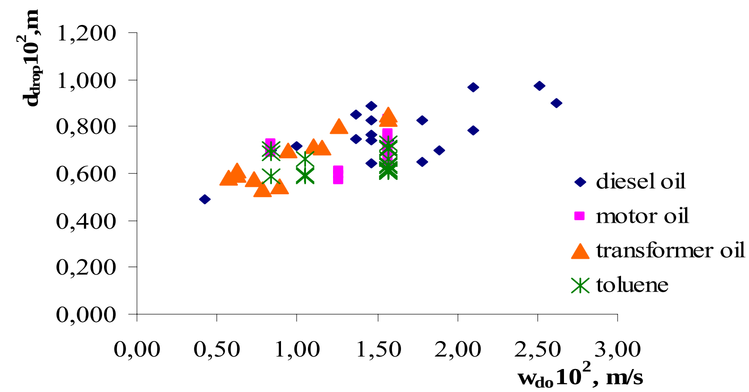
Table 1. Drop diameter values and heat transfer coefficients for petroleum fractions used in the counter stream circulation of liquids.

The petroleum fraction	**$d_{drop} \cdot 10^2$, m**	**k, $W/m^{2o}C$**
Toluene	0,588-0,726	253-432
Diesel oil	0,487-0,971	250-512
Transformer oil	0,534-0,854	246-359
Motor oil	0,568-0,831	294-490

Table 2. Drop diameter values and heat transfer coefficients for petroleum fractions used in the uniflow circulation of liquid.

The petroleum fraction	**$d_{drop} \cdot 10^2$, m**	**k, $W/m^{2o}C$**
Toluene	0,561-0,732	161-298
Diesel oil	0,831-0,985	221-370
Transformer oil	0,534-0,854	173-260
Motor oil	0,771-1,000	147-273

In figures 2, 3, 4, graphic representations have been drawn, that represent distributions of same values influenced by other ones that have helped the process of quality interpretations: drop diameter influenced by the speed of dispersed liquid in the nozzle [7, 8] heat transfer coefficient, k, influenced by the diameter of the accumulated drop, influenced by the speed of the drop in the layer of liquids.



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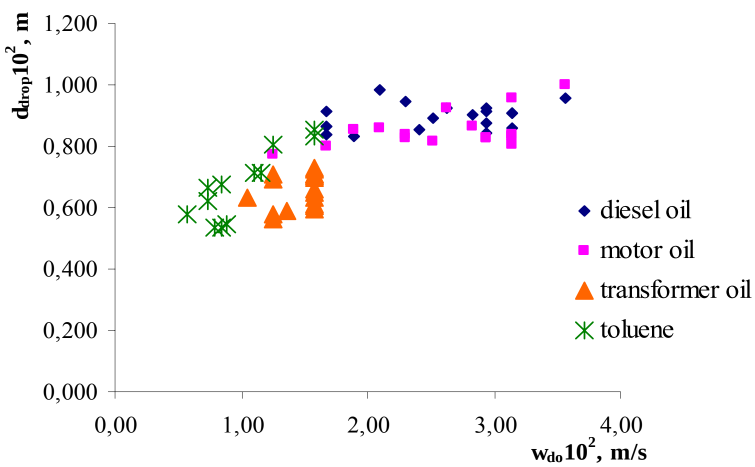

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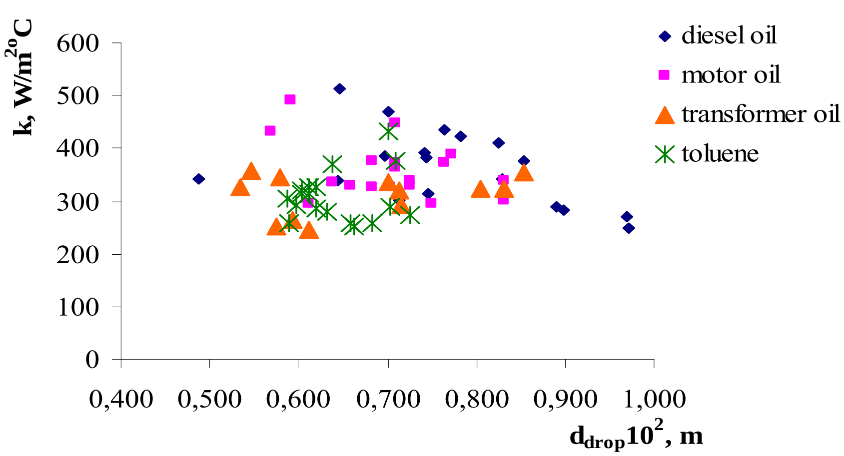
Fig 2. The distribution of drop diameters in warm petroleum with the speed of the drops in the nozzle (a- for the circulation in counter stream; b- for the circulation in uniflow).



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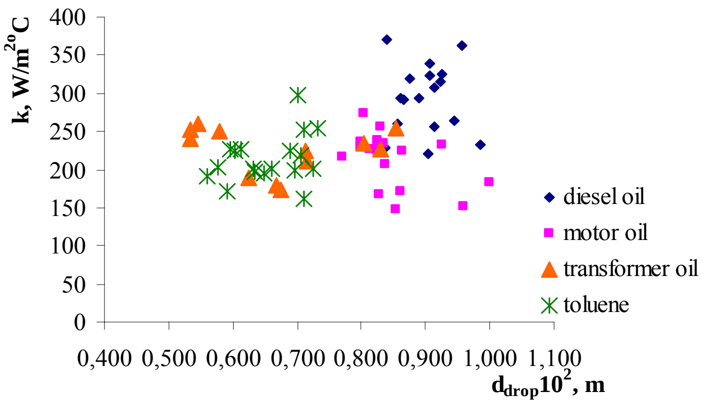

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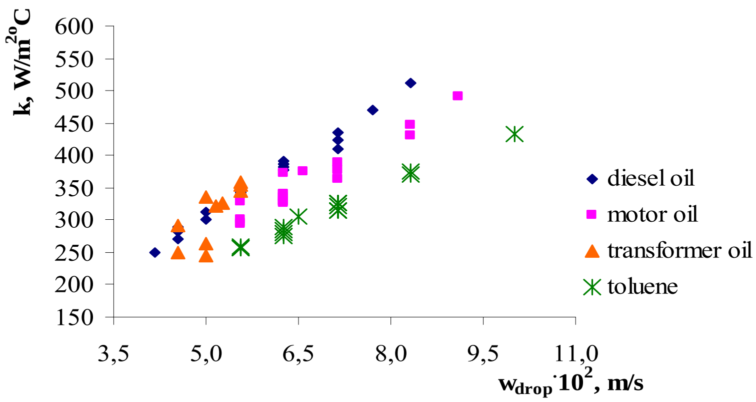
Fig 3. Distribution of heat transfer coefficients, influenced by the warm petroleum fraction drop diameters (a- for the circulation in counter stream; b- for the circulation in uniflow).



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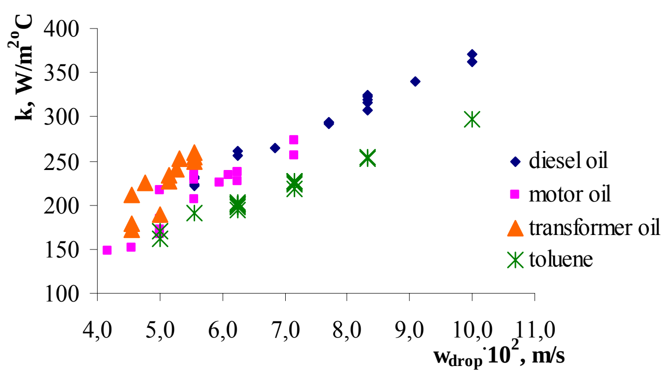

b)

Fig 4. Heat transfer coefficients distribution with the petroleum fraction drops displacement speeds in the continue phase-water (a- for the circulation in counter stream; b- for the circulation in uniflow).

Experimental and calculated measures, helped calculate the criteria of similitude, specific for the heat transfer (8, 9, 10). Thus, the Re, Pe, Nu criteria were determined with the following relations:

$$\mathrm{Re} = \frac{d_{drop} \cdot w_{drop} \cdot \rho_{fc}}{\mu_{fc}};\quad \mathrm{Pr} = \frac{c_p \cdot \mu}{\lambda};\quad \mathrm{Nu}_{exp} = \frac{k \cdot d_{drop}}{\lambda_{fd}};\quad \mathrm{Pe} = \frac{c_{pfd} \cdot d_{drop} \cdot w_{drop} \cdot \rho_{fd}}{\mu_{fd}}$$

where: the physical properties used in calculating the Nu and Pe belong to the petroleum fraction.

- d_{drop} – drop diameter, m; w_{drop} – drop displacement speed, m/s; ρ – density, kg/m^3; μ – dynamic viscosity, kg/m·s; c_p – specific heat, J/kg·^{o}C; λ – thermal conduction, W/m·^{o}C; index fc for continue phase and fd for dispersed phase.

It was experimentally observed that the temperatures of the two liquids and viscosity of the two immiscible liquids greatly influenced the heat transfer. Thus in order to reach a better correlation between the criteria similitude, two simplexes have been used:

- the ratio between the arithmetic average, between the entry and exit temperature for the petroleum fraction, water entry and exit arithmetic average, $\frac{\bar{t}_p}{\bar{t}_a}$;
- the ratio between the dynamic viscosity at the average temperature of petroleum fraction, and the dynamic viscosity at the average temperature of water, $\frac{\mu_p}{\mu_a}$.

Taking into account the influence of physical properties regarding heat transfer between the drops of petroleum fraction and water, the influence of the accumulated drops diameter and speed of drop displacement, the Pr relation was calculated for petroleum fraction and water. The experimental Nu criterion was determined.

The starting point was the general presupposed criterion, relation under the form of:

$$Nu = C \cdot \mathrm{Re}^m \, \mathrm{Pr}_{fp}^n \, \mathrm{Pr}_w^o \, Pe^p \left(\bar{t}_{fp} / \bar{t}_w\right)^r \left(\mu_{fp} / \mu_w\right)^s \tag{11}$$

Through mathematic regression the C constant and the exponents m, n, p and s have been determined. The similitude criteria and the two simplexes have been correlated so that the results were the following criteria relations that mould the heat transfer between immiscible liquids that have been chosen for the study.

For the circulation of immiscible liquids in counter stream when water is the continue phase:

When the ratio $\frac{\mu_{fp}}{\mu_w} < 1$, $Nu = 0{,}01058 Re^{0,4} Pr_{fp}^{0,12} Pr_w^{0,22} Pe^{0,5} \left(\bar{t}_{fp}/\bar{t}_w\right)^{0,4} \left(\mu_{fp}/\mu_w\right)^{0,4}$ (12)

When the ratio $\frac{\mu_{fp}}{\mu_w} > 1$, $Nu = 0{,}01058 Re^{0,4} Pr_{fp}^{0,12} Pr_w^{0,22} Pe^{0,5} \left(\bar{t}_{fp}/\bar{t}_w\right)^{0,4} \left(\mu_{fp}/\mu_w\right)^{-0,4}$ (13)

For the circulation of immiscible liquids in uniflows when water is the continue phase:

When the ratio $\frac{\mu_{fp}}{\mu_w} < 1$, $Nu = 0{,}012 Re^{0,32} Pr_{fp}^{0,12} Pr_w^{0,22} Pe^{0,5} \left(\bar{t}_{fp}/\bar{t}_w\right)^{0,4} \left(\mu_{fp}/\mu_w\right)^{0,4}$ (14)

When the ratio $\frac{\mu_{fp}}{\mu_w} > 1$, $Nu = 0{,}012 Re^{0{,}32} Pr_{fp}^{0{,}12} Pr_w^{0{,}22} Pe^{0{,}5} \left(\bar{t}_{fp}/\bar{t}_w\right)^{0{,}4} \left(\mu_{fp}/\mu_w\right)^{-0{,}4}$ (15)

4. Conclusions

After the experimental study has been finished, the measurements, the graphic representations and the correlations obtained, the following conclusion can be drawn.

We may observe an increase in the diameter of the drop when the speed of the liquid dispersed in the nozzle is increased. Diesel drops have the biggest diameter afterwards, diesel, generator oil, and toluene, for both situations for both situations of liquid contact.

When it comes to liquid circulation in counter stream, the heat transfer coefficients with the biggest value are encountered at diesel and motor oil, for average drop diameters. When it comes to liquid circulation in uniflow, the heat transfer coefficients with the biggest value are met at diesel.

With the increase of the drop displacement speed, the heat transfer coefficients for all petroleum fractions used is increased. When the case of the generator oil, the highest heat transfer coefficients.

At small diameters of petroleum fraction drops, the heat transfer coefficients have higher values, at ascending drop displacement speeds, drops of higher petroleum fraction, the heat transfer global coefficients are high.

Criteria relations 12, 13, 14, and 15, verify with an accuracy of more than 90%, the values of the experimental measurements.

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Studiul transferului de căldură prin contact direct între lichide nemiscibile

Rezumat

În lucrarea de faţă s-a studiat experimental schimbul de căldură prin contact direct între trei fracţiuni petroliere lichide calde, toluen cald şi apă rece. Contactarea a două lichide practic nemiscibile s-a făcut prin dispersarea în picături fie a fracţiunilor petroliere lichide calde, fie a toluenului, în apa rece care a constituit faza continuă.

Măsurătorile efectuate referitoare la debitul lichidului dispersat, frecvenţa şi viteza de deplasare a picăturilor în lichidul fază continuă au fost folosite pentru calcularea fluxurilor termice schimbate la nivelul fiecărui sistem format din două lichide practic nemiscibile, a diametrului picăturii de fracţiune petrolieră sau toluen ce traversează stratul de apă, a ariei de transfer de căldură între picăturile de fracţiune petrolieră caldă sau toluen şi apa rece, şi a coeficientul global de transfer de căldură între picăturile de fracţiune petrolieră caldă sau toluen şi apa rece.

Rezultatele experimentale au fost prelucrate prin metoda regresiei multiple, rezultând patru relaţii criteriale care modelează schimbul de căldură între lichidele practic nemiscibile alese.