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Enhancement of heat transfer of heat exchangers using in transport by pulsating flow

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Abstract. The oil coolers are used in the hydraulic system of transport vehicles. In the shell and tube water oil coolers, oil is can be located on the tube side, water in the shell side. Different enhancement of heat transfer methods is used in oil coolers. The paper presents the results of a numerical study of the effect of asymmetric flow pulsations on the enhancement of heat transfer in a pipe for a highly viscous fluid with a Prandtl number Pr 293. The pipe length was 12 pipe diameters. The Reynolds number Re calculated from the inner diameter of the pipe was 100. The Strouhal number Sh was inside the range from 0.14 to 1.13. The amplitude of the pulsations of the flow had a reciprocating motion. The dimensionless relative amplitude of the pulsations was 1, 3, and 5. An increase in heat transfer was observed over the entire range of pulsation frequencies and amplitudes. The intensity of the pulsating flow significantly increases the heat transfer in the pipe. A comparison of the effectiveness of harmonical and asymmetric pulsations for enhancement of heat transfer was carried out. It is noted that the efficiency of asymmetric pulsations increases with increasing amplitude and frequency of pulsations. The maximum enhancement of heat transfer with asymmetric and harmonic pulsations was 2.03 and 1.93, respectively.

1. Introduction

There are many engineering applications in which heat transfer occurs under pulsating or reciprocating flow conditions. Such flows can be found in the transport, energy, aviation, food, and other industries. Pulsating flow can also be created artificially to enhance heat transfer. The use of forced flow pulsations to enhance heat transfer has been considered by many researchers [1]. Shell and tube heat exchangers are widely used in heat exchange equipment. The main element of this equipment is a tube bundle. The enhancement of heat transfer in a shell and tube heat exchangers is used both for the shell side and tube side. Passive methods have become widespread [2]. However, active methods, which include flow pulsations, remain relatively poorly understood. The use of pulsations to the enhancement of heat transfer the tube space of a shell and tube heat exchanger is considered in [3]. It shows the possibility of enhancement of heat transfer, empirical correlations are given for predicting heat transfer of pulsating flows in pipes.

In the article [4], the heat transfer in a pipe under a pulsating flow was studied experimentally. The authors noted that the enhancement of heat transfer significantly depends on the pulsation frequency and, to a lesser extent, on Reynolds numbers Re. In [5], the effect of pulsations on heat transfer in a pipe was studied numerically. It is found that heat transfer increases with increasing frequency and amplitude of the pulsations. It is also noted that the enhancement of heat transfer depends on the Re number. In [6], it was also noted that the enhancement of heat transfer depends on the frequency and amplitude of the pulsations. In the article [7], heat transfer in a pipe with an expansion in a pulsating flow was studied. It is shown that the value of the Prandtl numbers Pr also affects the enhancement of heat transfer. The authors of [8,9] showed that heat transfer can both increase and decrease depending on the pulsation frequency. The authors of [10,11] showed that the local heat transfer along the length of the pipe can both increase and decrease depending on the Re number and the pulsation frequency. In [12], the numerical method was used to study the effect of pulsations on heat transfer in a convergent-divergent tube. The authors note a steady increase in heat transfer with increasing frequency and amplitude of the pulsations. In other work, the influence of pulsations did not have any effect on the heat transfer in the pipe [13].

Heat transfer in a pipe with pulsating flow depends on such parameters as the frequency and amplitude of the pulsations, Re number, and Pr number. The influence of the above parameters is mainly considered with a harmonical nature of the pulsations. There are no similar studies with forced asymmetric pulsations of flow in pipes. On the other hand, in the previous works of the authors [14–16], the efficiency of asymmetric pulsations in the enhancement of heat transfer in tube bundles of shell-and-tube heat exchangers was shown. This article presents the results of a numerical study of heat transfer in a pipe with asymmetric pulsations of the oil flow. The Reynolds number Re was 100, the Prandtl number Pr was 293. The pulsating frequency f was inside the range from 0.5 to 4 Hz, the dimensionless relative amplitude A/D of pulsating flow was inside the range from 1 to 5. The duty cycle ψ of the pulsating flow was 0.25 and 0.5.

2. Mathematical model

The geometrical parameters of the mathematical model are shown in figure 1. The diameter D of the pipe was 0.025 m. Length pipe L was 0.3 m. At the inlet to the computational domain, velocity pulsations were set. The velocity pulsations had the necessary frequency. The velocity pulsations had the necessary frequency f, relative amplitude A/D, and pulsation duty cycle ψ. The oil was used as a working fluid. The oil temperature t_{inlet} at the inlet to the computational was 50°C. The wall temperature t_{wall} was 49°C. The thermal properties of the oil corresponded to Pr = 293. The flow is assumed to be 3D and incompressible. Navier–Stokes, and energy equations are solved using the finite volume method. The computational grid consisted of 1179648 volumes with the following parameters 48x384x128 in radius, circumference, and length, respectively (figure 2). Numerical modeling was performed in the ANSYS Fluent [17].

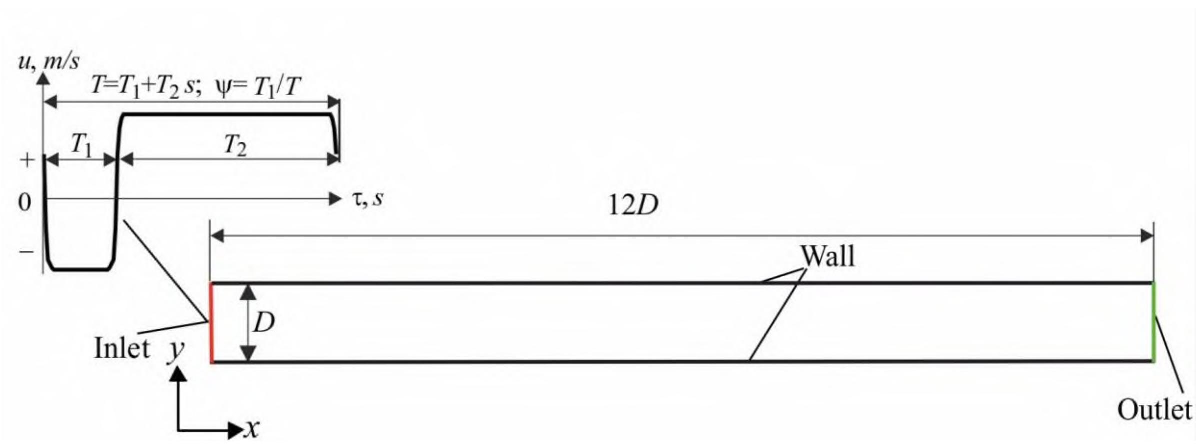

Figure 1. Computational domain.

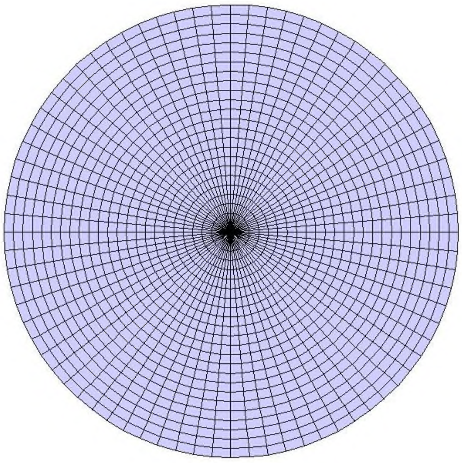

Figure 2. Numerical gird topology.

3. Results

The parameters of the pulsating flow used in the numerical simulation are given in table 1.

Table 1. Parameters of the pulsating flow.

Sh	0.14	0.28	0.42	0.57	0.71	0.85	0.99	1.13
f, Гц	0.5	1	1.5	2	2.5	3	3.5	4
A/D	1 3 5	1 3 5	1 3 5	1 3 5	1 3 5	1 3 5	1 3 5	1 3 5
Re	100	100	100	100	100	100	100	100

The average Nusselt number was calculated by equation (1)

$$\mathrm{Nu} = \frac{qD}{\lambda \Delta t} \quad (1)$$

where q – average heat flux of the wall of the pipe W/m^2, Δt – the average temperature difference between the wall and the temperature of the oil in the pipe C; λ – oil thermal conductivity W/(m · °C).

The result obtained for a steady flow at Re = 100 was compared with the empirical correlation (2) [18]. The difference in heat transfer with equation (2) was 23%. Equation (2) can be used for the ranges $0.48 \le \mathrm{Pr} \le 16700$, $\mathrm{Re} \le 2300$.

$$\mathrm{Nu} = 1.86 \cdot (\mathrm{Re} \cdot \mathrm{Pr} \cdot D/L)^{1/3} \quad (2)$$

Figure 3 shows the increase in heat transfer in the pulsating flow as a function of the Strouhal number Sh for different amplitudes A/D and the duty cycle of pulsating flow ψ. With an increase in Sh, the heat transfer increases, which agrees with the data of other authors [4-6]. However, with an increase in the Strouhal number at Sh = 0.99 and $\psi = 0.5$ heat transfer decreases. It is not clear what is associated with a decrease in heat transfer. In works [8,9], with an increase in the pulsation frequency, both a decrease and an increase in heat transfer also occur.

As can be seen from figure 3, the increase in the Nusselt number enhancement factor $\mathrm{Nu}_p/\mathrm{Nu}_{st}$ also effected by the duty cycle of pulsating flow ψ. Moreover, for some parameters of pulsating flow, the increase in heat transfer is higher for harmonical pulsations, for other parameters for asymmetric pulsations. For example, when $A/D = 1$, the increase in heat transfer was higher for harmonicla pulsations ψ= 0.5 in almost the entire range of Sh, except Sh ≥ 1. With an increase in A/D to 3, harmonical pulsations are more effective than asymmetric ones only when Sh < 0.5 with an increase in Sh; asymmetric pulsations are more effective. When A/D = 5 harmonical pulsations are more effective only with minimal Sh.

Figure 4 shows the enhancement of heat transfer in a pulsating flow depending on the number of relative dimensionless amplitude A/D for different Sh and ψ. As expected, an increase in the dimensionless amplitude of pulsations is proportional to the enhancement of heat transfer, which agrees with data from other authors [5,12]. Figure 4 also shows that the effect of A/D on the enhancement of heat transfer can be different depending on Sh and ψ.

Figure 5 shows the enhancement of heat transfer depending on the dimensionless number (A/D)Sh for harmonical and asymmetric pulsations. The dimensionless number (A/D)Sh characterizes the intensity of the pulsations. From figure 5 it is clearly seen that the enhancement of heat transfer significantly depends on the intensity of the pulsations (A/D)Sh. It is also seen that the asymmetric pulsations efficiency increases with increasing pulsating intensity (A/D)Sh, while the harmonical pulsations decreases, on the contrary, which was also shown in [14] for tube bundles. With asymmetric pulsations, the heat transfer is higher at (A/D)Sh > 1.8. The maximum heat transfer intensification at ψ = 0.25 and ψ = 0.5 was 2.03 and 1.93 respectively.

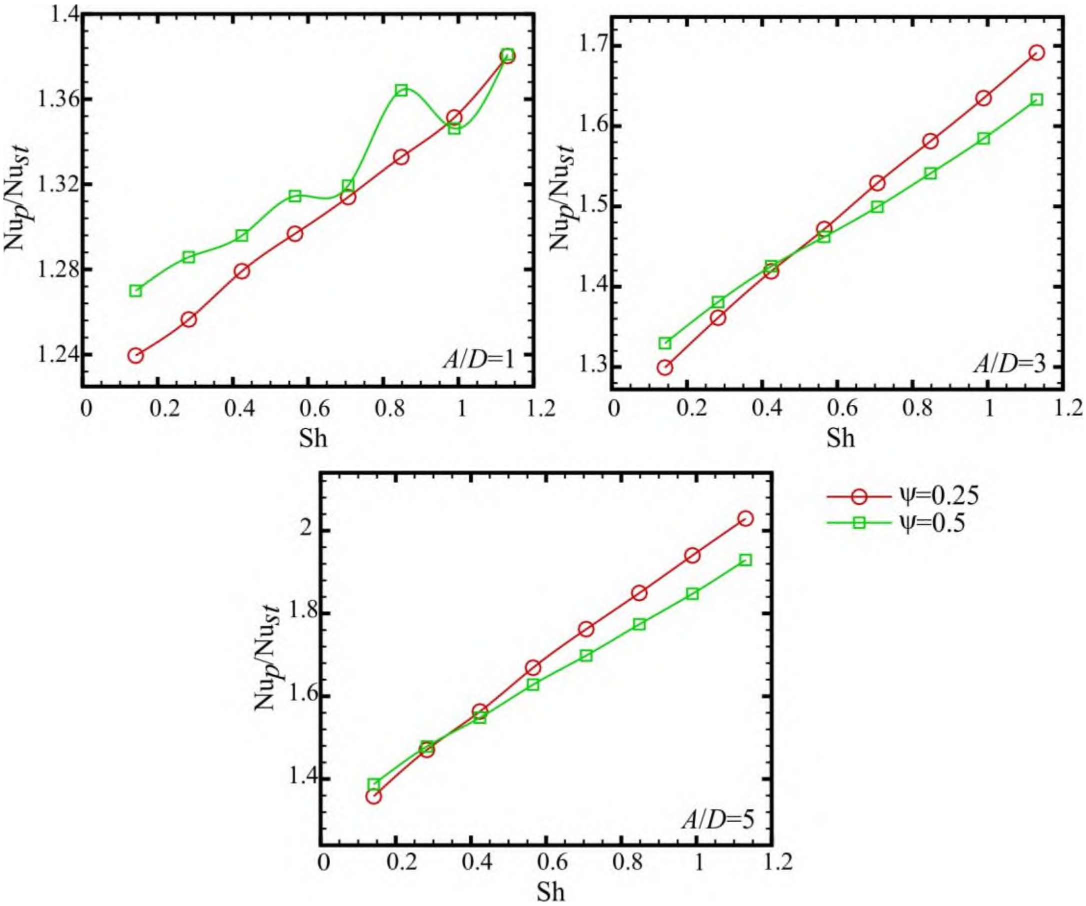

Figure 3. Heat transfer rate variation with Strouhal number.

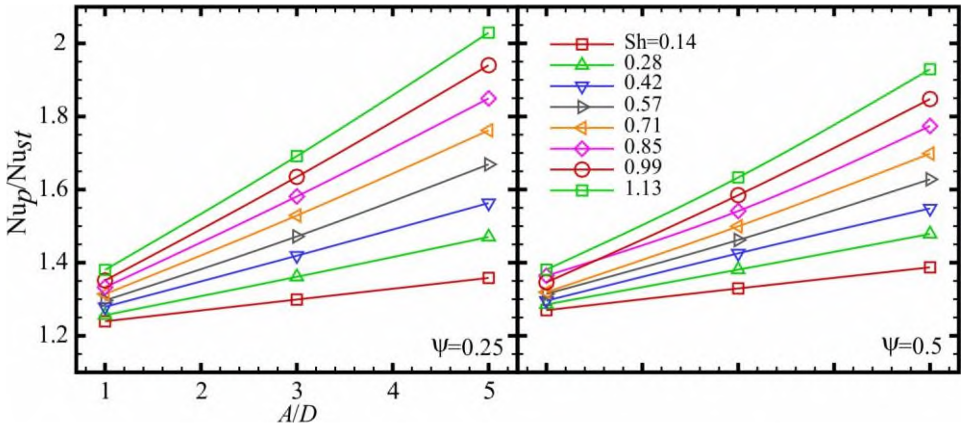

Figure 4. Heat transfer rate variation with relative amplitude.

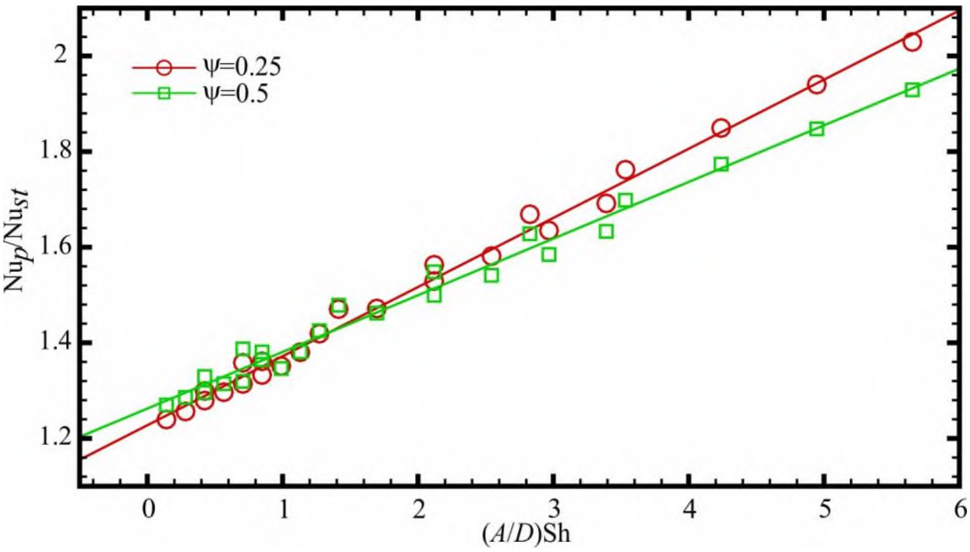

Figure 5. Heat transfer rate variation with dimensionless number.

4. Conclusion

The effect of asymmetric pulsations with reciprocating pulsations upstream of the oil flow in the pipe was investigated numerically. It was found that the enhancement of heat transfer significantly depends on the intensity of the pulsations. An increase in heat transfer in the pipe occurs with an increase in the frequency and amplitude of the pulsations. The enhancement of heat transfer is mainly higher with asymmetric pulsations. However, with a decrease in the frequency and amplitude of the pulsations to a certain value, the enhancement of heat transfer is higher for the harmonical pulsations. The maximum heat transfer enhancement for asymmetric pulsations was 2.03 with the Strouhal number Sh = 1.13 and the relative pulsation amplitude $A/D = 5$, for harmonical pulsations was 1.93 for the same Sh and A/D. The minimum enhancement of heat transfer with asymmetric and harmonical pulsations was 1.24 and 1.27, respectively, which corresponded to Sh = 0.14 and $A/D = 1$.

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