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Influence of Artificial Roughness on Heat Transfer in the Rotating Flow

T. Magrakvelidze, N. Bantsadze, N. Lekveishvili, Kh. Lomidze

Abstract**—**The results of an experimental study of the process of convective and boiling heat transfer in the vessel with stirrer for smooth and rough ring-shaped pipes are presented. It is established that creation of two-dimensional artificial roughness on the heated surface causes the essential (~100%) intensification of convective heat transfer. In case of boiling the influence of roughness appears on the initial stage of boiling and in case of fully developed nucleate boiling there was no intensification of heat transfer. The similitude equation for calculating convective heat transfer coefficient, which generalizes well experimental data both for the smooth and the rough surfaces is proposed.

Keywords**—**boiling, heat transfer, roughness.

I. Introduction

In the heat exchangers generally, and particularly in stirred tanks, which are widely used in chemical and food industry, heat transfer processes frequently accompany the chemical reactions. As a result, it is obvious that heat exchange intensification in such kind of apparatus has great practical value. Among of numerous methods of intensification of stirring and heat transfer currently the mostly effective and well studied is the method of using reflective spacers [1]. Together with this, the effectiveness of the method of artificial roughness appeared quite high in case of turbulent heat exchange in channels [2],[3] has not been investigated incase of rotating flow. First works dedicated to this issue, as far as we know, were published by authors [4],[5]. Boiling process in such conditions as far as we know was not studied as well.

II. Nomenclature

a	[m^2/c]	thermal diffusivity
α	[w/m^2K]	heat transfer coefficient
b	[m]	width of the paddles
c	[-]	constant
D	[m]	diameter of the vessel
d	[m]	diameter of the mixer
ΔH	[m]	different replacement levels between mixer and heated pipe
H	[m]	level of water in the vessel
h	[m]	height of roughness elements
λ	[W/mK]	coefficient of the heat conductivity
ν	[m^2/c]	cinematic viscosity
n	[1/c]	mixer RPMs
$Nu=\alpha D/\lambda$	[-]	Nusselt number
$Pr=\nu/a$	[-]	Prandtl number
q	[w/m^2]	heat flow density
s	[m]	pitch between roughness elements
t	[K]	temperature
z	[-]	quantity of the paddles

Subscripts

f	fluid
r	rough
s	smooth
st	saturated
w	wall

III. Test unit

The test unit **(**Fig.1) - stainless steel cylindrical vessel (1), with inner diameter D=200 mm and height 300 mm was created in order to investigate the influence of artificial roughness on heat transfer intensity in rotating flow. The heating low voltage AC electric power was supplied to experimental ring shaped stainless steel pipe (5) via copper conductors (7) installed through the bottom of the vessel. The outer diameter of pipe was 10 mm, average diameter of pipe ring -140 mm.

The heated pipe ring was located at 50 mm from the bottom of the vessel coaxially with mixer's shaft. The admitted heat was disposed with liquid (distilled water) in the vessel. The wall of the vessel was cooled from outside by water (16) using cooling jacket (13). In case of boiling vessel was insulated and vapor was condensed on the water (15) cooled coil (6). On the cover of the vessel electric motor (4) was mounted. The shaft of the mixer (2) was connected with electric motor. The paddles (3) with various dimensions were mounted on the mixer's shaft on the specific level from the bottom of the vessel. Thermocouple (10) with case (9) was immersed in the vessel with liquid for measuring liquid temperature. Level indicator measured level of the liquid in the vessel.

Experiments were carried out in case when the paddles of the mixer were located in the different levels from the heated experimental pipe. Impeller mixers with vertical paddles were used. Mixers with various diameters (d), with different quantity (Z) and width (b) of the paddles, were used: d=35 mm, 50 mm, 65 mm, 100 mm, 120 mm, 180 mm; Z=2, 4, 6; b=10 mm, 20 mm, 30 mm. The angles between paddles were equal.

Roughness elements- wire rings or washers were attached on the heated experimental pipe. The height (h) of the element of the roughness and the average pitch (s) between the elements varied: h=0.25 mm, 0.5 mm, 1.15 mm, 1.4 mm; s/h=3.5, 7.1, 7.5, 8, 10, 20, 40.

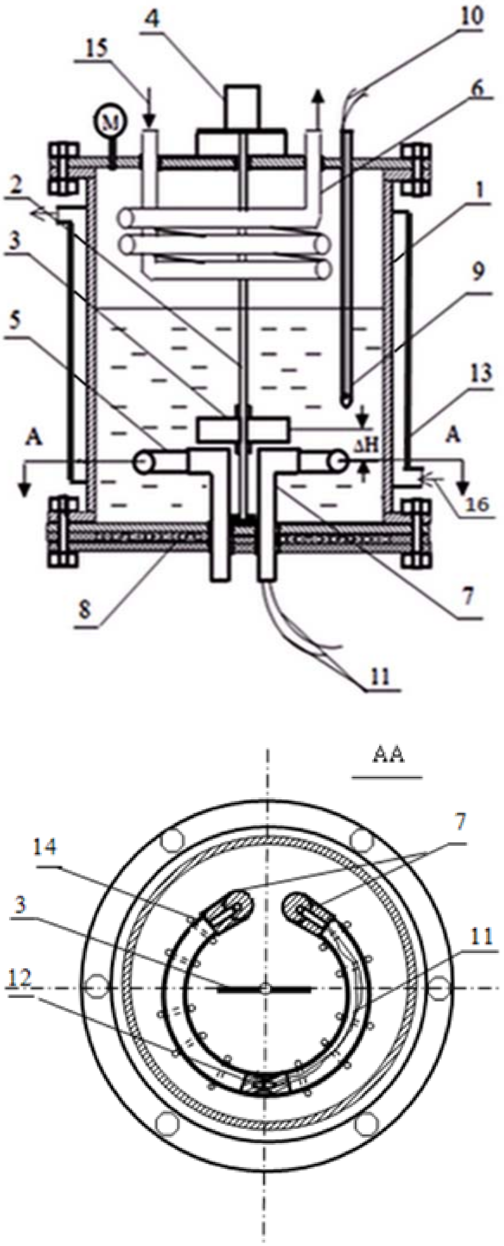

Fig. 1 Test unit
1-Vessel; 2-Shaft; 3- Paddle;4-El. motor; 5-Ring-shaped pipe; 6-Cooling coil; 7-Conductors; 8-Auxiliary heater; 9-Case; 10,11–Thermocouples; 12–Chamber; 13–Cooling jacket; 14–roughness elements; 15,16-Cooling water.

The inner surface temperature of the experimental pipe was measured by three chromel-alumel thermocouples, placed in Teflon chamber (12). The temperature of the outer surface of experimental pipe was calculated using well-known formula. The temperature of the distilled water in the vessel was measured also using chromel-alumel thermocouple, which was placed in the case (10) filled with oil. The voltage on the ends of thermocouples was measured by digital multimeter.

In case of convective heat transfer coefficient of heat transfer was determined by formula:

$$\alpha = \frac{q}{t_w - t_f} \tag{1}$$

In case of nucleate boiling:

$$\alpha = \frac{q}{t_w - t_{st}} \tag{2}$$

The results of the experiments are performed using modified Re number in the range: $10^4 \le \text{Re} \le 350 \cdot 10^3$; Pr number in the range: $2 \le \text{Pr} \le 6.5$.

IV. Convective Heat Transfer

Experiments were carried out both for smooth and rough surfaces (pipes). Part of experimental data is shown in Fig. 2.

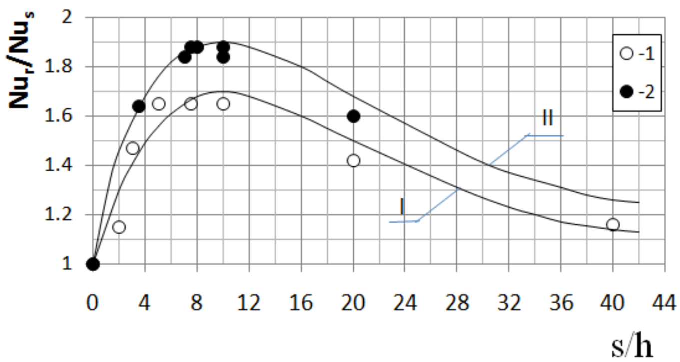

Fig. 2 Relation of heat transfer intensity from geometrical parameter s/h. $\text{Re}=2 \cdot 10^5$, Pr=3, d=120 mm, b=10mm.
1. Experimental data, □H=0; 2.Experimental data, □H=30mm.
I – According to formula (3), □H=0;
II – According to formula (3), □□=30 mm.

As it is clear from the fig. 2, the character of relation of $Nu_r/Nu_s=f(s/h)$ is similar despite of change of ΔH. It was found that the optimal range of artificial roughness geometrical parameter pitch-to height ratio is $7 \le s/h \le 10$. In the range $7 \le s/h \le 10$ the meaning of Nu_r/Nu_s is higher for 20% in case of ΔH=30mm, than in case of ΔH=0.

In the Fig. 3 the experimental results for smooth and rough surfaces are represented as a relation A=f (Re), where

$$A = \frac{Nu}{\Pr^m (D/d)^k (D/H)^{0.25}}$$

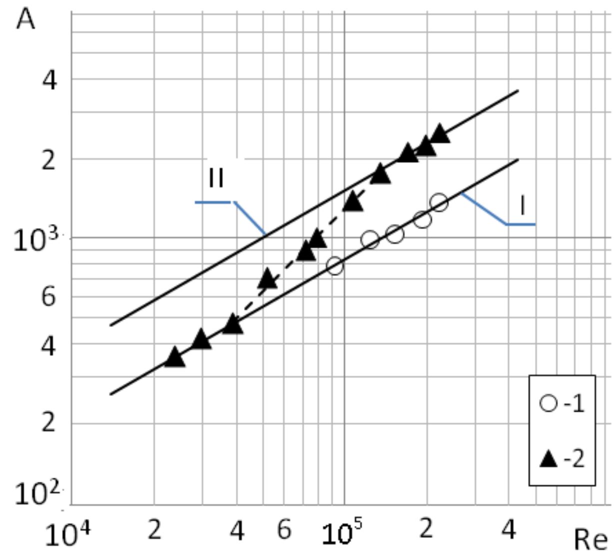

Fig. 3 Relation of heat transfer intensity from Reynolds number, b=10 mm; ΔH=30 mm.
1. Smooth surface; Rough surfaces: 2. h=0.25mm, s/h=10;

Three different regimes of roughness effect appearance can be seen: **1**. Roughness has no influence on heat transfer. The Reynolds number range $Re<40\cdot10^3$ coincides with the such regime. **2**. Regime of partial appearance of roughness effect, coincided the range $40\cdot10^3 \leq Re \leq 140\cdot10^3$; **3**. Regime, where roughness effect is fully developed $Re \geq 140\cdot10^3$. It should be mentioned, that in this regime when ΔH=30 mm intensification was far more high, than in case of ΔH=0.

Based on experimental study the following similitude equation for was obtained:

$$Nu = 0.82\,\mathrm{Re}^{0.62}\,\mathrm{Pr}^{0.33}\left(\frac{D}{d}\right)^{0.35}\left(\frac{D}{H}\right)^{0.25}\left(\frac{25b}{H}\right)^{0.35}\times \left(1+\frac{|\Delta H|}{b}\right)^{-0.12}\left(\frac{Z}{2}\right)^{0.35}(\mu/\mu_w)^{0.14}\varepsilon_r, \quad (3)$$

Where in case of smooth surface $\varepsilon_r=1$, and for rough surfaces

$$\varepsilon_r = \mathrm{Pr}^{0.05}\left(\frac{D}{d}\right)^{-0.15}\left(1+\frac{|\Delta H|}{b}\right)^{0.1}\left(\frac{Z}{2}\right)^{-0.1}\times (1+0.2(s/h)\exp(-0.1(s/h)))$$

In the Fig. 4 is represented comparison between formula (3) and experimental data as a relation $A^*=f(\mathrm{Re})$, where

$$A^* = \frac{Nu}{f(\mathrm{Pr},G)} \quad (4)$$

$$f(\mathrm{Pr},G) = \mathrm{Pr}^{0.33}\left(\frac{D}{d}\right)^{0.35}\left(\frac{D}{H}\right)^{0.25}\left(\frac{25b}{H}\right)^{0.35}\times \left(1+\frac{|\Delta H|}{b}\right)^{-0.12}\left(\frac{Z}{2}\right)^{0.35}(\mu/\mu_w)^{0.14}\varepsilon_r \quad (5)$$

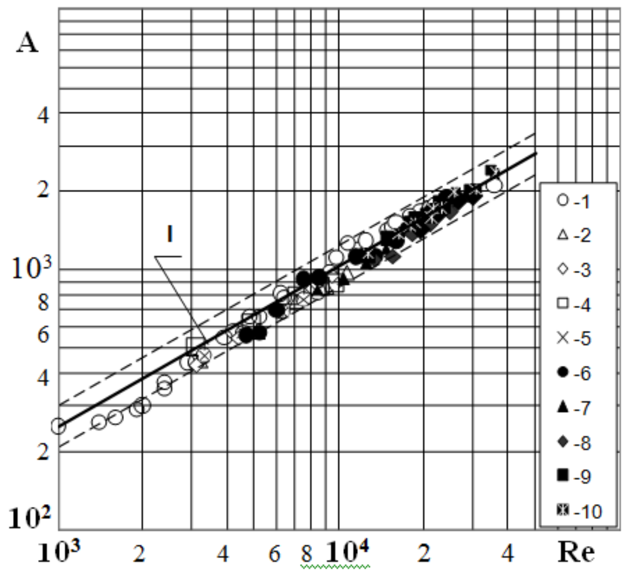

Fig.4 Relation of heat transfer intensity from Re number.

I – According to formula (3); Experimental data.Smooth surface: b=10 mm, **1**. Z=2; **2**. Z=4; **3**.Z=6;**4**. b =20 mm; **5**. b=30 mm; Rough surfaceses: b=10 mm, Z=2: **6**. s/h=5; **7**. s/h=8; **8**. s/h=10; **9**. s/h=20; **10**. s/h=40.

As it is clear from the figure, similitude equation (2) is in good agreement with experimental data obtained with smooth and rough surfaces.

V. Boiling

Researches done in [6] show that in case of nucleate boiling of subcooled liquid (distilled water) flow in annulus artificial roughness increased heat transfer intensity in the regime of initial boiling and did not affect in case of developed nucleate boiling.

To find if the similar mechanism works in case of rotating liquid flow experiments were carried out in apparatus with stirrer. Experiments were done both for smooth and rough pipes. It was used two paddle impeller type flat paddle stirrer with diameter 65 mm. Artificial roughness was created attaching wire rings to ring- shaped stainless steel pipe. Artificial roughness geometrical parameters were: element height - h=1.15 mm, pitch-to-height ratio- s/h=7.5. Distilled water was used with saturation temperature. Stirrer's RPMs for smooth surface were: n=0, n=3.17, n=9; for rough surface n=3.17, n=9.

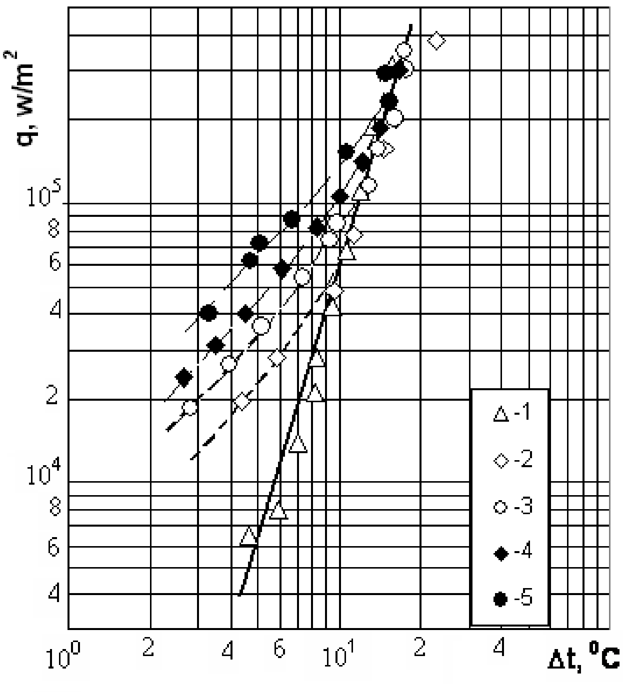

Fig.5 Relation of heat flux on (t_w-t_{st})
Smooth surface: 1. n=0 RPS; 2. n=3.17 RPS; 3. n=9 RPS;
Rough surface h=1.15 mm; s/h=7.5: 4. n=3.17 RPS; 5. n=9 RPS.

In the Fig. 5 results of experiments are performed as a relation q=f (t_w-t_{st}). It can be seen that two-dimensional artificial roughness increased heat transfer intensity in the regime of initial boiling, and did not in case of developed nucleate boiling. In case of developed nucleate boiling stirrer's RPS-s have no influence on heat transfer intensity.

VI. Conclusion

In case of convective heat transfer creating two-dimensional artificial roughness on the surface of ring shaped heated pipe immersed in the apparatus with mixer significantly increases heat transfer intensity; roughness effect is more when mixer and heated pipe are placed at different levels.

Optimal range of two-dimensional artificial roughness geometrical parameter was found - 7.5< s/h <10, where maximal intensification of heat transfer intensity (100%) was reached.

Similitude equation for calculating heat transfer coefficient generalizing well experimental data has been obtained.

In case of nucleate boiling two-dimensional artificial roughness increased heat transfer intensity in the regime of initial boiling, and did not in case of developed nucleate boiling.

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