Four-way shell-and-tube heater with ultrasonic generator

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Abstract. This article offers a heat-exchanger of improved design which allows reducing time between overhauls and maintenance. Since to date, the challenge of providing enterprises and public utility installations with heat-transfer media of required parameters is the most pressing. The collection chamber is equipped with a variable frequency ultrasonic radiator. Bays are installed with the possibility of extracting them. The case is made as one-piece and enclosing all bays. Heat exchange sections are made in the form of sectors. The dividers are equipped with windows that provide the flow of the annular medium in the opposite direction to the flow of the pipe medium. Tests were conducted on a four-way shell-and-tube heat exchanger. The heater was disassembled and inspected, after inspection it was found that scale on the heating surface was completely absent. As a result of the analysis, we can conclude that the design efficiency of the four-way shell-and-tube heater. When working on soft water and ultrasonic protection, there is no carbonate scale on the heating surface. When developing a combined vertical heat exchanger, a comparison was made with high-speed water sectional heat exchangers. The task of creating a simple and cheap design of the heat exchanger was performed by simplifying the design of the heat exchange sections and reducing the metal consumption. The stated technical problem was solved by improving the multi-pass heat exchanger with an ultrasonic emitter, which has a casing and heat-exchange sections in the form of tube bundles with tube sheets at the ends.

1. Introduction
Over the past decades, there has been a sustainable growth of energy consumption in many engineering processes of enterprises and a sharp rise in the cost of energy costs and production prime cost. This is due to many factors, which include the following: outperforming growth rates of fuel and electricity tariffs, lack of funds for technical upgrade and retrofit of supply systems for the industry enterprises, a significant reduction in the load on production capacities, etc.

The low efficiency of thermal energy and fuel consumption is largely due to the lack of a comprehensive procedure for heating system research. For this reason, it is impossible to justify the optimal parameters and modes for operation thereof, as well as to find reserves for heat and fuel economy. Reliable and cost-effective provision for enterprises and public utility installations with heat-transfer media of required parameters and introduction of new high-tech solutions for heat generation will guarantee the generation of cheap heat being one of the primary objectives in the energy industry and allows lowering utility tariffs for households.
Nowadays one of the pressing challenges in the energy industry is to provide enterprises and public utility installations with heat-transfer media of required parameters, together with the use of new high-tech solutions [1, 2, 3, 4, 5, 6].

2. Problem statement

The primary objective was to develop a simple and low-cost design of a heat exchanger by simplification the bay design and reducing the metal consumption along with overhaul life and maintenance periods [7, 8, 9, 10].

The stated engineering challenge is solved by improving a multi-pass heat exchanger with an ultrasonic radiator with a casing, identical bays in the form of tube banks with tube arrays at the ends. The bays are connected to the common collection chambers of the tube medium and the casing by means of flanges, therewith transversely to the tube arrays in the collection chambers of the tube medium, partitions are installed to form compartments communicating adjacent heat exchange sections (bays).

The novelty is that the collection chamber of the tube medium is additionally equipped with a variable frequency ultrasonic radiator, and the bays are inserted with the possibility of extracting into the casing. The casing is made as one-piece and enclosing all bays, which are made in the form of sectors using separators transversely to the tube arrays. Moreover, the separators are equipped with apertures to ensure the flow of the annular medium in the direction opposite to the tube medium flow.

3. Research results

The multi-pass heat exchanger with the ultrasonic radiator 1 is shown in Figure 1 and contains identical bays 2 (section view C-C) in the form of tube banks 3 (section view B-B) with tube arrays 4 and 4' at the ends connected to common collection chambers 5 of the tube medium using flanges 6, 7. Therewith, transversely to the tube arrays 4 in the collection chambers of the tube medium 5, partitions 8 are installed, forming compartments 9 (section views A-A and B-B) containing adjacent bays 2 (section view C-C). The collection chamber of the tube medium 5 is supplemented with an ultrasonic radiator 1 of variable frequency. The heat bays 2 (section CC) are inserted with the possibility of extraction into a single casing 10 with flanges 7 and are made in the form of sectors using perpendicularly installed tube sheets 4 dividers 11. The separators 12 (Figure 4.2) are equipped with apertures 11 to ensure the flow of the annular medium in the direction opposite to the tube medium flow. The ultrasonic radiator 1 (section AA) frequency change depends on the amount and type of salts dissolved in the tube medium.

The multi-pass heat exchanger with an ultrasonic radiator (Figure 1) works as follows. The tube medium flow (for example, cold water) passes through the collection chambers of the tube medium 5, tube banks 3 with tube arrays 4 and 4', the upper 4 of which is installed between the flanges 6 and 7, and the lower array 4' is hermetically inserted owing to the seal 13 in a one-piece casing 10, based on its annular limiter 14. In collection chambers of the tube medium 5 (section views C - C and B - B), partitions 8 are installed, forming compartments 9 connecting the hydraulically adjacent bays 1 in a way that they direct the flow of the tube medium through banks 3 of bays 2 (section C - C) only in one direction (clockwise or counterclockwise).

Therewith, the partitions 8 absorb axial loads during thermal compression occurring in the heat exchange sections 2 during heat exchange. At the same time, the annular medium flow in one of the collection chambers 5 (Figure 1) is processed by ultrasonic waves generated by ultrasonic radiator 1 to slow down the process of scale and sediment deposition by 8-10 times in pipe bundles 2. Therewith, ultrasonic waves act directly on the tube medium resulting in an intense deposition effect in this collector chamber 5 (the greatest positive effect is achieved with installation of an ultrasonic radiator in the lower collector chamber of the tube medium 5), the passage cross-section of which greatly exceeds the pipe clear opening 3, which increases the overhaul life.
In laboratory conditions, the tube medium with a different salt content was examined by treating with ultrasonic waves and identifying which frequency provides the maximum deposition effect. Then, after analyzing the annular medium passing through the multi-pass heat exchanger, the ultrasonic radiator 1 frequency was set in the most effective range for salt deposition in the collection chamber 5, which increases the overhaul life and maintenance period by 1.2 -1.5 times with regard to the uncontrolled ultrasonic radiator, i.e., in general, 10 - 15 times. Therewith, annular medium flow (for example, hot water) passes through a one-piece casing 10 through the windows 12 (Figure 2) of the separators 11 along the bays 2 (section view C - C) in the direction opposite to the tube medium flow. The results are that heat exchange takes place, i.e. one of the media is heated, and the other is cooled. Therewith, the number of bays 2 required for heat exchange is determined by the number of sectors, whereon the one-piece casing 10 is divided by separators 11 (Figure 1).
When carrying out the necessary maintenance, the upper collection chamber 5, tube banks 3 with tube arrays 4 and 4’ and separators 11 are removed and the collection chamber with an ultrasonic radiator is descaled. When inspecting the tubes 3 the decision is taken on the following:

first, with an insignificant clogging of the tube banks 3 the washing and cleaning thereof is to be performed;

second, with a significant clogging of tube banks 3, the tube banks 3 with the tube arrays 4 and 4’ and the separators 11 are to be replaced with new or previously cleaned tube banks 3 with the tube arrays 4 and 4’ with the separators 11, which significantly reduces the downtime of the device and equipment technologically connected with this device [11, 12].

Whereafter, the multi-pass heat exchanger is assembled in reverse order and put into operation.

Easy-to-assemble design of the heat exchanger is cost-effective and simple to manufacture and maintain with a longer overhaul life and maintenance period as compared to counterparts due to treatment of the tube medium by ultrasonic waves (in practice, 10...15 times).

To examine the effectiveness of the ultrasonic protection of the compound shell-and-tube heater manufactured by the PSP Teplogaz LLC, an ultrasonic single-channel generator of the Agropribor research and development enterprise was used.

For over 20 years, the Agropribor company has been analyzing ultrasonic methods, as well as mass-producing the "Volna" ultrasonic unit for these purposes. In boiler facilities of Moscow, Volgograd, Saratov, Orenburg, Vologda, Voronezh, Sverdlovsk regions and in other Russian regions, as well as in neighboring countries (Baltic States, Ukraine, Belarus), these units are successfully operated. With high efficiency, the "Volna" ultrasonic units are used to prevent scale formation in boilers of various capacities, as well as in waste-heat exchangers, in high-speed heat exchangers, in compressor coolers and other equipment.

The use of one unit provides an economic effect of 6-19 thousand rubles.

To date, a huge number of "Volna" units are in operation (more than 6 thousand units). Monitoring of operation of the "Volna" ultrasonic units made it clear that after the introduction of ultrasound, the scale deposition, as previously formed in boilers and heat exchangers, begins to peel off and then settle like flakes or loose mud. There is no further forming of scale. The mud produced in the course of operation is removed by periodic purges. During a preventive inspection, the boiler can be flushed with a jet of water. The water jet pressure shall be 0.2-0.3 MPa. Thereby, there is no longer any necessity in time-consuming and expensive equipment cleaning and all environmental issues associated with this, are resolved as well. If ultrasonic units run continuously, this allows operating the heat-power equipment in a nonscale-deposition mode. This allows keeping the efficiency factor at a level close to an optimal one, and this leads to significant fuel savings. The use of ultrasonic units allows increasing the service life of the equipment and reduces the number of possible emergencies because when exposed to ultrasound, the heated surfaces do not overheat to a great extent, the heat transfer increases and metal corrosion decreases.

When using the ultrasound method, environmental pollution by harmful wastewaters from water treatment plants is minimized.

After a few months of operation of the plants, all capital investments (acquisition, installation, and adjustment) will pay off. The units are easy to operate and maintain. After getting an insight into the design of the installation and the rules for operation thereof, the boiler room personnel can easily enter into operation.

To prevent scale formation in heat exchange equipment and boiler units, it is recommended to use "Volna" ultrasonic units.

By design, the "Volna" ultrasonic unit is presented as a pulse generator complete with two magnetostrictive converters [13]. The generator is needed to create shock electrical pulses, converters turn shocks into mechanical vibrations of ultrasonic frequency. To provide vibration transmission to the boiler unit, converters are welded to the boiler external surfaces. Using electric welding, these are
welded at certain points. The number of converters and their location points are selected depending on the design and the boiler unit capacity, and on the average amount of scale deposited during service.

4. Experimental results
The testing of the four-way shell-and-tube heat exchanger was conducted in the building No. 4 of the Perm State Technical University, wherein it was put into operation to heat the water fed to the hot water supply system.

Before putting into operation the heater was visually inspected. There was no scale on the heating surface.

The heater was heated by the system water of the Perm hydro-technical utilities. The subject for heating was the tap water of the Chusovsky water-intake facility of the Perm municipal water system.

The testing was conducted on November 1, 2002. The mode of operation of the heater during the test is described in Table 1.

Table 1. The mode of operation of the heater during the test

| Month   | Calcium content, mg-eq/l | Hydrocarbonate alkalinity, mg-eq/l | pH value | Average heating temperature, °C |
|---------|--------------------------|------------------------------------|----------|---------------------------------|
| November| 5.5                      | 4.06                               | 7.0      | 70                              |
| December| 10.0                     | 7.01                               | 7.0      | 70                              |
| January | 9.7                      | 7.32                               | 7.0      | 70                              |
| February| 11.3                     | 8.44                               | 7.0      | 70                              |
| March   | 12.2                     | 8.45                               | 7.0      | 70                              |
| April   | 11.2                     | 7.93                               | 7.0      | 70                              |
| May     | 1.25                     | 0.61                               | 7.0      | 70                              |
| June    | 1.9                      | 1.62                               | 7.0      | 70                              |

Table 2 provides the calculation data for the intensity of carbonate scale formation in the absence of ultrasonic protection.

Table 2. Estimated amount of carbonate scale without ultrasonic protection

| Month   | Intensity of scale formation, mg/h.m² | weight of scale per month, kg/m³ |
|---------|---------------------------------------|---------------------------------|
| November| 384.17                                | 0.277                           |
| December| 1206.00                               | 0.897                           |
| January | 1221.55                                | 0.909                           |
| February| 1640.78                                | 1.103                           |
| March   | 1773.56                                | 1.320                           |
| April   | 1527.99                                | 1.100                           |
| May     | 13.12                                  | 0.010                           |
| June    | 52.35                                  | 0.038                           |

The total weight of carbonate deposits, calculated according to Table 2, amounted to 5.654 kg/m³. Which corresponds to the estimated total thickness of the carbonate scale layer at the critical point - 2.262 mm.

On July 1, 2003, the heater was turned off and disassembled. When inspecting the disassembled heater, it was found that there is no scale on the heating surface (the inner surface of the brass tubes) whatsoever. As a result of the work performed, the conclusion on the design effectiveness of the four-
way shell-and-tube heater can be made. When operating on untreated water and ultrasonic protection, there is no carbonate scale on the heating surface.

5. Conclusion
When developing a joint vertical heat exchanger, comparisons were made with water-to-water high-speed sectional heat exchangers according to industry standards, and the following objectives were reached:

1. The scale formation and deposition of pipeline corrosion products on both heat exchange surfaces when using acoustic descaling devices, in particular in hot-water supply systems.
2. Facilitated clean-up of heating surfaces from impurities.
3. A compact heat exchanger was developed with overall dimensions in plan view with consideration of service passages, and similar to the overall dimensions of plate heat exchangers.

The developed joint vertical heat exchangers with the same heating surface with water-to-water high-speed sectional heat exchangers have approximately equal weight, metal consumption, and cost, but have a variety of advantages.

Based on the experience of State Unitary Enterprise Mosteploenergo, it is known that acoustic descaling devices generally protect the heating surface of conventional water-to-water high-speed sectional heat exchangers against scale and deposits in heat conductor facilities in Moscow better than plate heat exchangers.

References
[1] Shkulova N, Ivanova and Gusein Ya 2016 Method for increasing the efficiency of the long-running heat-exchanging equipment of the TVG-8M hot water boiler Journal of Resources of the European North, Technology and development economics 3 59 – 69 (in Russian)
[2] Fireushin A and Romanchuk A 2018 Improving the efficiency of heat transfer in apparatuses such as "pipe in pipe" Oil and gas business 16 (6) 65-71 (in Russian)
[3] Galkin P 2015 Application of ultrasound to intensify the heat transfer process in a shell-and-tube heat exchanger Materials of the VIII International Scientific and Practical Conference of Young Scientists "Actual Problems of Science and Technology - 2015" pp 140-141 (in Russian)
[4] Sharipov T, Chetvertkova O and Sharafiev R 2015 Study of the influence of structural parameters of transverse partitions on the thermal efficiency of a shell-and-tube heat exchanger Materials of the VIII International Scientific and Practical Conference of Young Scientists "Actual Problems of Science and Technology - 2015" pp 155-158 (in Russian)
[5] Novik A and Nezamaev N 2019 Intensification of the heat transfer process in shell-and-tube heat exchangers Abstracts of the IX scientific and technical conference "Science Week - 2019" St. Petersburg State Technological Institute (Technical University) pp 27 (in Russian)
[6] Pyazhskiy V, Konovalov D, Dakhin S, Bulygin Yu and Shatskiy V 2018 Mathematical model of heat surface cooling system in the starting mode. Bulletin of the South Ural State University. Series: Mathematical Modeling. Publisher: South Ural State University (National Research University) (Chelyabinsk) 11 (4) 136-145
[7] Wang Wei, Makeev A and Povorov S 2018 Thermal - hydraulic performance analysis cold side of the plate heat exchanger using water-waters Science and Practice Bulletin 4 (4) 263-276
[8] Blagin E, Shimanov A, Anisimov M and Uglanov D 2019 Study of the influence of the scale formation process in heat exchangers for preheating a distillation desalination plant on the efficiency of their work. Bulletin of the International Academy of Refrigeration. Publisher: Public Organization "International Academy of Refrigeration" (St. Petersburg) 2 37-42
[9] Qian Hao, Kudashev S and Plotnikov V 2019 Experimental study on heat transfer of pulsating flow enhanced the plate heat exchanger Science and Practice Bulletin 5 (8) 81-92
[10] Proskurin Yu, Kazantsev M, Grisha B and Dubrovkin M 2018 RU, Patent No. 177038 2018 (in Russian)
[11] Gnedochkin Yu, Kuneevsky V and Rudenko G 2005 RU, Patent No. 47504 "Heat exchanger" (in Russian)

[12] Kuneevsky V, Gnedochkin Yu, Rudenko G and Dunaev A 2005 RU, Patent No. 44375 2005 "Heat exchanger" (in Russian)

[13] Nikolaevsky N 2002 Ultrasonic method of preventing scale formation *Heat supply magazine* 10 (in Russian)