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(71) Applicant: **Kiknadze, Gennady Iraklievich**
Moscow 123060 (RU)

(72) Inventor: **Kiknadze, Gennady Iraklievich**
Moscow 123060 (RU)

(74) Representative: **Smirnov, Alexander**
A. Smirnov & Co
Patent and Trademark Agency
Alises 10-69
1046 Riga (LV)

(54) FRICTION REDUCING SURFACE AND A MASS AND HEAT TRANSFER ENHANCING SURFACE

(57) The present invention relates to aerohydromechanics, power engineering, in-line processing, transport efficiency problems, to medicine and other spheres of scientific-and-technical activities and everyday engineering problems. The disclosed surface for reduction of friction with gaseous and liquid media or with their mixtures is **characterized in that** recesses (dimples) are made on a smooth surface with or without a protective layer, which are formed by second-order convex and concave surfaces conjugate on common tangents; in so doing, the conjugation of a dimple with initially smooth surface is accomplished using convex surfaces that form slopes, for which the initially smooth surface is tangent at points of conjugation; the concave surface, which forms the bottom part of dimple, is made smooth or with a fairing, the ratio of depth $\mathbf{h_c}$ of dimple to dimension $\mathbf{L_1}$ of dimple along the direction of flow is in the range $\mathbf{0.001 \leq h_c/L_1 \leq 0.1}$, and the ratio of transverse dimension $\mathbf{L_2}$ of dimple to longitudinal dimension $\mathbf{L_1}$ of dimple is in the range $\mathbf{0.25 \leq L_2/L_1 \leq 1}$, with the surface density **f** of dimples being in the range $\mathbf{0.05 \leq f \leq 0.5}$. Dimples of the configuration described above are made on the disclosed surface for enhancement of heat and mass transfer as well; in so doing, $\mathbf{0.1 \leq h_c/L_1 \leq 0.5}$, $\mathbf{0.25 \leq L_2/L_1} \leq 1$, and $\mathbf{0.1 \leq f \leq 0.8}$.

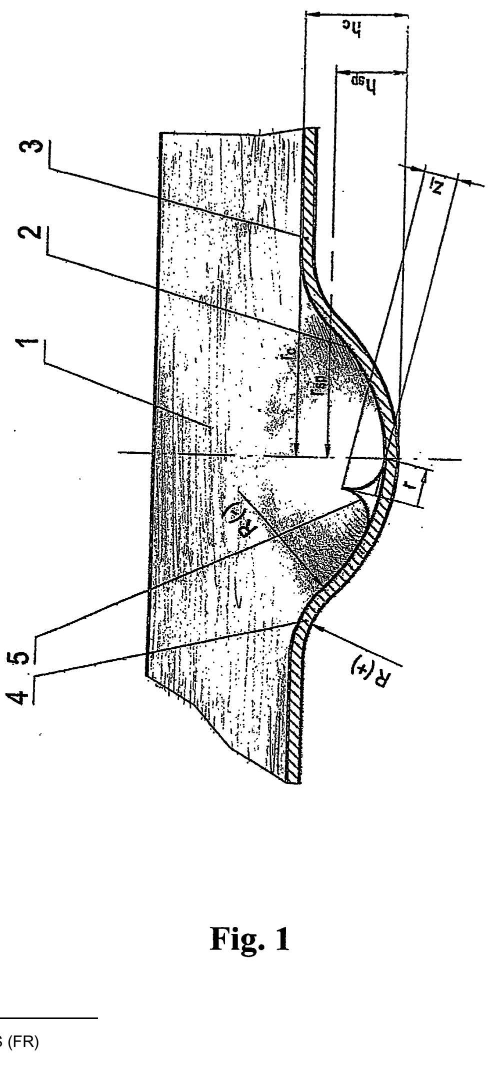

Fig. 1

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Description

Field of Invention

[0001] The present invention relates to aerohydrodynamics, power generation, and technologies involving flows of various media, to problems associated with raising the efficiency of transport, to medicine and other spheres of scientific-and-technical activities and engineering practice, in which the success of development and realization of continuous-production processes and equipment and their functional and technical-and-economic performance depend on the quality of flows of continuous medium and on the possibility of controlling the process of interaction between flow and surface by and large and, in particular, controlling the boundary layers of flows of gases and liquids and of their two-phase or multicomponent mixtures for the purpose of reducing aerohydrodynamic loss under conditions of relative motion of surface and continuous medium, reducing the cavitation damage to surfaces, and enhancing the exchange processes on these surfaces.

Prior Art

[0002] Closest of all to the surfaces disclosed herein is the technical solution under RU Patent 2,020,304 of September 30, 1994; this solution relates to surfaces subjected to flow, which are interfaces between a moving continuous medium (gases, liquids, and their two-phase or multicomponent mixtures) and a solid energy-exchange wall which is initially flat, cylindrical, conical, or of any other profile. The shape of surface disclosed in the cited patent, which is a three-dimensional concave or convex relief, makes it possible to enhance the heat transfer between the boundary surface and main flow under conditions of the rate of increase in aerohydrodynamic loss being not faster than the rate of increase in the level of enhancement, owing to formation of vortex structures on such reliefs. The ranges of sizes of the disclosed reliefs are related to the characteristics of boundary layers of flow; in so doing, in accordance with the disclosed solution, the surface subjected to flow contains distributed thereon three-dimensional concave or convex relief elements with rounded transition regions which conjugate these elements with initially smooth surface; any cross section of relief elements, which is parallel to the plane in which three nearest of their peaks lie, has the form of a smooth closed line.

[0003] The disadvantage of this prior art patent is that it is unidirectional and largely limited to solving problems of heat transfer; it does not offer optimal solutions for increasing critical heat loads in boiling processes, for reducing the cavitation wear of the surfaces, for reducing the rate deposition of impurities from the flows of energy carriers on the surfaces subjected to flow, for reducing the aerohydrodynamic drag and resistance between friction surfaces in friction pairs etc.; it is further disadvantageous in that no correlations are given between the curvatures of regions of disclosed surface which are opposite in sign on the concave and convex parts of the surface relief, such correlations being absolutely necessary for the design and construction of these parts.

[0004] The technical result of realization of the surface for reduction of friction and aerohydrodynamic drag of surfaces includes:

- the reduction of aerohydrodynamic drag of energy-exchange channels containing the disclosed curvilinear regions subjected to flows of continuous medium;
- the reduction of aerohydrodynamic drag of bodies with surfaces of the same shapes subjected to flow and moving in the air, by water, and by land at a velocity sufficient for self-organization of secondary tornado-like jets; and
- the reduction of friction between solid surfaces in gaseous or liquid media or in their mixtures (for example, in friction pairs placed in these media) owing to imparting curvilinear shapes to the friction surfaces to form between these surfaces a vortex boundary layer from the surrounding medium, which serves the function of vortex "bearings".

[0005] The technical result of realization of the surface for enhancement of heat and mass transfer includes:

- the increase in the rate of heat and mass transfer between the flows of heat-transfer agents and energy-exchange surfaces which contain the disclosed curvilinear regions of double curvature, on which tornado-like jets are formed; the latter jets cause the acceleration of exchange processes in gases, liquids, and their mixtures, with the level of hydraulic loss lagging behind the degree of enhancement;
- the increase in critical heat loads on energy-exchange surfaces cooled by liquid heat-transfer agents owing to imparting to these surfaces the disclosed curvilinear shapes which cause a variation of the kinetics of mass transfer in the process of phase transformation in liquid medium;
- the prevention of cavitation damage to the surfaces subjected to flows of liquid owing to imparting to these surface the shapes involving curvilinear regions and to developing conditions for the generation on these surfaces of secondary tornado-like jets which suppress the growth on such surfaces of vapor-gas formations (bubbles) and evacuate the nuclei of such formations beyond the surface subjected to flow; and

- the reduction of adsorption of contaminants and foreign matter and of growth of deposits from the moving medium on energy-exchange surfaces of the shapes disclosed above owing to the carry-over to the main flow of the impurities from these surfaces, for example, in the form of ashes or substances undergoing phase transformations, including the products of incomplete combustion of fuel, salt deposits, and other adsorbable substances including ice and snow.

Disclosure of the Invention

[0006] The technical result is attained owing to the fact that the surface for reduction of friction with gaseous and liquid media or their mixtures is **characterized in that** recesses of double curvature (dimples) are provided on a smooth surface with or without a protective layer, which are formed by second-order convex and concave surfaces conjugate on common tangents; in so doing, the conjugation of dimples with initially smooth surface is accomplished using convex shapes of surfaces forming slopes, for which the initially smooth surface is tangent at points of conjugation; the concave surface, which forms the bottom part of dimple, is made smooth or with a fairing, the ratios of depths $\mathbf{h_c}$ of dimples to dimensions $\mathbf{L_1}$ of dimples along the direction of flow are found in the range

$$0.001 \le h_c/L_1 \le 0.1, \qquad (A)$$

and the ratio of transverse dimension $\mathbf{L_2}$ of dimple to longitudinal dimension $\mathbf{L_1}$ of dimple is found in the range

$$0.25 \le L_2/L_1 \le 1, \qquad (B)$$

with the surface density **f** of dimples found in the range

$$0.05 \le f \le 0.5. \qquad (C)$$

[0007] The dimples may be made with the longitudinal and/or transverse dimensions varying along the flow.

[0008] The dimples may be made either mechanically, or electrochemically, or by applying a protective layer to the surface with subsequent polymerization of this layer, or by laser processing of the surface, or by employing combinations of these methods.

[0009] The slopes may be formed by a toroidal surface.

[0010] The slopes may be formed by a hyperbolic surface.

[0011] The slopes may be formed by an elliptic surface.

[0012] The surface with curvature radius $\mathbf{R_{(-)}}$ has toroidal slopes; on this surface, the radius $\mathbf{r_{sp}}$ of the concave spherical part of dimple is defined by the relation

$$r_{sp} = (2h_{sp}R_{(-)} - h_{sp}^2)^{0.5}, \qquad (D)$$

where $\mathbf{h_{sp}}$ is the depth of concave spherical part of dimple; in so doing, the curvature radius of the convex part of dimple $\mathbf{R_{(+)}}$ is related to its depth $\mathbf{h_c}$ and radius $\mathbf{r_c}$ by the relation

$$R_{(+)} = [(r_c - r_{sp})^2 + (h_c - h_{sp})^2]/2(h_c - h_{sp}). \qquad (E)$$

[0013] The surface is provided with a fairing which has the shape of a body of revolution with curvilinear base in the form of a part of the concave surface of dimple; in so doing, the projection of fairing onto any plane, in which the symmetry axis of these fairings and the tangent to the point of intersection of their symmetry axis with the concave surface of dimple lie, is defined by the relation

$$r_i^2 h_i = const, \qquad (F)$$

where $\mathbf{r_i}$ is the radius of fairing and $\mathbf{h_i}$ is its height, which assume their values in the case of selected curvature radius $\mathbf{R_{(-)}}$ in the ranges

$$10^{-5} \leq h_i/r_i \leq 1. \qquad (G)$$

[0014] The technical result is further attained owing to the fact that the surface for enhancement of convective heat and mass transfer with gaseous and liquid media or their mixtures is **characterized in that** recesses (dimples) are provided on a smooth surface, which are formed by second-order convex and concave surfaces conjugate on common tangents; in so doing, the conjugation of dimples with initially smooth surface is accomplished using convex surfaces forming slopes for which the initially smooth surface is tangent at points of conjugation; the concave surface, which forms the bottom part of dimple, is made smooth or with a fairing, the ratio of depth $\mathbf{h_c}$ of dimple to dimension $\mathbf{L_1}$ of dimples along the direction of flow is found in the range

$$0.05 \leq h_c/L_1 \leq 0.5, \qquad (H)$$

and the ratio of transverse dimension $\mathbf{L_2}$ of dimple to its longitudinal dimension $\mathbf{L_1}$ is found in the range

$$0.25 \leq L_2/L_1 \leq 1, \qquad (I)$$

with the surface density **f** of dimples found in the range

$$0.1 \leq f \leq 0.8. \qquad (J)$$

[0015] The dimples may be made with the longitudinal and/or transverse dimensions varying along the flow.

[0016] The dimples may be made either mechanically, or electrochemically, or by laser processing of the surface, or by shaping and polymerization of a surface protective layer, or by employing various combinations of these methods.

[0017] The slopes may be formed by a toroidal surface.

[0018] The slopes may be formed by a hyperbolic surface.

[0019] The slopes may be formed by an elliptic surface.

[0020] The surface of dimples with curvature radius $\mathbf{R_{(-)}}$ has toroidal slopes and concave spherical part, the radius $\mathbf{r_{sp}}$ of which is defined by the relation

$$R_{sp} = (2h_{sp}R(-) - h_{sp}^2)^{0.5}, \qquad (D)$$

where $\mathbf{h_{sp}}$ is the depth of concave spherical part of dimple; in so doing, the curvature radius $\mathbf{R_{(+)}}$ of the convex part of dimple is related to the depth $\mathbf{h_c}$ and radius $\mathbf{r_c}$ of dimple by the relation

$$R_{(+)} = [(r_c - r_{sp})^2 + (h_c - h_{sp})^2]/2(h_c - h_{sp}). \qquad (E)$$

[0021] The surface may be provided with a fairing which has the shape of a body of revolution with curvilinear base in the form of a part of the concave surface of dimple; in so doing, the projection of fairing onto any plane, in which the symmetry axis of these fairings and the tangent to the point of intersection of their symmetry axis with the concave surface of dimple lie, is defined by the relation

$$r_i^2 h_i = const, \qquad (F)$$

where $\mathbf{r_i}$ is the radius of fairing and $\mathbf{h_i}$ is its height, which assume their values in the case of selected curvature radius $\mathbf{R_{(-)}}$ in the ranges

$$10^{-5} \leq h_i/r_i \leq 1. \qquad (G)$$

[0022] The dimples on the surface of a heat-transfer plate may be arranged in the staggered or in-line order, and the size of dimples and their depth may be increased or reduced in the direction of flow along the plate.

[0023] Dimples of smaller longitudinal and transverse dimensions and smaller depth may be located around the main dimples.

[0024] Projections reciprocal to recesses are provided on the other side of the surface.

[0025] Ribs oriented along the plate in the direction of flow are provided on the other side of the plate surface.

[0026] Dimples may be arranged on the other side of the plate symmetrically or asymmetrically with respect to the dimples on the main side of the plate.

[0027] The additional surface of the plate, which contains dimples, is located relative to the main surface with the formation of a heat-transfer channel; in so doing, the surfaces of the main and additional plates with dimples are facing each other and are located in parallel owing to spacer elements in the form of projections of spherical, conical, cylindrical, or other shapes.

[0028] The surface of a pipe, in which the dimples along the pipe and across the pipe are arranged in the staggered or in-line order.

[0029] The size of dimples and their depth are increased or reduced in the direction of flow along or across the pipe.

[0030] Projections with second-order surfaces are located on the inner surface of the pipe.

[0031] Dimples may be located on the outer surface of the pipe, and projections may be located on its inner surface.

[0032] Longitudinal ribs with dimples may be located on the inner surface of the pipe.

[0033] Transverse ribs with dimples may be located on the inner surface of the pipe.

[0034] A curved twisted tape with dimples may be located within the pipe.

[0035] Dimples may be located on the inner surface of the pipe symmetrically or asymmetrically with respect to the dimples on the outer surface.

[0036] The longitudinal and transverse dimensions and the depth of dimples made on the inner surface of the pipe are increased or reduced in the direction of flow.

[0037] Dimples are located on the inner surface of the pipe, and a curved twisted tape with dimples is placed within the pipe.

[0038] The inner surface of the pipe is made without dimples, and a twisted tape with dimples is placed within the pipe.

Brief Description of the Drawings

[0039]

Figure 1 gives a fragment of a surface subjected to flow, which contains one dimple; a combination of such dimples forms the surface subjected to flow and realizes the disclosed method.

Figure 2 gives the surface of a dimple with a fairing in the form of double dimple made on the surface using one-inside-the-other technique.

Figure 3 gives the surface of a dimple with fairings in the form of a plurality of small dimples on said surface.

Figure 4 gives the surface of a dimple with a fairing in the form of dimple.

Figure 5 gives the scheme of lines of flow of the medium involved in the formation of a secondary swirling structure in a dimple on the surface at low velocities of relative motion of the surface and medium.

Figure 6 shows the same process visualized by photography.

Figure 7 gives the visualization of the process of compression of vortex into a dimple and of suction into the vortex of the medium from the wall layer of flow past the surface with dimples.

Figure 8 gives the visualization of the process of turbulent flow past a relief of three-dimensional dimples.

Figure 9 gives the result of measurement of the thickness of boundary layer on a surface with dimple: **1** - smooth surface, **2** - surface with dimple; the maximum on curve **2** corresponds to the coordinates of the zone of efflux of tornado-like jet from the dimple.

Figure 10 is a three-dimensional pressure profile measured on the surface of a dimple. The lower pressure on the periphery corresponds to suction of the medium from the boundary layer into the dimple, and the zone of higher pressure (dome) in the central part of the dimple defines the pressure at the end face of self-organizing tornado-like jet, which provides for the efflux into the main flow of the mass of medium sucked-in by tornado-like vortex; the zone of location of pressure maximum in the dimple coincides with the zone of location of maximum of boundary layer thickness above the dimple in Fig. 9 and with the coordinates of location of fairing constructed from Görtler surface vortexes in Fig. 11, which is indicative of "extraction" of the tornado-like jet from the dimple by the main flow.

Figure 11 is a photograph of visualization of the process of the main flow of liquid (water) past a dimple of double curvature on the boundary surface, which demonstrates the variation of the structure of boundary layer due to formation of Görtler surface vortexes which have the form of "braids" indicated by arrows. The braids "interwoven" into the boundary layer replace a part of shear stresses in the Prandtl attachment layer by the stresses of rolling of the "braids" on the surface, which is a necessary condition for self-organization of tornado-like vortexes and the basis for the reduction of friction drag on the disclosed surfaces. Recorded in the photograph is a fairing constructed from Görtler surface vortexes by secondary swirling flow in a dimple of selected shape. It follows from the photograph that the trunk of tornado-like vortex is filled with "braids", i.e., Görtler vortexes, sucked off by the tornado-like vortex together with the mass of boundary layer, which provides for its high intensity when such surfaces are employed for heat and mass transfer.

Figure 12 gives the surface of a heat-transfer plate with longitudinal ribs.

Figure 13 shows the arrangement of plates with the formation of heat-transfer channel.

Figure 14 gives the surface of a heat-transfer pipe.

Figure 15 gives the surface of a pipe with longitudinal ribs.

Figure 16 gives the surface of a pipe with transverse ribs therein.

Alternative Embodiments of the Invention

[0040] The claimed surfaces subjected to flow intended for reduction of friction drag **(TLJS-DR)** and for enhancement of heat and mass transfer **(TLJS-HMT)** provide necessary and sufficient conditions for the development of flows of new class, which offer the possibilities for raising the functional and technical-and-economic efficiency of actually the entire park of processes, apparatuses, and equipment involving flows of various media, and transportation units, which are employed in human research and practical activities.

[0041] The **TLJS-DR** (Tornado-Like Jet Surface-Drag Reduction) surfaces are used for:

- reducing the aerohydrodynamic drag of various bodies in the state of relative motion with continuous medium, including aircraft, automobiles, trains, river-going, sea-going, and ocean-going vessels, yachts, and other means of transportation; and
- reducing the loss of pressure in pressure channels employed for conveyance of gases, liquids, and/or their mixtures.

[0042] The **TLJS-HMT** (Tornado-Like Jet Surface-Heat and Mass Transfer) surfaces are used for:

- raising the functional efficiency of energy-exchange processes and equipment involving flows of various media, including heat and mass transfer equipment;
- reducing the cavitation wear of the surfaces of hydraulic turbomachines, propellers of marine propulsion units, hydraulic pumps, and other units subject to the effect of cavitation;
- heating and cooling of magneto-thermal units for conversion of low-potential heat fluxes to mechanical and electrical energy; and
- raising the functional efficiency of other energy-exchange processes and equipment involving flows of various media.

[0043] The spheres of application of the claimed invention define the diversity of its alternative embodiments. However, in formulating the concrete problem, common to all possible embodiments are:

- the quantitative determination of the main functional characteristics of processes or equipment, which are to be improved;
- the choice of shapes and sizes of reliefs, based on the results of analysis of parameters of the problems; and
- the choice of technology of applying reliefs onto the surfaces.

Given by way of example is a relief subjected to a flow of continuous medium, the convex part of whose elements is a segment of a torus of circular cross section, and the concave part - a segment of any second-order surface, for example, spherical. The convex part of the curvilinear surface of the dimples, i.e., slopes, which is external with respect to the geometric center of the dimples, is characterized by the curvature radius $\mathbf{R_{(+)}}$, and the other, or internal, part of this surface, for example, a segment of a sphere, which is located around the geometric center of curvilinear region, is characterized by the curvature radius $\mathbf{P_{(-)}}$; in so doing, the curvature and shape of the convex toroidal part is defined by the relation

$$R_{(+)} = [(r_c - r_{sp})^2 + (h_c - h_{sp})^2]/2(h_c - h_{sp}), \qquad \text{(E)}$$

and the shape of the concave part is defined by the relation

$$R_{(-)} = (r_{sp}^2 + h_{sp}^2)/2h_{sp}; \qquad \text{(D)}$$

in so doing, the ratio of the curvature radii of the convex and concave parts of dimple is found from the respective relation of conditions **(Q)** (see below) in the range

$$10^{-6} \leq R_{(+)}/R_{(-)} \leq 1;$$

given the validity of conditions which define the limit of stability of the boundary layer of flow on this surface with respect to the emergence of Görtler surface vortexes, we have

$$[\delta_2(x)/R_{(-)}]^{0.5} U_\infty \delta_2(x)/\nu \geq 7; \quad [\delta_2(x)/R_{(+)}]^{0.5} U_\infty \delta_2(x)/\nu \geq 7, \qquad \text{(K)}$$

where $\mathbf{U}_\infty$ is the velocity of flow impinging onto the curvilinear surface with curvature radii $\mathbf{R}_{(+)}$ and $\mathbf{R}_{(-)}$, $\delta_2(\mathbf{x})$ is the momentum thickness in the boundary layer formed by the flow of medium on the surface subjected to flow, and ν is the velocity of impinging medium; in so doing, it is taken into account that the values of critical velocity $\mathbf{U}_\infty$ for isothermal flow are lower for the concave regions of dimples compared to the value of critical velocity for convex regions.

[0044] A curvilinear relief is applied onto the surface subjected to flow (Fig. 1) in the form of individual dimples **1** of double curvature, each dimple consisting of a concave part **2** of the inner curvilinear surface of dimple, which has a selected curvilinear shape in the form of a second-order surface without acute angles thereon including, for example, a spherical shape with curvature radius $\mathbf{R}_{(-)}$ or an elliptic shape with curvature radii $\mathbf{R}_{\mathbf{min(-)}}$ and $\mathbf{R}_{\mathbf{max(-)}}$, conjugated with an initially smooth surface **3** by convex curvilinear slopes of toroidal shape of round, elliptic, parabolic, or hyperbolic cross sections with curvature radii for which the initially smooth surface is tangent at points of conjugation, and the surfaces of concave and convex shapes have common tangents at points of conjugation. The quantities $\mathbf{R}_{\mathbf{min(-)}}$, $\mathbf{R}_{\mathbf{max(-)}}$, $\mathbf{R}_{\mathbf{min(+)}}$, and $\mathbf{R}_{\mathbf{max(+)}}$ are determined, as is described above, from relations **(Q):**

$$\begin{gathered} 10^{-6} \leq R_{(+)}/R_{(-)} \leq 1; \quad 10^{-6} \leq R_{max(+)}/R_{(-)} \leq 1; \quad 10^{-6} \leq R_{min(+)}/R_{(-)}; \\ 10^{-6} \leq R_{min(+)}/R_{min(-)} \leq 1; \quad 10^{-6} \leq R_{max(+)}/R_{min(-)} \leq 1; \qquad \text{(Q)} \\ 10^{-6} \leq R_{max(+)}/R_{max(-)} \leq 1; \quad 10^{-6} \leq R_{min(+)}/R_{max(-)}. \end{gathered}$$

[0045] The surface for reduction of friction with gaseous and liquid media or their mixtures is characterized in that recesses (dimples) **1** are provided on a smooth surface with a protective layer in the form of polymer material applied onto this surface or without such layer; said dimples are formed by second-order convex **4** and concave **2** surfaces conjugate on common tangents; in so doing, the conjugation of dimples with an initially smooth surface **3** is accomplished using convex surfaces forming slopes, for which the initially smooth surface is tangent at points of conjugation; the concave surface, which forms the bottom part of dimple, is made smooth or with a fairing **5,** the ratio of depth $\mathbf{h_c}$ of dimple to dimension $\mathbf{L_1}$ of dimple along the direction of flow is found in the range:

$$0.001 \leq h_c/L_1 \leq 0.1, \qquad \text{(H)}$$

and the ratio of transverse dimension $\mathbf{L_2}$ of dimple to longitudinal dimension $\mathbf{L_1}$ of dimple is found in the range

$$0.25 \le L_2/L_1 \le 1, \qquad (B)$$

with the surface density **f** of dimples being found in the range

$$0.1 \le f \le 0.5. \qquad (C)$$

[0046] The dimples on the surface may be made with their longitudinal and transverse dimensions varying along the flow.

[0047] The dimples may be made either mechanically, or electrochemically, or by shaping and polymerization of a protective layer, or by laser processing of the surface, or by employing combinations of these methods.

[0048] The slopes may be formed either by a toroidal hyperbolic surface, or by a toroidal parabolic surface, or by a toroidal elliptic surface, or by a toroidal spherical surface.

[0049] In the case where the slopes have the shape of a sharp edge, the slope cross section is a circle bounding the dimple and the concave spherical part of this dimple has the curvature $\mathbf{1/R_{(-)}}$, the dimple radius $\mathbf{r_{sp}}$ is defined by the relation

$$r_{sp} = (2h_{sp}R_{(-)} - h_{sp}^2)^{0.5}, \qquad (D)$$

where $\mathbf{h_{sp}}$ is the depth of concave spherical part of dimple.

[0050] In the case of toroidal spherical shape of the slopes, the cross section of which is a circle of radius $\mathbf{R_{(+)}}$ and the central concave part has a spherical shape, the radius $\mathbf{r_c}$ is related to the dimple dimensions by the relation

$$R_{(+)} = [(r_c - r_{sp})^2 + (h_c - h_{sp})^2]/2(h_c - h_{sp}). \qquad (E)$$

[0051] The fairings on such surfaces have the shape of a body of revolution, the curvilinear base of which is provided by parts of the concave surface of dimple, and the projection of fairing onto any plane, in which the symmetry axis of the fairing and the tangent to the point of intersection of this axis with the concave surface of dimple lie, is defined by the relation:

$$r_i^2 h_i = \text{const}, \qquad (F)$$

where $\mathbf{r_i}$ is the radius of fairing and $\mathbf{h_i}$ is its height, which assume their values in the case of selected curvature radius $\mathbf{R_{(-)}}$ in the ranges

$$10^{-5} \le h_i/r_i \le 1. \qquad (G)$$

[0052] The fairings may be made in the form of dimples, double dimples, or dimples located on the surface of the main dimple (Figs. 2-4).

[0053] The surface for enhancement of convective heat and mass transfer with gaseous and liquid media or their mixtures is **characterized in that** recesses (dimples) **1** are provided on a smooth surface; said dimples are formed by second-order convex **4** and concave **2** surfaces conjugate on common tangents; in so doing, the conjugation of dimples with an initially smooth surface **3** is accomplished using convex surfaces forming slopes, for which the initially smooth surface is tangent at points of conjugation; the concave surface, which forms the bottom part of dimple, is made smooth or with a fairing **5,** and the ratio of depth $\mathbf{h_c}$ of dimple to dimension $\mathbf{L_1}$ of dimple along the direction of flow is found in the range:

$$0.1 \leq h_c/L_1 \leq 0.5, \qquad \text{(H)}$$

and the ratio of transverse dimension of dimple to longitudinal dimension of dimple is found in the range

$$0.25 \leq L_2/L_1 \leq 1, \qquad \text{(I)}$$

with the surface density **f** of dimples being found in the range

$$0.1 \leq f \leq 0.8. \qquad \text{(J)}$$

[0054] The dimples on the surface may be made with the longitudinal and/or transverse dimensions varying along the flow.

[0055] The dimples may be made either mechanically, or electrochemically, or by shaping and polymerization of a protective layer, or by laser processing of the surface, or by employing combinations of these methods.

[0056] The slopes may be formed either by a toroidal hyperbolic surface, or by a toroidal parabolic surface, or by a toroidal elliptic surface, or by a toroidal spherical surface.

[0057] The radius $\mathbf{r_{sp}}$ of the concave spherical part of curvilinear surface of the dimple has the curvature radius $\mathbf{R_{(-)}}$ and is defined by the relation

$$r_{sp} = (2h_{sp}R_{(-)} - h_{sp}^2)^{0.5}, \qquad \text{(D)}$$

where $\mathbf{h_{sp}}$ is the depth of concave spherical part of dimple; in so doing, the curvature radius $\mathbf{R_{(+)}}$ of the convex part of dimple is related to the depth $\mathbf{h_c}$ and radius $\mathbf{r_c}$ of dimple by the relation

$$R_{(+)} = [(r_c - r_{sp})^2 + (h_c - h_{sp})^2]/2(h_c - h_{sp}). \qquad \text{(E)}$$

[0058] In the case of toroidal spherical shape of the slopes, the cross section of which is a circle of radius $\mathbf{R_{(+)}}$, and the central concave part has a spherical shape, the radius $\mathbf{r_c}$ is related to the dimple dimensions by the relation

$$R_{(+)} = [(r_c - r_{sp})^2 + (h_c - h_{sp})^2]/2(h_c - h_{sp}). \qquad \text{(E)}$$

[0059] The fairings **5** may have the shape of a body of revolution with the curvilinear base in the form of a part of the concave surface of dimple; in so doing, the projection of fairing onto any plane, in which the symmetry axis of the fairing and the tangent to the point of intersection of this symmetry axis with the concave surface of dimple lie, is defined by the relation

$$r_i^2 h_i = \text{const}, \qquad \text{(F)}$$

where $\mathbf{r_i}$ is the radius of fairing and $\mathbf{h_i}$ is its height, which assume their values in the case of selected curvature radius $\mathbf{R_{(-)}}$ in the ranges

$$10^{-5} \leq h_i/r_i \leq 1. \qquad \text{(G)}$$

[0060] The dimples **1** on the surface of heat-transfer plate **6** may be arranged in the staggered or in-line order.

[0061] The size of dimples and their depth may be increased or decreased in the direction of flow along the plate.

[0062] Dimples of smaller dimensions and smaller depth may be symmetrically located around dimples of larger size.

Projections reciprocal to recesses may be located on the other side of plate **6.** Ribs **7** oriented along the plate in the direction of flow may be located on the other side of the plate.

[0063] Dimples on the other side of the plate may be arranged symmetrically or asymmetrically with respect to the dimples on the main side.

[0064] The additional surface of plate **12** may be located relative to the main surface of plate **6** with the formation of a heat-transfer channel; in so doing, the surfaces of the main and additional plates with dimples are facing each other and are located in parallel owing to spacer elements **8** in the form of projections of spherical, conical, cylindrical, or other shapes.

[0065] The dimples on the surface of pipe **9** may be arranged in the staggered or in-line order along the pipe and across the pipe.

[0066] The size of dimples and their depth may be increase or reduced in the direction of flow or across the flow.

[0067] Spherical projections (not shown in the drawing), longitudinal ribs **10** or transverse ribs **11,** or a twisted tape **13** with dimples may be located on the inner surface of pipe **9.**

[0068] Dimples on the inner surface of the pipe may be located symmetrically or asymmetrically with respect to the dimples on the outer surface.

[0069] Dimples may be located on the inner surface of the pipe, the size and depth of which are increased or reduced in the direction of flow along the pipe.

[0070] Dimples may be located on the inner surface of the pipe, and a curved twisted tape with dimples is placed within the pipe.

[0071] The curvature radii of relief, the radii of traces of dimples on the surface being shaped, the depths of relief, and the parameters of fairing in the case where the latter is located in dimples are determined by the foregoing relations and ranges lettered **(A), (B), (C), (D), (E), (F), (G), (H), (I), (J), (K), and (Q).** For example, a channel or a body is selected, the functioning of which is associated with the relative motion of their surface and continuous medium. The basic aerohydrodynamic characteristics are determined of flows of gases, liquids, or their two-phase mixtures in the case of formation of disclosed flow with built-in tornado-like jets in channels, or analogous characteristics for a body moving in the above-said media. The ranges are established of possible variation of the thermal properties of working medium, the characteristic dimension is determined which defines the conditions of relative motion of continuous medium and surface, the Reynolds number **(Re)** is calculated and possible ranges of variation of its values are determined. The results of analysis are used for varying the values of **Re** for the purpose of fitting possible values of radii (dimensions) of the trace of dimples on the surface being shaped with a view to accommodating their integral-valued amounts along and across the flow and in the direction of motion of the body. In accordance with the problem to be solved by forming a flow with built-in tornado-like jets, the shape of dimples, their curvature radii, and the density of relief **f** are selected using the ranges of their variation lettered **(A), (B), (C), (E),** and **(Q).** In view of the fact that

$$\mathbf{f = \pi r_c^2/t_1 t_2,}$$

$\mathbf{t_1}$ and $\mathbf{t_2}$, i.e., the transverse and longitudinal spacings between dimples on an initially smooth surface, respectively, are fitted such that, given the optimal closeness to the preassigned value of **f,** the number of dimples along and across the surface being shaped would be integral-valued. After fitting the values of **f,** $\mathbf{t_1}$, and $\mathbf{t_2}$, the radius of trace of dimple on the surface is determined from the relation

$$\mathbf{r_c = (f t_1 t_2/\pi)^{0.5}.}$$

[0072] The range of values of $\mathbf{h_c/r_c}$, which is lettered **(A)** or **(H)** depending on the problem being solved, is used to calculate the depth $\mathbf{h_c}$ of the relief being constructed. In accordance with the selected curvature radii, density of dimples, sizes of traces, and depths of relief, the surface shaping technology is developed, the appropriate tools are prepared, and channels or supporting surfaces are manufactured.

[0073] The disclosed invention is based on the phenomenon discovered by the authors approximately 30 years ago, namely, the phenomenon of self-organization of quasi-potential tornado-like jets of gases, liquids, and/or their two-phase mixtures in recesses with second-order boundary surface and of rearrangement of the boundary layer on such surfaces under conditions of flows of said media past surfaces with recesses. This phenomenon was experimentally investigated, theoretically described, visualized, and tested under laboratory and full-scale conditions in a wide range of velocities and pressures, including the ranges of subsonic and supersonic velocities of air flows, and at critical and supercritical parameters of liquid heat-transfer agents.

[0074] The velocity and pressure fields in the discovered tornado-like jets are described by exact solutions of basic unsteady-state equations of hydrodynamics of viscous liquid (Navier-Stokes and continuity equations); the knowledge and experience, which were gained from the investigation and development of shaped surfaces, provided for finding the necessary and sufficient conditions for their formation, which is the subject of invention.

[0075] We gave the discovered jets and the process of their self-organization the names of **Tornado-Like Jet (TLJ)** and **Tornado-Like Jet Self-Organization (TLJSOP),** respectively; the surface on which the **TLJSOP** arises received the name of **TLJ-Surface (TLJS),** and the technologies utilizing such jets- **Tornado-Like Jet Technologies (TLJT).**

[0076] The results of numerous aerohydrodynamic and thermophysical experiments and of development and testing of prototypes and full-scale samples of relevant equipment and transportation units highly reliably indicate the reduction, owing to the use of **TLJT,** of friction drag on surfaces subjected to flow (see Figs. 8-10) and the enhancement of heat and mass transfer with hydraulic loss lagging behind the rate of this enhancement. In so doing, **TLJs** are formed in flows of gases, liquids, and their mixtures under conditions of practical importance of motion of continuous medium, which correspond to Reynolds number values of $\mathbf{Re} \geq \mathbf{5\ 10^2}$ calculated by geometric dimensions of the selected curvilinear relief, for example, by the diameter of symmetric dimples $\mathbf{d_c}$ or by their depth $\mathbf{h_c}$, which define the characteristics of secondary flow in the dimple.

[0077] The visualization of the process of formation of **TLJ** flows, as is given in the photographs in Figs. 5, 6, 7, and 8, enables one to see a radially divergent tornado-like jet drawn out from a dimple and built into an incoming flow; the longitudinal dimension of said tornado-like jet significantly exceeds its transverse dimension, and its spatial orientation in the flow points to the interfacing of one end of the jet with the curvilinear surface of the dimple, from which the jet sucks off the mass of continuous medium and flows out, and to the interfacing of the other end of the jet either with the curvilinear surface of the neighboring dimple located downstream, into which the tornado-like jet injects the mass of continuous medium sucked off from the former dimple, or with the respective zone of the main flow, which receives this mass, where the pressures and velocities of swirling jet join with the pressure and velocity of the flow.

[0078] It has been experimentally proved that tornado-like jets **(TLJ)** are self-organized on **TLJS** in dimples of special relief described below under conditions of relative motion of formed boundary surface and viscous continuous medium.

[0079] In so doing, the flow of medium or motion of bodies in the medium are characterized by Reynolds number values of $\mathbf{Re} \geq \mathbf{500}$ calculated by the size of dimples along the flow or in the directions of motion of the body; the selected shapes and dimensions of curvature of the convex and concave parts of relief initiate the impact, which is made on the flow by the field of forces absent in the case of flow past smooth surfaces, and the restructuring of the boundary layer of flow from shear layer in its initially smooth regions to three-dimensional vortex boundary layer on curvilinear surface consisting of surface vortexes such as Görtler vortexes or their ensembles.

[0080] The dimensionless relation **(K),** which involves the radius vector of surface curvature $\mathbf{R_{(+)}}$ or $\mathbf{R_{(-)}}$ (hereinafter referred to as radius), the viscosity of the medium ν, the velocity vector of unperturbed flow of continuous medium $\mathbf{U_\infty}$, and the momentum thickness $\delta_2(x)$ in the boundary layer of flow, is the criterion of stability with respect to emergence in the boundary layer of surface vortexes such as Görtler vortexes and points to the possibility of controlling the vortex boundary layer with the aid of the parameters of flow of continuous medium and the curvature radius of the surface subjected to flow. In a boundary layer of this type, which we refer to as **Finely Divided Moving Boundary Layer (FDMBL),** the pattern of friction stresses on curvilinear surfaces varies from shear stress to that defined by rolling friction. This property is one of the main advantages of the disclosed **TLJS,** the necessary condition for self-organization of **TLJ,** and one of the main reasons for reduction of friction drag in the case of flow past concave curvilinear reliefs. The presence of three-dimensional vortex boundary layer **(FDMBL)** provides conditions for conjugation of **TLJ** with the concave surface of dimples without resulting in dissipation of energy in rotational flow, which is known to destroy vortex systems formed on smooth surfaces where the Prandtl "attachment" conditions are valid, which require that the velocity of flow be equated to the velocity of surface subjected to flow, and no **FDMBL** is present. In the case of three-dimensional vortex flow, this condition is met through the intermediary of surface vortexes arising at the ends of the tornado-like jet being formed which "straddles" these surface structures (see Fig. 11). Surface **FDMBL** vortexes move on the curvilinear relief like a roller or a wheel and exhibit at points of contact with the surface or on the line of conjugation therewith a velocity which, as was stated above, is equal to the surface velocity; in the case of **TLJS** of stationary channels or plates the velocity is equal to zero, and in the case of **TLJS** moving at preassigned velocity $\mathbf{U_\infty}$

- equal to this latter velocity, which corresponds to the "attachment" conditions. The remaining points of the surface of these vortexes move at other-than-zero velocities which correspond to the velocity of tornado-like swirling flow generating these vortexes and joined with them (see the photograph in Fig. 11). In the case of **TLJ,** the ensemble of vortexes which make up the **FDMBL** is formed by the swirling flow proper at the ends of the jet on curvilinear surface and is, figuratively speaking, utilized by tornado-like vortex for rolling on the vortexes of said ensemble over the surface of dimple. This explains the mechanism of reduction of dissipation of energy in self-organizing tornado-like jets. In addition to this process, the boundary layer on curvilinear surface is structured into large formations consisting of vortexes in the form of macroscopic "braids" visualized in the photograph of Fig. 11. As was observed above, the self-organizing vortex jets suck off the boundary layer consisting of such "braids" from the dimple surface and from the smooth part of relief surrounding the dimple and transfer the sucked-off mass to the main flow. Each one of such "braids" significantly exceeds in mass and volume the turbulent moles which define the efficiency of the mechanisms of heat and mass transfer in turbulent flows; this explains the advantages of **TLJS** compared to other shapes of reliefs which are traditionally employed for enhancement of heat and mass transfer.

[0081] The three-dimensional relief of dimples and the **TLJs** which are self-organized therein transform the shaped surface subjected to flow into:

- a system of sink of the working continuous medium from the boundary layer of flow into dimples, with the sink provided by the acceleration of flow on the convex slopes of relief, which causes the decrease in static pressure in this zone of jet formation, and the rate of sink is defined by the selected shape and curvatures of the boundary surface; and
- a system of sources of tornado-like jets, which flow out and suck from the dimples the surface vortexes and vorticity from the **FDMBL** formed on the region of curvilinear surface, and transfer to the main flow (as was stated above) masses of continuous medium flowing down into the dimples in the form of large formations, i.e., macroscopic "braids" visualized in the photograph of Fig. 11.

[0082] As was observed above, the mechanisms of these processes cause the reduction of friction stress on shaped surfaces and enhance the processes of heat and mass transfer thereon; in so doing, the regularities of these processes on surfaces with convexo-concave reliefs significantly differ from the regularities describing the processes of friction and exchange under conditions of flow of conventionally smooth and rough surfaces which "generate" turbulence in the wall layers of flow, for example, owing to natural or artificial roughness.

[0083] The tornado-like jets are formed, as was observed above, in dimples on the "surface-moving medium" interface under the effect of forces caused by the shapes of selected relief, including:

- braking forces arising under the effect of dynamic pressure of flow on downstream slopes of dimples, which cause (to the extent of the square of velocity of incoming flow $\mathbf{U_{in}^2}$) an elastic reflection of flow from the concave slopes and the emergence in the concave part of dimples of a return flow moving in the bottom part of dimple at a velocity differing little from $\mathbf{U_{in}}$. (**U** is the velocity of flow flowing into a dimple, which is measured at the boundary of conjugation of the dimple with initially smooth surface at a point 0.1 mm above said surface and in the return flow within the dimple at a point lying on the central meridian on downstream slopes.) On the slopes which meet the main flow coming to the dimples, said flow is joined with the return flow to generate within the dimples a vortex structure with circulation of the medium $\Gamma_0 \approx \mathbf{2\pi RU\varphi}$; in so doing, the azimuthal velocity of such circulation is $\mathbf{U\varphi} \approx \mathbf{U_{in}} \approx \mathbf{kU_\infty}$, where $\mathbf{k} < \mathbf{1}$ reflects the features of the velocity profile of flow above the initially smooth and curvilinear surfaces subjected to flow. Because of the small difference in the velocities of the incoming flow and of the return flow it generates (according to experimental data, the difference in **k** in the return and incoming flows is $\pm$4%, i.e., not more than 8%), the vortex jet formed in the dimple is acted upon by a pair of forces which cause its additional swirling and self-similarly turn the tornado-like vortex in the dimple through angle ($\beta \sim 45°$ relative to the direction of main flow;
- mass inertial forces which are directed along the curvature radii of dimples towards their center and form on convex slopes of relief in the moving medium a two-dimensional velocity field containing radial $\mathbf{U_r}$ and azimuthal $\mathbf{U_\varphi}$ (with respect to the central axis of dimple) components of velocity. In so doing, the motion of the medium on curvilinear convex slopes causes a decrease in the probability of separation of flow and, as was observed above, the formation of **FDMBL** three-dimensional vortex boundary layer on said slopes. It is known that the characteristics of surface vortexes arising in such a layer on curvilinear surface depend on the velocity $\mathbf{U_{in}}$, on the state of the boundary layer (laminar, turbulent), on the momentum thickness in said layer, and on the curvature radii of convexo-concave relief $\mathbf{R_{(+)}}$ and $\mathbf{R_{(-)}}$, respectively. As was stated above, such a boundary layer causes a decrease in the level of dissipation of energy in the flow, thereby reducing the probability of the separation of flow from the convex surface of slopes, and imparts high dynamism to the flow in the dimple owing to the transformation of the shear boundary layer into three-dimensional vortex one with which the swirling flow being formed is joined. Further forming of tornado-like jets occurs on concave slopes of dimples likewise under the effect of mass inertial forces directed in this zone from the surface to the main flow along the curvature radii towards its center. The choice of geometric shape of convexo-concave regions of boundary surface and of corresponding curvature radii of the relief of dimples defines the impact made on the swirling jet being formed by the inertial forces which impart the longitudinal component of velocity $\mathbf{U_z}$ to this secondary flow. This component arises owing to the impact made on the flow flowing down into dimples at velocity $\mathbf{U} = \mathbf{(U_\varphi^2 + U_r^2)^{0.5}}$ by accelerations $*\boldsymbol{a} = \mathbf{U^2/R}$ which are directed along the curvature radii **R** away from the concave surface to the flow, impart additional radial convergence to the jet, and cause an increase, with decreasing jet radius $\mathbf{r_i}$, in the azimuthal velocity of secondary flow $\mathbf{U_\varphi}$ and in the longitudinal pressure gradient defined by this latter velocity and by the longitudinal velocity $\mathbf{U_z}$. This mechanism provides in the **TLJ** a pressure profile required

for transfer and injection of the mass of medium sucked off by tornado-like jets onto the surface downstream of the flow or into the main flow; and

- forces of the type of Magnus force, which arise because of interaction between the main flow to dimples and the tornado-like vortex; the circulation Γ_0 in the dimple generates the lifting force **F** dependent on the velocity of incoming flow $\mathbf{U_{in}}$ and on the effective dimension of vortex structure across the flow **L,**

$$\mathbf{F \approx \rho U_{in} \Gamma_0 L,}$$

and directed away from the concave part of curvilinear surface into the flow on a normal to the plane which accommodates the velocity vector of the main flow and the vector defined by the direction of circulation in vortex structures, where $\mathbf{U_{in}}$ and Γ_0 are determined above, and ρ is the density of continuous medium in the vortex.

[0084] These forces, along with the mass inertial forces acting on the concave part of relief, provide for the "incorporation" of tornado-like vortexes into the incoming flow and draw out one of the ends of the vortex and its "trunk" into the main flow.

[0085] As was indicated above, the values of the above-said forces and the directions of their action on the structure of flow being formed are controlled by the preassigned shapes of dimples of double curvature, by the density of distribution of dimples with respect to the area of initially smooth surface, and by the modes of motion of flow of medium. For example, in the process of flow past dimples whose shape exhibits central axial symmetry and is defined by the curvature radii $\mathbf{R_{(+)}}$ and $\mathbf{R_{(-)}}$, the flow of continuous medium, which is characterized by Reynolds number values of $\mathbf{Re \geq 500}$ calculated by the diameter $\mathbf{d_c = 2r}$ of the trace of dimple on the surface being shaped and moves above convex slopes of dimples at velocity $\mathbf{U_{in}}$, is acted upon by mass inertial forces which urge the flow against convex slopes in accordance with the sign of curvature $\mathbf{R_{(+)}}$. These forces cause a decrease in the probability of separation of flow from the curvilinear surface of dimple and impart to the flow coming into the dimple a higher or lower (depending on the selected curvature radii) radial convergence and azimuthal velocity $\mathbf{U_{\varphi}}$. As was observed above, such motion causes the formation of **FDMBL** between the curvilinear surface and tornado-like flow; in so doing, such a boundary layer accompanies the flow being formed on the concave part of dimple as well. Surface vortexes such as Görtler vortexes impart to the swirling jet in the dimple the dynamism relative to the curvilinear surface, stabilize the efflux of said jet into the main flow, and make up a fairing formed by the structure of swirling tornado-like flow and curvilinear shape of dimple (see photograph in Fig. 11).

[0086] In accordance with the foregoing, the "continuous medium-surface subjected to flow" interface is imparted a curvilinear shape in the form of regularly alternating dimples of double curvature which develop force action to provide in the flow the self-organization in these zones of FDBML and secondary swirling jets directed away from said surface zone of flow into the main flow. In so doing, the arising forces cause an independent force action on the moving medium, which results in the curvature of shapes of lines of flow and, as a consequence, in the self-organization of tornado-like jets.

[0087] As was found in theoretical and experimental investigations, the dimple relief made on surfaces subjected to flow causes the variation of the structure of boundary layer of flow on the boundary surfaces and gives rise to the self-organization of tornado-like jets which suck off a part of continuous medium concentrated in the zone of location of dimples on the surface subjected to flow, thereby affecting the level of dissipation of energy of the flow and intensifying the exchange processes between swirling jet and surface. The choice of curvature radii and dimensions of curvilinear regions of the surface subjected to flow is based on the results of theoretical calculations supported by experimental results, the technology of producing dimples on the surface is developed, and provision is made for the validity of the conditions of self-organization of secondary tornado-like jets built in the flow past the surface. The flow of working continuous medium is directed to the surface shaped with dimples, or a relief of desired shape is made on the surface of bodies moving in a medium of gases, liquids, or their two-phase mixtures to attain the reduction of friction drag on shaped surfaces and enhance the processes of heat and mass transfer between the energy-exchange surface and flows of continuous medium.

Industrial Use of Invention

[0088] The disclosed surfaces are employed for reducing aerohydrodynamic drag of pressure channels and various bodies in the state of relative motion with continuous medium and/or for raising the functional efficiency of energy-exchange processes and equipment, including heat-transfer and mass-transfer processes, as well as in all other spheres where, compared to the conventional methods of heat and mass transfer, it is necessary to intensify exchange processes under conditions of restricted rise or reduction of hydraulic drag and reduce the cavitation wear of the surfaces of hydraulic turbines, hydraulic pumps, propellers of marine propulsion units, and other units operating in liquid medium. In particular, the present invention finds application in various means of transportation including aircraft, automobiles, high-speed railroad trains, sea-going and river-going vessels; in gas-turbine units with cooled blades, in nuclear-power uranium assemblies, in steam generators, in various heat-exchangers, in recuperators and other energy-exchange apparatuses and devices; in household appliances such as air conditioners, fans, heating equipment and in kitchen appliances such as tea kettles, pots, fiying pans etc.; in sports goods of various kinds including sports cars, motorcycles, bicycles, sportswear for motor sports, bicycle racing, swimming, running etc.; in various biochemical processes involving the motion of gaseous or liquid reagents, as well as in developing apparatuses and prostheses for blood circulation systems, in medical devices for artificial blood supply and for purifying blood from harmful impurities, in artificial respiration equipment, and so on; in other words, in technologies involving flows of various media, in which the process efficiency is defined by the motion of gases, liquids and their two-phase and/or multicomponent mixtures.

[0089] The above-said spheres of utilization of the disclosed invention define the diversity of its embodiments. However, common to all possible embodiments in formulating the concrete problem are the determination of the basis functional characteristics of processes or equipment to be improved and the choice of shapes, sizes, and the technology of making of reliefs on the surface.

Claims

1. A surface for reduction of friction with gaseous and liquid media or with their mixtures, **characterized in that** dimples are provided on a smooth surface with or without a protective layer, which are formed by second-order convex and concave surfaces conjugate on common tangents; in so doing, the conjugation of a dimple with initially smooth surface is accomplished using convex surfaces that form slopes, for which the initially smooth surface is tangent at points of conjugation; the concave surface, which forms the bottom part of dimple, is made smooth or with a fairing, the ratio of depth $\mathbf{h_c}$ of dimple to dimension $\mathbf{L_1}$ of dimple along the direction of flow is in the range $\mathbf{0.001 \leq h_c/L_1 \leq 0.1}$, and the ratio of transverse dimension $\mathbf{L_2}$ of dimple to longitudinal dimension $\mathbf{L_1}$ of dimple is in the range $\mathbf{0.25 \leq L_2/L_1 \leq 1}$, with the surface density $\mathbf{f}$ of dimples being in the range $\mathbf{0.05 \leq f \leq 0.5}$.

2. A surface as claimed in Claim 1, **characterized in that** dimples may be made with the longitudinal and/or transverse dimensions varying along the flow.

3. A surface as claimed in claim 1, **characterized in that** dimples are made either mechanically, or electrochemically, or by shaping and polymerization of the protective layer, or by laser processing of the surface.

4. A surface as claimed in Claim 1, **characterized in that** slopes are formed by a toroidal surface.

5. A surface as claimed in Claim 1, **characterized in that** slopes are formed by a hyperbolic surface.

6. A surface as claimed in Claim 1, **characterized in that** slopes are formed by an elliptic surface.

7. A surface as claimed in Claim 4, **characterized in that** the radius $\mathbf{r_{sp}}$ of the concave spherical part of dimple, which has the curvature radius $\mathbf{R_{(-)}}$, is defined by the relation

$$\mathbf{r_{sp} = (2h_{sp}R_{(-)} - h_{sp}^2)^{0.5}},$$

where $\mathbf{h_{sp}}$ is the depth of concave spherical part of dimple; in so doing, the curvature radius of the convex part of dimple is related to the dimple depth $\mathbf{h_c}$ and radius $\mathbf{r_c}$ by the relation

$$\mathbf{R_{(+)} = [(r_c - r_{sp})^2 + (h_c - h_{sp})^2]/2(h_c - h_{sp}).}$$

8. A surface as claimed in Claim 1, **characterized in that** fairings have the shape of bodies of revolution, the curvilinear base of which is provided by a part of the concave surface of dimple, and the projection of fairing onto any plane, in which the symmetry axis of the fairing and the tangent to the point of intersection of said symmetry axis with the concave surface of dimple lie, is defined by the relation

$$r_i^2 h_i = const,$$

where $\mathbf{r_i}$ is the radius of fairing and $\mathbf{h_i}$ is its height, which assume their values in the case of selected curvature radius $\mathbf{R_{(-)}}$, in the ranges

$$10^{-5} \leq h_i/r_i \leq 1.$$

9. A surface for enhancement of convective heat and mass transfer with gaseous and liquid media or their mixtures, **characterized in that** dimples are provided on a smooth surface, which are formed by second-order convex and concave surfaces conjugate on common tangents; in so doing, the conjugation of dimples with initially smooth surface is accomplished using convex surfaces that form slopes for which the initially smooth surface is tangent at points of conjugation; the concave surface, which forms the bottom part of dimple, is made smooth or with a fairing, the ratio of depth $\mathbf{h_c}$ of dimple to dimension $\mathbf{L_1}$ of dimples along the direction of flow is found in the range $\mathbf{0.05 \leq h_c/L_1 \leq 0.5}$, and the ratio of transverse dimension $\mathbf{L_2}$ of dimple to longitudinal dimension $\mathbf{L_1}$ of dimple is in the range $\mathbf{0.25 \leq L_2/L_1 \leq 1}$, with the surface density f of dimples being in the range $\mathbf{0.1 \leq f \leq 0.8}$.

10. A surface as claimed in Claim 9, **characterized in that** dimples are made with the longitudinal and/or transverse dimensions varying along the flow.

11. A surface as claimed in Claim 9, **characterized in that** dimples may be made either mechanically, or electrochemically, or by laser processing of the surface, or by shaping and polymerization of the surface protective layer, or by employing various combinations of these methods.

12. A surface as claimed in Claim 9, **characterized in that** slopes are formed by a toroidal surface.

13. A surface as claimed in Claim 9, **characterized in that** slopes are formed by a hyperbolic surface.

14. A surface as claimed in Claim 9, **characterized in that** slopes are formed by an elliptic surface.

15. A surface as claimed in Claim 12, **characterized in that** the radius r_{sp} of the concave spherical part of dimple, which has the curvature radius $\mathbf{R_{(-)}}$, is defined by the relation

$$r_{sp} = (2h_{sp}R_{(-)} - h_{sp}^2)^{0.5},$$

where $\mathbf{h_{sp}}$ is the depth of concave spherical part of dimple; in so doing, the curvature radius $\mathbf{R_{(+)}}$ of the convex part of dimple is related to the dimple depth $\mathbf{h_c}$ and radius $\mathbf{r_c}$ by the relation

$$R_{(+)} = [(r_c - r_{sp})^2 + (h_c - h_{sp})^2]/2(h_c - h_{sp}).$$

16. A surface as claimed in Claim 9, **characterized in that** fairings have the shape of bodies of revolution, which have a curvilinear base in the form of a part of the concave surface of dimple and the projection of fairing onto any plane in which the symmetry axis of said fairings and the tangent to the point of intersection of their symmetry axis with the concave surface of dimple lie; in so doing, the shape of said projection is defined by the relation

$$r_i^2 h_i = const,$$

where $\mathbf{r_i}$ is the radius of fairing and $\mathbf{h_i}$ is its height, which assume their values in the case of selected curvature radius $\mathbf{R_{(-)}}$ in the ranges

$$10^{-5} \leq h_i/r_i \leq 1.$$

17. A surface of heat-transfer plate as claimed in Claim 9, **characterized in that** the dimples are arranged in the staggered or in-line order.

18. A surface as claimed in Claim 17, **characterized in that** the size of dimples and their depth is increased or reduced in the direction of flow along the plate.

19. A surface as claimed in Claim 17, **characterized in that** dimples of smaller longitudinal and transverse dimensions and smaller depth are located around the dimples.

20. A surface as claimed in Claim 17, **characterized in that** projections reciprocal to recesses are provided on the other side of said surface.

21. A surface as claimed in Claim 17, **characterized in that** ribs oriented along the plate in the direction of flow are provided on the other side of the plate.

22. A surface as claimed in Claim 17, **characterized in that** dimples are arranged on the other side of the plate symmetrically or asymmetrically with respect to the dimples on the main side.

23. A surface as claimed in Claim 17, **characterized in that** it is contain an additional surface of the plate with dimples located relative to the main surface with the formation of a heat-transfer channel; in so doing, the surfaces of the plates with dimples are facing each other and are arranged in parallel owing to spacer elements in the form of projections of spherical, conical, cylindrical, or other shapes.

24. A surface of pipe as claimed in Claim 9, **characterized in that** dimples along the pipe and across the pipe are arranged in the staggered or in-line order.

25. A surface as claimed in Claim 24, **characterized in that** the size of dimples and their depth are increased or reduced in the direction of flow along or across the pipe.

26. A surface as claimed in Claim 24, **characterized in that** projections with second-order surfaces are located on the inner surface of the pipe.

27. A surface as claimed in Claim 24, **characterized in that** dimples are located on the inner surface of the pipe, the size and depth of which are increased or reduced in the direction of flow along or across the pipe.

28. A surface as claimed in Claim 24 or Claim 27, **characterized in that** longitudinal ribs with dimples on their surface are located on the inner surface of the pipe.

29. A surface as claimed in Claim 24 or Claim 27, **characterized in that** transverse ribs with dimples are located on the inner surface of the pipe.

30. A surface as claimed in Claim 24 or Claim 27, **characterized in that** a curved twisted tape with dimples is located within the pipe.

31. A surface as claimed in Claim 24, **characterized in that** dimples are located on the inner surface of the pipe symmetrically or asymmetrically with respect to the dimples on the outer surface.

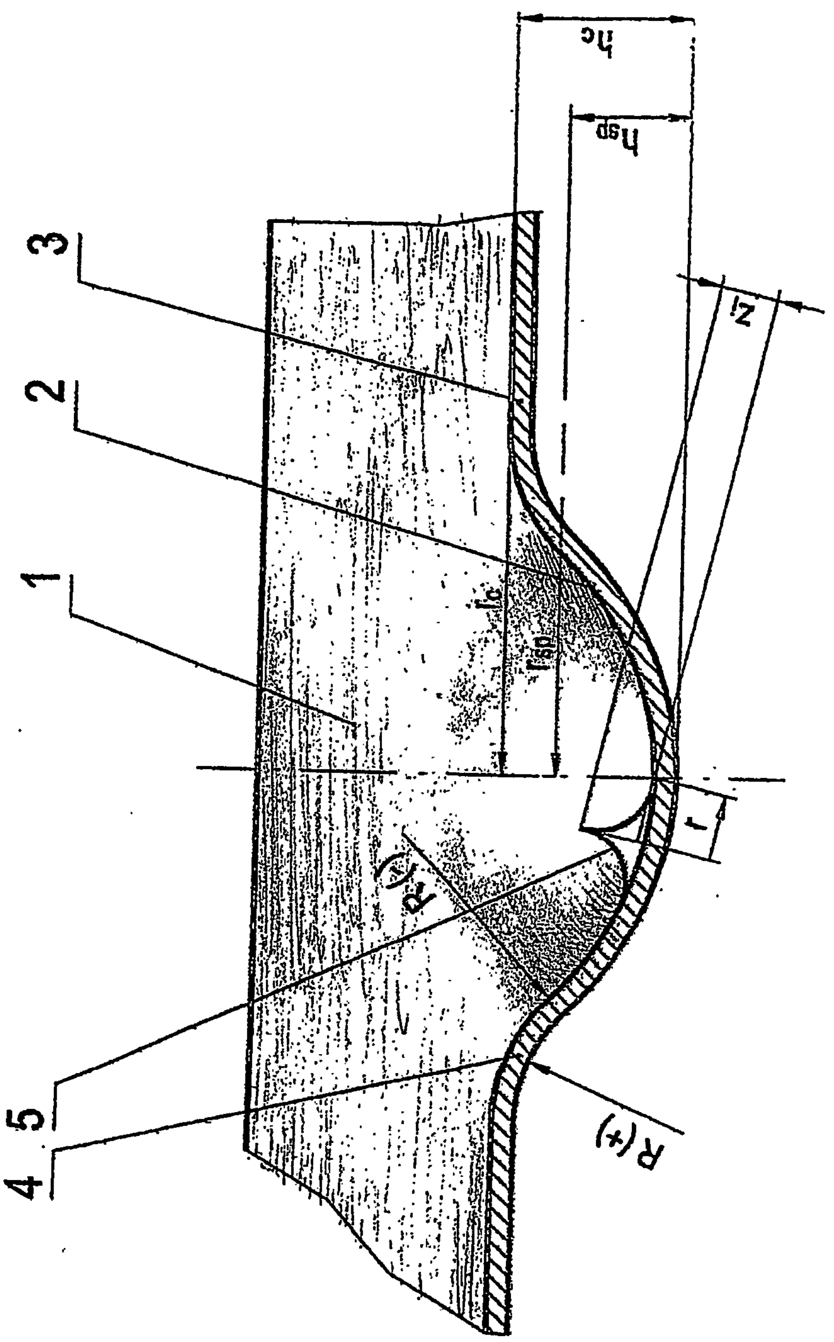

Fig. 1

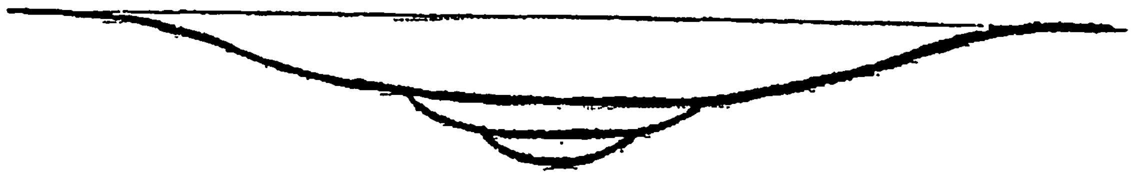

Fig. 2

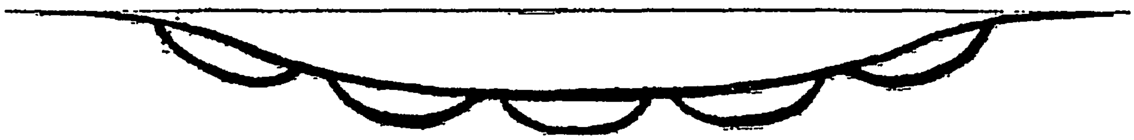

Fig. 3

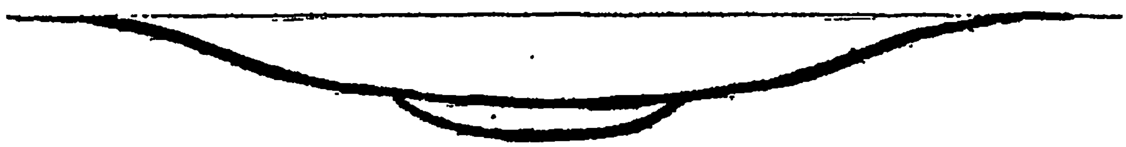

Fig. 4

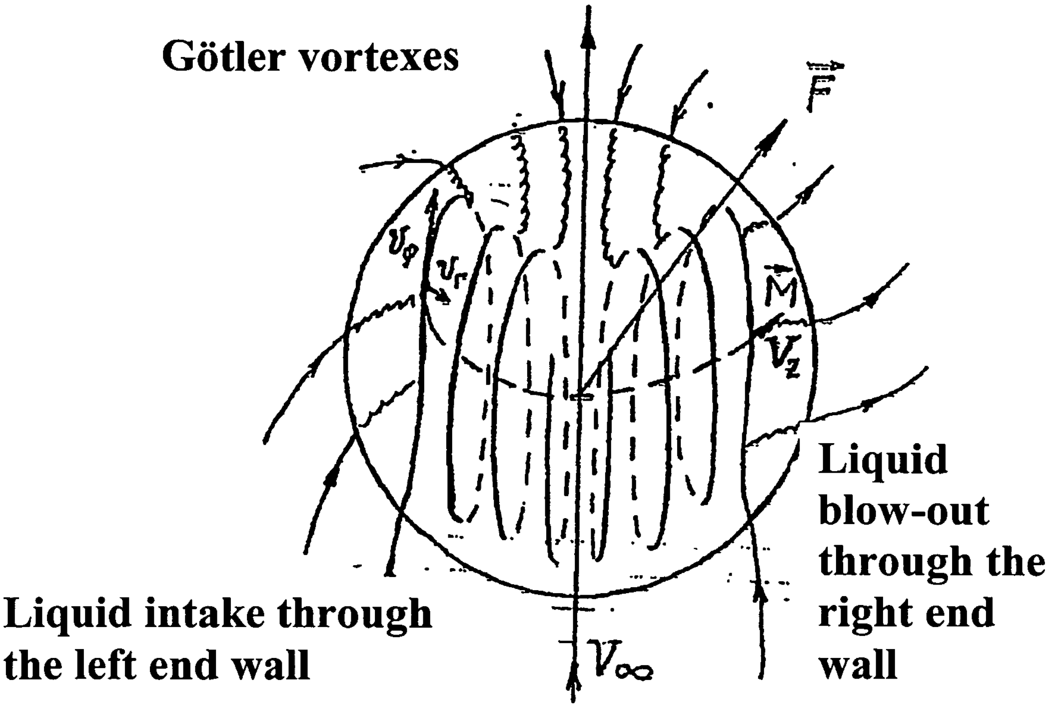
Götler vortexes
$\vec{F}$
v_φ
v_r
$\vec{M}$
V_z
Liquid blow-out through the right end wall
Liquid intake through the left end wall
V_∞

Fig. 5

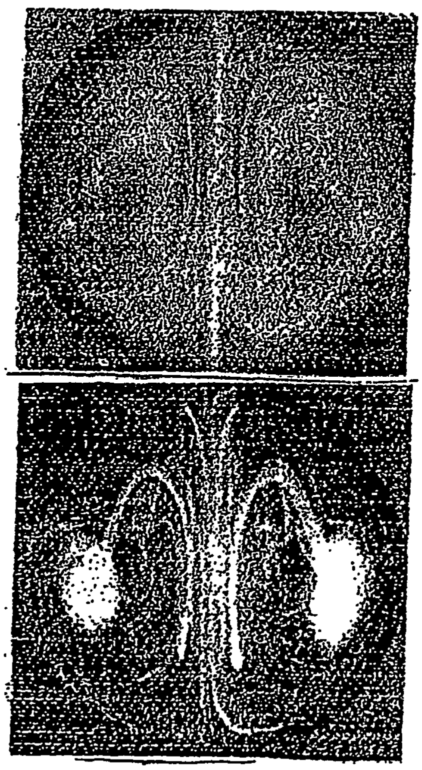

Fig. 6

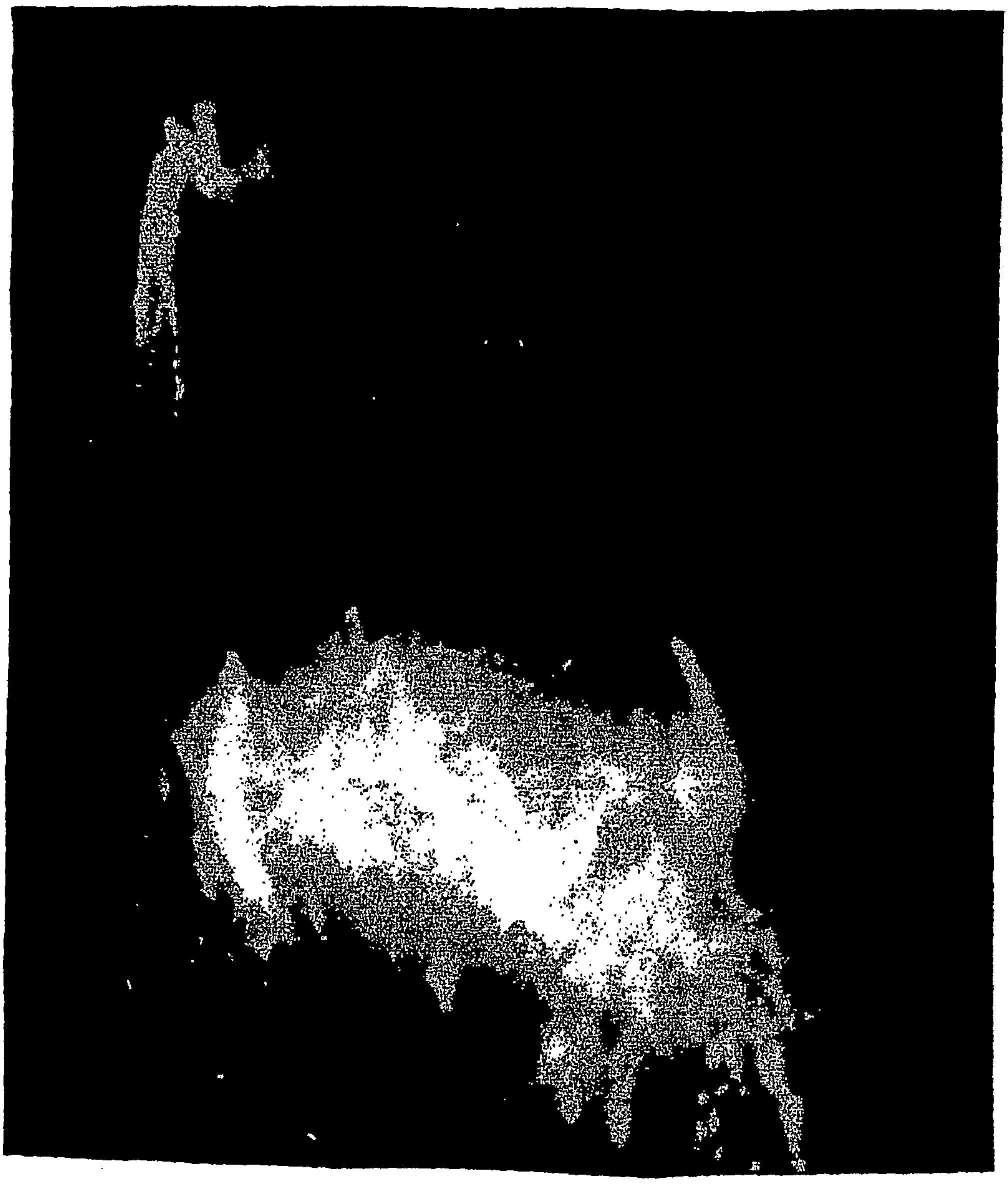

Fig. 7

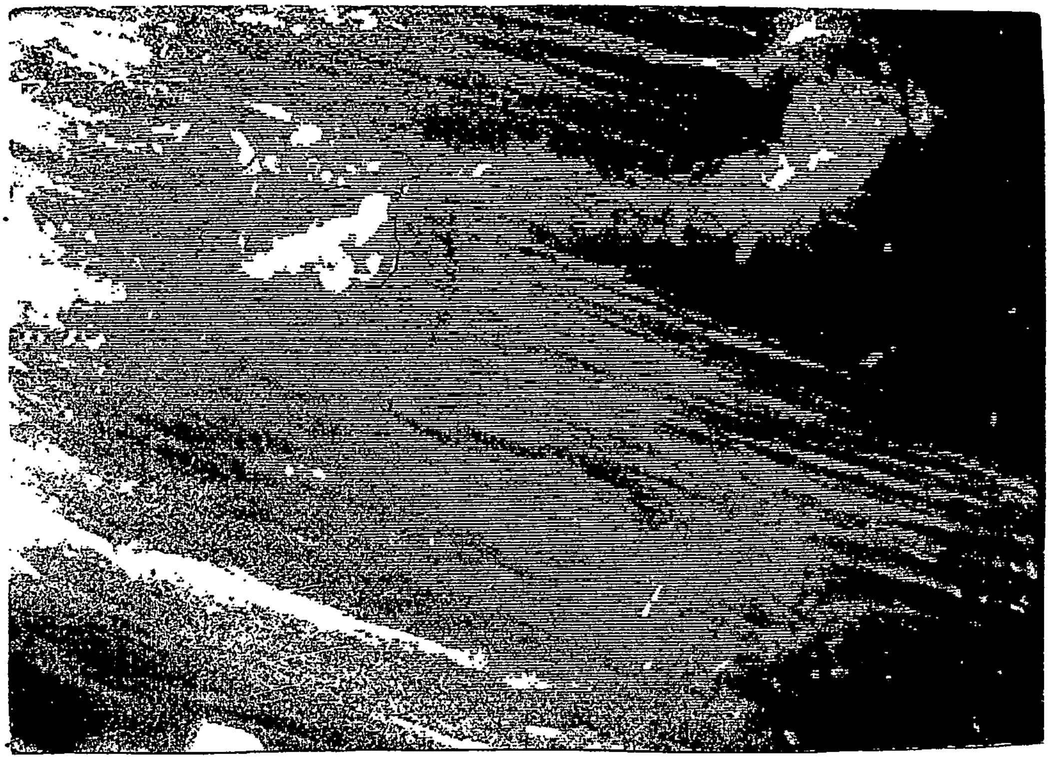

Fig. 8

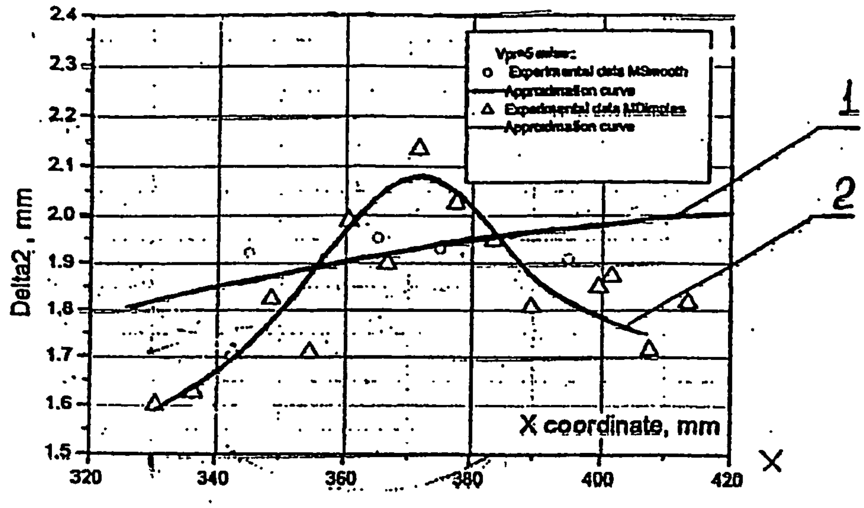

Fig. 9

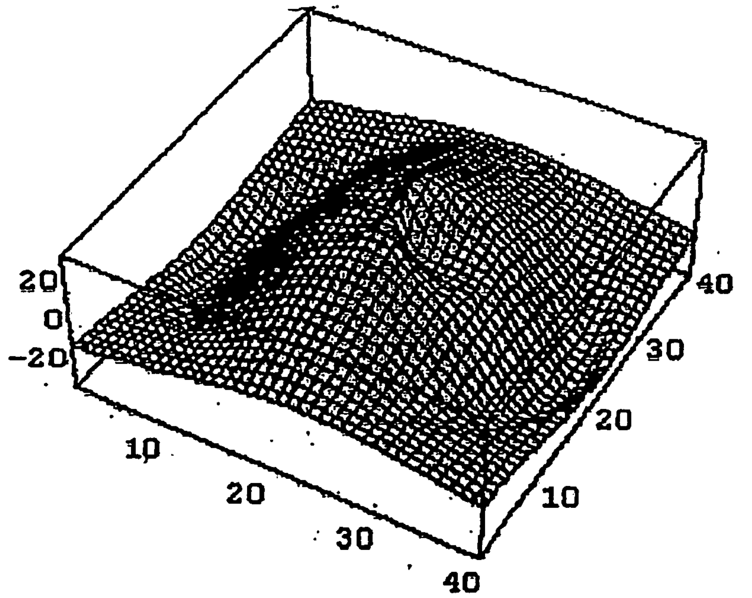

Fig. 10

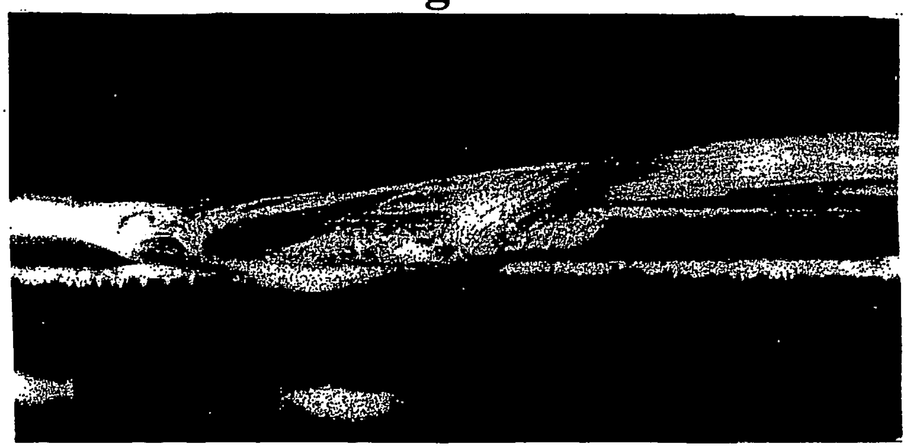

Fig. 11

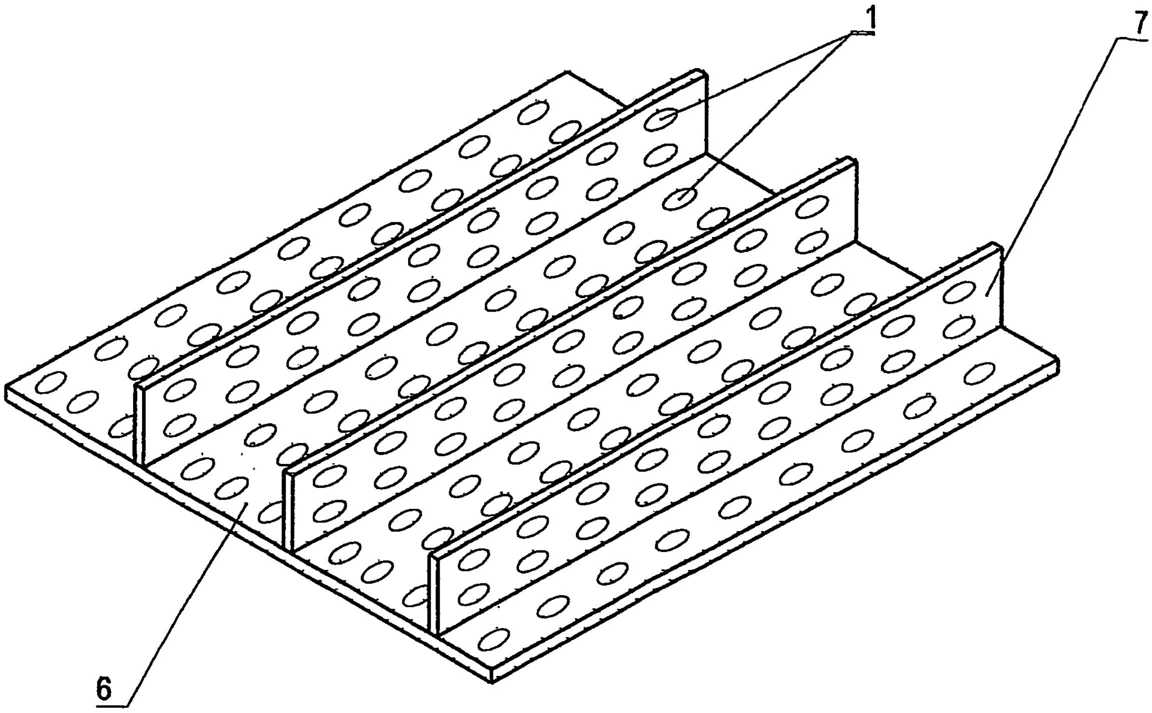

Fig. 12

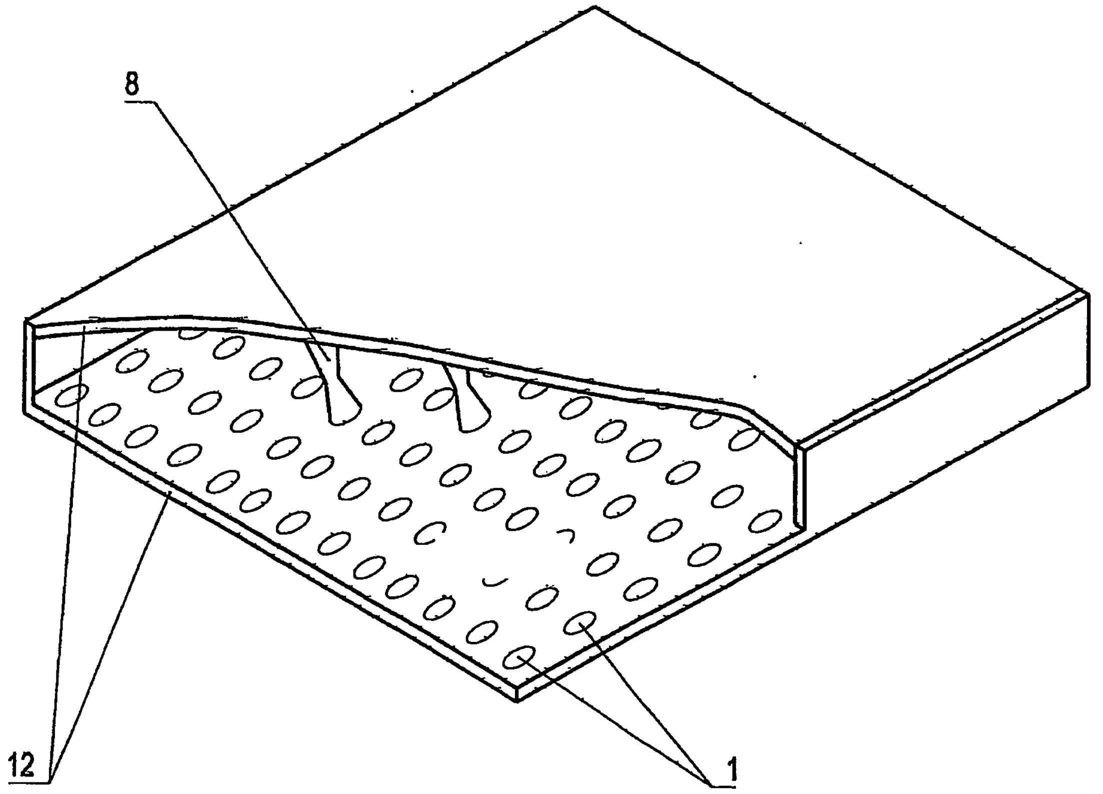

Fig. 13

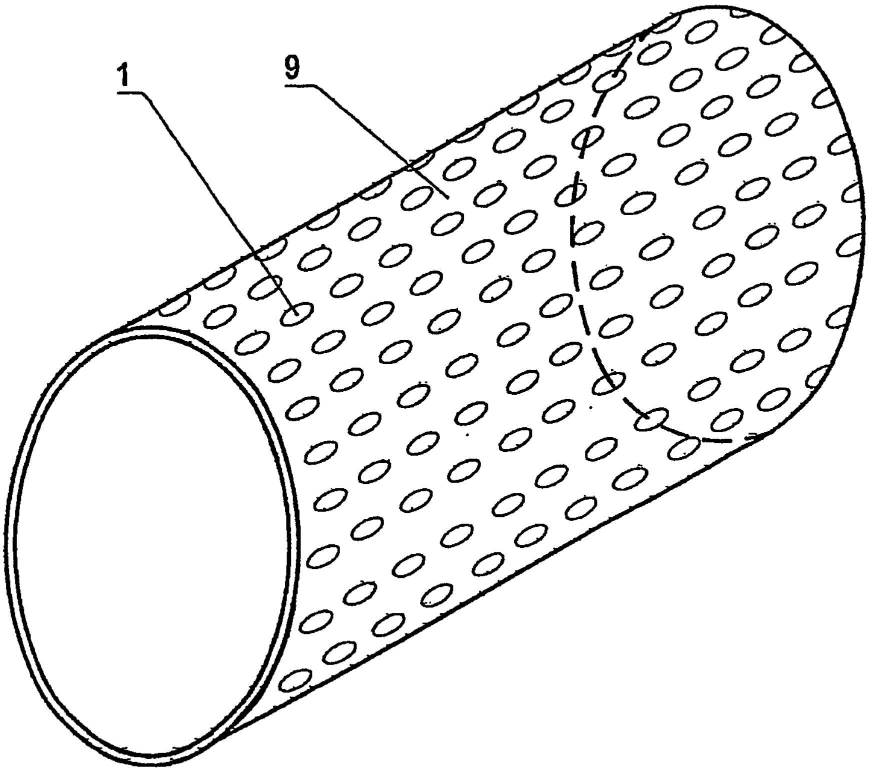

Fig. 14

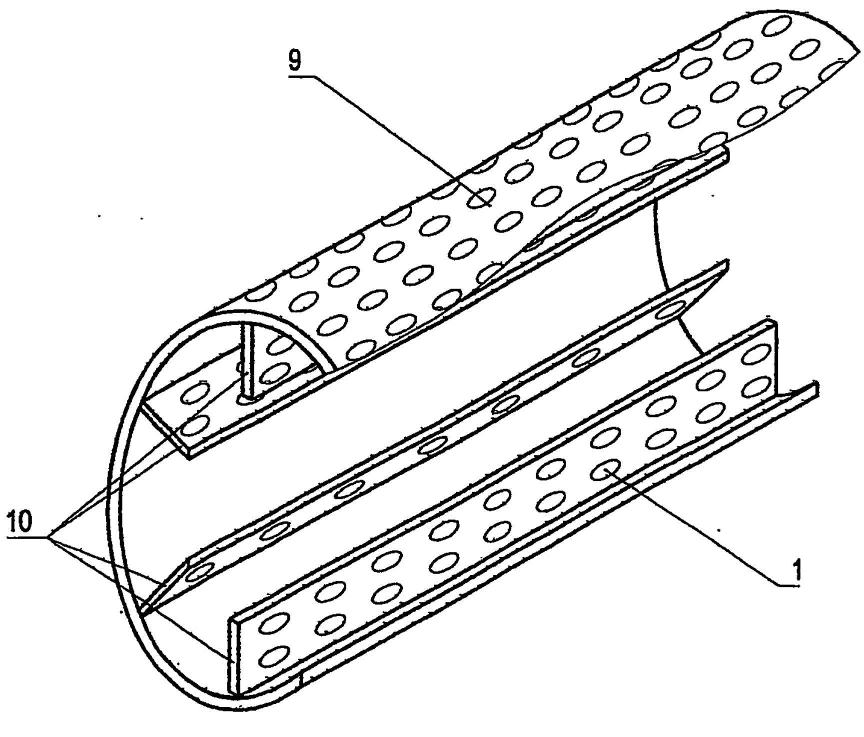

Fig. 15

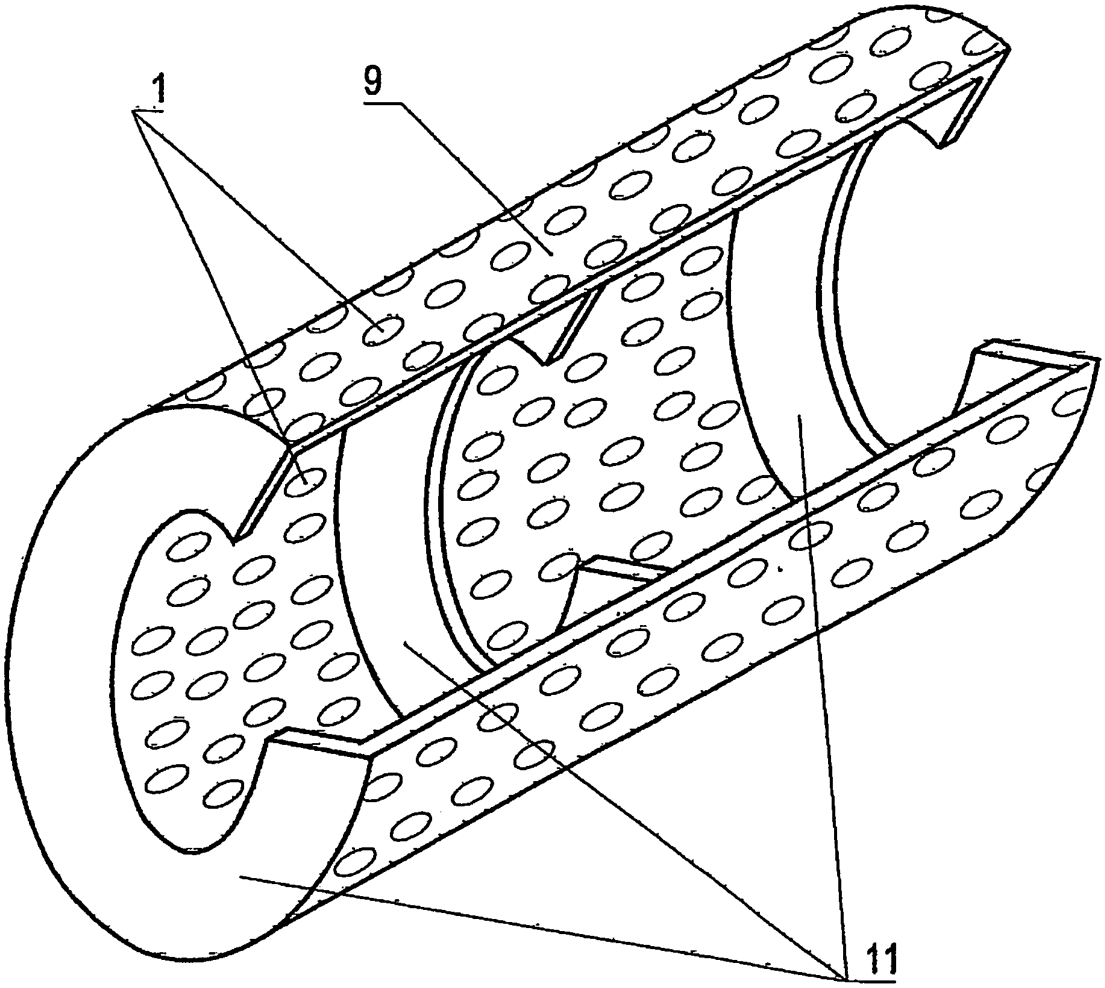

Fig. 16

INTERNATIONAL SEARCH REPORT

International application No.
PCT/RU 2006/000465

A. CLASSIFICATION OF SUBJECT MATTER

F15D 1/02 *(2006.01)*
F15D 1/12 *(2006.01)*
F28F 13/02 *(2006.01)*

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

F15D 1/00 1/02 1/06 1/10 1/12 F28F 13/00 13/02

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

RUPAT Esp@cenet USPTO DB

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	RU 2020304 C1 (KIKNADZE GENNADY IRAKLIEVICH et al.) 30.09.1994, the abstract, the claims	1-31
A	SU 1086246 A (I.S. VINOGRADOV) 15.04.1984, the claims	1-8
A	US 4690211 A (HITACHI, LTD. et al.) 01.09.1987, the abstarct, figure 8	9-31
A	WO 1997/004280 A1 (KIKNADZE GENNADY IRAKLIEVICH) 06.02.1997, the abstract, the claims	1-31

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
02 May 2007	07 June 2007

Name and mailing address of the ISA/	Authorized officer
RU	
Facsimile No.	Telephone No.

Form PCT/ISA/210 (second sheet) (July 1998)

INTERNATIONAL SEARCH REPORT

International application No.
PCT/RU2006/000465

Box No. II Observations where certain claims were found unsearchable (Continuation of item 2 of first sheet)

This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:

1. ☐ Claims Nos.:
because they relate to subject matter not required to be searched by this Authority, namely:

2. ☐ Claims Nos.:
because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:

3. ☐ Claims Nos.:
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

Box No. III Observations where unity of invention is lacking (Continuation of item 3 of first sheet)

This International Searching Authority found multiple inventions in this international application, as follows:

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.

2. ☒ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.

3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:

Remark on Protest

☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.

☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.

☐ No protest accompanied the payment of additional search fees.

Form PCT/ISA/210 (continuation of first sheet (2)) (April 2005)

INTERNATIONAL SEARCH REPORT

International application No.
PCT/RU2006/000465

According to Rule 13.1 of the PCT regulations, the requirement of unity of invention consists in that the international application shall relate to one invention only or to a group of inventions so linked as to form a single general inventive concept.

In the claimed invention, the requirement of unity of invention is not fulfilled, since the variants of the invention according to independent claims 1 and 9 are directed at the solution of different problems and are not linked by a single inventive concept due to the following reasons:

The above-mentioned variants of the invention according to claims 1 and 9 result in different technical results conditioned by the different purposes of flow airfoils, namely, according to claim 1, the claimed surface is used for reducing friction, whilst according to claim 9, the claimed surface is used for intensifying convective mass-and-heat transfer.

Moreover, said different technical results are obtained with different numerical values of relationships hc/L1 and L2/L1 and with a value of distribution density of recesses though a surface. Thus, the special technical features that define a contribution which each of the claimed variants of the invention makes over the prior art are not the same, thereby also proving the violation of unity of invention (Rule 13.2).

Thus, the International Searching Authority has discovered out two groups of inventions, the first of which comprises claim1 and claims 2-8, which are dependent thereon, and the second of which comprises claim 9 and dependent claims 10-31.

Form PCT/ISA/210 (extra sheet) (April 2005)

REFERENCES CITED IN THE DESCRIPTION

This list of references cited by the applicant is for the reader's convenience only. It does not form part of the European patent document. Even though great care has been taken in compiling the references, errors or omissions cannot be excluded and the EPO disclaims all liability in this regard.

Patent documents cited in the description

- RU 2020304 **[0002]**