HEFAT2010
7th International Conference on Heat Transfer, Fluid Mechanics and Thermodynamics
19-21 July 2010
Antalya, Turkey

HEAT TRANSFER INTENSIFICATION IN STIRRED TANKS USING ARTIFICIAL ROUGHNESS METHOD

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ABSTRACT

The results of an experimental study of the process of convective heat transfer in the apparatus with mixer for the smooth and rough ring-shaped pipes are presented. It is established that the creation of two-dimensional artificial roughness on the heated surface causes the essential (~100%) intensification of heat transfer for both the normal and crisis regimes of mixing. The similitude equation for calculating heat transfer coefficient, which generalizes well experimental data both for the smooth and the rough surfaces, is proposed. Considerations, satisfactorily explaining some special features of the process of the heat transfer of rough surfaces in the apparatus with mixer are given.

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 of this, 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 in apparatus with mixers. First works dedicated to this issue, as far as we know, were published by authors [4,5].

NOMENCLATURE

a	[m^2/c]	thermal diffusivity
α	[w/m^{2}K]	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]	difference between mixer and heated pipe replacement levels
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 RPM
$Nu=\alpha D/\lambda$	[-]	Nusselt number
$Pr=\nu/a$	[-]	Prandtl number
q	[W/m^2]	heat flow density
$Re=nd^2/\nu$	[-]	Reynolds number
s	[m]	pitch between roughness elements
t	[K]	temperature
Z	[-]	quantity of the paddles

Subscripts

f	fluid
n	normal
r	rough
s	smooth
T	tangential
w	wall

EXPERIMENTAL UNIT

The experimental unit (**fig.1**) was created in order to investigate the influence of artificial roughness on heat transfer intensity in apparatus with mixer. The main part of the experimental unit was stainless steel cylindrical vessel (1), with inner diameter D=200 mm and height 300 mm. Copper conductors (7) were installed through the bottom of the vessel. Through these conductors, the electric power was supplied to heated experimental ring shaped stainless steel pipe (5) with outer diameter 10mm. The average diameter of pipe ring was 140mm.

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 (13) using cooling jacket (6). On the cover of the vessel electric motor (4) was mounted. The shaft of the mixer (2) was connected with electric motor shaft by coupling. The paddles (3) with various dimensions were mounted on the mixer shaft on the specific level from the bottom of the vessel. Thermocouple with case (10) was inserted in the vessel with liquid for measuring liquid temperature. Level indicator measured level of the liquid in the vessel.

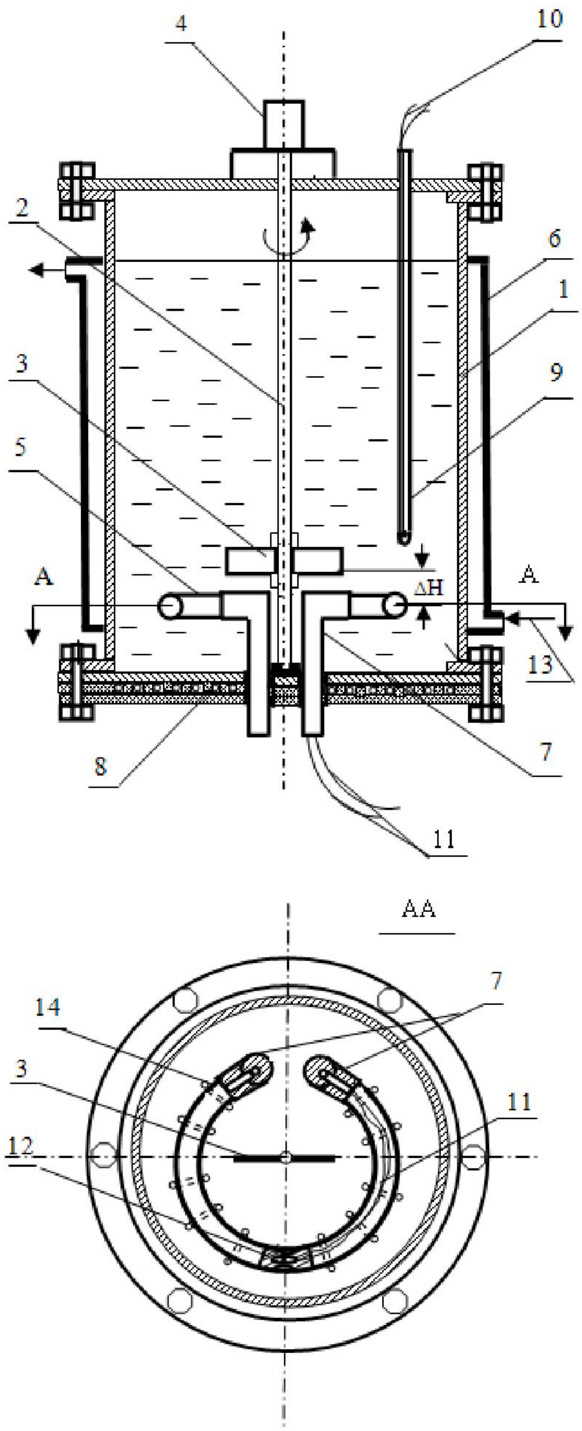


Figure 1 Experimental unit
1-Vessel; 2-shaft; 3- Paddle; 4- El. motor ; 5-Ring-shaped experimental pipe; 6-Cooling jacket; 7- Conductors; 8-auxiliary heater; 9- Case; 10,11 – Thermocouples; 12 –chamber; 13 –cooling water; 14 –roughness elements.

The 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.

On the heated experimental pipe the roughness elements were fixed. As the elements of roughness were used wire rings or washers fixed on the heated 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. The experimental pipe was heated using low voltage AC.

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.
Coefficient of heat transfer was determined by formula:

$$\alpha = \frac{q}{t_w - t_f}. \qquad (1)$$

The results of the experiments are performed using modified Re number in the range: $10^4 \le Re \le 350 \cdot 10^3$; Pr number in the range: $2 \le Pr \le 6.5$. Part of the results of investigations is given on **fig. 2-7**.

RESULTS AND DISCUSION

Relation between heat transfer intensity and different replacement levels between mixer and heated pipe, is shown on **fig. 2**, where

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

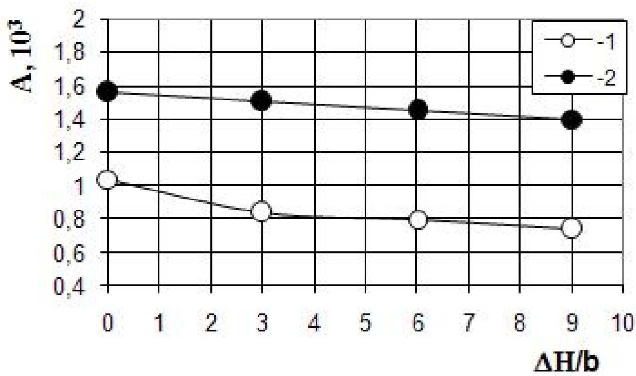
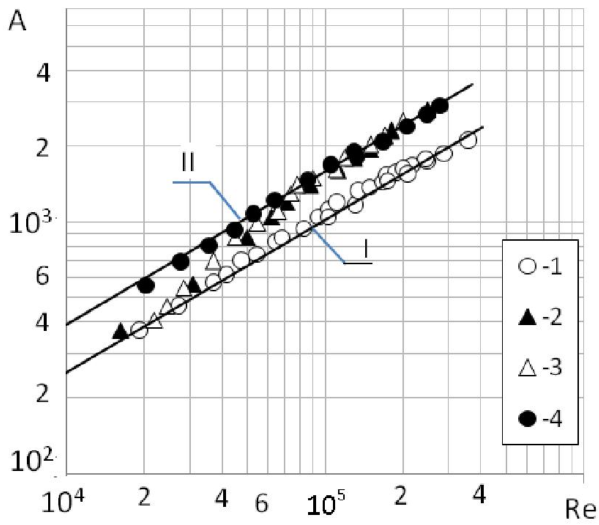
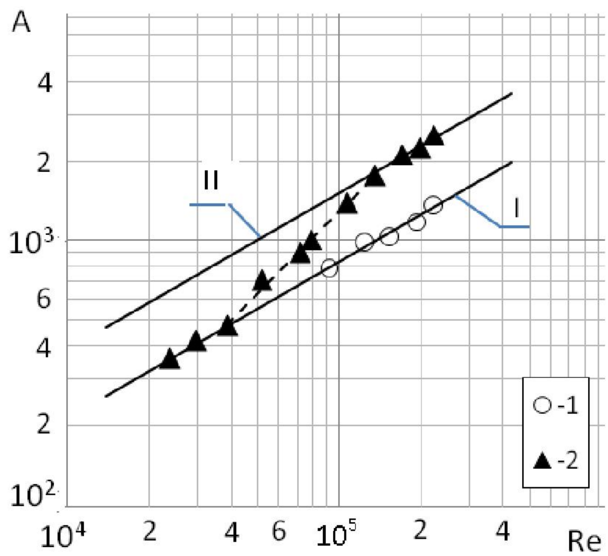


Figure 2 Relation between heat transfer intensity (A) and relative level (ΔH/b) of mixer's displacement. $Re=10^5$, b=10mm.
1. Smooth surface; 2.Rough surface: h=1.15 mm, s/h=7.5.

For smooth surface m=0.33 [1,5] and k=0.35 [4]; for rough surfaces m=0.38 and k=0.2 [4,5]. As we can see from the **fig.2**, the maximal intensity of heat transfer, both for smooth and rough surfaces, was reached in case of equal level displacement of mixer and heated pipe ΔH/b=0. Increasing ΔH/b heat transfer intensity decreases in both cases. Though, the mentioned decrease was most significant for smooth surface. Thus, the level of heat transfer intensification, caused by artificial roughness increases together with ΔH/b and by ΔH/b=9 reaches around 100%.



a)



b)

Figure 3 Relation of heat transfer intensity from Reynolds number, b=10mm. a - ΔH=0, b - ΔH=30mm.
1. Smooth surface; Rough surfaces: 2. h=0.25mm, s/h=10; 3. h=0.5mm, s/h=10; 4. h=1.4mm, s/h=7.1.

In the **fig. 3a** and **3b** the experimental results for smooth and rough surfaces, are represented as a relation A=f (Re). In both cases (ΔH=0, ΔH=30mm) three different regimes of roughness effect appearance can be seen: **1**. roughness has no influence on heat transfer. Surface with roughness element height 0.25mm in the Reynolds number range $Re<40\cdot10^3$ coincides with the such regime. **2**. Regime of partial appearance of roughness effect, where h=0.25mm, coincided the range $40\cdot10^3\leq Re\leq140\cdot10^3$; **3**. Regime of fully developed roughness effect when (**fig. 3a**) the height of roughness elements has no influence on heat transfer intensity at all. It should be mentioned, that in this regime when ΔH=30 mm intensification is far more high, than in case of ΔH=0.

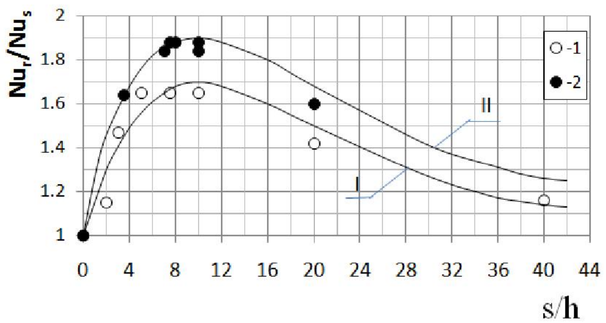
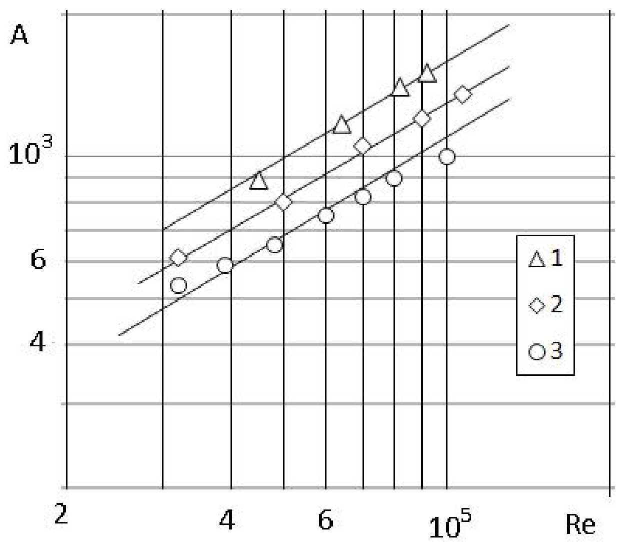


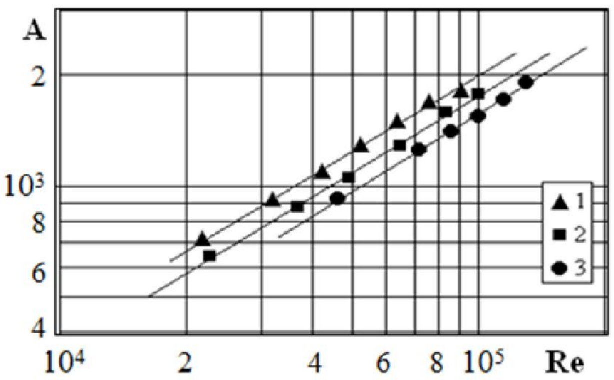
Figure 4 Relation of heat transfer intensity from geometrical parameter s/h. $Re=2\cdot10^5$, Pr=3, d=120 mm, b=10mm.
1. Experimental data, ΔH=0; 2.Experimental data, ΔH=30mm
I – According to formula (2), ΔH=0;
II – According to formula (2), ΔH=30 mm.

In **fig. 4** results of experimental investigation of influence of relative pith - s/h of two dimensional artificial roughness on heat transfer intensity are shown (ΔH=30mm, ΔH=0). As it is clear from the fig, the dependence of $Nu_r/Nu_s=f(s/h)$ is similar despite of change of ΔH. In the range $7\leq s/h\leq10$ the meaning of Nu_r/Nu_s is higher for 20% in case of ΔH=30mm, than in case of ΔH=0. The number of experiments was carried out to study the influence of paddle number of the mixer on heat transfer intensity.

It was established, that increasing the number of paddles, heat transfer intensity increases also both for smooth **(fig.5a)** and rough **(fig.5b)** surfaces. Though, the degree of that relation is different for smooth and rough surfaces: $Nu_s\sim(Z/2)^{0.35}$ and $Nu_r\sim(Z/2)^{0.25}$.



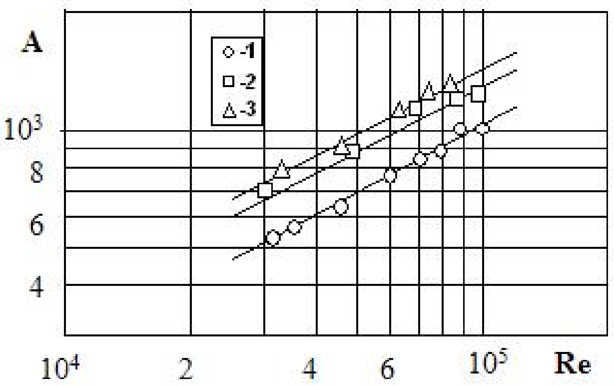
a)



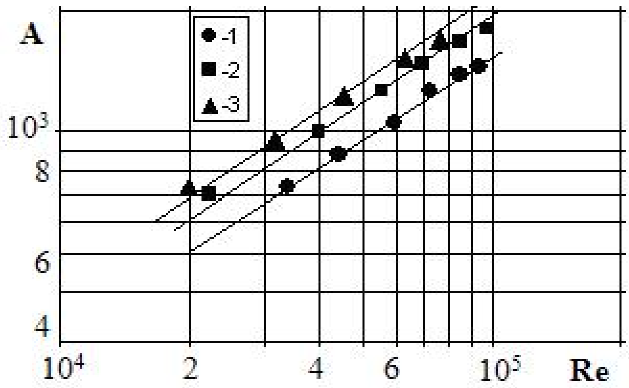
b)

Figure 5 Relation of heat transfer intensity from Re number.
ΔH=0, b=10 mm. a – Smooth surface; b – Rough surface,
h=1.15; s/h=7.5. 1. Z=6; 2. Z=4; 3. Z=2.

In the **Fig. 6** the results of experimental investigation of influence of paddle width on heat transfer intensity are shown. It can be seen, that with the growth of width heat transfer intensity increases both for smooth and rough surfaces proportionally to $(b/H)^{0.35}$.



a)



b)

Figure 6 Relation of heat transfer intensity from Reynolds number, ΔH=0.

a– Smooth surface; b- Rough surface: h=1.15 mm; s/h=7.51.
1. b=10 mm 2. b=20 mm; 3. b=30 mm.

From the practical point of view the investigation of heat transfer in case of appearing central funnel is of great practical interest. As we are informed this regime was not studied before even for smooth surfaces. This regime we call crisis regime.

The results of experimental investigation of such kind of regime are shown in **Fig.7**. According to the results of investigations the relation between Reynolds number and heat transfer intensity changes significantly both for smooth and rough surfaces when regime transforms into crisis: $Nu \sim Re^{0.27}$.

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

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

Where in case of smooth surface ε_r=1, and for completely developed roughness effect

$$\varepsilon_r = Pr^{0.05}\left(\frac{D}{d}\right)^{-0.15}\left(1+\frac{|\Delta H|}{b}\right)^{0.1}\left(\frac{Z}{2}\right)^{-0.1}\times (1+0.2(s/h)\exp(-0.1(s/h))) \quad (3)$$

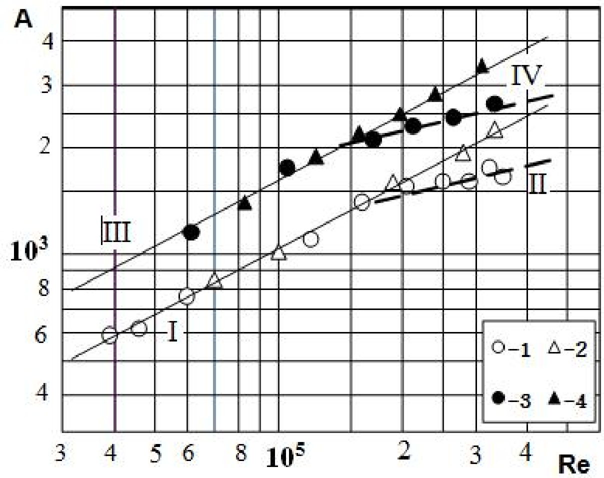


Figure 7 Relation of heat transfer intensity from Reynolds number, ΔH=0, b=10 mm.
Smooth surface: 1. d=65 mm, 2. d=100 mm; Rough surface – h=1.15mm, s/h=7.5: 3. d=65mm, 4. d=100mm. I. Normal regime, smooth surface; II. Crisis regime, smooth surface; III. Normal regime, rough surface;
IV. Crisis regime, rough surface.

In the **Fig. 8** is represented comparison between formula (2) and experimental data as a relation $A^*=f(Re)$, where

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

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

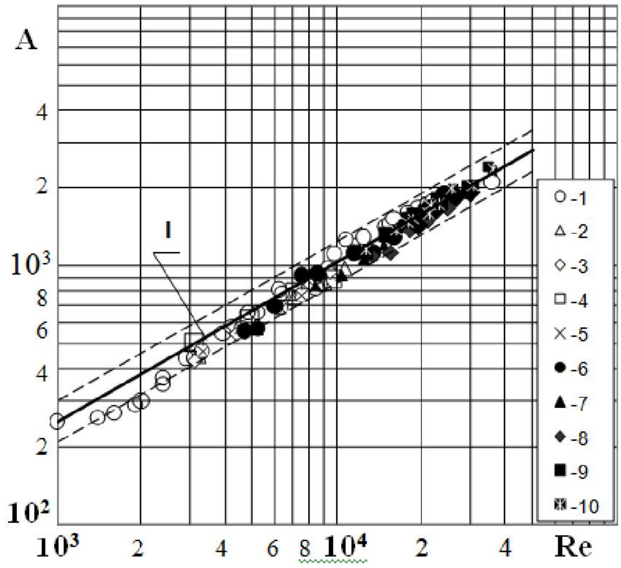


Figure 8 Relation of heat transfer intensity from Re number.
I – According to formula (2); Experimental data.Smooth surface: b=10 mm, 1. Z=2; 2. Z=4; 3.Z=6;4. b =20 mm; 5. b=30 mm; Rough surfaceses: b=10 mm, Z=2:
6. s/h=5; 7. s/h=8; 8. s/h=10; 9. s/h=20; 10. s/h=40;

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

According to the obtained results heat transfer intensification due to artificial roughness in apparatus with mixer is less, than in rough channels. This difference can be explained based on ideas below.

Let us consider that in mixed liquid movement consists of three components – tangential, radial and axial. If we consider that one part of pipe is overflowed with tangential component and another with normal (radial and axial) then for smooth surface can be written:

$$Nu_{s} = c_{1}Nu_{s\tau} + c_{2}Nu_{sn} \qquad (6)$$

Here c_1 and c_2 can be determined experimentally. Since in our case roughness elements are displaced transversal with tangential component of the flow, obviously heat transfer intensification can be caused only due to this component. Taking into consideration above mentioned,

$$Nu_{r} = c_{1}\varepsilon_{r}Nu_{s\tau} + c_{2}Nu_{sn} \qquad (7)$$

According to data, obtained by V. Gomelauri [3], in the case of channels when s/h=0-14, ε_r =2.4.

It can be seen from formula (7) in our case the growth of heat transfer intensity is less than in canals.

CONCLUSION

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 displaced 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 generalising well experimental data has been obtained.

The designated project has been fulfilled by financial support of the Georgia National Science Foundation (Grant #GNSF/ST08/7-482). Any idea in this publication is possessed by the author and may not represent the opinion of the Georgia National Science Foundation itself.

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