

Energy efficiency of pulsating flows at heat-transfer enhancement in a shell-and-tube water oil cooler

A I Haibullina¹, L S Sabitov^{1,2}, A R Hayrullin¹, V K Ilyin¹

¹Kazan State Power Engineering University, 51 Krasnoselskaya street, Kazan, 420066, Russian Federation

²Kazan Federal University, 18 Kremlyovskaya street, Kazan, 420008, Russian Federation

kharullin@yandex.ru

Abstract. In this paper the energy efficiency of pulsating flows during of enhancement heat transfer in a shell-and-tube water oil cooler was studied. A device for enhancement heat-transfer in an oil cooler based on a hydraulic system and a hydraulic cylinder is developed. A shell side flow of the oil cooler underwent pulsating. A Reynolds number of the oil flow based on the outside diameter of the tube was $Re_{oil} = 658$, a number of Prandtl $Pr_{oil} = 293$. It is established that with increasing frequency and relative amplitude of pulsations, an increase in heat transfer commensurate with increasing power consumption. It is shown that the energy efficiency of asymmetric pulsations is higher in comparison with the symmetric pulsations.

1. Introduction

To cool lubricating oil systems of various devices and installations (turbo generators, turbocompressors, hydraulic presses), oil coolers are used. Shell-and-tube water oil coolers were widely used. In shell and tube oil coolers, the oil is cooled by water. It is very often that oil is located outside the pipes (shell side), water inside the pipes (tube side). Therefore, the stable operation of lubrication systems of various devices and plants depends on the stable and uninterrupted operation of oil coolers. The oil temperature at the outlet of the oil cooler may increase due to a number of reasons. For example, in connection with an increase in the temperature of the cooling water or with the fouling of the heat transfer surface, which will lead to an increase in the flow of cooling water. [1].

In order to improve the efficiency of shell-and-tube heat exchangers, passive methods [2] of enhancement heat transfer are mainly used. At the same time, the existing passive methods of heat exchange intensification are difficult to apply for intensification of heat exchange of the existing heat exchange equipment, since they require a design change. However, using the active method of intensifying heat transfer (for example, the use of pulsating flows), it is possible to restore the heat transfer rate of the existing heat exchange equipment without parsing and replacing the structure.

The available pulsating flow studies are mainly devoted to non-stationary heat exchange in separate elements of heat exchange equipment. For example, unsteady heat transfer when flowing through a single cylinder or cylinder flow [3], tube bundles [4-6], different bodies (baffle bodies) [7] or flow in a pipe [8]. Despite the fact that positive results have been obtained in this direction, very few papers assess the energy efficiency of the application of flow pulsations using the example of industrial heat-exchange equipment.



The purpose of this paper is to estimate the energy efficiency of the application of flow pulsations during the intensification of heat transfer in shell and tube oil coolers. Also, the development of a technical solution for the implementation of this method.

2. Methods

In Fig. 1 shows the pulsation machine, which can be used to intensify the heat transfer in the oil cooler.

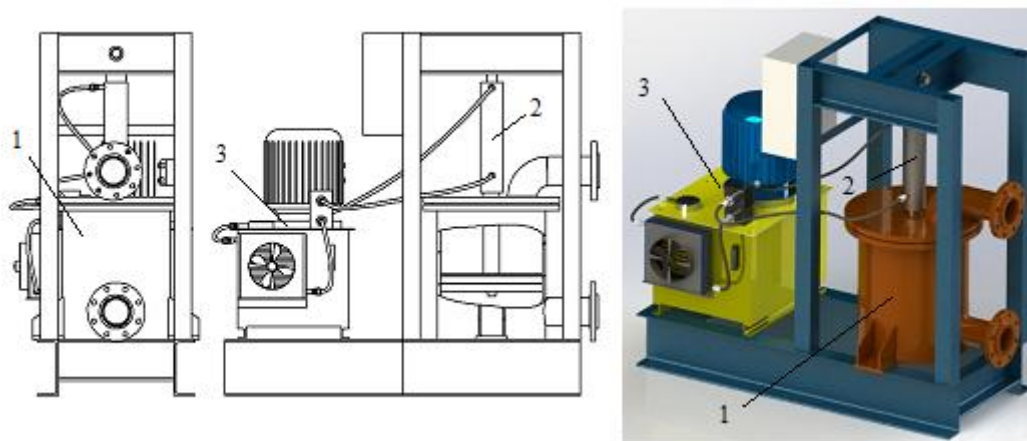


Fig. 1. Pulsation machine:

1 – pulsator; 2 – hydraulic cylinder; 3 –hydraulic system

Consider the principle of operation of the pulsation unit in conjunction with an oil cooler (Fig. 2). The pump 1 sucks the hydraulic fluid from the tank 9 and feeds it to the hydraulic cylinder 8 through the direction valve 7, then the hydraulic fluid returns to the tank through the radiator 6 and the filter 5. The hydraulic distributor serves to redirect the flow of the working fluid. Reciprocating motion of piston of hydraulic cylinder 8 occurs as a result of redirection of the flow of hydraulic fluid. The hydraulic cylinder is connected by a common piston rod with the piston of the pulsator, so the piston of the pulsator also performs a reciprocating motion (upwards).

Thus, the oil flow in the oil cooler reciprocates with a predetermined frequency f with relative amplitude β and pulsating ratio ψ . The required f and ψ are set using the hydraulic distributor. β is determined by the working path length of the pulsator piston.

The ripple frequency f is calculated by the following formula (1).

$$f = 1/T_p \text{ Hz} \quad (1)$$

where $T_p = T_1 + T_2$ – ripple period, s (T_1 – pulsator piston up time, s T_2 – pulsator piston down time, s). The ripple pulsation ψ is found by the formula (2).

$$\psi = T_1/T_p \quad (2)$$

The relative amplitude of pulsations β is determined by the formula (3).

$$\beta = A/D \quad (3)$$

where D – outer diameter of tube bundle, m; $A = \langle \dot{V} \rangle / S \cdot T_1$ – the distance that the oil travels in the opposite direction in the tube bundle of the oil cooler, when the pulsator piston moves upward, m. Here S – average cross-sectional area in the bundle of oil cooler tubes, m^2 ; $\langle \dot{V} \rangle$ – average volume volumetric flow over time T_1 , m^3/s calculated by formula (4).

$$\langle \dot{V} \rangle = \frac{1}{T_1} \int_0^{T_1} \dot{V}_t(t) dt \quad (4)$$

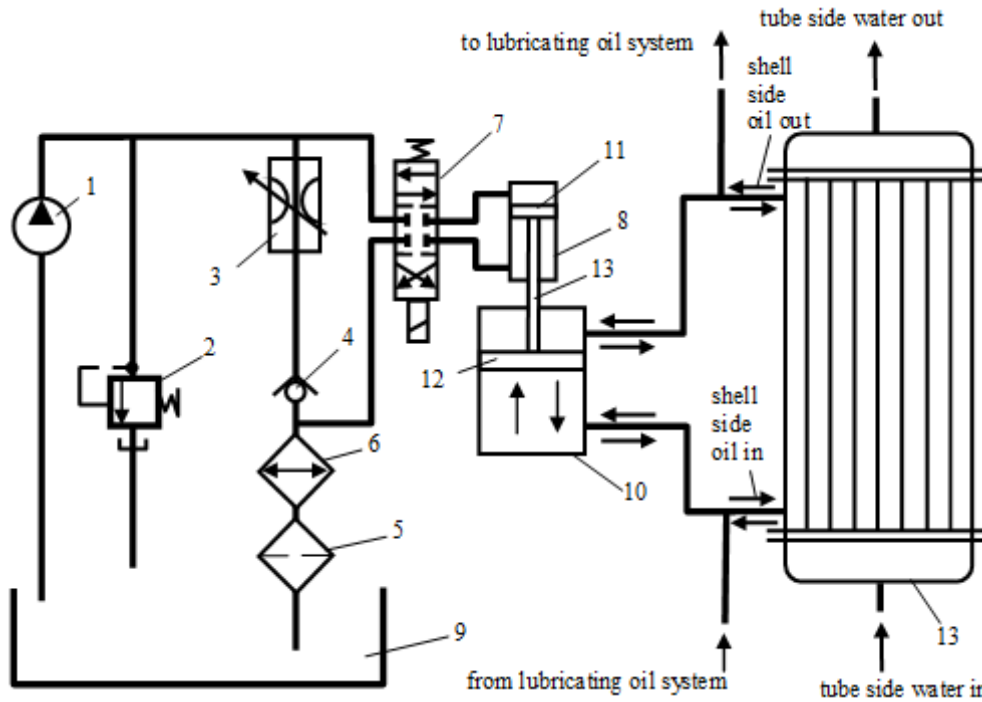


Fig. 2. The scheme of connection of the pulsating machine to the oil cooler:

1 – pump; 2 – relief valve; 3 – flow control valve; 4 – check valve; 5 – filter; 6 – air oil cooler; 7 – direction valve; 8 – hydraulic cylinder; 9 – reservoir; 10 – pulsator; 11 – hydraulic cylinder piston; 12 – pulsator piston; 13 – oil cooler

The energy efficiency of the oil cooler in the operation of a pulsating machine is calculated by the Kirpichev criterion (5) [9].

$$\frac{E_p}{E_{st}} = \frac{Q_p / (N_{pm} + N_p)}{Q_{st} / N_{st}} \quad (5)$$

where E_{st} – Kirpichev's criterion for the operation of an oil cooler in a stationary mode; E_p – Kirpichev's criterion in pulsation mode (when a pulsating machine is operating). N_{pm} – the power required to operate a pulsating machine, W; N_{st} , N_p – power of pumps spent on pumping a cooling and heating medium through a heat exchanger in a stationary and pulsating mode, W; Q_{st} – heat transfer rate of an oil cooler in a stationary mode, W; Q_p – heating capacity of oil cooler in pulsating mode, W.

The value of N_{pm} is calculated depending on the intensity of pulsations and the parameters of the oil cooler. To calculate N_{pm} , the mathematical model presented in [10] was used. N_{st} , N_p are calculated depending on the oil cooler parameters.

The heat output in the stationary and pulsating mode was calculated by formula (6).

$$Q = UA\Delta T_m \quad (6)$$

where A – heat transfer surface area, m^2 ; ΔT_m – mean temperature difference, $^{\circ}C$; U – coefficient of overall heat transfer coefficient, $W/(m^2 \cdot ^{\circ}C)$ calculated by formula (7).

$$U = \frac{1}{\frac{1}{h_1} + \frac{\delta}{k_{wall}} + \frac{1}{h_{2(p,st)}}} \quad (7)$$

where h_1 – heat transfer coefficient inside the tubes, $W/(m^2 \cdot ^\circ C)$ is calculated by equation of Dittus-Bolter [11]; h_2 – coefficient of heat transfer outside of tubes, $W/(m^2 \cdot ^\circ C)$ is calculated in dependence of the mode. For stationary mode $h_{2(st)}$ is calculated by formula (8).

$$h_1 = Nu_{st} \frac{k_{oil}}{D} = 0,354 \cdot Re^{0,6} Pr^{0,33} \varphi^{-0,1} \cdot (s_1 / D)^{-0,45} \cdot (\mu_{water} / \mu_{wall})^{0,14} \frac{k_{oil}}{D} \quad (8)$$

where Nu_{st} – Nusselt number for stationary flow; k_{oil} – thermal conductivity of oil, $W/(m \cdot ^\circ C)$; Re – Reynolds criterion; Pr – Prandtl criterion; φ – tube layout angle; s_1 – tube pitch, m; μ – dynamic viscosity, $Pa \cdot s$.

During the operation of the pulsation unit, $h_2(p)$ was determined by the equation (9, 10). Equation (9) was obtained in [12] for nonstationary heat transfer in the flow of oil in a bundle of tubes of different configurations.

$$\frac{Nu_p}{Nu_{st}} = 0,954 Re^{-0,201} \cdot Pr^{-0,211} \cdot \beta^{0,184} \cdot Fo^{-0,230} \cdot \psi^{-0,053} \cdot \varphi^{0,085} \cdot s_1 / D^{0,287} \quad (9)$$

$$h_{2(p)} = h_{2(st)} \frac{Nu_p}{Nu_{st}} \quad (10)$$

where $Fo = a/(f \cdot D^2)$ – Fourier criterion, where a – thermal diffusivity of oil, m^2/s . Equation (9) is found out from the range $215 \leq Pr \leq 363$, $0,25 \leq \psi \leq 0,5$, $100 \leq Re \leq 1000$, $15 \leq \beta \leq 35$, $5,81 \cdot 10^{-4} \leq Fo \leq 14,53 \cdot 10^{-4}$. The definition of the parameters entering into equation (9) is given in [12].

3. Results and discussion

Next, energy efficiency is considered when the oil cooler operates in a pulsating mode. The calculation was introduced for a range of parameters: volumetric flow rate of oil $\dot{V}_{oil} = 90 \text{ m}^3/\text{h}$, water $\dot{V}_{water} = 120 \text{ m}^3/\text{h}$, heat exchange area $A = 63 \text{ m}^2$, $Re_{water} = 41450$, $Re_{oil} = 653$, $Pr_{water} = 4,5$, $Pr_{oil} = 293$, $\varphi = 60^\circ$, $s_1/D = 1,25$, $0,2 \leq f \leq 0,5 \text{ Hz}$, $0,25 \leq \psi \leq 0,5$,

In Fig. 3 shows the dependence of E_p/E_{st} on β . According to Fig. 3 that the increase in the relative amplitude of ripple β does not have a significant effect on E_p/E_{st} . An increase in ψ leads to a decrease in E_p/E_{st} (Fig. 4). The ripple frequency f as well as β has no significant effect on E_p/E_{st} (Fig. 5). However, when $\beta = 15$, $\psi = 0,5$, E_p/E_{st} decreases from 0.88 to 0.79. When $\beta = 15$, $\psi = 0,25$, $f = 0,312 \text{ Hz}$, the energy efficiency had a maximum value of $E_p/E_{st} = 1,03$. When $\beta = 15$, $\psi = 0,25$, $f = 0,312 \text{ Hz}$, the energy efficiency had a minimum value of $E_p/E_{st} = 0,73$.

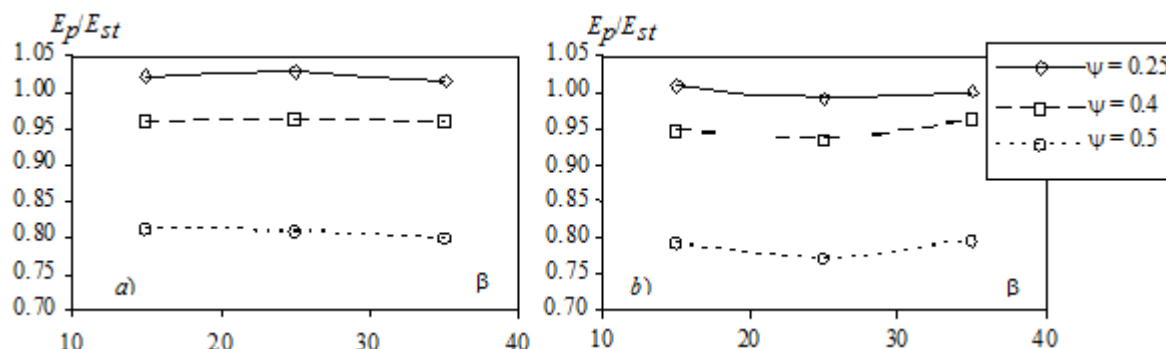


Fig. 3. Dependence E_p/E_{st} on β : a) $f = 0,312$ Hz; b) $f = 0,5$ Hz

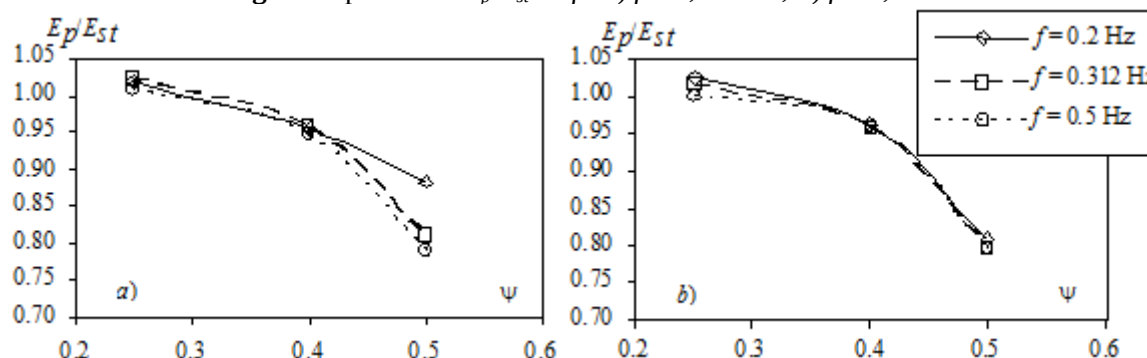


Fig. 4. Dependence E_p/E_{st} on ψ : a) $\beta = 15$; b) $\beta = 35$

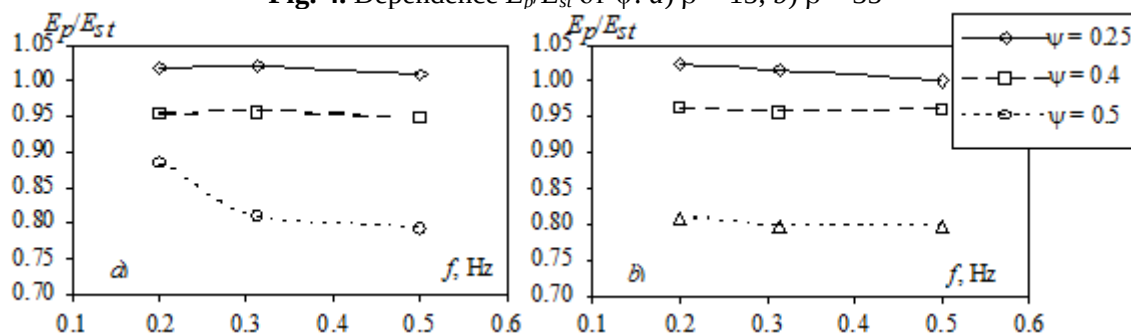


Fig. 5. Dependence E_p/E_{st} on f : a) $\beta = 15$; b) $\beta = 35$

4. Conclusion

The conducted research shows that flow pulsations can be used to intensify heat exchange in shell and tube oil coolers. To implement this method, you can use a pulsation machine. The dimensions of the pulsating machine and the power it consumes depend on the intensity of the pulsations and the parameters of the oil cooler. With an increase in the intensity of pulsations, it is possible to achieve a significant intensification of heat transfer. However, an increase in the intensity of pulsations leads to an increase in the power consumption. Therefore, it is necessary to find the optimum between the intensification of heat transfer and the increase in the power consumption. The conducted research shows that pulsation regimes with a minimum ripple ripple ψ have the highest energy efficiency.

Pulsation modes should be selected based on the maximum allowable pressure in the heat exchanger, since the higher the pulsation intensity, the higher the pressure jumps in the oil cooler.

The advantage of the proposed method is that the pulsating machine can be used to increase the heat exchange of existing oil coolers without changing their designs.

The article is executed within the framework of the scientific project 18-79-10136 «Theoretical methods for modeling and developing energy-efficient import-substituting cleaners and deep processing of hydrocarbon raw materials at enterprises of the fuel and energy complex».

References

- [1] Brodova U M *et al* 2003 *Teploobmenniki energeticheskoy ustanovki* (Ekaterinburg: Socrates Press) p 965
- [2] Popov I A *et al* 2009 *Fizicheskiye osnovy i promyshlennoye primeneniye intensivatsii teploobmena*. (Kazan: Centre for Innovative Technologies) p 560
- [3] Ashish S and EYK N 2017 *J. of Thermophysics and Heat Transfer* 1–13
- [4] Ilyin V K, Sabitov L S, Haibullina A I and Hayrullin A R 2017 *IOP Conf. Ser.: Mater. Sci. Eng.* **240** 012025
- [5] Ilyin V K, Sabitov L S, Haibullina A I and Hayrullin A R 2017 *IOP Conf. Ser.: Mater. Sci. Eng.* **240** 012026
- [6] Khaibullina A, Khairullin A *et al* 2014 *The European Phys. J. Conf.* **76** 01004
- [7] Kim S Y and Kang B H 1998 *Int. J. Heat Mass Transfer* **3** 625–34
- [8] Li H 2007 *Int. Conf. on Power Eng.* 23–7
- [9] Grigoriev B A *et al* 2017 *J. Phys.: Conf. Ser.* **891** 012151
- [10] Hajbullina A I *et al* 2016 *Energy Problems.* **11-12** 56–67
- [11] Dittus F W Boelter L M K 1930 *University of California, Berkeley, Publications* **2** 443
- [12] Ilyin V K, Sabitov L S, Haibullina A I and Hayrullin A R 2017 *IOP Conf. Ser.: Mater. Sci. Eng.* **240** 012027