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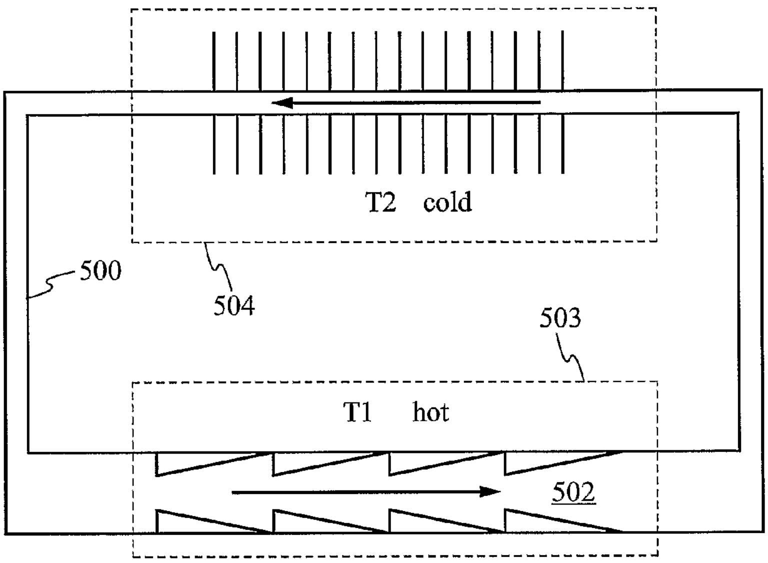
(54) **Title:** THERMALLY-POWERED NONMECHANICAL FLUID PUMPS USING RATCHETED CHANNELS



(57) **Abstract:** Thermally-powered non-mechanical fluid pumps induce flow of fluid through a channel [500] when the temperature in a ratcheted segment [502] of the channel exceeds a pump activation temperature. Channel diameters may range from several centimeters down to several micrometers. The drag between the fluid and the ratcheted channel wall is extremely small at the pump activation temperature due to film boiling of the fluid at the pump activation temperature and/or the use of superhydrophobic surfaces inside the channel. The pumps may be used in thermally-driven heat exchangers for various large-scale and micro-scale applications. They may also be used as agitators for mixing microfluids, and as droplet ejection or spraying devices.

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THERMALLY-POWERED NONMECHANICAL FLUID PUMPS USING RATCHETED CHANNELS

FIELD OF THE INVENTION

The present invention relates generally to devices and techniques for pumping fluids. More specifically, it relates to non-mechanical pumps powered by a source of thermal non-equilibrium.

BACKGROUND OF THE INVENTION

Non-mechanical pumps induce fluid transport without mechanical movements. There exist various classes of non-mechanical pumps, many of which are important in a wide variety of applications. Non-mechanical micropumps, just to give one particularly relevant example, are useful in miniature thermal management systems for cooling microelectronics, chemical microreactors, and lab-on-a-chip devices. Non-mechanical pumps operate by directly converting some form of non-mechanical energy (e.g., electric, magnetic, thermal, chemical, or surface tension forces) into kinetic energy of the fluid. Examples of non-mechanical pumps include capillary pumps which are based on the capillary effect, electrokinetic pumps which use electric fields to pump fluids, magnetohydrodynamic pumps which use a combination of electric and magnetic fields to propel a fluid, and thermally-driven pumps which use thermal energy to drive fluid movement.

Notably, many non-mechanical pumps that involve thermal energy are not actually powered by thermal energy but are driven by a precisely controlled electrical energy source. For example, US Pat. No. 6,071,081 discloses a pump that uses an electrically powered laser to deliver pulses of localized thermal energy to a liquid. The thermal energy vaporizes a portion of the liquid to create a vapor bubble in a reservoir, and an associated pulse of pressure pushes the fluid out of the reservoir through a check valve. In another example, US Pat. No. 6,130,098 discloses a technique for propelling microdroplets through channels by differentially heating the channels with an array of electrically controlled heating elements. The resulting temperature gradient along the length of the channel produces a difference in the surface tension that causes the droplet to move. Because these pumps only indirectly involve thermal energy and are fundamentally powered by an electrical source, they are quite different from thermally-driven pumps whose fundamental source of power is thermal.

Brownian motors, or thermal ratchets, are a type of particle transport based on the ratchet effect. It is well known that Brownian motion (i.e., random particle motion due to thermal fluctuations) does not normally result in any net movement of particles. It is possible, however, for the particles to experience a net directed movement if the particles experience a spatially asymmetric energy potential (i.e., a "ratchet") and a displacement from thermal equilibrium (e.g., by pulsing the potential on and off, or by cycling the temperature up and down). This non-mechanical, thermally-driven technique for particle transport, however, acts upon individual microscopic particles. It is not suitable for pumping entire fluid streams or drops.

In the article "Moving droplets on asymmetrically structured surfaces," *Phys Rev E* 1999 Sept.; 60(3):2964-72, Sandre *et al.* discuss the movement of a liquid droplet on a surface structured with a locally asymmetric pattern when either the drop volume is modulated or an electric potential is modulated. In both cases, movement is based on electrowetting effects powered by a source of electrical energy. Thus, this type of non-mechanical pump is not thermally driven.

In the thesis "Self-propelled motion of film boiling droplets on ratchet-like surfaces," University of Oregon, June 2003, Melling discloses the motion of 1 mm diameter droplets on surfaces having periodic asymmetric grooves whose spacing is slightly smaller than the droplet diameter. When the surface temperature is sufficiently high to cause the droplets to experience film boiling (e.g., the "dancing" of water drops on a hot pan), the droplets spontaneously move in a direction perpendicular to the grooves, and also can move uphill when the surface was slightly inclined. The effect was observed with various different liquids, including nitrogen, ethanol, and water. To produce the motion it is sufficient to have 1) a temperature gradient (between the surface and liquid) sufficient to produce film boiling and 2) a static asymmetric potential (due to surface topography and gravity) with period slightly smaller than the drop size. Thus, this thermally-powered non-mechanical fluid transport effect is extremely simple. No modulation in time is required, and the thermal gradient does not need to be oriented in the direction of movement. This phenomenon, however, has somewhat limited practical use due to 1) its strictly linear propagation on a planar surface, 2) its sensitivity to orientation in the gravitational field, and 3) its realization only for 1 mm droplets.

In view of the above, it would be an advance in the art of pumping fluids to provide a thermally powered non-mechanical pump that is simple, inexpensive, does not require any electrical control or electrical power source, is not limited to propelling drops across a level surface, and can operate relatively independent of gravitational orientation.

SUMMARY OF THE INVENTION

In one aspect, the present invention provides a simple and elegant technique for thermally-powered non-mechanical fluid transport through a channel. The pump automatically and non-mechanically induces flow of a working fluid through the channel when the temperature of the channel exceeds a desired pump activation temperature, creating a temperature gradient between the channel and the working fluid. During operation, most of the working fluid is in liquid phase at a temperature below that of the channel. A non-mechanical pump realizing this technique includes a channel through which the working fluid may flow in liquid phase. The channel may be, for example, an open groove in a material, or an enclosed tunnel or pipe. The diameter of the channel may be in the range from several centimeters down to several micrometers. In a pumping segment of the channel, at least one surface of the channel is ratcheted, i.e., shaped to have a longitudinally asymmetric topography (e.g., a periodic sawtooth surface profile). The ratchet pattern is preferably periodic in the longitudinal direction with period in the range from several centimeters down to several micrometers. The pump is characterized in that the frictional force of the working fluid as it flows through the pumping segment of the channel (i.e., the drag) is extremely small at the pump activation temperature. In one embodiment, the drag is made small by virtue of film boiling of the working fluid at the pump activation temperature. In variations of this embodiment, the channel includes vents (e.g., pores, slits, holes, or other openings) through which a vapor phase of the fluid may pass. These variations may also include a supplementary channel through which the vapor phase may flow. In another embodiment, the drag is made small by virtue of a superhydrophobic or analogous surface property of the channel surface in the pumping section. Such a property may be created, for example, by small topographic surface modifications at the micrometer-scale or smaller that significantly reduce the contact between the surface and the liquid.

The pumping technique of the present invention has many useful applications. For example, a thermally-driven heat exchanger may be formed by fabricating a closed-cycle channel with hot and cold portions. The ratcheted pumping segment is placed at the hot portion of the cycle and a heat sink is placed in thermal contact with the cold portion of the cycle. For example, the cold portion of the channel may be fabricated in a thermally conductive material that conducts heat from the surface of the channel to the heat sink. When the temperature at the hot end rises to the pump activation temperature, the pump activates and fluid begins to flow through the channel, carrying heat from the hot end to the cold end. This heat exchanger has the virtues that it is powered by the very energy that one wants to dissipate and is automatically activated and deactivated as necessary. This type of heat exchanger may be of particular value in various small-scale applications such as cooling electronic circuits and chemical microreactors. Another possible application of the pumping technique is to use the pump as an agitator for mixing microfluids. After two microfluid streams are combined in a common channel, the fluid mixture is agitated as it propagates through a ratcheted pumping segment.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a sequence of nine side-view cross-sectional diagrams illustrating the observed motion of a film-boiling droplet on top of a level ratcheted surface.

FIG. 2 is a side or top cross-sectional view showing a droplet and a slug being pumped by a ratcheted channel according to an embodiment of the invention.

FIGS. 3A-J are side or top cross-sectional views showing variations of ratcheted channel designs according to several embodiments of the invention.

FIGS. 4A-B are side or top cross-sectional views showing variations of ratcheted channel designs according to several embodiments of the invention.

FIGS. 5A-B are schematic diagrams of a heat exchanger incorporating a ratcheted channel to induce circulation at a desired pump activation temperature according to embodiments of the present invention.

FIGS. 6-8 are schematic diagrams of various heat exchangers incorporating several ratcheted channel segments to induce circulation at a desired pump activation temperature according to embodiments of the present invention.

FIG. 9 is an axial cross-sectional view of a ratcheted channel including vents and secondary gas channels according to an embodiment of the invention.

FIG. 10 is a side or top cross-sectional view illustrating a fluid mixer incorporating a ratcheted channel that serves to both pump and agitate a mixture of liquids.

FIG. 11 is a side or top cross-sectional view illustrating an embodiment of the invention including gas vents and a secondary channel for carrying gas vapor.

FIG. 12 is a side or top cross-sectional view of a droplet ejection device incorporating ratcheted channels according to an embodiment of the present invention.

FIG. 13 is a side or top cross-sectional view of a ratcheted channel whose surface is fabricated with a microstructure to provide the surface with a superhydrophobic property to reduce drag in the channel according to an embodiment of the invention.

FIGS. 14A-B are longitudinal and axial cross-sectional views, respectively, of a concentric flow, counter-current heat exchanger incorporating a ratcheted outer channel according to an embodiment of the present invention.

DETAILED DESCRIPTION

Various embodiments of the invention take advantage of a novel phenomenon discovered by the inventor wherein a liquid adjacent to a ratcheted surface experiences spontaneous movement when the ratcheted surface is hotter than the liquid and when the drag of the liquid flowing along the ratchet surface is negligible. In particular, this phenomenon is observed in film boiling droplets on a ratcheted surface heated above the Leidenfrost temperature of the liquid. In film boiling, the droplet is suspended above the surface on a cushion of vapor, thereby eliminating wetting contact with the surface and dramatically reducing drag forces. FIG. 1 is a sequence of nine cross-sectional diagrams illustrating the observed motion of a film-boiling droplet 100 along the length of a level ratcheted surface 102. Liquid droplet 100 is suspended on a vapor cushion 104, reducing the friction between the droplet 100 and surface 102. In this example, droplet 100 is composed of liquid nitrogen (boiling point is 77 K), and ratcheted surface 102 is composed of brass at room temperature. However, similar results can be observed with water droplets, ethanol droplets, and 1,1,1,2 tetrafluorethane (R134a) droplets on metal or plastic ratchet surfaces heated in each case above the Leidenfrost temperature of the liquid. The ratchet height in this example is H=0.3 mm and the ratchet length L=1.5 mm. Although the droplet shape changes, the mean horizontal droplet radius is approximately equal to the ratchet length L, so that the droplet spans two steps of the ratchet. The nine sequential diagrams are separated in time by a time interval of 8 ms, and the droplet moves with a constant velocity of about 3.5 cm/s. No external forces are present (other than gravity, oriented perpendicular to the movement).

In contrast with FIG. 1 which shows a droplet free to move on a level surface, FIG. 2 shows a droplet 200 in a ratcheted channel 204 fabricated within a plate 208. By confining the fluid to channels, the phenomenon can be used to pump droplets in fluidic circuits. Channels also make it possible to create fluidic pump devices that operate at various orientations with respect to gravity. Moreover, ratcheted channels provide various other advantages that will become more apparent as the various embodiments of the invention are described in detail. In the context of the present description, a channel is defined to include both open channels (e.g., grooves in a surface) or closed channels (e.g., tunnels or pipes). Channels may be formed with any number of discrete linear walls, with curved walls, or with a combination of the two. In addition to a droplet 200, the liquid in the channel 204 may also take the form of a slug 202 or a continuous stream. The surface 206 of channel 204 is shaped to have a ratchet profile so that when the surface 206 is heated appropriately the droplet 200 or slug 202 is pumped through the channel. Although it is sufficient for just one of the walls of the channel to be ratcheted, it is preferable in most applications if two or more of the walls are ratcheted to provide additional pumping power.

In the context of this description a ratchet or a ratcheted surface is defined to be a surface shaped to have a plurality of topographic ratchet features, each of which is locally asymmetric in the longitudinal direction, i.e., the surface shape of each ratchet feature (e.g., each "tooth") as seen when traveling in one direction through the channel is not the same as the shape seen when traveling in the opposite direction through the channel. In various embodiments, the ratchet has a periodic or approximately periodic ratchet pattern. The prototypical ratchet shape is the periodic sawtooth ratchet, illustrated in FIG. 3A. As shown in the figure, a ratchet of this type is characterized by a sawtooth height H and length L. Opposite walls 304 and 306 of channel 302 both have the same sawtooth ratchet shape. The channel has a mean diameter D and contains an exemplary droplet 300 and slug 308. The parameters L, H, and D may be independently altered to produce other ratcheted channels, as shown in FIGS. 3B, 3C, and 3D, respectively. In addition, the absolute scale of the ratcheted channel can be varied as well. Ratcheted channels also can be tapered, as shown in FIG. 3E, which shows a channel whose mean diameter decreases from a mean diameter D1 to a mean diameter D2. FIG. 3F shows a ratcheted channel where the opposing faces are ratcheted such that their teeth are displaced in the longitudinal direction by a distance ΔL. Displaced ratchets such as this provide a more uniform channel diameter and thus may be used in some embodiments to reduce drag due to fluid bottlenecks between opposing ratchet peaks. In addition to the sawtooth-shaped ratchet, FIGS. 3G-J illustrate various other ratchet shapes that, like the sawtooth ratchet, have a longitudinally asymmetric topography.

As shown in FIG. 4A, a ratcheted channel 402 with exemplary droplet 400 may have differently shaped opposing surfaces or walls 404 and 406. In this case, wall 404 is not ratcheted while wall 406 has a sawtooth-shaped ratchet. Similarly, FIG. 4B illustrates a channel 412 with exemplary droplet 400 where channel walls 408 and 410 are both ratcheted, but with different ratchet shapes. In addition to allowing different walls in a channel to have different ratchet shapes, it should also be noted that any of the above ratchet shapes can be combined in series to form ratchets with hybrid shapes. Thus, although it is preferable for simplicity of fabrication to have locally periodic ratchet shape, the shape of the ratchet can change along the length of the channel. In addition to open channels with three walls, open channels may also be formed with just two walls, or with a wall having a parabolic, circular, elliptical, or other curved shape. In addition, closed channels (i.e., tunnels) can be formed having three walls, four walls, or more walls, as well as with curved walls.

Ratcheted channels according to various embodiments of the invention may be fabricated using many different techniques which are appropriately selected depending on the size of the channels, the type of materials, and the requirements of the pumping application. For ratchets formed in metal substrates, various known metal machining techniques may be used. Other materials and appropriate fabrication processes may also be used to form ratchets, such as molding techniques for polymer materials. For ratchets formed in semiconductor and other substrates, various techniques well known in the art of micro fluidic system fabrication may be used, such as surface micromachining using standard micro-electro-mechanical systems (MEMS) fabrication processes, and various types of etching techniques (e.g., wet etching, dry etching, anisotropic etching, isotropic etching). Details regarding relevant microchannel fabrication techniques can be found, for example, in US Pat. 6,521,516, US Pat. 6,785,134, US Pat. 6,130,098, US Pat. 5,544,696, US Pat. 5,522,452, and US Pat. 6,071,081, which are all incorporated herein by reference. Imprinting and molding techniques may also be used for plastic and polymer materials. Preferably, the channels are formed or processed to have precisely controlled surface quality, e.g., using cleaning methods such as oxide etching, solvent cleaning, sonification, and/or rinsing, depending on the substrate material. In addition, in some embodiments it may be preferable to fabricate the ratcheted surface so that different portions are composed of distinct materials, as illustrated in FIG. 3G where ratchet teeth 312 are composed of a different material than ratchet substrate 310. The two materials may differ with respect to one or more material properties such as thermal conductivity, heat capacity, surface roughness, and hydrophobicity. For example, primary substrate material 310 could be a metal while secondary substrate material forming ratchet teeth 312 could be a plastic. Although a portion of the substrate may possibly be a thermal insulator, at least one portion of the substrate in the ratcheted segment of the channel is preferably a thermal conductor that efficiently transfers heat from an external heat source to the walls of the channel. It may be of advantage in some embodiments to vary the substrate materials along the length of a channel to provide differences in thermal conductivity, heat capacity, or other properties along the length of the channel. Such variations may be provided in either the ratcheted or smooth portions of the channel, or both. Such variations may be useful to control the heat flow along the channel, and/or to create slight differences in different pump activation temperatures in different areas of the ratchet segment. Such adjustments may be used to control ratchet performance.

Both the working fluids and material substrate for the channels are selected with consideration to the desired operating temperature of the device. In pumps that rely upon film boiling to reduce drag, the fluid is preferably selected so that the Leidenfrost point of the fluid is at or near the desired pump activation temperature. For example, R134a has a Leidenfrost point just above room temperature, making it suitable for applications where the desired pump activation temperature is just above room temperature. Other fluids that may be used include water, ethanol, liquid nitrogen, and any of various customized liquids which are commercially available with specified boiling points (e.g., methyl perfluoropropylether which boils at approximately 30 C and can be used for a pump activation temperature of 70–80 C). Although the onset of pumping occurs at the pump activation temperature, it should be noted that the pumping force varies (not necessarily linearly) as the operating temperature continues to rise above the pump activation temperature. It is preferable in some embodiments of the invention that the pump activation temperature is just below the desired operating temperature (e.g., within a few degrees). In other embodiments, it is preferable that the pump activation temperature is substantially below the desired operating temperature range, so that the desired operating temperature range corresponds to an approximately linear dependence of the pumping force on operating temperature. In most embodiments, the thermal energy used to power the pump is preferably ambient or waste heat in the environment thermally coupled to the ratcheted channel. In some embodiments, however, it may be preferable to heat the ratcheted channel using power from an electrical, chemical, or other power source.

In one embodiment of the invention, illustrated schematically in FIG. 5A, a closed-cycle channel 500 with a ratcheted segment 502 provides a simple and elegant thermally-powered heat exchanger. Ratcheted segment 502 is positioned at the hot end 503 which is thermally coupled to a source of heat (not shown) through a portion of the substrate material. When the temperature T1 of the ratcheted segment 502 rises above the pump activation temperature, the working fluid in the channel is pumped by the ratcheted channel, causing the fluid in the closed-cycle channel 500 to circulate. As the fluid circulates, heat is carried from hot end 503 to cold end 504 which is coupled through a portion of the substrate material to a heat sink at temperature T2. After cooling in the cold end 504, the fluid continues to circulate back to the hot end 503 where it is heated and pumped by the ratcheted segment 502. When the temperature of ratcheted segment 502 drops below the pump activation temperature, the fluid stops circulating automatically.

Advantageously, this heat exchanger is powered by the very heat to be dissipated. It thus requires no additional power source to pump the fluid, and is highly reliable since there is no dependence on additional pumping components, no additional power sources required to produce pumping, no additional heat generated by additional pumping components, and no moving parts. It may also be noted that all prior teaching in the art considers film boiling in a heat exchanger to be a serious problem to be avoided. In sharp contrast, heat exchangers of the present invention take advantage of film boiling in the ratcheted segment of the channel. Moreover, the heat transfer rate in a ratcheted channel is higher than that in a conventional non-ratcheted channel. In addition, to the extent that heat transfer rates are reduced by film boiling, other steps can be taken to provide the desired heat transfer in these ratcheted heat exchangers. For example, FIG. 5B shows a heat exchanger in which the heat transfer from the channel 506 to the working fluid takes place both in a ratcheted segment 508 and an adjacent non-ratcheted segment 510 in the hot end of the cycle. To provide efficient heat transfer to the working fluid just prior to entering the ratcheted segment, the non-ratcheted segment 510 is preferably located just upstream from the ratcheted segment 508. The heat source 514 (e.g., a microprocessor) is preferably located proximate to the ratcheted section 508 so that it is the hottest portion of the channel. In some applications, it may be advantageous to also include a heat dissipation element 512 (e.g., made of a heat conductive material such as copper) in between the heat source 514 and the channel 506 to facilitate spreading the heat from the heat source 514 to the non-ratcheted segment 510. Note that heat dissipation element 512 may be composed of a thermally conductive portion of the substrate material itself. A thermally conductive material 516 in the cold end dissipates heat from the channel to a heat sink such as ambient air, external fluid, or other substance. This embodiment is otherwise identical to that shown in FIG. 5A. Heat transfer to the working fluid can also be enhanced using various other techniques. For example, FIG. 6 shows a heat exchanger whose closed-cycle channel 600 transfers heat from a hot end 602 at temperature T1 to a cold end 604 at temperature T2. Segments of channel 600 in hot end 602 are ratcheted to provide pumping when T1 increases above the pump activation temperature. Note that heat transfer to the working fluid may take place in both ratcheted and non-ratcheted segments of channel 600 in hot end 602. To increase heat transfer, the channel snakes through the hot end 602 as well as the cold end 604. In some embodiments, the channel segments in hot end 602 may be thermally insulated from channel segments in cold end 604.

In another embodiment of a heat exchanger according to the present invention, two distinct closed-cycle heat exchangers, each like that just described in relation to FIG. 6, are thermally coupled to form a single cascaded heat exchanger, as shown in FIG. 7. A first closed-cycle channel 700 circulates a first working fluid between hot end 704 at high temperature T1 and middle section 706 at intermediate temperature T2. A second closed-cycle channel 702 circulates a second working fluid between middle section 706 and cold end 708 at temperature T3. As temperature T1 rises above pump activation temperature for the first fluid in the first channel 700, heat exchange carries heat from hot end 704 to middle section 706. Similarly, when T2 rises above pump activation temperature for the second fluid in the second channel 702, heat exchange carries heat from middle section 706 to cold end 708 which is coupled to a heat sink at temperature T3. The fluids in the two channels 700 and 702 may be selected to control the pump activation temperatures of the two exchangers. The relative sizes and heat exchange capacities of the two exchangers may also be adjusted. Thus, this cascaded system can provide cooling of different components at different temperatures and with different heat exchange capacities. Extending the principles of this example, multiple heat exchangers of differing capacities can be thermally coupled to satisfy various cooling requirements.

FIG. 8 illustrates an embodiment of a heat exchanger having a single closed-cycle channel 800 divided into a hot end 802 at temperature T1 containing a first ratcheted segment of channel 800, an intermediate section 804 at temperature T2 containing a second ratcheted segment of channel 800, and a cold end 806 coupled to a heat sink at temperature T3. This embodiment uses a two-component working fluid, where the two components have different boiling points. In one mode of operation, the lower-boiling-point component can provide pumping and cooling in the hot end 802 of the cycle, providing complete forced-convection liquid cooling in the intermediate section 804. In another mode, the lower-boiling-point component provides pumping and cooling in the intermediate section while the higher-boiling-point component (and any residue of the lower-boiling-point component) provides pumping and cooling in the hot end 802. In these and other heat exchanger embodiments, the volume of working fluid present in the channel or channels is preferably sufficient to ensure that fluid will be present in the hot end irrespective of the device orientation, thereby allowing orientation-independent operation. In some embodiments it may be preferable to provide an over-pressure valve or other device to regulate the fluid pressure in the heat exchanger. For example, the heat exchanger of FIG. 8 has an over-pressure valve 808 which releases gas when the fluid pressure reaches a predetermined threshold. Other pressure-regulation devices well-known in the art may be used as well.

FIGS. 14A-B illustrate a concentric counter-current heat-exchanger employing a ratchet pump according to an embodiment of the present invention. FIG. 14A is a longitudinal cross-sectional view of a portion of the heat exchanger, and FIG. 14B is an axial cross-sectional view of the same. A central channel 500 carries a hot stream of fluid in one direction, while an annular outer channel 504 carries a working fluid 502. The inner surface of the outer channel 504 is ratcheted. As a result, when the hot stream within the central channel 500 reaches the pump activation temperature, the ratcheted surface is heated and the fluid 502 in the outer channel 504 is pumped, providing counter-current heat exchange between the two fluids. In a variation of this embodiment, the direction of the ratchets is reversed so that the two fluids flow in the same direction, rather than counter-current.

In various embodiments of the invention, film boiling in the heated ratcheted channels results in a phase transition of a portion of the working fluid from liquid to gas. Accordingly, in some embodiments the channels may be provided with vents (e.g., pores, slits, holes, or other openings) that allow the gas to escape from the main portion of the channel carrying the liquid phase. FIG. 9 is an axial cross-sectional view of a ratcheted channel 900 having four walls 902 containing an exemplary droplet 904. It should be noted again that three channel walls may be used to form a channel having a triangular cross-section, or multiple walls may be used to form a channel having any polygonal cross-section. Vents 908 in the corners of walls 902 allow gas to escape from the main channel 900 into secondary longitudinal channels 906. These secondary channels 906 allow the gas to freely propagate either with or against the flow of the liquid 904 in channel 900. Many variations on this principle are possible, including providing separate channels 1106 for the gas, connected to the main channel 1102 by connecting passages 1108, as shown in FIG. 11. As droplet 1110 passes through ratcheted segment 1104, a vapor phase of the droplet fluid escapes through vents

1108 and flows out through separate channel 1106. Channels 1106 and 1102 may be recombined at a later stage in the fluid cycle. In other variations, portions of the channel walls may be fabricated of porous material to allow gas to escape into secondary channels for gas propagation. In some embodiments it may also be preferable to gradually taper the channel diameter (e.g., as shown in FIG. 11) to account for the loss of liquid due to the phase transition from liquid to gas in the ratcheted segment of the channel.

Heat exchangers such as those described above may be used in a variety of thermal management applications including, for example, large-scale industrial heat exchangers and fluid cooling, integrated cooling in lab-on-a-chip devices, chemical microreactors, and microelectronics. For example, a heat exchanger may be integrated directly into the semiconductor chip it is designed to cool, e.g., by processing the side of the chip opposite the side containing the microelectronics and/or microreactors. A heat exchanger can also be separately fabricated and subsequently attached to the chip using a material that provides thermal coupling.

In other embodiments of the invention, a ratcheted channel is used to enhance mixing of two or more fluids. FIG. 10 illustrates an embodiment illustrating a fluid mixer according to one embodiment of the invention. Two channel segments 1002 and 1004, carrying first and second fluids, join to form a single channel segment 1006 where the two fluids are combined to form a two-component mixture. Similarly, multiple channel segments may join to combine multiple fluids to form a multi-component mixture. Channel segment 1006 contains a ratcheted segment 1000 that pumps the fluid mixture when the temperature T1 of segment 1000 rises above a pump activation temperature. As the fluid mixture passes through ratcheted segment 1000, it is also agitated by transient contact with the hot ratcheted surface and thereby enhances the mixing of the two components. This technique for enhancement of mixing across the fluid streams may be used to realize a non-mechanical micromixer in microchannels where slow diffusion rates and laminar flow inhibit mixing. Such micromixers are of use in a chemical microreactors, lab-on-a-chip (LOC) devices, and other small-scale applications.

In another embodiment of the invention, an array of ratcheted channels, such as channels 1200, 1202, 1204 may be used to eject droplets 1212, 1214, 1216 in a droplet ejection device. Such a device may be used to spray uniformly sized droplets at uniform rates, which may be useful in various applications. Each channel can be individually controlled by separate heating elements 1206, 1208, 1210, or all can be heated uniformly by a single source (not shown).

In various embodiments, the drag of the working fluid as it flows through the ratcheted pumping section may be reduced by virtue of a superhydrophobic or analogous surface property of the channel surface in the pumping section. FIG. 13, for example, shows a ratcheted channel 1300 whose surface is fabricated with a small topographic surface modification 1304 at the micrometer-scale or smaller. This microscale or nanoscale surface feature 1304 significantly reduces the contact between the surface 1304 and the liquid 1302, dramatically reducing wetting and hence drag. In addition to providing the ratcheted segment of the channel with surface feature 1304, the inside of the entire channel is preferably provided with the surface feature 1304 as well. This technique for reducing the drag may be used to reduce the pump activation temperature below the temperature that would otherwise be required.

CLAIMS

1. A non-mechanical fluid transport device comprising:
a substrate material; and
a channel formed in the substrate material for carrying a working fluid in liquid phase;
wherein the channel comprises a ratcheted segment for non-mechanically pumping the working fluid, wherein the ratcheted segment comprises a plurality of ratchet features, wherein each of the ratchet features is locally asymmetric in a longitudinal direction of the ratcheted segment.

2. The device of claim 1 wherein the ratchet features are periodic in the longitudinal direction.

3. The device of claim 2 wherein the ratchet features have a sawtooth profile.

4. The device of claim 1 wherein the ratcheted segment has multiple surfaces with an asymmetric topography in the longitudinal direction.

5. The device of claim 1 wherein the channel includes vents for carrying a vapor phase of the working fluid.

6. The device of claim 1 wherein a portion of the channel has a surface with a superhydrophobic surface property.

7. The device of claim 1 further comprising a thermally conductive portion for conducting heat from a heat source to the ratcheted segment.

8. The device of claim 1 wherein the channel is a closed-cycle channel having a hot portion and a cold portion, and wherein the hot portion of the channel comprises the ratcheted segment.

9. The device of claim 8 further comprising a first thermally conductive portion for conducting heat from a heat source to the hot portion, and a second thermally conductive portion for conducting heat from the cold portion to a heat sink.

10. The device of claim 1 wherein the channel comprises multiple segments that join into the ratcheted segment for combining and mixing multiple fluids.

11. The device of claim 1 further comprising an array of channels comprising ratcheted segments.

12. A non-mechanical fluid transport method comprising:

providing a channel formed in a substrate material;

providing a working fluid within the channel; and

heating the channel to a temperature above a pump activation temperature to pump the working fluid through the channel;

wherein the channel comprises a ratcheted segment comprising a plurality of ratchet features, wherein each of the ratchet features is locally asymmetric in a longitudinal direction of the ratcheted segment.

13. The method of claim 12 wherein the pump activation temperature is equal to a Leidenfrost point of the working fluid.

14. The method of claim 12 wherein heating the channel comprises heating the ratcheted segment to induce film boiling of the working fluid in the ratcheted segment.

15. The method of claim 12 wherein heating the channel comprises conducting ambient thermal energy to the channel.

16. The method of claim 12 wherein the channel is a close-cycle channel having a hot portion and a cold portion, wherein the hot portion of the channel comprises the ratcheted segment, and wherein the method further comprises dissipating heat from the cold portion of the channel.

17. The method of claim 12 wherein a portion of the channel has a surface with a superhydrophobic surface property.

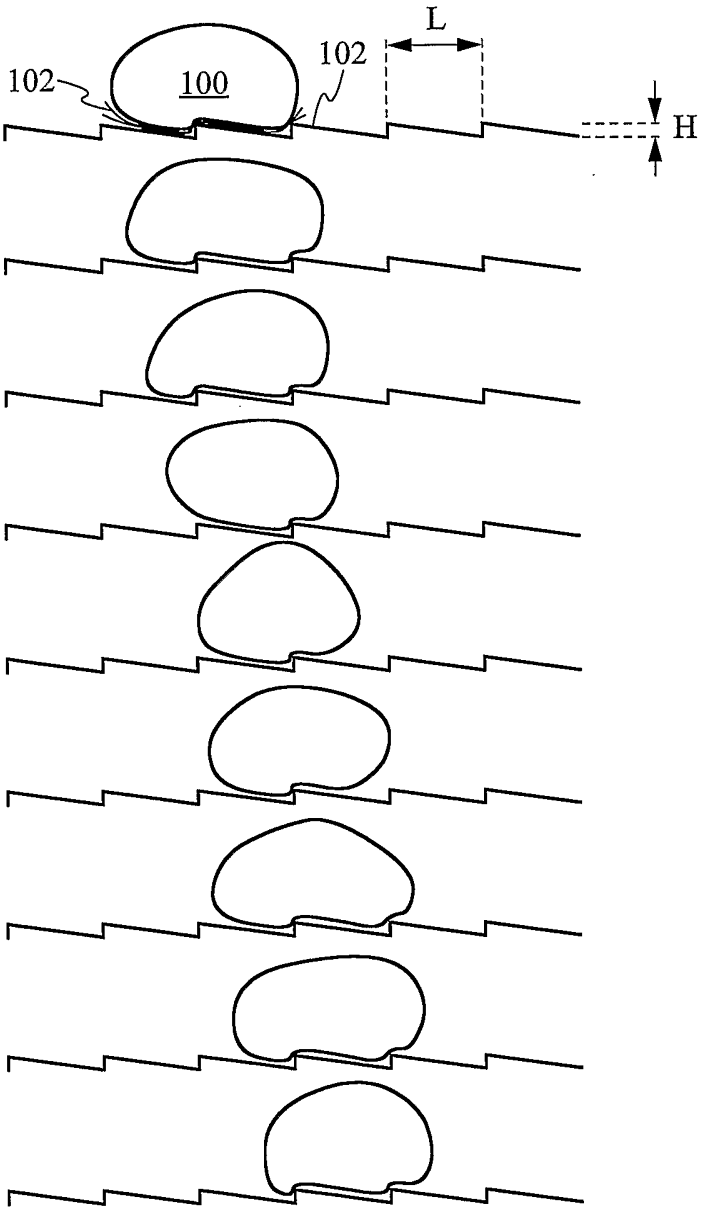
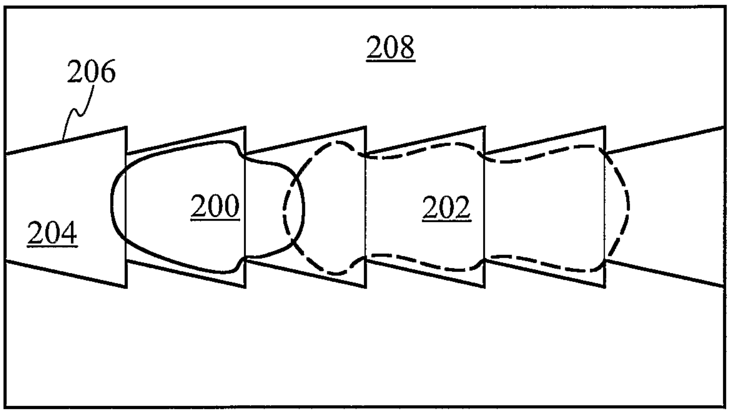


FIG. 1

FIG. 2



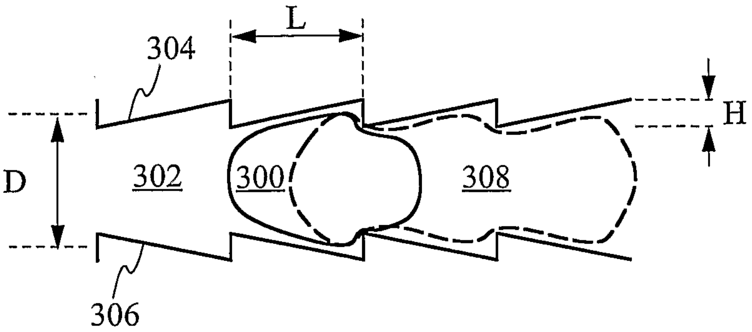


FIG. 3A

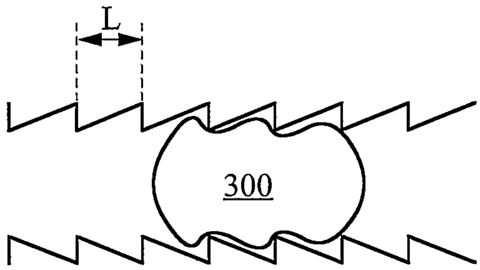


FIG. 3B

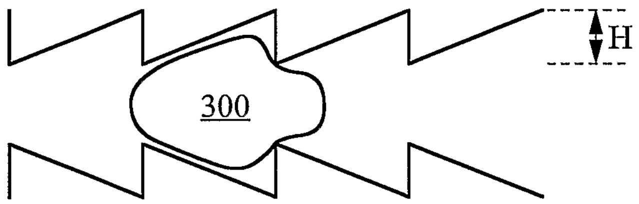


FIG. 3C

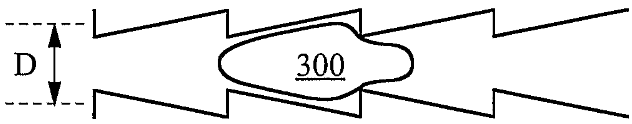


FIG. 3D

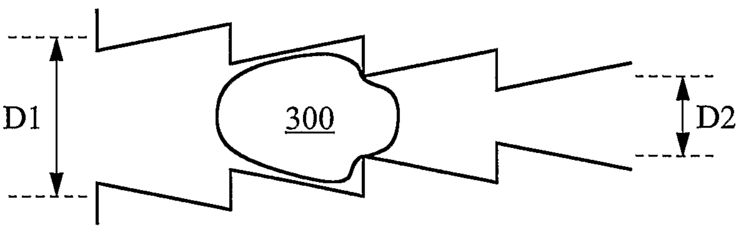


FIG. 3E

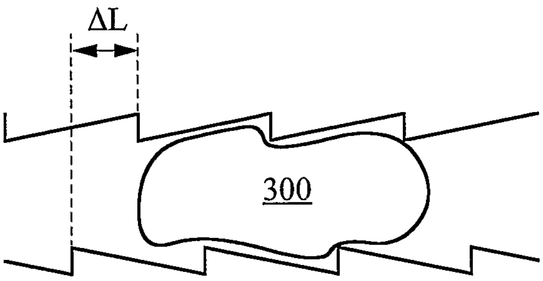


FIG. 3F

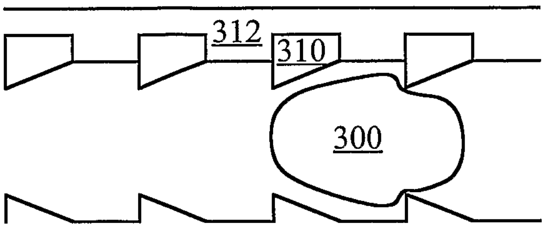


FIG. 3G

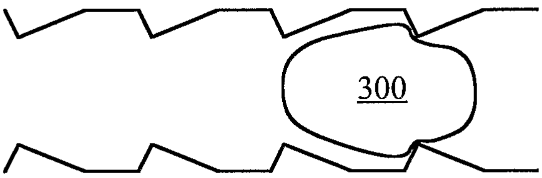


FIG. 3H

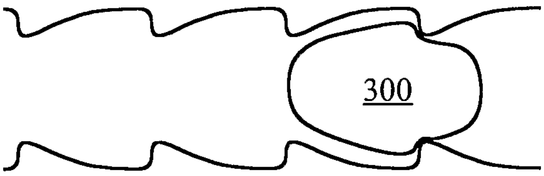


FIG. 3I

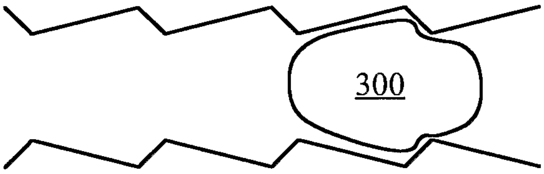


FIG. 3J

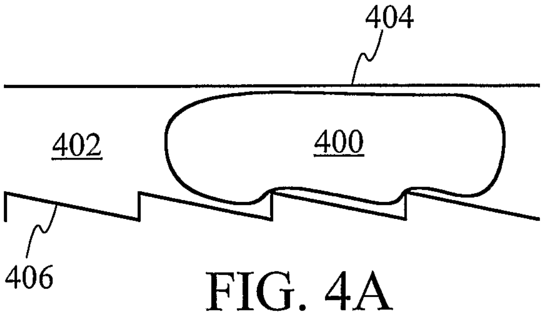


FIG. 4A

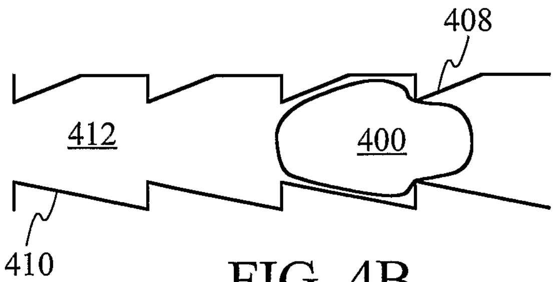


FIG. 4B

FIG. 5A

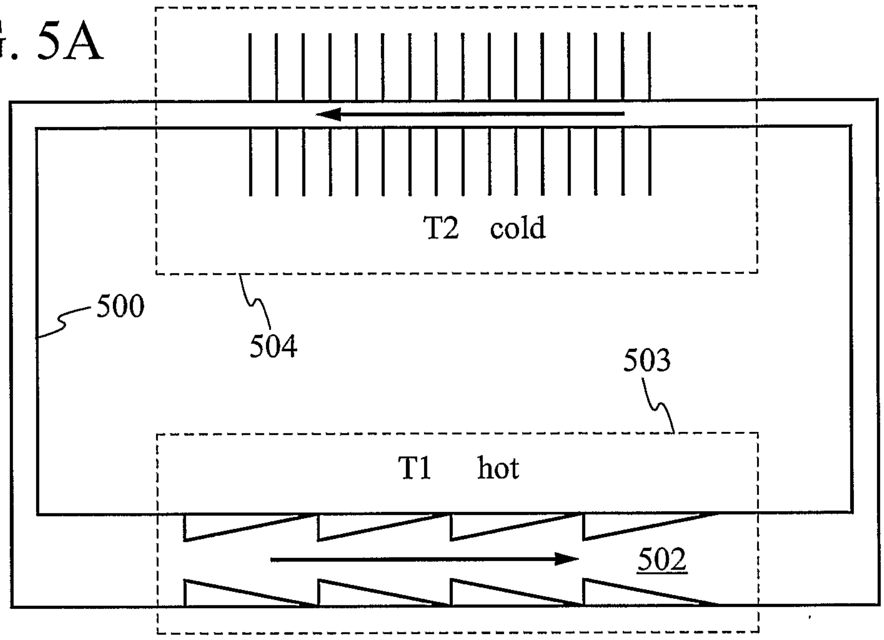
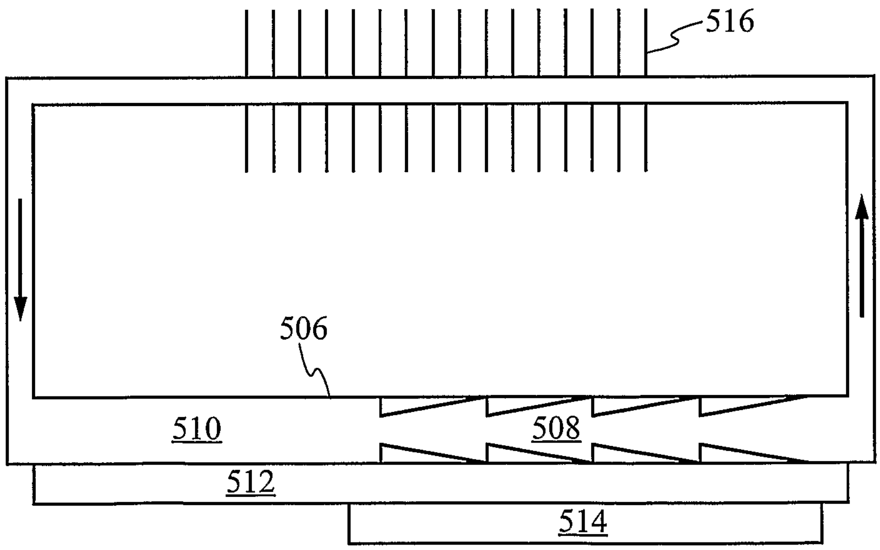


FIG. 5B



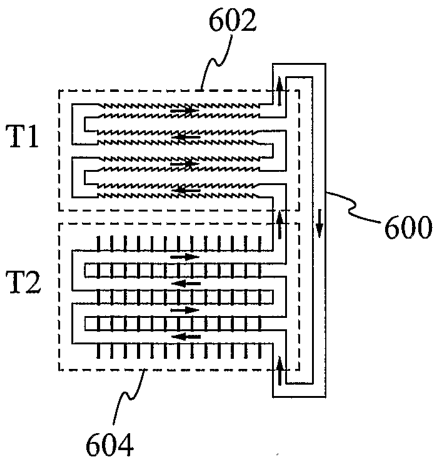


FIG. 6

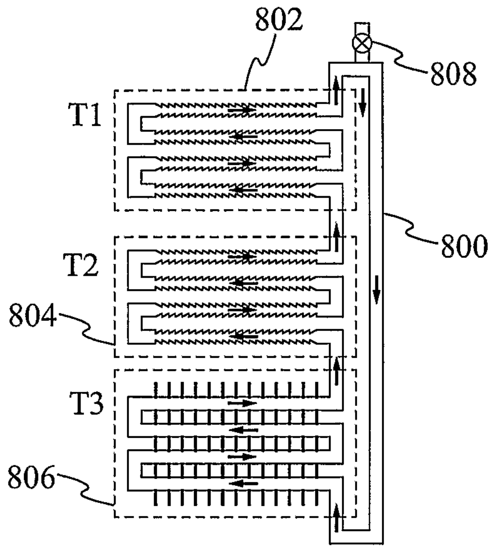


FIG. 8

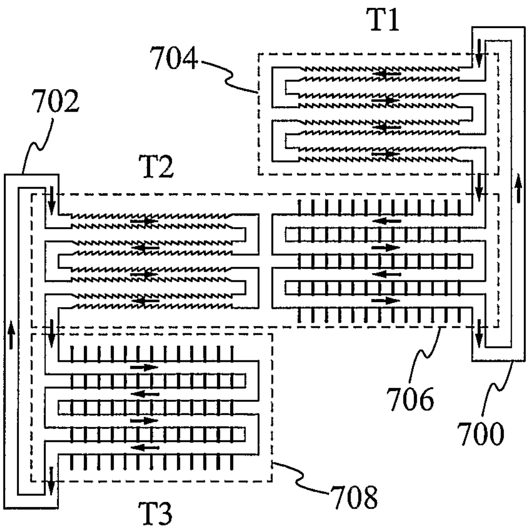
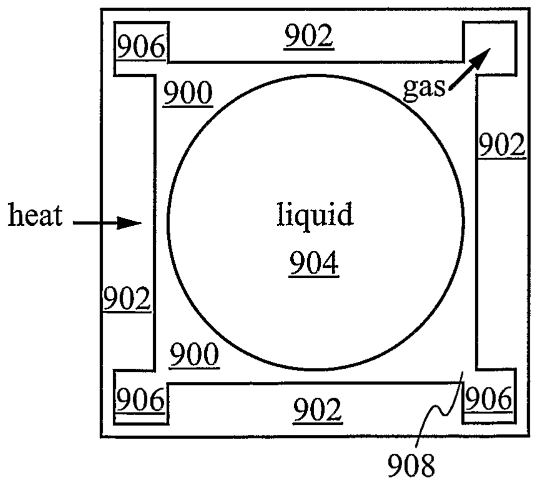


FIG. 7

FIG. 9



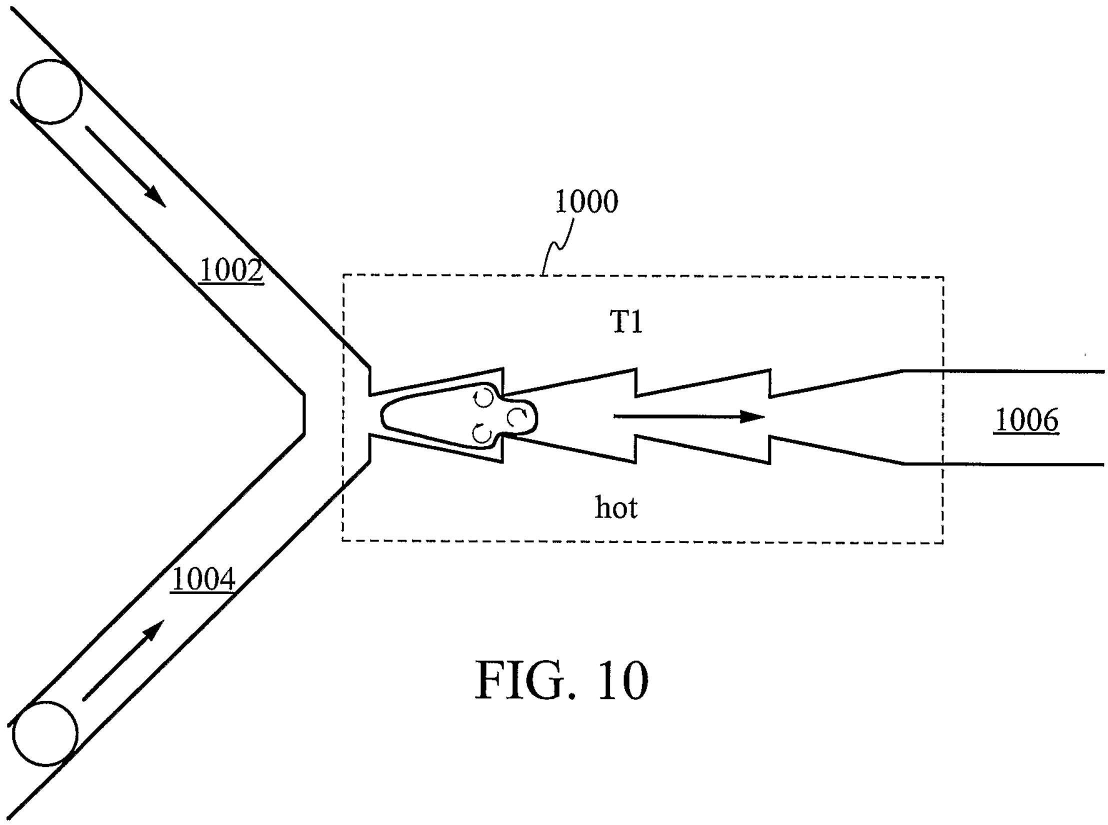


FIG. 10

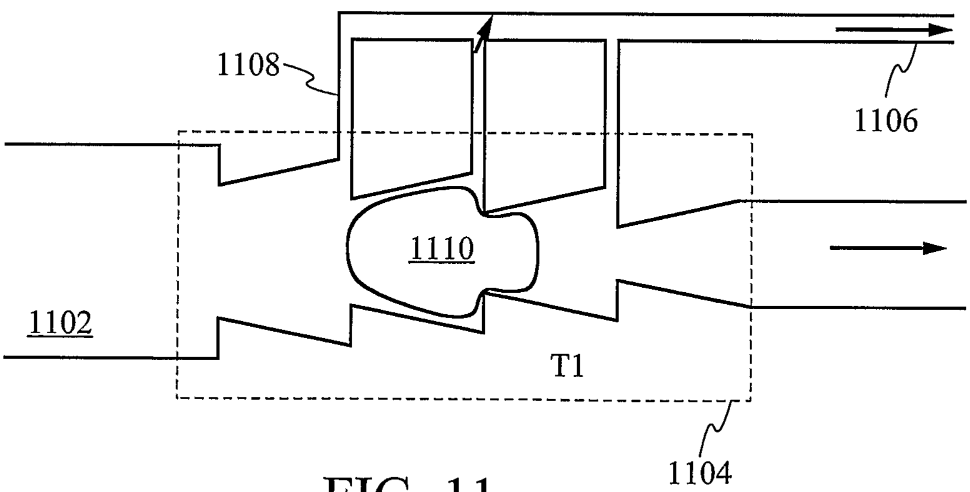


FIG. 11

FIG. 12

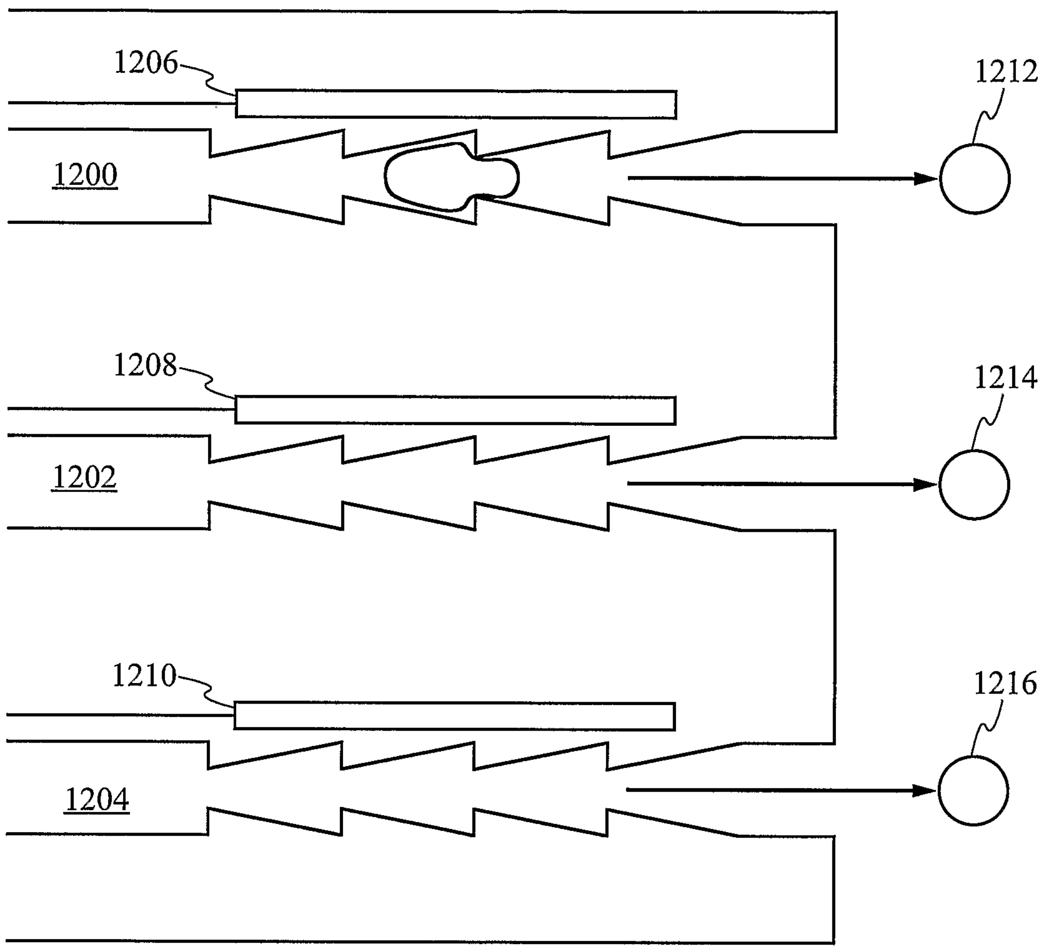


FIG. 13

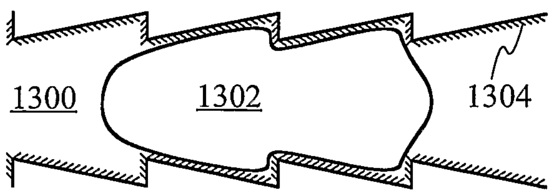
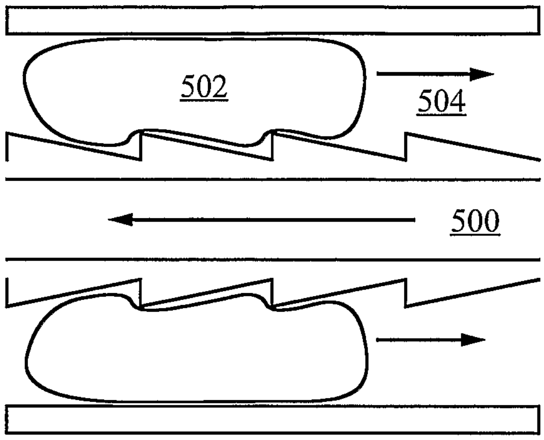


FIG. 14A



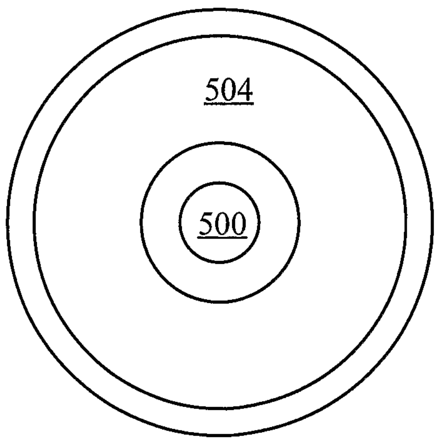


FIG. 14B

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US06/12395

A. CLASSIFICATION OF SUBJECT MATTER
IPC: **F04B 19/24**(2006.01)

USPC: 417/53,207
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)
U.S. : 417/53,207

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)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2004/0146409 A1 (LEE et al) 29 July 2004 (29.07.2004), see figure 4B.	1-4,7,11,12
X	US 2002/0187503 A1 (HARROLD et al) 12 December 2002 (12.12.2002), see figures 13 and 14.	1-4,10,11
X	US 2005/0095143 A1 (BERNARD et al) 05 May 2005 (05.05.2005), see figures 11 and 12.	1-4,7,10-12

☐ 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 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
14 August 2006 (14.08.2006)	27 SEP 2006

Name and mailing address of the ISA/US	Authorized officer
Mail Stop PCT, Attn: ISA/US Commissioner for Patents P.O. Box 1450 Alexandria, Virginia 22313-1450 Facsimile No. (571) 273-3201	Michael Koczo, Jr. Telephone No. 703-308-0861