Investigation of modes and conditions for superimposing ultrasonic vibration on heat exchangers

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Abstract. The article presents investigations results of ice destruction on heat exchange surfaces (radiators) using intense ultrasonic vibrations for subsequent research of cavitation resistance of heat exchangers. Possible locations and methods of mounting the ultrasonic vibratory system were identified for the typical construction of heat exchanger. Several constructions of ultrasonic vibratory systems have been studied for use in further researches.

1. Introduction
Intensive evaporation of the refrigerant occurs with the absorption of heat from the environment on the heat exchanger of an external unit (evaporator) during operation for heating. At the same time, water vapours on the evaporator are condensed and crystallized due to a sharp decrease in temperature. Intensive freezing of the heat exchanger results in reduced efficiency of heat removal.

At present, periodic switching of the heat pump to direct conditioning mode is used to ice destruction, which significantly reduces the efficiency of all system.

Ultrasonic exposure is known to be one of the most effective methods of removing ice from cooled surfaces in various fields of the technique [1-4].

Therefore, checking the principle possibility of using ultrasonic exposure and finding optimal modes and conditions of exposure for further research of cavitation resistance of heat exchangers has become necessary.

As objects of investigation, heat exchangers of standard design were used (figure. 1).

Standard methods and means of measurement have been used to control and investigate the parameters of ultrasonic exposure, which have proved to be good in the process of scientific and research activity:

- analyzer of impedance characteristics of ultrasonic vibratory systems [5];
- piezoelectric amplitude sensor with point contact [6];
- low-frequency signal generator G3-112/1 and amplifier G3-112/1;
- digital storage oscilloscope GDS-71022.
The special stand has been developed and made for the operation of heat exchangers at low temperatures for experimental investigations (figure. 2). Ultrasonic exposure was performed by means of ultrasonic devices for excitation of vibrations of physical objects of USTA-0.4/22-O model [6].

Extrusion foam polystyrene (XPS) was used for the chamber walls (100 mm thick). A hole in the rear wall has used for quick replenish the bath with liquid nitrogen providing cooling. The front wall of the chamber is made of a triple glazing unit for visual observation of the experiment.

The use of liquid nitrogen kept the temperature in the chamber in the range of -20°C to -35°C. The heat exchanger was completely filled with ethyl alcohol, and the input and output nozzles were plugged. The heat exchanger was placed vertically with a slight inclination above the bath with liquid nitrogen. The heat exchanger was held for an hour to reduce its temperature to a predetermined value (e.g. -20°C).

Fan was installed inside the chamber and operated during the experiment for uniform cooling.

A method of periodically fine spraying water in an experimental chamber has been used to form the ice cover efficiently. This procedure was repeated up to 4 times.

2. Ultrasonic equipment

The analysis of the actual heat exchangers constructions shown that they represented a complex multi-resonance mechanical system consisting of a set of tubes interconnected by heat sink plates and side
barrel plates. However, many resonances are not effective for ice removal. They do not allow making vibrations with sufficient amplitude, uniformly distributed over a large part of the surface.

The process of vibrations of the heat exchanger in a wide frequency range was important to investigate, in order to detect effective resonance. A frequency range of 24 to 40 kHz was chosen for the investigations and vibratory systems (VS) were used for 24 kHz, 30 kHz and 40 kHz frequencies. Two systems of different power are used on the middle frequency [7—10].

Diagrams of developed piezoelectric vibratory systems are shown in figure 3, and their technical characteristics are shown in table 1.

![Figure 3. Diagram of piezoelectric vibratory systems. A – VS#1 – 24 kHz; B – VS#2 – 30 kHz; C – VS#3 – 40 kHz; D – VS#4 – 30 kHz: 1 – the radiating slip; 2 – piezoceramic rings; 3 – reflecting strip.](image)

A special vibration distributor is used to distribute vibrations along the heat exchanger surface. The vibration distributor is a bending-vibrating plate with attachment unit for an ultrasonic vibratory system. It has resonance frequencies of 23 kHz, 30 kHz and 38 kHz (figure 4).

![Figure 4. Diagram of vibration distributor.](image)

Table 1. Main technical characteristics of vibratory systems.

| Piezoelectric transducer | Self-resonance frequency, kHz | Maximal power consumption, W at continue mode | At pulse mode (no more 10 s) |
|--------------------------|------------------------------|----------------------------------------------|-----------------------------|
| VS №1                   | 24                           | 250                           | 500                         |
| VS №2                   | 30                           | 250                           | 500                         |
| VS №3                   | 40                           | 150                           | 350                         |
| VS №4                   | 30                           | 650                           | 1500                        |
Effective realization of the ultrasonic exposure requires reliable transmission of ultrasonic vibrations from the piezoelectric transducer to the heat exchanger surface. The main limiting factor of transmission of ultrasonic vibrations is the composite structure of the heat exchanger. Traditionally, a threaded connection is used in ultrasonic engineering. It provides maximum abutment of structural elements surfaces, quality of acoustic contact, and strength of connection, ease of mounting and demounting.

Three piezoelectric transducer mounting place were investigated:

- Threaded holes in left and right parts of heat exchanger tanks. External view of the mounting place is shown in figure 5.

![Figure 5. Mounting place on heat exchanger tank.](image)

- The bushings with internal thread M8 soldered to two tubes to improve the transmission quality of ultrasonic vibrations. The external view of the mounting place is shown in figure 6.

![Figure 6. The bushings with internal thread M8 for VS mounting.](image)

- Mounting by means of the vibration distributor. The ultrasonic vibration distributor was soldered to the heat exchanger tubes instead of bushings. The external view of this connection is shown in figure 7.

![Figure 7. Vibration distributor soldered to heat exchanger.](image)

The use of various vibratory systems, their mounting methods and mounting points ensured the detection of optimal modes and conditions for vibration formation. Amplitude of mechanical vibrations and uniformity of vibrations distribution on tubes of heat exchanger are used as optimality criterion. A piezoelectric sensor with a point contact was used to measure vibrations amplitude.
The ultrasonic vibratory systems were mounted to the side tanks of the heat exchangers. Next, they were mounted to the power beams which are completely filled with solder (figure 8). Frequency responses of ultrasonic systems No. 1 at different mounting points are shown on figure 9. Analysis of the results showed that all mounting points are absolutely equal (lines practically coincide, except for minor differences). The resonance frequency of the entire construction increases by about 3 kHz. The impedance at the most pronounced resonance frequency increases by 10 times. This is suggesting poor resonance properties of the construction.

![Figure 8. Single ultrasonic vibratory system #1 mounted on heat exchanger.](image)

The construction was connected to the ultrasonic generator to check the vibration distribution in the working mode. Vibration amplitude on heat exchanger tubes surface are very small and does not exceed measurement error at generator power consumption equal to 400 W. This amplitude is not sufficient to achieve the aim. Three equal ultrasonic vibratory systems were mounted to the heat exchanger to make a final decision. In this case, there was no significant change.

![Figure 9. Impedance characteristic of ultrasonic vibratory system #1 mounted to all contact pads of heat exchanger. 1 – VS#1, 2 – VS#1 mounted in different points on heat exchanger tank.](image)

Next, the second mounting method was applied using threaded bushings soldered to the heat exchanger tubes (figure 10). Such a mounting method is effective only at large number of vibratory systems, since there is practically no vibration transmission between the elements of the heat exchanger structure. Five vibratory systems #1 were mounted.
Figure 10. The heat exchanger with mounted five VS#1.

This construction was connected to the ultrasonic generator to check the vibration distribution in the working mode. Some vibration amplitude was generated on the surface of the heat exchanger tubes at generator power consumption equal to 400 W. However, this amplitude was not sufficient for local spraying of water thin layer (about 10 μm). Analysis of the vibration amplitude distribution map showed that the vibrations were not uniform and significantly smaller than in subsequent construction.

Figure 11. Heat exchanger with mounted vibration distributor.

All subsequent investigations were carried out using the third mounting method (vibration distributor) and only types of vibratory systems were changed. External view of heat exchangers with mounted vibrations distributor and vibratory system is shown in figure 11.

Impedance characteristics are shown in figure 12. Maximal efficiency of ultrasonic ice destruction is provided at frequencies up to 25 kHz according to the analysis. The resonance frequency of the entire construction in all cases was not less than 40 kHz. The lowest frequency construction was with vibratory system #4.

The quality factor of vibratory system is significantly reduced by combining the vibration distributor with the heat exchanger. The heat exchanger substantially dampens a vibratory system due to its complex heterogeneous construction.

The maps of amplitudes distribution of mechanical vibrations measured on the tubes of heat exchanger was drawn in the process of the investigation. Amplitude was measured by means of a sensor with a point contact at different mounted methods and type of piezoelectric transducer. Measurements were made at constant frequency of mechanical vibrations and then averaged by a sliding window with a size 3x3.
Figure 12. Impedance characteristic of vibratory system #1 (A), #2 (B), #4(C). 1 – VS, 2 – VS mounted on vibration distributor, 3 – vibration distributor with VS mounted on heat exchanger tank, vibration distributor with VS mounted on heat exchanger tank filled by water.

The distribution map for the best case is shown in figure 13.

Figure 13. The distribution map of mechanical vibrations amplitude on heat exchanger tube.

The light cell is the area with the minimum vibration amplitude; the dark cell is the area with the maximum amplitude. This method does not allow obtaining absolute values of amplitude, but only
relative values. Therefore, it is possible to make summary about uniformity of vibration amplitude distribution and compare value of amplitude in different conditions. Table 2 summarizes the distribution maps.

**Table 2.** Summarizes the distribution maps.

| Map description | Frequency, Hz | Value of vibration amplitude, mV |
|-----------------|--------------|----------------------------------|
|                 |              | Min | Max | Average |
| The heat exchanger with 5 VS#1 | 28230 | 5   | 98  | 24      |
| The heat exchanger with 5 VS#1 is filled by water | 28649 | 8   | 97  | 23      |
| The heat exchanger with vibration distributor and VS#1 | 30530 | 3   | 32  | 11      |
| The heat exchanger with vibration distributor and VS#1 is filled by water | 30530 | 5   | 28  | 12      |
| The heat exchanger with vibration distributor and VS/#2 is filled by water | 43500 | 12  | 170 | 62      |
| The heat exchanger with vibration distributor and VS#3 is filled by water | 48220 | 14  | 244 | 69      |
| The heat exchanger with vibration distributor and VS#4 is filled by water | 37127 | 19  | 432 | 107     |

Preliminary summary:

- The amplitude of the horizontal vibrations is more uniform compared to the vertical in each case. Also, the vibration amplitude decreases significantly from the piezoelectric transducer.
- Since all measurements were made at the same voltage on electrodes of piezoelectric transducers, the amplitude of the vibrations differs up to 5 times between the different mounting conditions.
- The vibration distributor provides greater uniformity in the distribution of vibration amplitude, especially at the ends of horizontal lines.
- Filling with water of the heat exchanger slightly affects the distribution of vibrations amplitude.
- The construction consisting of heat exchanger, distributor/fasteners and piezoelectric converter has large amplitude of oscillations at higher frequencies.

3. *Investigations results of ultrasonic exposure on heat exchanger deposit*

The following parameters of pulse ultrasonic exposure were applied in all further experiments:

- Pulse duration of ultrasonic - 1 s, then pause - 5 s, at power consumption of ultrasonic generator 400 W.
- Continuous exposure at power consumption 400 W.
- Pulse duration of ultrasonic - 1 s, then pause - 5 s, at power consumption of ultrasonic generator - 1300 W.
- The ultrasonic device is stabilizing the set parameters of operation during the whole time of the experiment [11].
A series of experiments was carried out in a made stand. Part of the experiments did not allow the desired effect to be obtained under all modes of ultrasonic exposure. Consider only experiments with positive effect.

The following results (Figure 14) were obtained when examining the construction with vibratory system No.1 and the vibration distributor. There is no breaking off of ice pieces. Local heating of heat exchanger tubes takes place. Ice melted gradually and evaporated at constant temperature in the chamber -30°C. The process is more intensive under continuous exposure mode (400 W); in pulse mode, the effect is less pronounced. The shape of the resulting melting ice is well correlated with the vibration amplitude distribution map. The upper region is most likely due to the heating of this region by ultrasonic vibrations and vapors of evaporated ice.

![Figure 14. Result of ultrasonic exposure of vibratory system #4 with distributor.](image1)

During investigation of the construction of ultrasonic system No.4 with the vibration distributor, the following results were obtained (Figure 15):

- Ice melting does not occur under all variants of exposure.
- Ice is locally peeled and discarded in case of pulse exposure (option 3). The location of ice separation corresponds quite accurately to the area with maximum vibration amplitude (Fig. 13).

![Figure 15. Result of pulse ultrasonic exposure of vibratory system No.4 with vibration distributor.](image2)

4. Conclusion

Analysis of the results of the investigations showed:

- The most efficient method of ultrasonic vibratory systems mounted to a heat exchanger (effective energy transmission) is soldering to tubes using a vibration distributor.
- Exposure at low frequency is more effective.
- The construction of the heat exchanger does not fully realize the advantages of the ultrasonic method of breaking the ice on the surface of the heat exchangers, because the cells are not
attached to the tubes of the heat exchanger, but are fixed only by friction force. It is not possible to transmit vibrations.

- However, research has confirmed the effectiveness of ultrasound and its possible application in practice. However, its effective application requires investigations of cavitation resistance of heat exchange surfaces and, accordingly, the development of special constructions of heat exchangers.

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