The use of a pulsating flow of the heat carrier for the intensification of heat transfer in plate heat exchangers in the production of liquid nitrogen fertilizers

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Abstract. The article describes a method for improving the quality of produced liquid complex fertilizers by intensifying heat exchange using a pulsed flow of liquid in plate heat exchangers. The article is devoted to the question of the influence of impulse flow on the intensification of heat transfer in plate heat exchangers. Analysis of the literature shows that the increase in heat transfer is influenced by such factors as the shape of the channel, the location of the pulsation generator, as well as their amplitude and frequency. Changing the shape and pattern of the plates allows you to increase heat transfer, due to the receipt of greater flow turbulization. The results of the study of the heat transfer coefficient at various pulsation frequencies and coolant flow rates are also considered, from which the dependence of the heat transfer intensity on the pulsation frequency of the generator itself is visible.

1. Introduction
The use of organic and mineral fertilizers is one of the main conditions for increasing agricultural crops. Soil fertilization is an important link in crop growing technologies. This is due to the fact that the functioning of agrocenoses is based on the systematic extraction of large amounts of biogenic elements. The use of fertilizers allows nutrients to be reclaimed and involved in the cycle of nutrients instead of withdrawn. This ensures a certain sustainability of production processes [1].

Every fourth live on the planet is currently provided with food from the products obtained with the help of fertilizers according to statistics. This leads to an increase in the demand for agricultural chemicals over time [2]. Fertilizers and soil structure formers are needed by plants to grow and increase yields. Plants also need pesticides and herbicides to protect them from pests, diseases and harmful weeds. Modern chemical fertilizers contain essential nutrients, such as nitrogen, phosphorus, potassium, sulfur, magnesium and calcium [3].

Liquid compound fertilizers are highly effective, fast-acting fertilizers. Liquid complex fertilizers contain condensed phosphates (70-80% of the total mass of P2O5) and nitrogen compounds, and may also contain sulfur and magnesium. All nutrients are in the form of a solution, so they are easily accessible to plants [4]. Liquid complex fertilizers are obtained by neutralizing super phosphoric acid with gaseous ammonia. The main advantage of liquid complex fertilizers is that they make it possible to completely mechanize the loading, unloading and application of fertilizers and evenly distribute
them in the soil. The production of liquid compound fertilizers requires less capital expenditure than the production of solid fertilizers.

The production of synthetic nitrogen fertilizers is extremely energy intensive. Small deviations from the fertilizer production process can have big consequences. Plate heat exchangers are used in the production of such fertilizers to improve the production process, save energy and use the minimum floor area.

Improvement of heat transfer in a plate heat exchanger will lead to a decrease in the cost of producing nitrogen fertilizers and an increase in the competitive advantages of both the obtained liquid complex fertilizers and agricultural products. There are various ways to change the indicators of the energy efficiency of the heat exchanger. For example an additive to the coolant or the development of the profile of the plates. However, one of the least studied methods of changing the indicators of the energy efficiency of a heat exchanger is to provide a pulsed flow of the coolant. The purpose of this article is to investigate the influence and characteristics of a pulsating flow on the intensity of heat transfer.

2. Materials and methods

The pulsed flow of the coolant is characterized by short periods of transient processes. Namely, the pulsed flow is characterized by a reduction in the time for changing the flow rate between the maximum and minimum peak values [5]. Thus, the coolant flows through the heat exchanger in jerks at a speed exceeding the average value. This affects the heat transfer coefficient from the side of the impulse flow. The frequency and amplitude of the pulsations, the location of the pulsation source, the waveform of the pulsations, the physical parameters of the fluid, and the geometric parameters of the system can affect the heat transfer between the pulsating fluid and the metal of the heat exchanger.

One of the options for increasing heat transfer is to change the shape of the plate pattern. The plate heat exchanger is formed from packs of corrugated plates. The plates have ribbed heat transfer surfaces. Plates are stamped from stainless steel, their working surface is polished. Currently, there are two types of plate configurations in use: a grid-flow configuration and a ribbon-flow configuration. The ribbon flow configuration is also named "Free Flow" in accordance with US terminology [6]. The plates in the mesh-flow configuration have corrugations directed at an angle $\varphi$ from 30 to 60° to the longitudinal axis of the plate. The profiles of adjacent plates are mirrored. Therefore, the channel height is fixed when adjacent plates are combined into a package. The channel height is fixed not only due to giving a special profile to the edges of the plates or due to their peripheral connection by soldering or welding, but also due to the contact of adjacent plates with the tops of the corrugations. In the tape-flow configuration the plates have transverse corrugations (figure 1 b and 1 d) [6].

Adjacent plates have equidistant profiles and form a wavy sinusoidal channel. The plates have rubber gaskets that are attached to the periphery of the plate by soldering or welding. Stamped longitudinal stiffeners ensure a constant distance between the plates. Stiffeners divide the channel between the slabs into several parallel channels over the entire width. Prefabricated plate corrugation provides additional turbulization of the flow by periodically deflecting and detaching the coolant jet from the plate surface.

The flow of the coolant in the channels formed by adjacent plates is accompanied by a periodic restructuring of the profiles of the rates and temperatures of the coolant. There is also an artificial turbulence of the flow due to the periodic ejection of vortices into the core of the flow. As a result of these effects, a significant intensification of transport processes is observed and the formation of deposits is significantly slowed down. This leads to an increase in the lifespan of the heat exchangers without cleaning them [7].
Figure 1. Types of plates and general view of plate packs:

a – plates with corrugations «Free Flow»

b – plates with straight transverse corrugations

c – mesh-flow configuration of the plate package «Free Flow»

d – tape-flow configuration of plates with straight longitudinal ribs

3. Results

To study the effect under consideration, a study of the dependence of the heat transfer coefficient on the pulsation frequency was carried out. The experiment examined the efficiency of heat transfer in a plate heat exchanger for flow rates from 0.09 to 0.18 kg/s at frequencies in the range between 0.4 and 2.3 Hz. Figure 2 shows a series of experiments to determine the heat transfer coefficient at different coolant flow rates and vibration frequencies. It should be noted that the maxima of the graphs are observed in the frequency range of about 1.78 Hz at any coolant flow rates. Figure 3 (a) shows a monotonic increase in the heat transfer coefficient with an increase in the flow rate of the coolant in a plate heat exchanger for a frequency of 2.23 Hz. In this case, the traffic of the same dependence for a frequency of 1.78 Hz has a bend at a flow rate of 0.155 kg/s. The superposition of natural oscillations and those produced by the source leads to different consequences due to the resonance effect. Figure 4 shows free oscillations of the system at inlet and outlet ports of heat exchanger, which amounted to 5.2 Hz at a pulsation source frequency of 0.45 Hz.

The value of the actual speed of the coolant is an important feature that affects the heat transfer. It increases in pulse mode depending on the amount of time with the pulse generator valve open. There
is a gradual increase in pressure in the channels of the heat exchanger at a frequency of 0.89 Hz, according to the data taken from the graph of pressure fluctuations (figure 2). The increase takes place in a longer period of time than at a frequency of 1.78 Hz. Thus, when adding the forced oscillations created by the outside source and the oscillations of the system itself, it can affect the pressure difference both inside the heat exchanger and before it in different ways. The pressure difference across the heat exchanger can both increase and decrease at a different pulsation frequency created by the shock valve due to the fact that the natural frequency of the system changes insignificantly. Therefore, there is a change in time up or down, during which the maximum flow rate of the coolant will be reached with the valve open.

Figure 3. Dependences of the heat transfer coefficient:
a) on the mass flow rate of the coolant;
b) on the Reynolds number

Figure 4. Pressure change in pulse flow mode, set frequency 0.45 Hz.

4. Discussion
Heat transfer from a pulsating flow can be characterized by a number of patterns. Modern studies disagree on the effect of impulse flows on improving heat transfer inside plate heat exchangers. In a
number of experiments, it was possible to achieve an increase in the heat transfer coefficient [8-9].

In these experiments, a pulsating flow regime was created using a single-valve flow transducer. The heat supply system with impulse circulation of the coolant [10] was used on the basis of these experiments. The introduction of this scheme provides for a 12% improvement in the heat transfer coefficient of the exchanger.

The results of modern research have shown that the shape of the heat exchanger channel affects the intensification of heat transfer by impulse flow. The influence of flow pulsation on heat transfer has been studied at the moment for ribbed [5; 11], cylindrical [12] and wavy [12] types of channels. Fluctuations of the coolant in the undulating channel lead to a greater intensification of heat transfer. This fact is associated with the mechanics of vortex formation and dispersion during flow pulsations. The location of the vibration source also affects heat transfer. In one of the works, an increase in heat transfer of a shell-and-tube heat exchanger by 300% was achieved due to the installation of a source of pulsations at an oscillation frequency from 0 to 2 Hz in front of the heat exchanger [5]. In this experiment, the amplitude was 155 - 400 mm, and the Reynolds number was varied in the range from 150 to 1000. In another work, the effect of flow pulsation on the intensity of heat transfer from a heat carrier in a pipe of a steam-water heat exchanger was studied [11]. A piston pump of a special design created fluctuations in the flow of the coolant in front of the heat exchanger with a pulsation frequency of 1.6 Hz. The experiment was carried out for Reynolds numbers from 30,000 to 85,000.

The location of the pulsation generator plays an important role in the intensification of heat exchange processes [5; 12]. Several studies report that the heat transfer coefficient did not increase when the pulse source was installed after the heater [12]. Whereas the location of the pulse source before the heater can cause an increase in heat transfer coefficient by 90% at a Reynolds number of 6000 and a pulsation frequency of 2.7 Hz. In another experiment, the effect of frequencies in the range from 0 to 40 Hz on a heated coolant at a constant amplitude was investigated. The heated coolant moved through the outer space of the heat exchanger in a pulsed mode. The pulsation caused changes in the Reynolds number in the range between the maximum and minimum values of 10200 and 2000, respectively [13]. A constant flow of heating coolant with a temperature of 270-300 K passed through the inner space of the shell-and-tube heat exchanger. The Nusselt number increased 1.2 times with forward flow and 1.9 times with counterflow. The influence of the shape of pulsations on heat transfer was also studied [14]. Three waveforms were studied: rectangular, sinusoidal, and half-sinusoidal. Simulations have shown an improvement in the thermal characteristics of equipment with a pulsating coolant supply as compared to a steady coolant supply. In addition, the sinusoidal ripple shape leads to the best heat transfer intensification among the proposed shapes. Therefore, sinusoidal input is more beneficial for enhancing heat transfer in practical applications.

The next experiment is interesting in that the installation of a source of pulsations in front of the heat exchanger did not have a significant effect on heat transfer [15]. In this work, heat transfer in a circular channel with a Reynolds number of 200 was investigated in the frequency range from 1 Hz to 20 Hz. Finally, one of the experiments was devoted to studying the influence of the amplitude of pulsations and their frequency on the effects of friction and the efficiency of heat transfer [16]. In the course of the study, it was revealed that the friction of fluid layers increases with an increase in both the amplitude and frequency of pulsations. It is noted that the Reynolds number also obeys the influence of flow pulsation. In areas of transient laminar-turbulent flow and in areas of flow with small values of the critical Reynolds number, the effect of flow pulsations on friction forces is clearly expressed. However, the numerical ratio of the increase in thermal power when the installation is applied to the energy consumption for creating oscillations of the coolant flow is not given.

5. Conclusion

The pulsation of the coolant flow can increase heat transfer in the heat exchanger under certain conditions. The frequency and amplitude of the pulsations, the location of the pulsation source, the waveform of the pulsations, the physical parameters of the fluid, and the geometric parameters of the system can affect the heat transfer between the pulsating fluid and environment. Location of the
generator, the properties of the coolant, the flow mode and the final frequency of the system can affect the throughput of the system in different ways. Changing the shape and pattern on the plates makes it possible to artificially turbulize the flow of the coolant and to increase heat transfer in the channels that are formed by adjacent plates. The disadvantages of corrugation include complicated cleaning from dirt and additional pressure drop. The pulse method of increasing heat transfer is not common due to the complex operation of converting devices and their low reliability.

The possibility of transporting liquid complex fertilizers through pipelines makes it possible to create a single mechanized and automated manufacturing complex. The use of plate heat exchangers in such a complex makes it more compact. Additional intensification of heat transfer will reduce energy losses and improve the quality of the final product.

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