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Geometric Channels Produced By Laser-Selective Thermal Sintering Metal Powder Exhibit Hydraulic Characteristics Using ANSYS Fluent

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ABSTRACT

A laser selective sintering of metal powder is used to generate channels with spatial lattice structures, and the study covers the hydraulic features of these channels. Under conditions of increasing heat generation of the current element base, the study use ANSYS Fluent and investigate the challenges of cooling and thermal stabilisation of heat-loaded elements of radio-electronic and electrical power equipment during the course of their investigation. The investigation of porous heat exchange elements and the application of these components with high-tech spatial lattice structures receives a lot of focus and consideration. When it comes to optimising heat transfer and ensuring that constructions have good strength qualities, the utilisation of spatial lattice structures as heat exchange elements is taken into consideration. Radiators that are based on spatial lattice structures have the potential to be used in cooling and thermal stabilisation systems. These radiators offer an excellent mix of hydraulic and heat transmission characteristics, as demonstrated by the findings of the survey.

1. Introduction

Problems related with the cooling and thermal stabilization of heat-loaded elements of electronic and electrical power equipment are among the most essential challenges that experts in the field of heat and mass transfer are tasked with addressing. This is as a result of the fact that over the course of the last fifteen to twenty years, there has been a huge leap in the development of microelectronics all over the world [1] .Passive cooling was used in early electronic computers, heat sink was a basic radiator for cooling system and the insufficient passive cooling led to the switch from natural to induced convective heat transfer, maintaining an operating temperature through the use of a passive cooling system is one strategy to increase the efficiency of systems [2].

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Cooling systems have become increasingly complicated and require careful monitoring and control since they use fans or pumps to deliver air or incompressible working fluids or working nanofluid's enhanced thermophysical characteristics allow it to be incorporated into high heat transfer devices, such as heat exchangers and heat sinks, this change enabled qualitatively new thermal quality assurance methods, with take in to account the heat sinks positions greatly influence the heat transfer rate [3,4].

Microelectronics makers had to optimize processor architecture to maintain processing power. This led to constant miniaturization and more transistors per layer of an electrical component. Everything increased heat generation permanently. In order to increase radiator efficiency, current cooling and thermal stabilization systems required to use heat transfer intensifiers and shape heat-removing surfaces.Porous heat exchange elements (PHE) are a type of heat-removing surfaces that show great potential. Their extensive practical utilization commenced throughout the latter half of the twentieth century, primarily owing to their favourable physical, technical, and structural attributes. Using porous materials allows for a substantial increase in the effective heat transfer area, which is crucial due to limited weight and space constraints, while utilizing materials with high thermal conductivity, because of the effect of density which important to control the material's thermal characteristics [5]. Furthermore, PHE possess commendable structural and strength characteristics, enabling their utilization as load-bearing components in certain scenarios. PHE with disordered and organized structures are most common. Thus, disorganized porosity heat exchange elements with large specific surface areas have high heat exchange intensity. The downsides are equally numerous. Disorder, dead-end pores, and unpredictability are examples. This causes hydraulic flow resistance during growth. Thus, porous materials should be limited to short parts of heat exchange equipment under high thermal loads. For a heat transfer surface of comparable area, PHE with ordered porosity will have lower hydraulic resistance, improving thermal-hydraulic efficiency. PHE with ordered structures include spatial lattice structures. Numerous papers in the actual sector of the economy show that spatial lattice structures' practical applications have grown rapidly in recent years [6].

An ordered lattice structure offers the benefit of a large surface area within a single volume, while avoiding closed and dead-end pore volumes. This allows for the potential of achieving maximum and repeated mixing of the coolant flow, resulting in significantly lower hydraulic resistances compared to structures with disordered porosity [7].

An in-depth analysis of topical literature sources enables us to emphasize the primary areas of practical advancement in lattice structures. Firstly, spatial structures are extensively employed in the design of intricate structural components. Through prior topological optimization of the primary elements, they enable a substantial reduction in the mass of the final product or component while preserving its fundamental mechanical properties [8].

Furthermore, the utilization of lattice spatial structures enables the deliberate creation of structural components with a specified anisotropy, both longitudinally and transversely. This method enables the creation of novel designs for preexisting structural components and even complete products. Simultaneously, the utilization of innovative digital technology in design ultimately diminishes forthcoming operational expenses. Furthermore, spatial lattice architectures offer exceptional strength properties in the final products. Occasionally, these structures can partially assume the load-bearing role, thus maximizing material efficiency. Furthermore, lattice radiators that possess adequately tiny volumes exhibit a substantial usable area, so guaranteeing optimal contact between the working surface and the coolant. By employing structures of various forms, the hydraulic characteristics can be optimized and heat transfer can be maximized, based on the qualities and physical condition of the coolant. Simultaneously, contemporary research published in [6,9-12] supports the notion that spatial lattice patterns effectively enhance heat transfer, both in convective heat transfer and during coolant boiling. Radiators utilizing lattice structures have been extensively employed in systems that require cooling and thermal stabilization of heat-loaded components in radio-electronic and electrical power equipment [13-15].

However, lattice systems' structural intricacy, high cost, and technological challenges limit their use. Develop additive manufacturing technologies like 3D printing and SLM [16,17], makes complicated structures possible and reduces cost, increasing lattice structure possibilities, with model simulation using Ansys Fluent CFD that predicted temperature profile was higher than the experimental one due to mechanical losses during experimentation [18,19].

First, contemporary additive technologies are used to construct structurally complicated materials like porous heat exchange elements made from spatial lattice structures. Today, prototyping methods are expensive and rarely used in mass production. Production costs are driven by powders with the right mechanical and thermophysical characteristics. Granule shape (sphericity) and dispersion determine product quality. However, additive technologies are the only way to create single copies of unique high-tech products because they can create structural micro- and nanostructural elements of complex shapes that traditional machining cannot [20,21]. The hydraulic properties of channels with inserts in the form of lattice-ordered structures are examined in this work.

Also, previous studies [22] did not fully take into account the complex processes of interaction of the flow with the surface of lattices and structures created by the LSTS method. Also, local pressure drops, vortices and turbulent jets arising in such channels have not been studied deeply enough. Moreover, there are no comprehensive studies that combine the production of geometric channels using the LSTS method and the subsequent analysis of their hydraulic characteristics using numerical simulations.

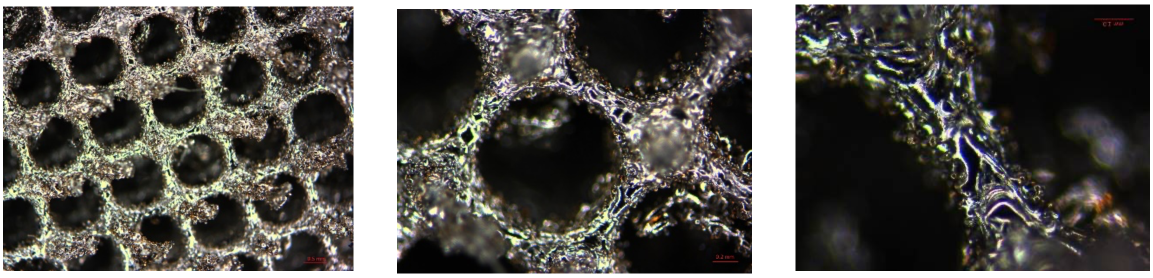
The novelty of this research lies in its comprehensive approach, which combines laser selective thermal sintering to create complex channel geometries with detailed numerical modeling of their hydraulic characteristics. Thanks to this, our research will allow us to more accurately assess the impact of production parameters on channel performance, which will lead to improved design and optimization of hydraulic systems.

2. Methodology

2.1 Method for Manufacturing Spatial Lattice Structures

Selective laser sintering is used to create spatial lattice structures. The mean pore diameter ranged from 1.2 mm with a standard deviation of 25 µm. A 3D work section was produced using an EOSINT M270 laser selective sintering machine to create prototypes and finished metal powder products. While operating the installation, the powder is applied to either the surface of the working platform or the prior layer using a specialized feeding mechanism. The layer is smoothed at the same time as the substance is applied. The thickness of the layer varies based on the particular installation and the material employed, ranging from 0.015 mm to 0.15 mm. Next, the laser selectively fuses the areas of the layer that are included in the object, while also fusing them with the previous layer. Following the subsequent sintering, the platform is decreased to match the thickness of the layer, a fresh layer of powder is administered, and the cycle is performed once more. The surface roughness of the working parts was measured using a model 130 profilometer, specifically intended for determining profile parameters and roughness. The measurements were conducted using the center line system, following the guidelines outlined in GOST 25142-82. The measuring instrument is classified as a first-class accuracy device. The inductive sensor of the profilometer has a sensitivity of

0.002 microns, allowing it to accurately measure surface imperfections with a height of 0.005 microns. Figure 1 shows the spatial lattice of working area No. 3 magnified at various magnifications. The presented lattice structures were made from PH1 grade powder [23].



(a) (b) (c)

Fig. 1. Structure of spatial lattices with different degrees of resolution: – 0.5 mm, (b) – 0.2 mm, (c) – 0.1 mm

2.2 Hydraulic Characteristics Studied

Pressure loss (Pa) through the studied lattice "insert" in the channel is determined as:

$$\Delta P = P_{inlet} - P_{outlet} \tag{1}$$

To determine hydraulic resistance in practice, it is customary to use the dimensionless coefficient of hydraulic resistance ξ, which is determined by the Eq. (2) [24]:

$$\xi = \frac{\Delta P \cdot 2 \cdot d_n \cdot \Pi}{\rho \cdot w^2 \cdot L} \tag{2}$$

Where: dп – hydraulic diameter of the channel, [m], is taken as the characteristic dimensions described in most literature sources for determining the Reynolds number and Nusselt number [25]; Π is the porosity of the lattice insert, determined by the ratio of the volume of voids to the total volume of the porous body; ρ – air flow density at the entrance to the lattice part of the channel, [kg/m3]; L – length of the lattice structure, [m]; w – air flow speed at the entrance to the lattice part of the channel, [m/s].

The numerical modelling makes it possible to most effectively study the hydraulic and thermal efficiency of lattice structures. In modern thematic literature, quite a lot of attention is paid to practical studies of various characteristics of spatial lattice structures based on modern numerical studies, as evidenced by a significant number of works in this area [26-29].

In the work, mathematical modelling was implemented using the Ansys Fluent package based on solving the Navier–Stokes in Eq. (3). The system of equations was closed using the standard k-ε turbulence model (4,5) [30]. The momentum conservation equations for an incompressible fluid were defined as:

$$\rho\left(\frac{\partial \nu}{\partial t} + \nu \cdot \nabla \nu\right) = -\nabla p + \mu \nabla^2 \nu + \rho f \tag{3}$$

where: ρ — the density of the liquid, v— velocity vector, t — time, p — pressure, μ— dynamic viscosity, f— external forces (e.g. gravity). The equation for the kinetic energy of turbulence κ:

$$\rho\left(\frac{\partial v}{\partial t}+v\cdot\nabla\kappa\right)=\nabla\bullet\left(\left(\mu+\frac{\mu_t}{\sigma_\kappa}\right)\nabla\kappa\right)+P_\kappa-\rho\varepsilon \tag{4}$$

where:μ_t — turbulent viscosity (depends on κ и ε), σ_k — empirical constant, P_k — production of kinetic energy of turbulence. The equation for the rate of energy dissipation ε:

$$\rho\left(\frac{\partial \varepsilon}{\partial t}+v\cdot\nabla\varepsilon\right)=\nabla\bullet\left(\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\nabla\varepsilon\right)+C_{1\varepsilon}\frac{\varepsilon}{\kappa}P_\kappa-C_{2\varepsilon}\rho\frac{\varepsilon^2}{\kappa} \tag{5}$$

where: σ_ε — the empirical constant,$C_{1\varepsilon}$ и $C_{2\varepsilon}$— empirical constants.

The minimum orthogonal quality of the calculated grid is 0.317041. The cellular zone contains 2.9 million polyhedral cells. The density of the grid varied from 370 to 548 mm-2, defined as the ratio of the number of cells per area of the lattice radiator. The range of y+ values for this grid varies from 0.22 to 1.3, which indicates a fairly accurate modeling of the boundary layer.

A coarser grid with large cells was used at the entrance and exit to the channel. This approach made it possible to significantly reduce computing resources, since the initial flow conditions could be set with less detail. The area of the lattice insert required a more detailed (refined) grid. This was due to the fact that complex processes of interaction between the flow and the lattice surface took place in this zone, including vortices, turbulent jets and local pressure drops. The optimal detail of the grid in this area made it possible to simulate these effects more accurately. In Figure 8 (a,b) n.

The computational model of a channel with a lattice radiator, in addition to the computational mesh, included boundary conditions, turbulence models and solver settings. The boundary conditions at the entrance to the computational domain (at the beginning of the channel) are as follows: mass flow 0.00439 kg/s, initial/gauge pressure at the channel entrance 4370 Pa, total temperature 295.15 K. The inlet pressure was set in accordance with field test data . Boundary conditions at the outlet: pressure at 0 Pa (gauge), return flow temperature 300 K. Boundary conditions at the walls: stationary wall, no slip, standard roughness model, constant sand-Grain Roughness 0.5.

2.4 Experimental Work

Experimental studies were carried out on a stand, which is an open air flow circuit equipped with means for measuring static and total pressure, as well as the temperature of the working fluid at the entrance to the section. The appearance of the experimental stand, equipped with means for measuring the main parameters, as well as the working diagram are presented in Figure 2 and Figure 3. The working section was mounted inside the outlet pipe of the stand and was fixed with a locking bolt, thereby ensuring its immobility and precise coordination Figure 4. Ambient air was used as a working fluid without preliminary purification. The speed of the oncoming air flow varied in the range from 5 m/s to 60 m/s. The study of hydraulic characteristics was carried out in three working sections, the appearance of which, as well as the structure with dimensions, are presented in Figures 5, 6 and 7. Two sections were rectangular channels 20x20 mm wide and 50 mm long, filled with porous heat exchange elements with different densities. The degree of porosity of area No. 1 was Π = 0.0914, area No. 2 - Π = 0.1096. As follows from Figure 5, the increase in the degree of porosity of the channel was carried out by increasing the number of layers. At the same time, the pore size decreases Figure 8.The third section was a hollow (smooth) channel, 50 mm long and 20x20 mm wide. This work area served as a basis for testing, as well as comparison with the hydraulic parameters of channels filled with lattice structures.

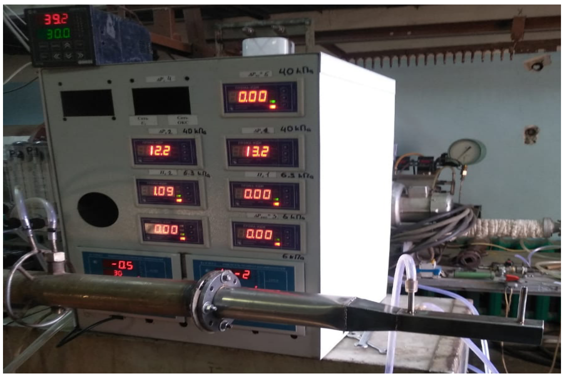


Fig. 2. External view of the experimental setup

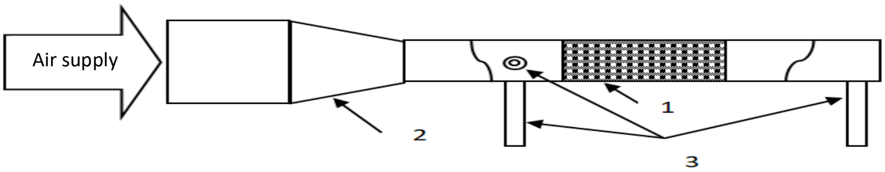
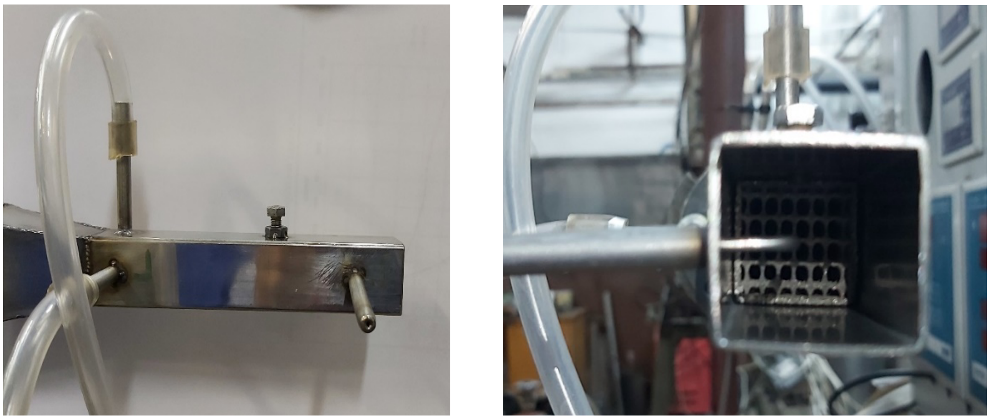


Fig. 3. Work area layout:1 – Installation location of the lattice element, 2 – Inlet confuser, 3 – Static and total pressure taps



(a) (b)

Fig. 4. Appearance of the working area: (a) longitudinal , (b) cross-section

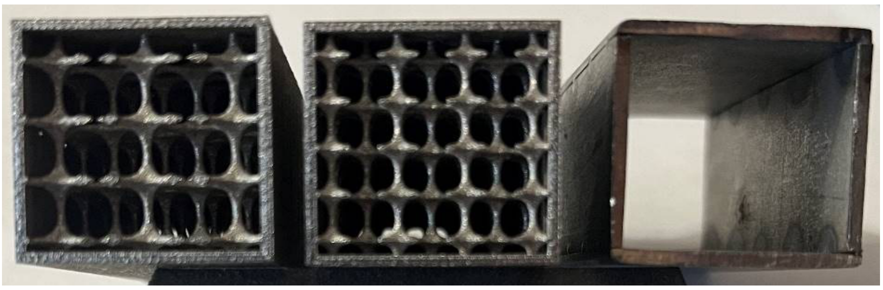


Fig. 5. Appearance of working lattice sections. 1 – “large”, 2 – “medium”, 3 – “smooth”

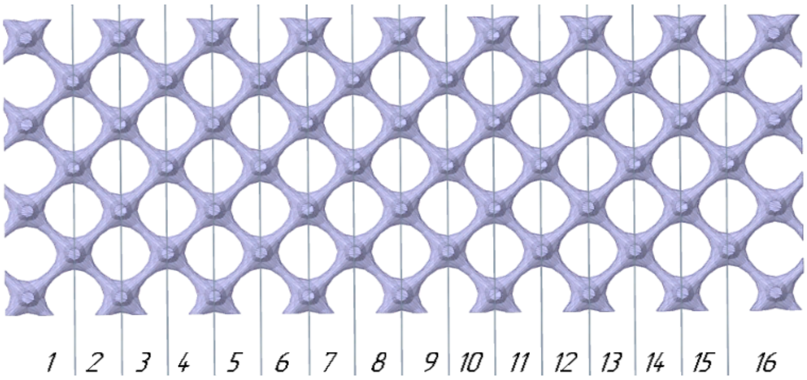
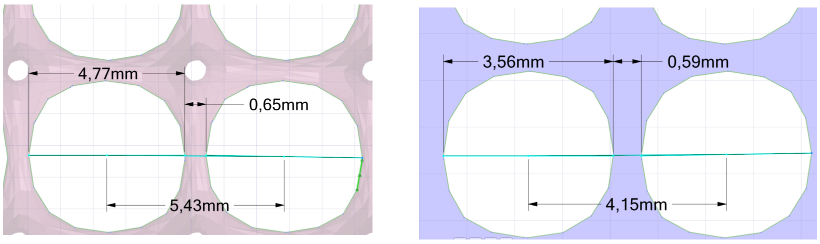


Fig. 6. Scheme of a longitudinal section of working areas

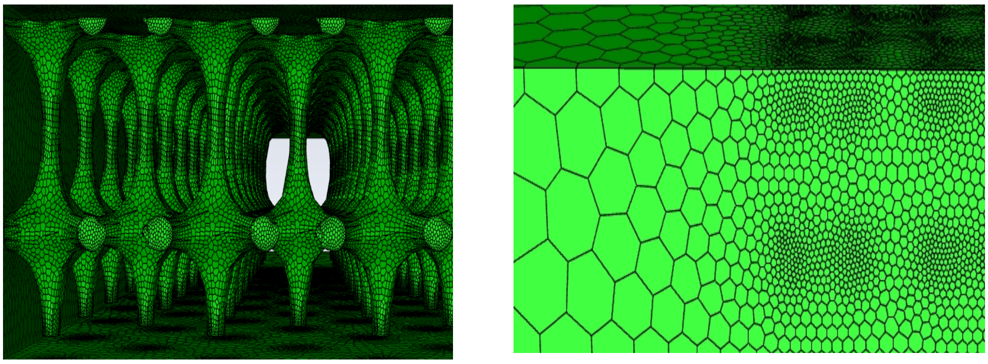


1 – “large” (channel No. 1) 2– “medium” (channel No. 2)

Fig. 7. Geometric parameters of the pores of three working sections

3. Results

The 800th iteration of ANSYS Fluent test numerical modeling of hydraulic processes in a channel with lattice radiators found convergence. This computation model solves the Navier-Stokes equations to provide pressure and velocity fields over the solution area. The entry and outflow total pressure differs from the experimental one by 4–10%.A computational grid is shown in Figure 8 a,b. Pressure distribution model in the working area is shown in Figure 9.



(a) (b)

Fig. 8. a) Mesh for the computational model, b) Mesh for the computational area of the grille radiator

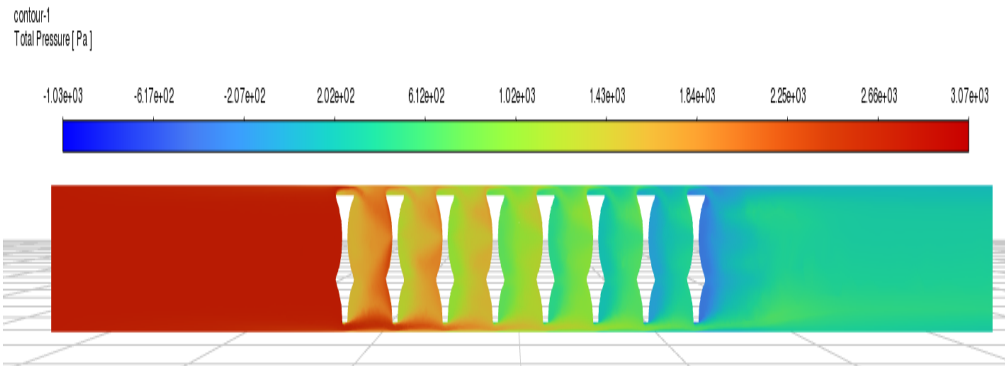


Fig. 9. Example of pressure distribution in a grill radiator

Working parts have tight pressure loss due to low coolant flow rates (≈12-13 m/s). Due to inherent losses in three-dimensional lattice systems, initial flow velocity raises pressure drop substantially. Lattice element No. 2, having more internal components, increases pressure drop quicker than No. 1. Thus, the pressure loss was 4.5 kPa at 47-53 m/s, 8 at 64-66, and above 12 at 75 m/s. Thus, pressure reductions across working components varied dramatically at flow velocities over 40 m/s. Channels having spatial lattice characteristics lower pressure similarly to smooth channels over the whole range of coolant velocities.

At Reynolds numbers larger than 90,000, sections 1 and 2 stratify in "hydraulic resistance" according to the dependence. Increased Re numbers cause channel narrowing. The Ansys Fluent numerical research improved hydraulic examinations of channels using spatial lattice structures. Qualitative results match [33,34]. In section No. 1, the difference in Reynolds numbers from 42000 to ≈95000-100000 averages 42%, and at Re>105000, it is already 34%. Site 2 is qualitatively similar. Re from 45000 to 85000-90000 has a 25% difference, while Reynolds numbers exceeding 90000 have a 15% difference.

4. Conclusion

Modeling shows that the dependence of hydraulic resistance on the operating parameter corresponds to the data obtained by other authors. This confirms theoretical ideas about the behavioral patterns of the flow of liquids and gases in systems with a lattice structure. The simulation results show lower hydraulic resistance values compared to experimental data at all levels of the Reynolds number. This may indicate the need for additional refinement of the model or consideration of additional factors in the modeling process, such as surface effect or inaccuracies in the initial parameters. The conclusions of the article can be used for further numerical modeling of hydraulic parameters. The simulation results can help to improve existing heat exchange devices, improve their efficiency and reduce energy consumption.

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