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Experimental research of highly viscous fluid cooling in cross-flow to a tube bundle

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Abstract

The paper deals with the results obtained during experimental research of the heat transfer performances of cross-flow heat exchanger with highly viscous fuel oil flowing normal to the tube bundle with $Re < 1$ and $Pr \sim 2000$. Experimental research was performed on the oil cooler that consist of 50 in-line, with 10 mm outside tube diameter, 100 mm tube length, with both longitudinal and transversal tube pitch of 19.5 mm. Comparison of experimental results with equations from literature sources showed that dispersion of measured and calculated values is significant. In order to obtain more accurate equation statistical analysis was performed and dimensionless equation in the form

$$Nu_D = 3.17 \cdot Re_{Dc}^{0.1} \cdot Pr^{1/3} \cdot \left(\frac{Pr}{Pr_w}\right)^{0.25}$$

is obtained. Similar form of equation can be obtained when Reynolds–Colburn analogy is applied on previous experimental research of pressure drop.

Keywords: Tube bundle; Cross-flow; Heat transfer; Highly viscous fluid; Laminar flow

1. Introduction

Shell-and-tube heat exchangers and double-pipe heat exchangers are commonly used for heating or cooling of highly viscous fluids, such as fuel oils. Cross-flow heat exchangers can also be used for same purposes, with viscous fluid flowing normal to a tube bundle. The problem of cooling of highly viscous fluid flowing outside tube bundle is treated in few open literature sources, especially in case of low Reynolds and high Prandtl numbers.

In order to further investigate the problem we have built experimental setup with two cross-flow heat exchangers, presented in Fig. 1. The main elements of experimental setup are: storage tank (pos. 1), pump (3), cross-flow heat exchanger – heater (4), cross-flow heat exchanger – cooler (5) and atmospheric steam boiler (7). Process fluid (water and highly viscous heating oil) was heated by saturated steam at atmospheric pressure in heat exchanger 4, and than cooled by cold tap water in heat exchanger 5. Electric boiler (6 kW) was used for steam production. Steam condensed in exchanger 4 and condensate returned to boiler, passing through reservoir (6) with steam trap (11). Additional cooling of process fluid was done in the storage tank by pipe coil in order to achieve more stationary conditions. Test heat exchanger was cooler. Flow rates were controlled by valves (2, 8, 9 and 10). Process fluid flow rate was varied from 0.036 kg/s to 0.847 kg/s. Cold water flow rate was in order 0.59–0.84 kg/s providing laminar and transition flow in tubes.

Both heater and cooler consist of 50 vertical bare cooper tubes, with $D/d = 10/8$ mm tube diameter. The tube

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Nomenclature

a, a_1, a_2 parameters
c_p specific heat capacity at constant pressure J/(kg K)
c_r correction factor for the number of tube rows
d inner diameter of tube (m)
D outer diameter of tube (m)
f_A arrangement factor
k overall heat transfer coefficient (W/(m^2 K))
L characteristic length (m)
LMTD logarithmic mean temperature difference (°C)
$\dot{m}$ mass flow rate (kg/s)
MTD real mean temperature difference (°C)
n number of experimental runs
N number of tube rows
NTU number of transfer units
Nu_D Nusselt number calculated using characteristic length D
Nu_L Nusselt number calculated using characteristic length L
P heat efficiency parameter $P = \frac{t_{2o} - t_{2i}}{t_{1i} - t_{2i}}$
Pr Prandtl number $Pr = \frac{c_p \cdot \mu}{\lambda}$
$\dot{Q}$, W heat duty
R ratio of heat equivalents $R = \frac{t_{1i} - t_{1o}}{t_{2o} - t_{2i}}$
Re_D Reynolds number calculated using characteristic length D and velocity in minimal cross-section
Re_{Dc} Reynolds number calculated using characteristic length D and velocity in empty channel
Re_L Reynolds number calculated using characteristic length L and velocity in minimal cross-section
s tube pitch (m)
S heat transfer surface calculated for outside tube diameter (m^2)
t temperature (°C)
w fluid velocity (m/s)
z_i measured value of parameter z in the ith experimental run
z_i^c correlated value of parameter z in the ith experimental run
z_{av} average value of parameter z for the complete set of the experimental data $z_{av} = \frac{\sum_{i=1}^{n} z_i}{n}$

Greek symbols
α heat transfer coefficient (W/(m^2 K))
Δ_{av} standard deviation $\Delta_{av} = \sqrt{\frac{\sum_{i=1}^{n} \left(\frac{z_i - z_i^c}{z_i}\right)^2}{n}}$
Δm_1 uncertainty of mass flow rate measurement (kg/s)
Δt uncertainty of temperature measurement, characteristic temperature difference (°C)
Δ_{st} unsteadiness of working regime
ε correction factor for mean temperature difference
λ thermal conductivity (W/(m K))
μ dynamic viscosity (Pa s)
ν kinematic viscosity (m^2/s)
ρ density (kg/m^3)
ξ friction factor (loss coefficient) in Darcy–Weisbach form of pressure drop equation

Subscripts and superscripts
1 hot
2 cold
av average
c channel
i inlet/inside
l longitudinal
lam laminar
m mean
max maximal
min minimal
o outlet/outside
t transversal
tur turbulent
w wall

arrangement is in-line with $s_l = s_t = 19.5$ mm longitudinal and transversal pitch, placed in 100×100 mm channel. Heat exchangers contain $N = 10$ tube rows each with 5 tubes in a row. Viscous fluid used in experiment was heavy fuel oil with the following properties in temperature range from 25 °C to 100 °C

$$\rho = 976 - 0.677 \cdot t,\ \text{kg/m}^3 \tag{1}$$

$$c_p = 1644 + 3.84 \cdot t,\ \text{J/(kg K)} \tag{2}$$

$$\lambda = 0.075\ \text{W/(m K)} \tag{3}$$

$$\nu = 1.71 \times 10^{-6} \cdot \exp\left(\frac{223.6}{t}\right),\ \text{m}^2\text{/s} \tag{4}$$

where t is fluid temperature in °C.

All temperatures were measured with calibrated laboratory thermometers with 0.1 °C accuracy. Temperatures of process fluid were kept in range 24–62 °C corresponding to Prandtl numbers from 4.7 (minimal value for water) to 2315 (maximal value for oil). Fluid flow rates of process fluid and cold water were measured by volume–time measurement method.

2. The calculation of experimentally obtained heat transfer coefficient

Three heat duties can be calculated from each set of test data for cooler:

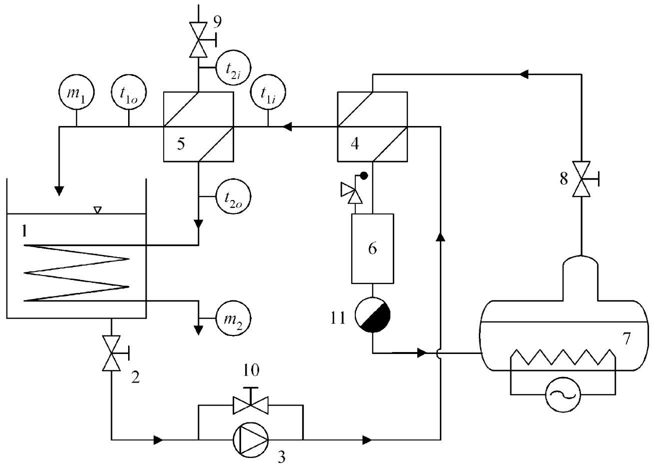

Fig. 1. Experimental setup.

- heat duty calculated for hot fluid

$$\dot{Q}_1 = \dot{m}_1 \cdot c_{p1} \cdot (t_{1\mathrm{i}} - t_{1\mathrm{o}}) \tag{5}$$

- heat duty calculated for cold fluid

$$\dot{Q}_2 = \dot{m}_2 \cdot c_{p2} \cdot (t_{2\mathrm{o}} - t_{2\mathrm{i}}) \tag{6}$$

- mean value of heat duty

$$\dot{Q}_\mathrm{m} = \frac{\dot{Q}_1 + \dot{Q}_2}{2} \tag{7}$$

Unstationarity of working regime is defined by

$$\Delta_\mathrm{st} = \frac{\sqrt{\left(\dot{Q}_1 - \dot{Q}_\mathrm{m}\right)^2 + \left(\dot{Q}_2 - \dot{Q}_\mathrm{m}\right)^2}}{\dot{Q}_\mathrm{m}} \tag{8}$$

and in further analysis measurements were treated as steady-state and taken into account in cases when Δ_st was less than 7%.

Following heat duties take into consideration the uncertainties of measurements of the fluid flow rates and bulk temperatures

$$\dot{Q}_{1,\max} = (\dot{m}_1 + \Delta\dot{m}_1) \cdot c_{p1} \cdot (t_{1\mathrm{i}} - t_{1\mathrm{o}} + 2 \cdot \Delta t) \tag{9}$$

$$\dot{Q}_{1,\min} = (\dot{m}_1 - \Delta\dot{m}_1) \cdot c_{p1} \cdot (t_{1\mathrm{i}} - t_{1\mathrm{o}} - 2 \cdot \Delta t) \tag{10}$$

$$\dot{Q}_{2,\max} = (\dot{m}_2 + \Delta\dot{m}_2) \cdot c_{p2} \cdot (t_{2\mathrm{o}} - t_{2\mathrm{i}} + 2 \cdot \Delta t) \tag{11}$$

$$\dot{Q}_{2,\min} = (\dot{m}_2 - \Delta\dot{m}_2) \cdot c_{p2} \cdot (t_{2\mathrm{o}} - t_{2\mathrm{i}} - 2 \cdot \Delta t) \tag{12}$$

Mean temperature difference for cross-flow heat exchangers is calculated by

$$\mathrm{MTD} = \varepsilon \cdot \mathrm{LMTD} \tag{13}$$

where

- $\mathrm{LMTD}_\mathrm{min}$, °C is the minimal value of mean logarithmic temperature difference which take into account the uncertainty of temperature measurements

$$\mathrm{LMTD}_\mathrm{min} = \frac{(t_{1\mathrm{i}} - t_{2\mathrm{o}} - 2 \cdot \Delta t) - (t_{1\mathrm{o}} - t_{2\mathrm{i}} - 2 \cdot \Delta t)}{\ln \frac{t_{1\mathrm{i}} - t_{2\mathrm{o}} - 2 \cdot \Delta t}{t_{1\mathrm{o}} - t_{2\mathrm{i}} - 2 \cdot \Delta t}} \tag{14}$$

- $\mathrm{LMTD}_\mathrm{max}$, °C is the maximal value of mean logarithmic temperature difference which take into account the uncertainty of temperature measurements

$$\mathrm{LMTD}_\mathrm{max} = \frac{(t_{1\mathrm{i}} - t_{2\mathrm{o}} + 2 \cdot \Delta t) - (t_{1\mathrm{o}} - t_{2\mathrm{i}} + 2 \cdot \Delta t)}{\ln \frac{t_{1\mathrm{i}} - t_{2\mathrm{o}} + 2 \cdot \Delta t}{t_{1\mathrm{o}} - t_{2\mathrm{i}} + 2 \cdot \Delta t}} \tag{15}$$

- ε is the correction factor for mean temperature differences for cross-flow heat exchanger with hot fluid mixed and the cold fluid unmixed

$$\varepsilon = \frac{\ln\left(\frac{1-P}{1-R \cdot P}\right)}{\mathrm{NTU}_2 \cdot (R-1)} \tag{16}$$

- NTU_2 is the number of transfer units (NTU_2) for cold fluid

$$\mathrm{NTU}_2 = \frac{N}{R} \cdot \ln \frac{1}{1 - \frac{R}{N} \cdot \ln\left\{\frac{1}{1 - \frac{N}{R} \cdot [1 - (1 - R \cdot P)^{1/N}]}\right\}} \tag{17}$$

Four overall heat transfer coefficients (reduced to the outside tube diameter) are determined as follows:

$$k_{1,\max} = \frac{\dot{Q}_{1,\max}}{S \cdot \mathrm{MTD}_\mathrm{min}} \tag{18}$$

$$k_{1,\min} = \frac{\dot{Q}_{1,\min}}{S \cdot \mathrm{MTD}_\mathrm{max}} \tag{19}$$

$$k_{2,\max} = \frac{\dot{Q}_{2,\max}}{S \cdot \mathrm{MTD}_\mathrm{min}} \tag{20}$$

$$k_{2,\min} = \frac{\dot{Q}_{2,\min}}{S \cdot \mathrm{MTD}_\mathrm{max}} \tag{21}$$

Mean overall heat transfer coefficient (referent value of k reduced to the outside tube diameter) is calculated as follows:

$$k_\mathrm{m} = \frac{k_{1,\max} + k_{1,\min} + k_{2,\max} + k_{2,\min}}{4} \tag{22}$$

and the heat transfer coefficient for fluid flowing normal to tube bundle is

$$\alpha_\mathrm{o} = \frac{1}{\frac{1}{k_\mathrm{m}} - \left(\frac{1}{\alpha_\mathrm{i}} \cdot \frac{D}{d} + \frac{D}{2 \cdot \lambda_\mathrm{w}} \cdot \ln \frac{D}{d}\right)} \tag{23}$$

where the heat transfer coefficient for fluid flowing through the tubes (α_i) is calculated using Hausen's equation [1] for turbulent and Schmidt's equation [2] for laminar flow. In further text α will be used instead of α_o.

3. Experiments with water flowing normal to a in-line tube bundle

In order to check the experimental procedure the experiments with water as the process fluid were performed.

3.1. Open literature survey for fluid flowing normal to a in-line tube bundle

Gnielinski [3] proposed the correlation for heat transfer in cross-flow across the tube bundle that is mostly cited in referent books (for example in [4–7]). For the cooling of liquid in heat exchanger with 10 or more tube rows with in-line tube arrangement, the Nusselt number is calculated using

$$Nu_L = \frac{\alpha \cdot L}{\lambda} = \left(0.3 + \sqrt{Nu_{\mathrm{lam}}^2 + Nu_{\mathrm{tur}}^2}\right) \cdot f_{\mathrm{A}} \cdot \left(\frac{Pr}{Pr_{\mathrm{w}}}\right)^{0.11} \tag{24}$$

where

- Nu_{lam} is the Nusselt number in case of laminar flow
$$Nu_{\mathrm{lam}} = 0.664 \cdot \sqrt{Re_L} \cdot \sqrt[3]{Pr} \tag{25}$$
- Nu_{tur} is the Nusselt number in case of turbulent flow
$$Nu_{\mathrm{tur}} = \frac{0.037 \cdot Re_L^{0.8} \cdot Pr^{1/3}}{1 + 2.443 \cdot Re_L^{-0.1} \cdot (Pr^{2/3} - 1)} \tag{26}$$
- Re_L is the Reynolds number
$$Re_L = \frac{w \cdot L}{\nu \cdot \left(1 - \frac{\pi \cdot s_1}{4 \cdot d_{\mathrm{o}}}\right)} \tag{27}$$
- f_{A} is the arrangement factor
$$f_{\mathrm{A}} = 1 + \frac{0.7}{\left(1 - \frac{\pi}{4} \cdot \frac{d_{\mathrm{o}}}{s_{\mathrm{t}}}\right)^{1.5}} \cdot \frac{\frac{s_1}{s_{\mathrm{t}}} - 0.3}{\left(\frac{s_1}{s_{\mathrm{t}}} + 0.7\right)^2} \tag{28}$$

The characteristic length in Reynolds and Nusselt numbers is

$$L = \frac{\pi \cdot D}{2} \tag{29}$$

Fluid velocity is calculated for minimal flow area of tube bundle and the fluid properties (except Pr_{w}) are evaluated at the average temperature of fluid. The domain of Eq. (24) is $Re_L = 10$–10^5 and $Pr = 0.6$–1000.

In [8] the following correlations for in-line tube bundle are given

$$Nu_D = \frac{\alpha \cdot D}{\lambda} = \begin{cases} 0.855 \cdot Re_D^{0.59} \cdot Pr^{1/3} & \text{for } Re = 1\text{–}100 \\ 0.548 \cdot Re_D^{0.492} \cdot Pr^{1/3} & \text{for } Re = 100\text{–}300 \end{cases} \tag{30}$$

In [9] Bell gave the following equation for in-line (so-called 90° arrangement with $s_1 = s_{\mathrm{t}}$) tube bundle

$$Nu_D = \frac{\alpha \cdot D}{\lambda} = a_1 \cdot \left(1.33 \cdot \frac{D}{s_{\mathrm{t}}}\right)^a \cdot Re_D^{a_2} \cdot Pr^{1/3} \cdot \left(\frac{\mu}{\mu_{\mathrm{w}}}\right)^{0.14} \tag{31}$$

where a is calculated using

$$a = \frac{1.187}{1 + 0.14 \cdot Re_D^{0.37}} \tag{32}$$

Parameters a_1 and a_2 are to be taken from Table 1.

Zhukauskas in [10] proposed the following correlation for tube bundle:

$$Nu_D = \frac{\alpha \cdot D}{\lambda} = 0.52 \cdot Re_D^{0.5} \cdot Pr^{0.36} \cdot \left(\frac{Pr}{Pr_{\mathrm{w}}}\right)^{0.25} \cdot c_{\mathrm{r}} \tag{33}$$

for range $Re_D = 100$–1000. Parameter c_{r} takes the number of tube rows into account.

Correlations (30), (31) and (33) are based on outer tube diameter as the characteristic length and fluid properties evaluated on average temperature. Reynolds number for these correlations is defined as

$$Re_D = \frac{w \cdot D}{\nu} \tag{34}$$

using fluid velocity in the minimal flow area of tube bundle.

3.2. Results and discussion for experiments with water

Twenty five experimental runs with water flowing across the tube bundle were performed in the following range:

- mass flow rate $\dot{m}_1 = 0.027$–0.067 kg/s;
- temperature $t_1 = 39$–24 °C;
- Prandtl number $Pr = 4.7$–6.1.

Eq. (24) gave very good agreement with experimental results ($\Delta_{\mathrm{av}} = 8.2\%$), as can be seen in Fig. 2. The range of Reynolds number was $Re_L = 186$–495, and the range of laminar and turbulent Nusselt numbers calculated using (25 and 26) is $Nu_{\mathrm{lam}}/Nu_{\mathrm{tur}} = 3.35$–$4.85$.

For other three correlations (30), (31) and (34) the range of Reynolds number is $Re_D = 71$–188, and it must be noted that they show very poor agreement with experimental results ($\Delta_{\mathrm{av}}(30) = 45.2\%$, $\Delta_{\mathrm{av}}(31) = 54.7\%$, $\Delta_{\mathrm{av}}(33) = 45.5\%$), as presented in Fig. 2.

General conclusion is that the correlation of Gnielinski (30) can be assumed as reliable.

Table 1
Parameters a_1 and a_2

Re_D	a_1	a_2
100–1000	0.408	0.540
10–100	0.900	0.369
<10	0.970	0.333

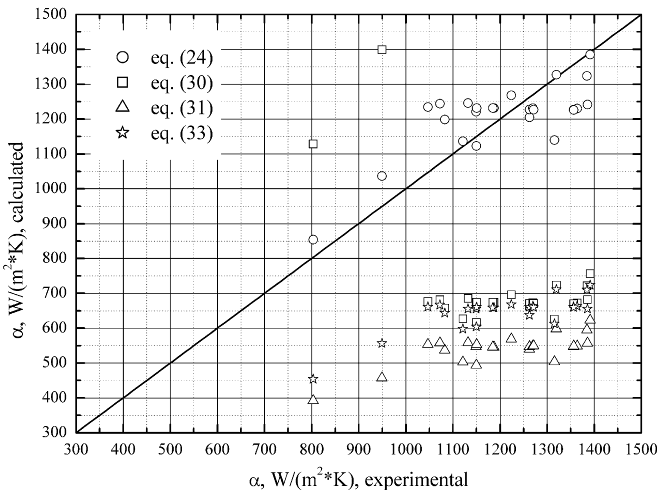

Fig. 2. Correlation field for experiments with water.

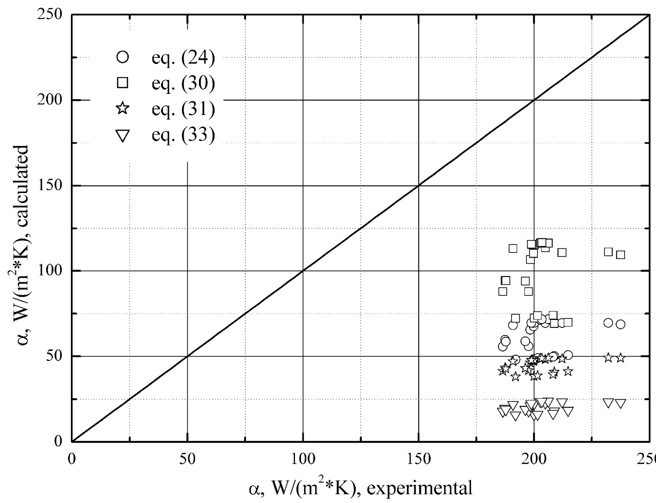

Fig. 3. Correlation field for experiments with fuel oil for correlations (24), (30), (31) and (33).

4. Experiments with highly viscous fuel oil flowing normal to a in-line tube bundle

Experiments with fuel oil in cross-flow over tube bundle were performed in the following range (24 experimental runs):

- mass flow rate $\dot{m}_1 = 0.034$–0.075 kg/s;
- oil temperature $t_1 = 62$–47 °C;
- Prandtl number $Pr = 1910$–2370.

Statistical parameters for correlations (24), (30), (31) and (33) are given in Table 2 and measured and calculated values for α are presented in Fig. 3. The range of laminar and turbulent Nusselt numbers calculated by (25) and (26) is $Nu_{\mathrm{lam}}/Nu_{\mathrm{tur}} = 23$–$34$.

Since the correlation of the experimentally obtained and calculated heat transfer coefficients is very poor, further investigation was performed. Since the Reynolds number and $Nu_{\mathrm{lam}}/Nu_{\mathrm{tur}} = 23$–$34$ indicates deeply laminar flow regime and the tube pitch is large $s_l/D = s_t/D = 1.95$ we have asked ourselves can we treat the flow regimes as the ones for single tube in cross-flow.

4.1. Literature data on flow of viscous fluid normal to a single cylinder

In [11] Gnielinski states that, for a single tube, “in the region of very low Reynolds number ($Re_L < 1$) the thickness of the boundary layer is not small compared to the dimensions of the tube” and recommends the following equation:

$$Nu_L = \frac{\alpha \cdot L}{\lambda} = 0.75 \cdot \sqrt[3]{Re_L \cdot Pr} \tag{35}$$

For Eq. (35) characteristic length is calculated using (29), velocity is in minimal cross-section area, and fluid properties are evaluated at the average fluid temperature.

Whitaker [12] proposed a correlation in the form

$$Nu_D = \frac{\alpha \cdot D}{\lambda} = \left(0.4 \cdot Re_{Dc}^{1/2} + 0.06 \cdot Re_{Dc}^{2/3}\right) \cdot Pr^{0.4} \cdot \left(\frac{\mu}{\mu_w}\right)^{1/4} \tag{36}$$

in which all properties (except μ_w) are evaluated at average fluid temperature. Eq. (36) is valid for $Re_{Dc} = 1$–10^5, $Pr = 0.67$–300 and $\mu/\mu_w = 0.25$–5.2.

The correlation proposed by Zhukauskas [13] is given by

$$Nu_D = \frac{\alpha \cdot D}{\lambda} = 0.75 \cdot Re_{Dc}^{0.4} \cdot Pr^{0.36} \cdot \left(\frac{Pr}{Pr_w}\right)^{0.25} \tag{37}$$

where $Re_{Dc} = 1$–40, $Pr > 10$ and thermophysical properties (except Pr_w) are evaluated on average fluid temperature.

Churchill and Berenstein [14] proposed the equation that covers the range $Re_{Dc} \cdot Pr > 0.2$ in the form

$$Nu_D = \frac{\alpha \cdot D}{\lambda} = 0.3 + \frac{0.4 \cdot Re_{Dc}^{1/2} \cdot Pr^{1/3}}{\left[1 + \left(\frac{0.4}{Pr}\right)^{2/3}\right]^{1/4}} \cdot \left[1 + \left(\frac{Re_{Dc}}{28,200}\right)^{5/8}\right]^{4/5} \tag{38}$$

where all properties are evaluated on film temperature.

Reynolds number in correlations (36)–(38) is defined in the following form:

$$Re_{Dc} = \frac{w_c \cdot D}{\nu} \tag{39}$$

Table 2
Statistical parameters for correlations (24), (30), (31) and (33)

Correlation	Reynolds number	Δ_{av},%
(24)	$Re_L = 1.83$–4.95	69.5
(30)	$Re_D = 0.7$–1.88	52.1
(31)		77.9
(33)		89.9

Table 3
Statistical parameters for correlations (35)–(38)

Correlation	Reynolds number	Δ_{av},%
(35)	$Re_L = 1.83$–4.95	65.6
(36)	$Re_{Dc} = 0.35$–0.94	79.8
(37)		74.4
(38)		80.3

where w_c is the fluid velocity based on empty channel flow area.

4.2. Results and discussion for experiments with highly viscous fuel oil

Statistical parameters for correlations (35)–(38) are given in Table 3, and measured and calculated values for α are presented in Fig. 4.

Eq. (35) is also tested against measured values in rearranged form

$$Nu_L = \frac{\alpha \cdot L}{\lambda} = 0.75 \cdot \sqrt[3]{Re_L \cdot Pr} \cdot f_A \cdot \left(\frac{Pr}{Pr_w}\right)^{0.11} \tag{40}$$

which Gnielinski [4] has found suitable for tube bundle. Standard deviation for Eq. (40) is $\Delta_{av} = 60.4\%$, and measured and calculated values are presented in Fig. 4.

General conclusion is that the measured values are greater than calculated for all experimental runs, so we have tried to establish the new correlation. Since the Nusselt number shows weak dependency on Reynolds number, we have found that the following correlation is suitable:

$$Nu_D = \frac{\alpha \cdot D}{\lambda} = 3.17 \cdot Re_{Dc}^{0.1} \cdot Pr^{1/3} \cdot \left(\frac{Pr}{Pr_w}\right)^{0.25} \tag{41}$$

with $\Delta_{av} = 4.78\%$. Correlation (41) is presented graphically in Fig. 5. Fluid properties for Eq. (41) are taken at average fluid temperature.

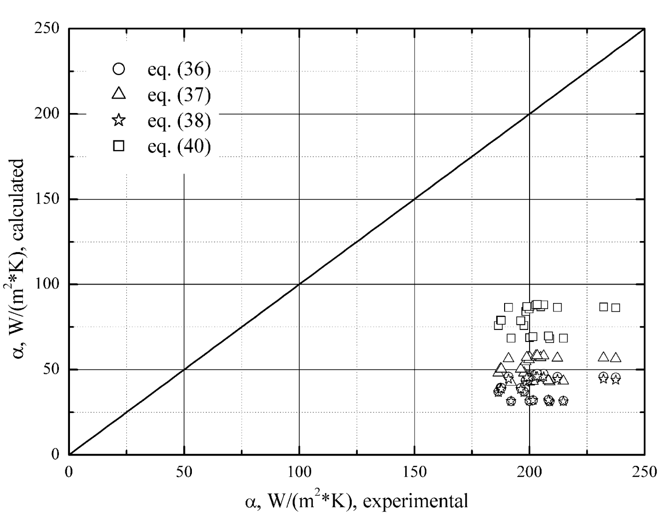

Fig. 4. Correlation field for experiments with fuel oil for correlations (36)–(38) and (40).

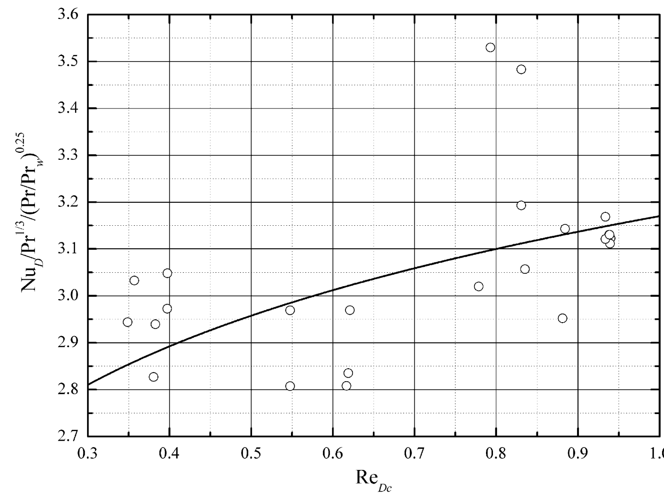

Fig. 5. Experimental results and correlation (41).

It must be noted the following. Lapple and Shepherd [15] gave the equation for determination of the friction factor for cross-flow over a single circular cylinder in the form

$$\xi = \frac{24.72}{Re_{Dc}^{8/9}} \tag{42}$$

which they have found to be valid for $Re_{Dc} < 2$. If the Reynolds–Colburn analogy (as described in [16]) is applied on Eq. (42) the Nusselt number is

$$Nu_D = \frac{\alpha \cdot D}{\lambda} = 3.09 \cdot Re_{Dc}^{1/9} \cdot Pr^{1/3} \tag{43}$$

which gives a similar form when compared with the correlation (41).

5. Conclusion

Subject of this article is a research of the intensity of heat transfer during the cross-flow of highly viscous fluid in tubular heat exchanger. In order to test the correlations from the open literature experimental research was performed on cooler that consists of 50 bare cooper tubes, with 10/8 mm outside/inside tube diameter, 100 mm tube length, with both longitudinal and transversal tube pitch of 19.5 mm and in-line arrangement.

The verification of experimental setup was performed using water as a fluid in cross-flow (25 working regimes), and it was found that Gnielinski correlation is suitable one for describing the process.

Experimental research on cooling of highly viscous fluid in tubular cross-flow heat exchanger includes 24 working regimes. It was found that the correlations from literature sources give significant scattering when they were compared to the measured values of heat transfer coefficient. For highly viscous fuel oil flowing normal to tube bundle with $Re_{Dc} < 1$ and $Pr = 1910$–2370, in case of oil cooling, it was found out that the correlation

$$Nu_D = \frac{\alpha \cdot D}{\lambda} = 3.17 \cdot Re_{Dc}^{0.1} \cdot Pr^{1/3} \cdot \left(\frac{Pr}{Pr_w}\right)^{0.25} \tag{41}$$

describes the phenomenon with standard deviation $\Delta_{av} = 4.78\%$. Similar form of equation can be obtained when Reynolds–Colburn analogy is applied on Lapple and Shepherd [15] experimental research of pressure drop.

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