REVIEWS

# POROUS HEAT EXCHANGERS — CLASSIFICATION, CONSTRUCTION, APPLICATION

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Heat exchange between a porous material and a heat-transfer agent flowing through it is characterized, due to the very extensive contact surface between them, by an extremely high intensity, so that the use of permeable matrices in heat exchangers is a promising and effective means for intensifying the process. Its practical realization in the last two to three decades was made possible by the development of powder metallurgy, which led to the creation of various types of materials. The wide range of structural, hydraulic, thermophysical, chemical, and other properties of these materials, the possibility of fabricating from these materials structural elements in power plants, and the peculiarities of heat exchange accompanying phase transformations of the heat-transfer agent create the conditions and prospects for their extensive and multipurpose use in different areas of science and technology.

Classification of Porous Heat Exchangers. We shall call setups in which heat exchange is realized between a permeable matrix and a fluid flowing inside it porous heat exchangers (PHE). In this case, the heat-transfer agent can undergo phase or chemical transformations. We shall examine PHE in which the flow is driven by an external pressure drop (and not by a capillary effect).

In spite of the large number of different types of heat exchangers with porous elements, with regard to their purpose, structural formulation, properties and the phase state of the heat-transfer agent, a common feature of all of these steups is heat exchange between a porous material and a heat-transfer agent, and the main difference lies in the conditions under which heat is delivered inside the permeable structure. According to the method of heat input, all PHE in a forced operational state can be divided into the following basic types (Figs. 1-4).

In transpiration cooling elements (Fig. 1), an amount of heat q is fed by convection or radiation to the external surface of a transparent porous wall. The coolant moves with specific mass flow rate G opposite to and absorbs the input heat flux.

In elements with volume heat liberation, an amount of heat $q_V$ is liberated within a permeable material (Fig. 2) of a different physical nature: resistive heating, fissioning of a nuclear fuel, volume absorption of penetrating radiation, or radiant heat flow inside a semitransparent medium. The direction of motion of the heat-transfer agent may coincide with or be opposite to the radiant and radiation fluxes.

In PHE with heat input (output), heat is introduced into and extracted from a porous material by heat conduction from an airtight, heated (cooled) surface having a perfect thermal contact with the element (Fig. 3). There are four basic variants here: a channel with a permeable insert (a); a space filled with a porous matrix between tubes (b); a surface with fins, whose vertices are connected to a permeable barrier (c); a surface covered by a layer of porous material, containing channels (d). In the last two variants, the heat-transfer agent passes through the porous structure and moves along channels parallel to the surface.

Finally, there are regenerative PHE with periodic heating of a permeable additive by a flow $G_1$ of hot heat-transfer agent and subsequent transfer of the heat to the flow $G_2$ of the cold heat-transfer agent (Fig. 4).

In the basic types of PHE illustrated in Figs. 1-4, uniform porous materials were used. The efficiency of the PHE increases markedly when multilayered permeable structures, in which the separate layers have different properties and functions, are used.

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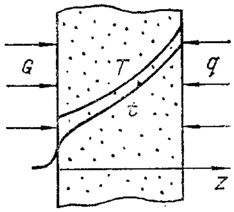



Fig. 1

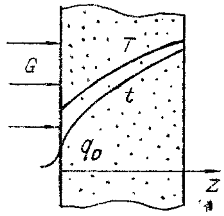



Fig. 2

Fig. 1. Transpiration cooling element.

Fig. 2. Permeable element with volume heat liberation.

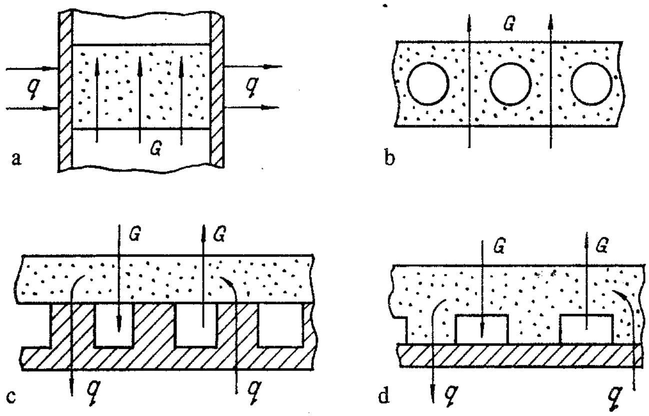



Fig. 3. PHE with heat input (output) into a permeable matrix by heat conduction from an airtight wall.

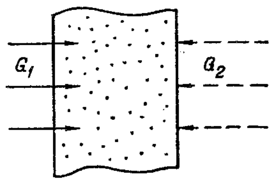



Fig. 4. Regenerative PHE.

Porous Cooling Elements. The method of transpirational cooling of structures on which external convective or radiant heat flows of high density act (see Fig. 1) has a number of important advantages over other types of heat shielding: a) high efficiency of utilization of the coolant; b) significant decrease of the external convective heat flux reaching the surface: the injection effect; c) decrease of the external radiant heat flux with injection of radiation-absorbing gas or vapor; d) no limitations on the magnitude of the external heat flux, with the form and integrity of the surface being cooled remaining unchanged. In many cases, involving extremely high heat fluxes, complicated construction, or inaccessibility of the surface, porous cooling is the only possible method of heat shielding.

The properties indicated above led to extensive practical application of this method: heat shielding of aerodynamically heated surfaces; cooling of combustion chambers and nozzles in gas-turbine and rocket engines, blades on gas turbines, electrical-arc gas heaters, and MHD generators; cooling of permeable current input leads to cryogenic electric setups. Porous gaseous cooling systems have now been studied in greater detail, and the results of these studies are generalized in [1-7].

Another advantage of transpirational cooling when it is used in electric-arc gas heaters (EAGH) is the considerable increase in the efficiency of the plasmotron, since all of the heat absorbed by the cooling gas again enters the main flow. This method is applicable for cooling of different elements (anodes [8], interelectrode inserts [9]), while intense injection of the plasma-forming gas through a porous wall of a discharge channel stabilizes the arc discharge and permits regulating its power and the enthalpy of the flow by changing the intensity of the electric field with a limited current strength. These properties open up the possibility of decreasing the erosion of electrodes and making electric-arc systems with a high density of energy liberation and long operational lifetimes with the possibility of using working gases that are chemically active with respect to the wall material [4, 10].

Qualitatively new phenomena are observed to accompany cooling of porous electrodes in electric-discharge setups and MHD generators by injection of inert gas containing an ionizing additive of alkali metals. In this case, together with the heat and chemical shielding of the electrodes, the electrodes are also shielded from erosion, since the addition of an ionizing additive into the injected gas permits achieving high current densities at the cathode of up to 15 $A/cm^2$ in the distributed arc-free discharge state with a working surface temperature of 1200-1600°K [11-13].

Transpirational cooling accompanying injection of radiation absorbing gases or vapors can be used to decrease the intensity of thermal radiation from heated elements for the purpose of shielding from infrared radiation [14].

The porous cooling system acquires a number of qualitatively new properties with the use of a liquid coolant that evaporates within the permeable wall: a large increase in the efficiency of the latter due to the heat of vaporization; low specific volume of the liquid coolant; possibility of achieving low, including cryogenic, temperatures. These properties also lead to new areas of application of this system. An analysis of the data from theoretical and experimental studies is given in [15, 16].

Porous walls consisting of refractory metals with transpirational cooling by a liquid metal [17], as well as with permeation of or forcing through a sublimating compound, are especially effective for heat shielding. The use of alkali metals permits combining heat shielding with simultaneous introduction of vapor into the working flow in MHD generators as the ionizing additive. An electric-arc evaporator, whose tubular permeable electrode is cooled by an evaporating metal, can be used to obtain finely dispersed metallic powder [18].

The layout of a setup and the results of tests of a porous metalloceramic injector for a liquid-fuel motor are presented in [19]. Several variants of such injectors were studied (Fig. 5). In the design shown in Fig. 5a, both fuel components were mixed, evaporated, and began to react inside the permeable tungsten. In the porous aluminum injector (Fig. 5b), the components are injected separately. Such setups make it possible to solve the problem of heat shielding of the injector with simultaneous evaporation of fuel components, which decreases considerably the dimensions of the combustion chamber in the liquid-fuel motor.

The operational reliability of the transpirational cooling system increases significantly with the use of a multilayered wall. Several such variants exist [20-22]. It is shown in [23] that the most suitable variant is a two-layer wall [22], in which the inner structural wall consists of a heat-conducting material with low porosity, high strength, and a high hydraulic resistance. The outer heat-shielding layer consists of a refractory material with low thermal conductivity, high porosity, and high permeability.

A solar-heated, permeable, blackened, metallic wall is used in efficient low-temperature solar air heaters [24-26]. When the density of the matrices used is low (multilayered grids [24], perforated foil [25] or felting [26]), the absorption of radiation in them acquires a volume character and such systems must be included amongst PHE with volume heat liberation.

Porous Elements with Volume Heat Liberation. The primary area of application of porous electric heaters is for heating gases and liquids [27-32]. Their great advantage over the usual resistive heaters with high-temperature heating of gas lies in the fact that with an identical limiting temperature of the refractory material the gas temperature in the porous heater reaches higher values due to the high intensity of the volume heat liberation [28, 30].

A porous electric heater can also be used as an evaporator [33-35], for example, in vapor-jet vacuum pumps [34, 35]. In this case, in order to increase its operational reliability, an additional layer, which controls the fluid flow, consisting of a permeable, electrically

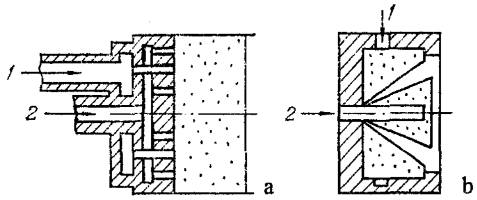
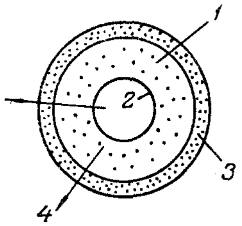



Fig. 5. Porous metalloceramic injectors in liquid-fuel motors [19]: 1) fuel; 2) oxidizer.



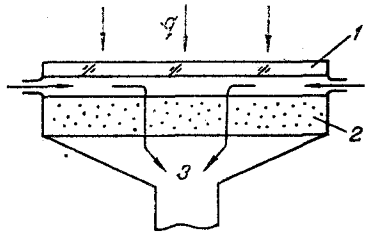




Fig. 6 Fig. 7

Fig. 6. Porous tubular fuel element for a nuclear reactor [37].

Fig. 7. High-temperature volume solar collector [42].

insulating material with low thermal conductivity and high hydraulic resistance, which eliminates boiling of the liquid before entrance into the porous structure and ensures a uniform distribution of the liquid over the surface, is placed on the inner inlet surface [33, 35, 36].

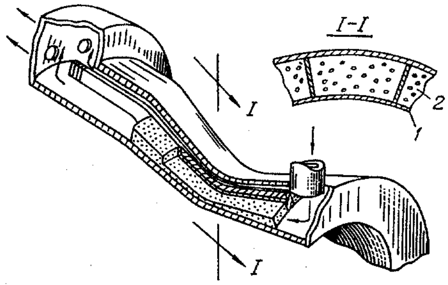
Another area of application of PHE with volume heat liberation is in the fuel elements of nuclear reactors. Figure 6 shows the transverse section of a tubular fuel element with a porous fuel material 1, which is contained between the inner reticular jacket 2 consisting of stainless steel and the outer porous ceramic structural jacket 3. The heat-transfer agent 4 is injected along the central channel, and then passes radially through the permeable mass containing particles of nuclear fuel or spherical microfuel pellets [37].

The temperature fields in PHE in the presence of constant volume liberation of heat, heating up a single-phase flow, are studied in [38]; a similar study for the evaporator mode is performed in [39-41].

A gas-permeable wall consisting of a semitransparent material positioned at the focal point of a paraboloidal solar collector can be used as a high-temperature source of heat for direct heating of the working body in rocket motors [42]. The solar radiation passing through a transparent quartz wall 1 of a volume solar collector (Fig. 7) is absorbed, scattered, and re-emitted in the volume of the porous semitransparent matrix 2, heating it. The high absorptivity and the extended heat-exchange surface create significant advantages for volume solar collectors over surface collectors with high-temperature heating of gas 3, especially with direct flow through, when the directions of the gas flow and of the incident radiation coincide. In this case, the amount of energy absorbed by the porous additive increases in the direction of gas flow and its maximum temperature is reached in the bulk of the additive. At the same time, the less heated layers of the matrix at the inlet screen the radiation from the inner, more heated layers, which decreases the effective backward emission of the additive.

The cold gas entering the housing first cools the quartz wall. For this reason, in this variant, the gas can be heated up to temperatures greatly exceeding the admissible temperature of the quartz glass (1170°K). The best operating conditions for such a solar collector are obtained when the porous material is transparent to and does not scatter the radiation in the solar spectrum, but is opaque to and does scatter infrared radiation [43].

The use of a liquid heat-transfer agent in the counterflow arrangement permits obtaining vapor heated up to high temperatures in the volume of the solar collector.



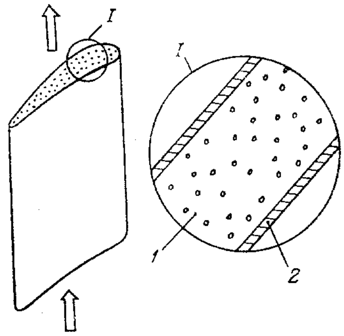




Fig. 8 Fig. 9

Fig. 8. Liquid-fuel motor, in which the wall 1 of the neck of the nozzle is cooled by the component of the fuel flowing through the permeable insert 2 [45].

Fig. 9. Permeable, gas-turbine blade with small dimensions [46].

Volume liberation of heat depending exponentially on the distance $q_V = q_{V0}\exp(-\gamma z)$ occurs in the heat-shielding elements of nuclear reactors due to absorption of the penetrating radiation. Their fabrication out of a porous material and direct flow-through cooling by a permeating flow of coolant reduces the temperature and the temperature gradient much more than the usual convective cooling of continuous elements [44].

Porous Heat-Exchange Elements with Heat Input from a Continuous Wall. The main purpose of such PHE is to intensify the heat exchange between a surface and the heat-transfer agent flowing over it. Here the mechanism of heat transfer is qualitatively different: heat is transmitted from the wall by heat conduction through the framework into the permeable matrix and is then absorbed by the flowing heat-transfer agent due to intense interstitial heat exchange. The porous fill must have a high thermal conductivity and high-quality thermal and mechanical contacts with the wall.

This method of intensification permits cooling, with the help of a single-phase heat-transfer agent, a continuous wall subjected to the action of large thermal fluxes, for example, the fluxes accompanying convective cooling of walls in rocket motors (Fig. 8) and the blades of their gas turbines and elements in electronic equipment and other thermally stressed systems [45-48]. In particular, cooling by pumping water through a permeable substrate allowed reliable operation of a laser reflector with heat fluxes up to $8 \cdot 10^7$ W/m$^2$, while the thickness of the heated wall was reduced to several tens of microns [48]. This method of cooling is at the present time the only method available for heated structures with small dimensions or a complex shape, in which it is impossible to make channels for the coolant. For example, the blades of small gas turbines in rocket motors with a maximum profile thickness of the order of 3 mm, a chord of about 2 cm, and 1 to 2 cm long are usually not cooled, which limits the temperature of the gas flow and the efficiency of such turbines. Fabrication of blades out of a fibrous metal 1 (Fig. 9), covered on the outside by a thin airtight layer of ceramic 2 and cooled by a longitudinal gas flow, flowing out of the apex, eliminates these limitations [46].

The obvious physical idea of this method of intensifying heat exchange was the reason that a large number of designs of diverse heat-exchange systems, in which the channels or intertubular space was filled with such metals, were proposed simultaneously with the development of the technology for fabricating porous metals. Publications reporting the results of studies, including experimental studies [47-49], were delayed for a long time, but their number has recently been rapidly increasing. A generalization of the analytical data in the literature on this problem as well as the most complete theoretical and experimental study of intensification of convective heat exchange in channels containing a permeable fill are given in [50, 51].

The principal designs of heat-exchange systems with the use of PHE of this type are shown in Fig. 10.

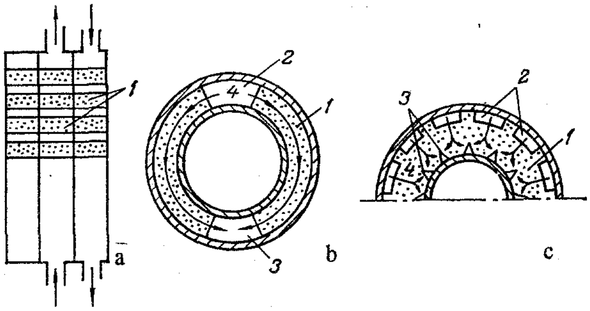



Fig. 10. Heat-exchange systems with permeable inserts with high thermal conductivity in channels: a) data from [52]; b) [53]; c) [54, 55].

Figure 10a shows a heat exchanger in which the porous transverse inserts 1 are positioned both in the inner and outer tubes [52]. These inserts have the same thickness and are located in the same plane.

As is evident from Fig. 10b, the permeable matrix 1 fills the gap between the walls, forming two diametrically opposed channels 2, 3 for longitudinal injection and extraction of the heat-transfer agent 4 [53]. Here, a longitudinal—transverse motion of the heat-transfer agent is realized: longitudinal motion in the injection 2 and extraction 3 channels and transverse motion through the fill 1 in a circular direction.

In Fig. 10c the porous material 1 also fills the space between the two shells, but the longitudinal injection 2 and extraction 3 channels are positioned uniformly along the circle and lie adjacent to the walls [54, 55]. The transverse flow of heat-transfer agent 4 through the matrix is realized in a radial direction, which reduces to a minimum the power required to pump it. It is interesting to note that here the permeable framework can transmit significant mechanical stresses from the inner tube to the outer tube. If the inner wall is a jacket of a fuel element, then this makes it possible to completely unload the pressure on it from the gaseous fission products and to fabricate a jacket with minimum thickness. In [55] it is proposed that the design shown in Fig. 10c be used for cooling elements subjected to the action of high mechanical loads, for example, bearings.

More complicated designs of heat exchangers, in which PHE with heat injection through a continuous wall are used, are described in [56-59].

In order to simplify the fabrication of large systems with PHE, it is proposed in [60] that they be assembled from separate modules. The latter consist of tubes, surrounded by a layer of permeable matrix, and have a contour such that they can be closely packed into a heat exchanger with the desirable form.

There are prospects for the use of porous metals for fabricating heat-dissipating panels. Several variants are presented in [61], where it is established that such panels are much more efficient than the usual finning under conditions of both forced and free convection.

Qualitatively new properties are achieved with a phase transformation of the heat-transfer agent flowing inside a permeable material adjacent to the continuous wall. First of all, the transport of heat from the wall by heat conduction through the porous framework (or in the opposite direction) eliminates the high thermal resistance at the wall, created by the continuous vapor film accompanying boiling of the heat-transfer agent or the continuous film of condensate accompanying condensation of the vapor flow in smooth channels. This permits realizing completely a phase transformation of the flow with high intensity of heat exchange. In addition, capillary forces create a uniform saturation of the porous structure by the liquid, which eliminates the stratification of the two-phase flow in the channel under the action of external forces. For this reason, this method of arranging forced heat exchange with phase transformations is typically used in, for example, systems whose orientation relative to the direction of the force of gravity changes or under conditions of weightlessness.

The peculiarities and quantitative characteristics of heat exchange and resistance in channels with a porous fill with high thermal conductivity accompanying evaporation or condensation of flows of heat-transfer agent are analyzed in [62-64].

All of the heat-exchange systems presented above with the permeable fill with high thermal conductivity in channels or intertubular space (for example, in Figs. 3 and 10) can be used to organize a phase transformation of the flow of heat-transfer agent. We shall point out some of the most interesting designs. An evaporating element for shedding heat flowing up to a continuous surface is described in [65] (see Fig. 3d). The coolant is distributed along the channels and as it moves through the porous matrix into the surrounding space it absorbs heat and is evaporated. In the evaporating element [66], the porous coating on the heat-emitting surface does not have channels, but rather is fabricated in the form of three layers with the side and central layers having different permeability; in addition, the latter has a higher hydraulic resistance. The cooling liquid is distributed along the heat-emitting surface inside the layer with high permeability next to it. Furthermore, the directions of heat flow and of the flow of evaporating liquid in the porous structure coincide: along the normal from the heat-transfer surface.

The main element of the condenser [67] is the porous metallic plate with the tubes positioned in it for passage of the coolant (Fig. 3b). Under the action of a pressure drop, the vapor flows into the interior of the cooled structure and completely condenses, and the condensate formed is squeezed out into the outflow collector.

A porous metalloceramic barrier with cooled tubes positioned inside it was used in [68] to create a sublimation condenser. The vapors of the sublimated product are frozen in the form of a permeable structure onto its input surface, and the noncondensing gas passes through both the product frozen onto and the porous barrier. In order to periodically defrost the frozen product, electric heaters are placed inside the porous matrix.

In addition, there are shell-and-tube condensers [69-71] in which the design of the condensation PHE is close to that shown in Fig. 3c. In these structures, the tubes carrying the coolant can have a different form, but the common element is that they are surrounded by a permeable metalloceramic barrier, connected to the tube with the help of fins or protrusions in such a way that longitudinal channels are formed between the wall of the tubes being cooled and the porous barrier. The vapor squirts through the permeable barrier and completely condenses inside it, and the condensate enters the output collector along longitudinal channels. The heat liberated with condensation is removed by heat conduction from the porous metal through the region where it is connected to the wall of the tube being cooled.

Other designs of evaporators with PHE were proposed in [72, 73], and condensers—separators with PHE for separating the vapor—gas mixture and for drawing air are described in [74-76].

Porous Heat-Exchange Elements with a Chemically Reacting Heat-Transfer Agent. The extended surface of permeable matrices with the required catalytic properties, together with intense injection or extraction of heat, accelerates the flow of chemical reactions in the flow of heat-transfer agent. This makes it possible to develop chemical reactors.

Thus, for example, the use of catalytically active porous materials and grids, fabricated from refractory materials and alloys which are coated or saturated with palladium, platinum, osmium, ruthenium, rhodium, or irridium in gaseous infrared emitters permits greatly decreasing (up to 400°C) the combustion temperature of the gas—air mixture and, therefore, the temperature of the emitting surface also. Such a catalytic emitter emits soft radiation, which, when it is used to dry plants or other materials, protects them from decay [77].

Porous metals have also been used as a basis for developing gas-flame burners with a wide homogeneous flame [78, 79]. Their principal element is a metalloceramic barrier, in which lateral water cooling or cooling with the help of a coil positioned inside the porous metal, following the arrangement shown in Fig. 3b, is used to avoid melting of the barrier. Such burners permit obtaining a flat, uniform flame with a wide range of variation of the composition of the fuel mixture and its efflux velocity.

An analysis of porous cooling with the use of a dissociating coolant, performed in [80-83], revealed that its efficiency increases significantly due to absorption of heat accompanying the endothermal decomposition reaction. In addition, the decomposition of the coolant reduces the molecular weight of the gas mixture injected, which increases the blocking effect of the cooling accompanying convective heating.

Different schemes of PHE can be used to organize decomposition of a single-component fuel in gas-generator rocket motors or in hybrid and single-component rocket motors [84]. The reaction rate is controlled by the selection of a permeable matrix with the required catalytic properties.

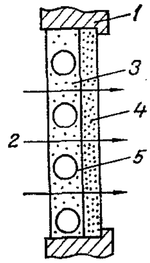



Fig. 11

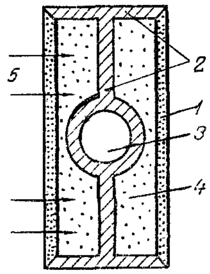



Fig. 12

Fig. 11. Filter—heat-exchanger [85].

Fig. 12. Cryosorption panel of a vacuum pump [86].

Multipurpose Porous Heat-Exchange Elements. The specific properties of porous materials permit organizing, together with intense heat exchange, the flow of a number of other important processes. We shall examine some interesting examples.

Porous metalloceramics are used most extensively for filtering liquids and gases. Figure 11 shows a filter—heat-exchanger [85], containing a porous filtering metalloceramic barrier in a housing 1, consisting of layers of rough 3 and fine 4 scrubbers, arranged sequentially along the flow 2; the heat-exchange tubes 5 are placed in the first layer. This layout permits performing the filtering under thermostatically controlled conditions with heating or cooling of different liquids, gases, and alloys, including also chemically active materials, in a wide range of temperatures from cryogenic to the melting temperatures of metals.

The permeable metalloceramic wall 1 in the cryosorption panel of the vacuum pump [86, 87], presented in Fig. 12, performs the dual function of filtering and thermal insulation. The closed cavity between the porous screen 1 and the profile 2, cooled by the cryogenic liquid flowing along the channel 3, is filled with a crystalline adsorbent 4. The gas pumped out 5 passes through the porous wall, is cooled in it, and is then absorbed by the adsorbent. The screen absorbs the thermal radiation flux incident on it as well as the heat carried by the pumped gas and transmits it via heat conduction to the cooled profile. Thus the porous wall simultaneously fulfills the function of thermal insulation, which prevents heat from reaching the adsorbent, and of a filter, which prevents the fine-grained adsorbent from being dispersed throughout the vacuum system. This makes it possible to make the design of the cryosorption pump highly efficient technically and extremely compact.

The lyophobic or lyophilic properties of permeable materials, combined with the small diameter of the pores, ensure very efficient separation of a vapor—liquid mixture, which is especially important, for example, under conditions of weightlessness. The construction and working parameters of a tubular evaporator for obtaining mercury vapor in an ion motor are described in [88, 89]. The porous tungsten plug inside the molybdenum tube is heated by an electric heater placed on its outer surface. The liquid mercury is injected under pressure into the permeable insert and is vaporized. The insert simultaneously plays the role of a vapor—liquid separator, preventing the flow of liquid mercury through it. In this case, when the liquid wets the porous matrix being heated, a layer of permeable lyophobic material, for example, fluoroplastic, is placed on its output surface in order to prevent the liquid from bursting through and in order to obtain a dry vapor [90]. Condensers—separators with PHE for separating a vapor—gas mixture are described in the previously cited papers [74—76].

The large pressure drop, created in a porous structure with the motion of the liquid—vapor mixture through it, is used in PHE in order to realize the Joule—Thompson effect (Fig. 13). The Joule—Thompson element is fabricated in the form of a tube 1, filled with a low-porosity metal, which is placed inside the heat-exchange tube 2 containing a metal with high permeability. The liquid coolant 3 enters the inner tube, is gradually evaporated due to the drop in the pressure accompanying the flow through the porous additive, and is injected into the evaporator. The flow 4 of the cold vapor from the evaporator moves in the opposite direction through the annular channel surrounding the inner tube. It cools the two-phase flow in the inner tube, thereby lowering the final temperature of the refrigerant and increasing the refrigeration capacity of the setup, and is then injected into the compressor.

A Joule—Thompson heat-exchange element, fabricated in the form of a tube filled with a permeable matrix and placed into a cryogenic liquid, is used for thermal stabilization of the liquid [92]. Here, an insignificant part of the liquid passes through the plug, where its temperature decreases, and it is then evaporated and absorbs heat from the remaining liquid, thereby cooling it.

The thermal resistance of a porous material, confined in an airtight shell, can be regulated over a wide range by controlling the dosage of the injected gas or liquid, in particular, liquid metals [93]. This permits smoothly varying its effective thermal conductivity in the range from $10^{-3}$ to $10^{+4}$ W/(m·K). The "ultrahigh" thermal conductivity of such PHE is attained by boiling the liquid and condensing the vapor inside the permeable structure near the heated and cooled airtight sealed surfaces. This arrangement can be used to organize intense heat exchange. For example, electrodes, cooled in this manner, in an arc gas heater were proposed in [94].

Porous Heat Exchangers in Cryogenic Technology. It is especially important to intensify heat exchange in cryogenic systems, where the exterior surface area of the heat-exchange apparatus and, therefore, the inflows of heat into it under conditions when at very low temperatures the removal of heat becomes increasingly more complicated and expensive, can be reduced to a minimum only in this manner. Some of the previously analyzed heat-exchange systems with a permeable fill inside channels or in the intertubular space were specially developed for cryogenic temperatures. For example, in the heat exchanger (Fig. 10a), in order to avoid lowering its efficiency due to longitudinal heat conduction, the porous material is not made in a continuous form, but rather in the form of sequentially positioned separate inserts. A design of a heat exchanger with a permeable metal for rapid cooling of bodies to cryogenic temperatures is proposed in [95].

In addition to the usual heat exchangers, there also exist different systems operating at cryogenic temperatures in which porous metals are used to intensify heat exchange. Several designs of superconducting electrical transmission lines, in which a permeable matrix is used to cool the superconducting conductors, exist [96-98]. The most efficient cooling is achieved in the superconducting cable shown in Fig. 14. When the cooling liquid helium 1 is introduced under pressure into the inner perforated tube 2, part of it passes radially straight through the porous current-carrying element 3 and the electrical insulation 4, efficiently cooling them, after which it is removed through the gap 5 near the jacket 6. The alternating layers of conductor and electrical insulation can be used to transmit both single and multiphase current.

An important problem in developing different cryogenic electrical equipment is to provide for efficient cooling of the current input leads. The main method for solving this problem involves the utilization of the vapor of helium evaporating in a cryostat for longitudinal cooling of the permeable current lead. One of the first designs is the current input lead consisting of a collection of wire braids formed into a bunched conductor [99]. Structurally similar current input leads were proposed in [100-103]. A composite current input lead, whose resistive part consists of sintered metallic powder, reinforced by longitudinal elements with a continuous structure, for example, capillary tubes or a grid, is presented in [104]. In addition, some of the superconducting buses are placed in the porous resistive part, thereby making it possible to achieve a permanent connection. The available information on the problems of designing current input leads with permeable matrices for cryogenic equipment are generalized in [105].

Porous metals with high thermal conductivity are also used in the fabrication of heat exchangers with concentrated heat exchange (discrete type) in dilution refrigerators for obtaining superlow temperatures [106]. A maximally extended surface of a heat exchanger with a porous structure makes it possible to decrease the limiting thermal Kapitsa resistance, which gives rise to a temperature jump at the liquid—solid interface through which heat is transmitted. Such a heat exchanger consists of a block, containing two chambers, filled with a permeable material with high thermal conductivity and high specific surface area [107]. Usually, both the porous matrix and the block are made out of copper. When $He^3$ is dissolved in $He^4$, the temperature of the mixture obtained in the porous additive in one of the cells can be decreased to 0.011°K. As a result, the entire block as well as the $He^3$ flow flowing through the other cell are cooled. The results of analytical and experimental studies of such heat exchangers are presented, for example, in [108, 109].

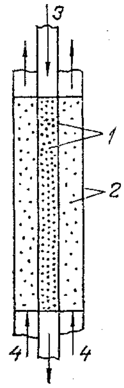



Fig. 13

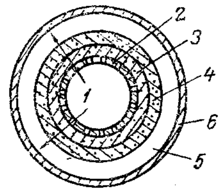



Fig. 14

Fig. 13. Joule—Thompson heat exchanger [91].

Fig. 14. Superconducting cable [97].

Heat Exchange and Resistance to Motion of the Heat-Transfer Agent in Porous Materials. Thermal and hydraulic calculations of different types of PHE require information on the thermal conductivity of porous materials as well as on the mechanism and quantitative characteristics of heat exchange and resistance accompanying the motion of single-phase flows and flows with a phase transformation of the heat-transfer agent in structurally different porous materials. Such data are now being actively accumulated.

Metals are the most suitable porous material for fabricating PHE. This is explained by their properties: high thermal conductivity, strength, heat resistance, resistance to corrosion; extended interstitial surface area; possibility of regeneration and fabrication of elements with arbitrary shape; suitable mechanical qualities for connecting them with one another and with structural elements; and the possibility of monitoring and changing many of the indicated properties over a wide range. The technology of fabrication of parts made of porous powders and fibrous and porous metals is described in detail in [110]. The results obtained thus far from studies of the motion of single-phase liquids and gases in such structures are also generalized therein. As a supplement to this reference, it is shown in [111], based on a careful analysis of published work, that the main reason for the undesirable appearance of the nonuniform and nonreproducible decrease of the flow of a drop liquid, purified of mechanical contaminants, accompanying its motion in permeable matrices with an average pore size exceeding one micron (obliteration), is the clogging-up of the pores by bubbles of gas dissolved in the liquid. In order to avoid this, the liquid must first be degassed. All known data on the thermal conductivity of porous metals are systematized in [112], while information on the intensity of interstitial volume convective heat exchange accompanying motion of a single-phase heat-transfer agent in them is analyzed in [7].

The study performed in [15] revealed that there is practically no information on the mechanism and quantitative characteristics of heat exchange and resistance accompanying motion of evaporating or condensing flows of heat-transfer agent in porous materials. Since then, data, which to a large extent fill in this omission, have been presented in [40, 41, 62-64, 113-115].

The main difficulties which at the present time hold up extensive practical utilization of heat-exchange systems with PHE are the very strict requirements on the purity of heat-transfer agents and the as yet undeveloped technology for obtaining them. For example, during prolonged operation, the mechanical contaminants must be continuously removed from the heat-transfer agent with filters, whose average pore size is three to four times smaller than the size of the pores in the PHE. There is hope, however, that the qualitatively new properties and considerable advantages, uncovered in this review, over other types of heat exchangers as well as the extremely wide range of application of PHE will increase interest in them enough to stimulate further development of research on their application.

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