Experimental study on heat exchange in a compact porous aluminium foam heat exchanger

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Abstract. In this paper the results of experimental study on hydrodynamics and heat transfer during a single-phase coolant flow in a heat exchanger made of porous foam aluminium are presented. The study was carried out on a specially designed and manufactured experimental setup provided with measuring equipment. The setup is capable of testing in a wide range of thermal and hydraulic characteristics and recording the measurement results automatically. The results allowed verification of previously obtained analytical solutions. This made it possible to use them to develop universal methods for calculating specifications of new porous compact heat exchangers used for cooling heat-stressed elements in various devices. The results obtained in this experimental study confirmed the possibility of using porous compact heat exchangers in thermal protection systems with a specific heat release of up to 100 W/cm².

1. Introduction
Porous materials are widely used to produce compact devices in various areas, such as microelectronics, mobile power plants, satellite communication systems, etc. Nowadays it is necessary to develop universal methods for calculating specifications of compact porous heat exchangers for protection against high-intensity and/or high-temperature thermal effects. At present, within the framework of existing calculation methods and analytical solutions, the results of numerical simulation in the packages ANSYS, COMSOL, etc., as well as the results of experimental studies are used. The amount of experimental data exceeds significantly the results obtained analytically and numerically. However, experimental data often cannot be used for a wide range of material properties and coolant flow rates. In this case, the use of accurate analytical solutions is the most preferred, for example [1-5]. Comparison with experimental data is required to confirm the correctness of their usage. The purpose of this work is to conduct experimental studies of hydrodynamics and heat transfer in prototypes of porous compact heat exchangers under single-phase coolant flow conditions for verification of the obtained analytical solutions, with the subsequent use of the latter in the universal calculation method development.

2. Experimental setup and prototypes
To carry out the research on hydrodynamics and heat transfer, an experimental setup was developed and manufactured. The setup was capable of providing measurements, archiving and automatically reporting the following parameters: coolant flow rate from 0 to 24 l/min; the coolant temperature at the inlet/outlet of the prototype from minus 40 to 150°C; overpressure in the system from 0 to 3 bar; thermal capacity of the device to simulate heat load from 0 to 1 kW. The schematic diagram of the setup is shown in figure 1, and its general view is in figure 2.
Figure 1. Schematic diagram of the experimental setup: 1, 2, 3 – external heat exchange units with fans (liquid-air); 4 – heat transfer unit; 5, 6 – expansion tanks; 7 – throttle valve; 8-14 – overpressure transducers; 15-24 – sensors measuring temperature values; 25 – control valves; 26-32 – gate valves; 33, 34 – centrifugal pumps; 35, 36 – flow meters; 37 – flow rectifier; 38 – device for modelling thermal load; 39 – filter.

Figure 2. General view of the experimental setup.

The setup consists of two fluid circuits. In the first (main) circuit, the coolant is supplied by the pump 33 from the expansion tank 5 to the experimental sample, and then to the heat exchange unit 4 based on thermoelectric modules. After that, the coolant enters the external heat exchange unit 2 (fluid-air, 1 kW) and then returns to the expansion tank 5. The pump 33 is equipped with a frequency power control. The intensity of heat transfer in the external heat exchange unit 2 is controlled by fans, and in the heat exchange unit 4 on the basis of thermoelectric modules it varies by the amount of input current.

A number of temperature (15, 18-21, 23) and pressure (8-11, 13) sensors are installed in the first fluid circuit, as well as a flow meter 35. A sensor 17 is also provided for monitoring the temperature in the heating element.
The setup is equipped with slide power control units for the heat load modeling device and a heat exchange unit based on thermoelectric modules. To create thermal loads, a heat load simulation device is used on which an experimental sample of a porous heat exchanger is installed.

The use of a heat exchange unit 4 based on a thermoelectric module is necessary if the external heat exchange unit 2 does not provide heat transfer fluid cooling to the required temperature, as well as if it is necessary to cool it below the ambient temperature.

The heat exchange unit 4 based on thermoelectric modules is made according to a fluid-fluid scheme and consists of a set of profiled tubes with thermoelectric modules installed between them. Depending on the connection, half of the tubes are adjacent to the hot side of thermoelectric modules, and the remaining tubes are adjacent to the cold side of thermoelectric modules. The power of the heat exchange unit based on thermoelectric modules is equal to the power of the thermal load simulation device.

All elements are connected by pipelines, which are insulated.

In the second fluid circuit, the coolant is pumped (by centrifugal pump 34) into a heat exchanger 4 based on thermoelectric modules, after which it enters an external heat exchange unit 3 (fluid-air) and then into an expansion tank 6. In the second fluid circuit, two temperature sensors (22, 24) and two pressure sensors (12, 14) are installed at the inlet and at the outlet of the heat exchange unit 4 based on thermoelectric modules, respectively, which provides monitoring of the coolant parameters.

Temperature sensors are installed directly into the flow, and the pressure sensors are installed remotely through the flexible hoses, on a special mount.

The experimental setup is equipped with a system for collecting and transmitting measured parameters data.

A heat exchange element, which was a continuous porous medium in the form of a regular parallelepiped, was used as a prototype. A general view of the experimental sample of the heat exchange element is presented in figure 3. The porous heat exchanger was made of aluminum by injection molding into vacuum. This made it possible to obtain a monolithic heat exchanger billet in which the porous part and the base are integral, thus avoiding the occurrence of thermal resistances.

![Figure 3. General view of the experimental sample: 1 – heat exchange element; 2 – fitting; 3 – sealing ring; 4 – cover; 5 – gasket; 6 – frame; 7 – mounting screws; 8 – compactor.](image)

![Figure 4. Monolithic heat exchanger billet.](image)
When selecting a pore-forming filler, the choice was made on common salt due to its availability and ease of extraction from the heat exchange channels. Subsequently, the resulting heat exchanger element was machined, an Al₂O₃-based dielectric coating was applied to the surface in contact with the heat source, and the heat exchanger was assembled as a whole.

In the process of obtaining porous element prototypes by the vacuum casting method, a GE 4KG vacuum molding machine, a 5P 13.9 kW water cooling chiller, an XD-63 vacuum pump, a Programix TX50 muffle furnace, and a d200 vacuum jolt table were used.

3. Experimental results and discussion
The experiments were carried out at the flow range from 0.02 m³/h to 0.1 m³/h. The heat load was varied in steps from 20% to 100% of the rated power in 20% increments. In the process of experimental sample testing, temperature fluctuations did not exceed 1.6°C. The minimum specific heat flux for the heat exchanger was 17.639 W/cm², and the maximum specific heat flux was 100.106 W/cm². The results of the experiment are presented in figure 5.

![Figure 5](image.png)

**Figure 5.** Dependence of the specific heat flux on the flow rate for the experimental sample.

Earlier, in works [3-5], exact solutions of the hydrodynamics and heat exchange problems in porous compact heat exchangers with a single-phase heat carrier flow were obtained. Despite the available comparisons with the other authors results, they were verified with the results of our own experiment.

The manufacturing technology of the porous elements presented for the experiment does not allow direct calculation of viscosity and inertial coefficients, since these quantities in the mathematical model include the diameter of the particles that make up the porous medium. In the manufacture of experimental porous elements, molten metal was poured into the mold. The geometric characteristics of the salt, which is washed out of the element after solidification of the metal, were known. The diameter of the salt particles was from 0.35 to 0.63 mm. Thus, the porous medium had a pseudo-foam structure.

The physical model of verification is based on the comparative analogy method, which implies replacing the pseudo-foam structure of the environment with a dense package of monodisperse spheres that has the same permeability and porosity as the pseudo-foam structure. To compare the experimental results and calculations using the previously obtained mathematical model, the influence of heterogeneity of the porous structure on the hydraulic characteristics of the porous layer was determined. The porous layer heterogeneity was defined as a set of equal porous layer zones with different porosities from 0.3 to 0.6. The physical model of such an inhomogeneous porous layer and its combinations with different porosities are presented in figure 6.
Considering the salt particles size range, the hydraulic characteristic of the obtained sample was determined for several schemes. Subsequently, the test data of a specific sample were compared with the hydraulic characteristics of each considered circuit and the closest option was determined.

The hydrodynamics of the coolant flow in the porous layer is described by the Darcy-Brinkman-Forchheimer phenomenological model, and the Xu-Cheng equations obtained by the volume averaging method for the three-dimensional coordinate system for each porous section. The result of comparison with experimental data is presented in figure 7. Of the theoretical models of the porous structure considered, the model corresponding to figure 6d is the closest to the experimental model. To determine the viscosity and inertial coefficients of an experimental sample, we use the method [20]. The results are presented in figure 8. The discrepancy between the experimental and calculated data was less than 0.17 %.

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**Figure 6.** Possible combinations of porous areas for an inhomogeneous layer (numbers inside squares – particle diameter, µm).

**Figure 7.** Comparison with experimental data.

**Figure 8.** Dependence of differential pressure on coolant flow.
The results of the thermal experiment are presented in the form of graphs of temperature dependences on the flow rate of the cooler in figures 9, 10. They also show the results of previously obtained analytical solutions. The error of results between the theory and experiment was less than 0.52%.

Figure 9. Dependence of the heat exchanger outlet temperature on the coolant flow rate.

Figure 10. Dependence of the heat exchanger base temperature on the coolant flow rate.

4. Conclusion
As a result of research, new experimental data on hydrodynamics and heat transfer in a compact porous heat exchanger made of aluminum foam were obtained. During the subsequent verification, it was established that the previously obtained analytical solutions have good convergence (less than 6%) with the results of experimental studies. Comparison of analytical and experimental data allowed us to confirm the basic laws of hydrodynamics and heat transfer identified as a result of the mathematical models development. The proposed mathematical models that meet the conditions of adequacy and correctness give reason to consider them as the tools when choosing rational parameters of porous heat exchangers that provide the required thermophysical characteristics.

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