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(71) Applicant (for all designated States except US): **RAMOT**

AT TEL-AVIV UNIVERSITY LTD. [IL/IL]; Tel Aviv
University Campus, The Senate Building, Floor-1, P.O.
Box 39296, 61392 Tel Aviv (IL).

(72) Inventors; and

(75) Inventors/Applicants (for US only): **ROSENFELD,**
Moshe [IL/IL]; PO Box 84, 42870 Beit Halevi (IL).
ZEMACH, Efi [IL/IL]; 23 Nili Street, 76217 Rehovot
(IL).

(74) Agent: **REINHOLD COHN AND PARTNERS;** P.O.B.

13239, 61131 Tel Aviv (IL).

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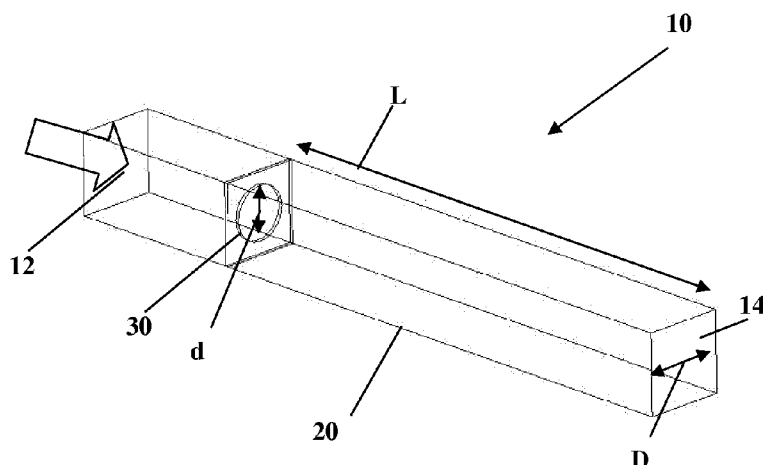


FIG. 1

(57) Abstract: A heat exchange device is presented, the device comprises one or more channels having inlet and outlet ports configured to direct flow of a predetermined fluid to and from said one or more channels. Said one or more channels of the device comprise at least one channel having at least one orifice of a predetermined hydraulic diameter configured such that a flow of said predetermined fluid through said orifice and through said channel thereby generating a vortex ring-like fashion of the flow within the channel to provide efficient heat transfer by the fluid.



- 1 -

HEAT EXCHANGER DEVICE

FIELD OF INVENTION

5 The present invention relates to a heat exchange device, and in particular to a miniature scale heat exchange device.

REFERENCES

10 The following is a list of references that can be used for better understanding of the background of the invention:

1. Lesshafft L, Huerre P and Sagaut P, (2007), Frequency selection in globally unstable round jets, *Phys. Fluids*, **19**, doi: 054108.
2. Obabko AV and Cassel KW, (2002), Navier-Stokes Solutions of Unsteady Separation Induced by a Vortex, *J. Fluid Mech*, **465**, pp. 99-130.
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4. Benteboula S. Lauriat G., (2009), Numerical simulations of anisothermal laminar vortex rings with large density variations, *International Journal of Heat and Fluid Flow*, Vol. 30, Issue 2, pp. 186-197
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BACKGROUND

25 Heat transfer is a major obstacle in the miniaturization process of high power elements, such as CPUs, GPUs etc. Conventional heat exchangers in general and heat sinks in particular that are based on fins and fans cannot cope with high power density within a reasonable volume limit. For example, existing air-based heat sinks need a volume of 200-2000cm³ (not including the fan) to dissipate 100-150Watts.

- 2 -

Therefore, alternative heat dissipating solutions are being sought being capable for heat removal from modern high power miniature devices. Some of the most popular solutions utilize coolant flow through microchannels. Typically, such “channels based” heat exchange devices are relatively small, and can be in the sub-
5 millimeter range. The small size of these devices lead to the operation with small Reynolds numbers, indicating laminar flow of the coolant, and yielding weak convection resulting in low heat transfer coefficients. To compensate for the low convection, liquids (mostly water) with high heat capacity are used as coolant. Some experimental studies have been published relating to the friction factor, laminar to
10 turbulent transition and pressure drop in microchannels. The Nusselt number for various liquids and gases were presented as well. Another known air-based alternative that gained recently popularity is using synthetic (micro) jets.

GENERAL DESCRIPTION

15 There is a need in the art for a novel heat exchange system utilizing flow of a coolant/heater fluid (gas and/or liquid) in the vicinity of a surface (e.g. of a body) to be cooled/heated.

The present invention provides for a novel technique utilizing one or more channels (e.g. micro-channels) configured to direct flow of a heat exchange fluid for
20 providing high efficiency heat exchange.

As indicated, multiple techniques have been developed in the field of heat exchange, including different techniques for enhancing heat transfer in microchannels by adding fins, pins or grooves. The use of liquid cooling in microchannels while being a necessity when dealing with heat fluxes beyond 100 Watt/cm², suffers from severe
25 disadvantages when used for electronic equipment cooling. Liquid systems are usually more complex than air systems and consequently their reliability is lower and the maintenance costs are high. Furthermore, the pressure drop increases significantly because of the small size of the microchannels and the high density of the liquids. Hence, air cooling is preferred whenever possible. The implementations of the
30 recently developed air-based heat exchange systems using synthetic (micro) jets, however, do not show better performance as compared to the conventional solutions, except for those using smaller volume. The *Nu* number that could be obtained is in a range of 4-23, depending on the operating frequency.

- 3 -

Thus, while many air based cooling techniques are widely used, these techniques require large volume for the air to flow through fins or grooves. Still these techniques are somewhat limited in their performances. Some alternative techniques utilize coolant flow through microchannels, which enables miniaturization of the heat exchange device but typically provides laminar flow of the coolant (i.e. flow characterized by low Reynolds number). Such laminar flow of the coolant is limited in convection and mixing of the coolant portions flowing near the walls of the microchannels with the coolant portions flowing in the center of the stream. In order to compensate for the low convection, liquids (e.g. water or water based liquids) are used as coolant fluid due to their high heat capacity. However, liquid based heat exchange system are somewhat complex, require relatively high maintenance and generally undesirable near electronic equipment. Today, air is considered as the preferred coolant for electronic components, but due to its limitation in removing high heat fluxes, liquid is chosen in many applications of high power density. According to various works, conventional air cooling systems, and in particular systems utilizing microchannels, are limited by the heat transfer of $350 \text{ Watt/m}^2 \cdot ^\circ\text{K}$.

The present application describes a novel approach for heat exchange techniques used for either heating or cooling a target element/device. The technique of the present application is operable with respectively heating or cooling fluid which preferably provides a compressible flow (e.g. subsonic flow velocity of Mach number of the order of 0.5) being directed through channels of a heat exchange system. For simplicity, such heat exchange system and the fluid flowing therein are at times referred to herein below as respectively "cooling system" and "coolant". It should however be understood that the invention should not be limited to the "cooling" embodiment and may be useful for heating as well. Accordingly, these terms should be interpreted broadly to cover both "cooling" and "heating" embodiments.

The technique of the present invention is based on the inventors' understanding that the coolant flow in a micro-channel is generally laminar, this is due to the small scale of the system which leads to relatively low Reynolds number. This is contrary to the fact that the most efficient heat exchange mechanism is typically based on convection, i.e. transport of heat by transporting of hot fluid (i.e. liquid or gas) to a relatively cool region. For this purpose, the inventors have found that more efficient heat exchange can be achieved by introduction of vortices into the

- 4 -

flowing fluid. To this end, creation of vortex ring (which will be described further below) in the fluid passing through a channel provides mixing of hot fluid from the vicinity of the channel's walls with cooler fluid flowing at the center of the channel and thus enables efficient heat exchange.

5 With regard to vortex rings, the following should be noted. Vortex rings in general are toroidal regions of rotating fluid with concentrate vorticity, typically self-propagating through the same or different fluid. Vortex rings can be formed in various ways. One of the simplest formation methods is by injecting fluid through a nozzle or an orifice. However, in general, the formation of vortex ring is inherently unsteady. It
10 has been shown that the presence of a large-scale vortex near a wall may induce an adverse streamwise pressure gradient along the wall leading to the formation of a secondary recirculation region followed by a narrow eruption of the near-wall fluid. The locally thickening of a boundary layer in the vicinity of the eruption provoked an interaction between the viscous boundary layer and the outer flow. To this end, the
15 inventors have found that creation of a vortex ring within a channel (or microchannel) provides mixing of fluid flowing at the periphery of the channel (i.e. near the walls) with the fluid flowing at the center of the channel. Thus, the fluid flowing near the wall of the channel collects heat therefrom while being repeatedly replaced to provide efficient convection and thus efficient heat exchange.

20 The inventors have found that efficient heat transfer can be achieved by utilizing the phenomena associated with a flow of fluid within an enclosure (such as a channel) while generating vortex rings along the flow. The vortex rings provide effective mixing of the fluid at the region where such phenomena occurs during the fluid flow through the channel, i.e. mixing the fluid flow components of the periphery
25 of the channel (closer to the walls) with the fluid flow components at the center thereof. The efficient mixing of fluid portions by a vortex ring during the fluid propagation through the channel provides for heat exchange by convection and thus increases the efficiency of heat exchange.

 In comparison to the conventional air-based heat exchange systems, a heat
30 exchange system configured according to the present invention provides significantly high efficiency for the same volume of the system. According to some configurations, a heat exchange system of the present invention can extract 15 Watt/cm³ and beyond. This performance enables the use of relatively smaller heat exchange systems which can provide similar or higher power density dissipation.

- 5 -

It should be noted that according to the invention the vortex rings created in a channel can survive in turbulent flow as well as in laminar flow of the fluid. The effect of vortex rings enhancing heat transfer is generally more pronounced in laminar flow in which the mixing of fluid components is relatively low (mixing due to
5 diffusion). However the technique and device of the present invention can be used to enhance heat transfer in both laminar and turbulent flow of the fluid.

The present invention thus provides a heat exchange channel (e.g. microchannel) of a certain cross-sectional dimension **D**. The channel comprises inlet and outlet ports, and has at least one orifice having a predetermined cross-sectional
10 dimension **d**. Passage of a fluid through the orifice affects a flow of the fluid through the channel by creating a vortex ring-like fashion of the flow within the channel. The geometrical parameters of the channel and the orifice(s) therein are selected in accordance with the properties of the fluid to flow in the device, as well as the flow characteristic, in order to provide efficient generation of vortex rings within the
15 channel. To this end, the more vortex rings are created, and the longer the distance they travel (or lifetime of the vortex rings), the better the heat exchange efficiency.

A heat exchange device may be formed by one or more heat exchange block units or blocks, where each of the blocks includes a certain number of channels (a single channel or an array of channels) including at least one orifice located at one end
20 of the channel(s). The heat exchange block unit is preferably made of a material composition having high heat conductivity, e.g. Copper, Aluminum or Stainless Steel, and is configured to be brought into thermal contact with a target element/structure to be heated/cooled. A manifold arrangement is provided to direct input flow towards the inlet ports of the channels and to collect/evacuate output flow from the outlet ports of
25 the channels to thereby provide flow of heat exchange fluid through the channels while avoiding mixing of input and output flows. The heat exchange fluid may be air, being forced through the channels by one or more fans.

Preferably, dimension of the orifice in the channel is about 66% of the cross-sectional dimension of the corresponding channel.

30 According to some embodiments of the invention, the heat exchange device (tube) comprises a micro-channel. The flow of the fluid within the micro-channel tube is a laminar one.

A heat exchange system of the present invention preferably includes an array of channels (e.g. micro-channels) arranged in a spaced-apart parallel relationship

- 6 -

along an axis substantially perpendicular to the general flow direction (i.e. input direction). Each channel is configured as described above. The input fluid flow is thus split into spatially separated flows through multiple channels respectively. Passage of the flow through the at least one orifice of the channels results in vortex ring-like fashion of the flow. An outer surface of such a heat exchange system may be placed in contact with a surface of a target element/structure to be heated/cooled. The vortex ring fashion of the flow increases mixing of the fluid portions within the channels and thus provides for convection type heat transfer within the fluid.

Thus, the device/system of the present invention may comprise miniature channels with one or more orifices in each channel. A heating/cooling fluid, preferably air, is forced through the orifices into the channels, generating a plurality of propagating compressible subsonic vortex rings. This set up enhances heat exchange significantly, allowing the use of very small volume heat exchangers using compressible fluid.

Thus according to one broad aspect of the present invention there is provided a heat exchange device comprising one or more channels having inlet and outlet ports to direct flow of a predetermined fluid to and from said one or more channels. Said one or more channels comprise at least one channel having at least one orifice of a predetermined hydraulic diameter, a flow of said predetermined fluid through said orifice and through said channel thereby generating a vortex ring-like fashion of the flow within the channel. The hydraulic diameter of said at least one channel may be between 100 to 1000 micrometers. Typically the device may be configured such that a ratio between a hydraulic diameter of said at least one channel and said predetermined hydraulic diameter of said at least one orifice is selected to be between 1.3 to 1.6. According to some embodiments this ratio may be equal to 1.5. Additionally, any one of the channels or orifice in the device may have a circular, rectangular or other polygonal cross section, and made of a thermally conductive material composition. For example, the said one or more channels may be made of at least one of the following materials: Copper, Aluminum and Stainless steel.

The heat exchange device may be configured to direct compressible flow of a predetermined heat exchange fluid through said at least one channel. Passage of the flow through said at least one orifice generates one or more vortex rings thereby providing efficient mixing of fluid portions from periphery of said channel with fluid portions from central region thereof.

- 7 -

The channels of the heat exchange device, or at least some of them, may be arranged together in one or more layers. Typically, at least one of said layers is configured to be in contact with a target element. The inlet ports of the channels may be arranged to face a predetermined direction for fluid input. And the heat exchange device may comprise a manifold arrangement for directing input heat exchange fluid towards the inlet ports of said one or more channels.

According to one other broad aspect of the invention, there is provided a heat exchange system comprising one or more heat exchange blocks. at least one of the heat exchange blocks comprises a plurality of channels of a predetermined hydraulic diameter, each comprising at least one orifice of a predetermined hydraulic diameter. Passage of fluid through said channels and through said orifice therein generating vortex ring downstream of said orifice with respect to a general fluid flow direction through the channel, thereby increasing efficiency of heat exchange by convection of fluid within said channels.

According to yet another broad aspect of the invention there is provided a method for use in heat transfer to and from a target element. the method comprises: providing a compressible laminar flow of a fluid through one or more channels being in contact with said target element, and directing said flow through at least one orifice located near an inlet port of said one or more channels, to thereby generate a vortex ring-like flow, providing high-efficiency heat transfer for a relatively small length of said one or more channels.

BRIEF DESCRIPTION OF THE DRAWINGS

In order to understand the disclosure and to see how it may be carried out in practice, embodiments will now be described, by way of non-limiting example only, with reference to the accompanying drawings, in which:

Fig. 1 illustrates a channel unit configured for use in a heat exchange device according to some embodiments of the present invention;

Figs. 2A-2C illustrate an example of a specific configuration of a channel unit according to the invention (**Fig. 2A**) and simulation result of fluid flowing through the channel showing velocity map (**Fig. 2B**) and temperature map (**Fig. 2C**);

Figs. 3A-3G show simulation results exemplifying generation of vortex rings' train along a channel unit of the invention, the results are shown at different simulation times;

- 8 -

Fig. 4 shows a comparison of calculated Nusselt number for as a function of the ratio between the channel's hydraulic diameter and the orifice hydraulic diameter for three values of orifice diameter;

Fig. 5 shows a comparison of calculated efficiency between a heat exchange device according to the present invention and a standard microchannel heat exchange device;

Fig. 6 shows a comparison between the thermal efficiency of heat exchange unit according to the present invention and of a standard channel based heat exchange device;

Fig. 7 shows a comparison of heat flux per contact area relative to flow rate for single layer array of heat exchange units according to the invention and for a standard channels-based heat exchange system;

Fig. 8 exemplifies a heat exchange device configured according to some embodiments of the present invention;

Fig. 9 exemplifies a heat exchange device made of a bulk material including multiple layers of microchannels according to some embodiments of the present invention;

Fig. 10 schematically illustrates a heat exchange device including several blocks/arrays of microchannel and configured to direct inlet and outlet flow to provide efficient heat exchange according to some embodiments of the present invention; and

Figs. 11A-11B show two examples of heat exchange unit/channel according to embodiments of the present invention, **Fig. 11A** exemplifies a U-shaped channel and **Fig. 11B** exemplifies a multi-orifice channel.

25 DETAILED DESCRIPTION OF EMBODIMENTS

As indicated above, the technique of the present invention is based on the inventor's understanding that one of the most effective heat transfer mechanisms is provided by convection. More specifically, formation of vortex rings in a flow of fluid along a channel provides mixing of fluid from the periphery of the channel with fluid flowing near a central region thereof. Such mixing enables evacuation and replacement of fluid portions exchanging heat with the channel's walls and thus provides heat exchange between the channels' walls (the environment) and the flow within the channel.

- 9 -

The present invention provides a heat exchange system utilizing one or more channels (e.g. microchannels) directing flow of a predetermined fluid (e.g. air or other compressible coolant) to provide heat exchange of a target structure with a heat/cold source and/or the surrounding. The channels of are configured such that a flow of heat
5 exchange fluid (coolant) therethrough generates vortex rings along the flow. It should be noted, and is indicated above, that the system and technique of the present invention are capable of heating or cooling of the target structure. However, for simplicity, the heat exchange system and the fluid flowing therein are at times described herein below as respectively "cooling system" and "coolant". It should
10 however be understood that the invention should not be limited to the "cooling" embodiment and may be useful for heating as well.

As indicated above, vortex ring is a toroidal region of rotating fluid with concentrated vorticity moving through the same or different fluid. Vortex rings are commonly created by fluid injections through a nozzle or an orifice into a wider
15 region. It should be noted that vortex rings and the formation of such is inherently unsteady.

The heat exchange system of the present invention may include one or more basic heat exchange units or blocks, where each basic block includes one or more channels or microchannels associated with a common input port. An example of such
20 basic heat exchange unit is shown in **Fig. 1** being generally designated **10**. The unit **10** includes an inlet **12** and an outlet **14**, and at least one channel, single channel **20** being shown in the present not limiting example, having a cross-section dimension (hydraulic diameter) **D** for directing a flow of a predetermined heat exchange fluid there through. The channel **20** is typically of a micrometric dimension, i.e. having a
25 hydraulic diameter of 100-1000 micrometers. The channel **20** includes at least one orifice, single such orifice **30** being shown in the present not limiting example placed therealong. The orifice **30** is of a cross-sectional dimension (hydraulic diameter) **d** smaller than that of the channel **20** and may be of a circular-like (e.g. elliptic), rectangular or any other polygonal cross-sectional shape. The orifice **30** may typically
30 be of a hydraulic diameter **d** being about 0.8D to 0.5D.

It should be noted that the term *hydraulic diameter* is well known in the art and is used for handling flow in both circular-like and non-circular tubes or channels. The hydraulic diameter D_H of a channel is defined as $D_H=4A/P$, where A is the cross-section area of the channel and P is the length of the perimeter/circumference that is

- 10 -

in touch with the fluid. Preferably, a ratio between the cross-sectional dimension of the channel (having circular-like, rectangular or any other cross-sectional shape) along different axes (longitudinal and lateral) is between 0.8-1.2 and more preferably is almost 1.

5 The basic (micro) channel unit **10** may typically be of 1-5 millimeter in length, but may be longer in some applications, and typically utilizes compressible flow of coolant/fluid. The fluid, being air or any other gas (it should be noted the for simplicity, the term “air” is used herein below but should be interpreted broadly as referring to gas of any composition), or liquid, flows through the channel, preferably
10 with subsonic velocity, i.e. Mach number of about 0.5-0.8 and in any case smaller than 1. The coolant flow is typically of a relatively small Reynolds number being in the laminar range of $2500 > Re > 1500$. This small Reynolds number results from the small cross-sectional dimension (diameter) of the channel **20** which, as indicated above, is typically of a micrometric dimension. As described above, a laminar flow
15 typically provides relatively poor mixing of the coolant and makes it difficult to obtain high heat transfer rates. Higher Reynolds number values correspond to transition to a turbulent flow, where the heat transfer is typically enhanced. To this end, Reynolds number is a dimensionless coefficient defining characteristics of a flow and is given by $Re = \rho v L / \mu = v L / \nu$, where ρ is the fluid density, v is the mean velocity, L
20 is a characteristic length/width dimension of the flow, μ is the dynamic viscosity and ν is the kinetic viscosity of the fluid.

 The inventors have studied the characteristics of the flow field in channels and microchannels like that exemplified in Fig. 1 using Computational Fluid Dynamics (CFD) tools (employing the Ansys CFD package). The numerical model was verified
25 using well established methods (such as time-step and mesh refinement studies). **Figs. 2A-2C** illustrate the specific configuration of a heat exchange unit **10** used in the numerical simulations (**Fig. 2A**), a resulting velocity map from such numerical simulation (**Fig. 2B**), and a resulting temperature map along the flow in the channel (**Fig. 2C**).

30 **Fig. 2A** illustrates a model of heat exchange unit **10** as used for the simulations below. The figure shows a section of the unit **10** from a central axis **22** to the walls **20** of the channel, i.e. the diameter **D** of the channel **20** is thus shown as **D/2** and the diameter **d** of the orifice **30** is shown as **d/2**. A coolant **40** is forced through the inlet **12** of the unit and is removed from the channel through the outlet **14** thereof.

- 11 -

Several numerical simulations considered the channel's length **L** of 6 millimeter. It should however be noted that the length **L** of the channel may be either longer or shorter than this specific value used in the simulations. The numerical simulation conducted by the inventors provided substantially similar results for various channel
5 lengths.

The numerical simulations considered flow of a compressible fluid through the unit **10** with Reynolds number of $Re=1500$ and maximal Mach number of 0.5. The fluid was considered as air having heat capacity of $C_p=1006 \text{ J/Kg}^\circ\text{C}$, thermal conductivity of $k=0.024\text{W/m}^\circ\text{C}$ and dynamic viscosity of $\mu=1.86\cdot 10^{-5} \text{ Nsec/m}^2$. The
10 temperature of the input air was considered as 30°C and the walls temperature of the channel was 70°C .

Fig. 2B shows simulation results in the form of a velocity map of a compressible fluid flowing through the unit **10**. In the present example, the channel **20** is a cylindrical channel of diameter $D=0.45\text{mm}$, the orifice **30** is also cylindrical and
15 has a diameter $d=0.3\text{mm}$, and the flow is characterized by Reynolds number of 1500. The channel section shown in this figure is of 2 millimeter length downstream of the orifice **30** with respect to the fluid flow direction through the channel.

As can be seen from this example, a series of vortex rings **V1-V3** is formed downstream of the orifice **30**. The vortex rings propagate with the flow through the
20 channel **20** and provide effective mixing of fluid portions from the periphery of the channel (near the wall) with fluid portions close to the longitudinal axis of the channel (the central region of the channel). This is due to the proximity of the vortex rings to the walls which induces the eruption of the boundary layer into the core flow region.

The numerical (computer) simulations reveal formation of vortex rings due to
25 the fluid passage through the orifice **30** into the channel **20**. The vortex rings are formed while being attached to the orifice and thereafter propagating downstream along the channel generating an inherently unsteady flow (although the inflow is steady). As seen in **Fig. 2B**, the vortex rings **V1-V3** are associated with flow vorticity mixing fluid portions from different layers relative to the channel wall, and thus enable
30 significant heat transfer by convection.

It should be noted that a flow characterized by low Reynolds number is a laminar flow, where the viscosity of the fluid is a significant factor. Such laminar flow in the vicinity of the channel's walls creates boundary layers of fluid which do not mix very well.

- 12 -

The formation of vortex rings in the heat exchange unit configured according to the present invention provides significant (effective) mixing and thus enables heat transfer in the form of convection. Additionally, interactions of the vortex rings with the walls of the channel induce eruption of counter-vorticity fluid that stops the formation of the vortex ring and disconnects it from the orifice, and thus allows the formation of subsequent vortex ring, and so on. An additional major mechanism that enhances the disconnection of the vortex rings and the generation of a propagating train of vortex rings is the baroclinic torque that introduces instability and thus cause continuous formation of vortex rings.

The temperature field resulting from the flow through the channel is shown in **Fig. 2C**. In this simulation the walls of the channel are at a temperature of 40°K above the temperature of the coolant flowing in the channel. The dark regions shown in the figure correspond to higher temperatures while the lighter regions correspond to colder temperatures (i.e. the coolant temperature). As shown, the formed vortex rings mix warm air (coolant) flowing near the walls with colder air flowing at the central regions, thereby increasing the flow temperature within the channel significantly beyond the temperature of the air (coolant) injected therein. This indicates a significant heat transfer from the walls into the flowing coolant due to the mixing action of the propagating vortex rings.

It should be noted that in contrast to the effect of vortex rings, the flow in conventional microchannels is typically laminar creating a layered flow, which cannot transfer significant heat by convection and thus the heat transfer from/to the walls is significantly reduced.

As indicated above, the formation of multiple propagating vortex rings provides a major advantage to the efficiency of the heat exchange device of the present invention. It should be noted that in general, a flow through an orifice may generate a jet-like flow which exists for a transient time and dies out leaving the flow laminar and layered.

The inventors have found that by selecting properly the orifice size (diameter or area) relative to the channel size (diameter or area) and/or generating subsonic compressible flow (with an orifice Mach number of the order of 0.5-0.8), a train of vortex rings is continuously formed, even in the steady state, as a result of the interaction between the formed vortex ring and the adjacent walls. The effect is also a

- 13 -

result of the baroclinic torque due to the compressibility of the coolant (e.g. air). Moreover, the inventors have found that this effect applies at any scale, where the compressibility of the fluid and an appropriate relation between the hydraulic diameters of the orifice and the channel is applied. However, the most relevant scale of a heat exchange unit or system utilizing the technique of the invention is the sub-
5 mm (micro) scale. In this scale the flow of almost any coolant is laminar and appropriate selection of compressible coolant is simple. Moreover, providing the heat exchange unit in a micrometric scale enables increasing of contact area between the heat exchange fluid and the surface(s) of the system, utilizing plurality of such units,
10 with the target element/structure to be cooled/heated.

Reference is made to **Figs. 3A-3G** showing simulation results in the form of vorticity map of flow through a heat exchange unit **10** configured as described above at different times during the fluid flow. These figures illustrate the formation and propagation of vortex rings after passing through the orifice and along the channel.
15 **Fig. 3A** shows the vorticity map of the flow at a certain time during the formation of a vortex ring **v3** and a while after the formation of vortex rings **V1** and **V2** which are propagating through the channel. Due to the bounded flow within the channel, the growth of the created vortex ring **v3** is limited by the wall of the channel. This causes creation of a second vorticity center **v3'** shown in **Fig. 3C** which while propagating is
20 combined with vortex ring **v3** to form a larger vortex ring **V3** as shown in **Fig. 3E**. The formed vortex ring **V3** detaches from the orifice forming an additional sub-ring **v3''** (**Fig. 3F**), which combines to **V3** (**Fig. 3G**), and an additional vortex ring **v4** which will eventually form a newly developed vortex ring while propagating through the channel.

25 It should be noted that the created vortex rings separate from the orifice due to their interaction with the channel walls and due to the compressibility (low Mach number, between 0.5-0.8) of the flow providing baroclinic torque. Additionally, during the formation of the vortex rings, while growing in size and approaching the channel's walls, the fluid rotation induces radial eruption of the flow from the
30 boundary layer into the core flow. This eruption mechanism continues while the vortex rings propagate and convects heat from the walls' surface into the core of the flow. This eruption mechanism plays a role in continuous generation of vortex ring. However, multiple vortex rings are typically generated even when the channel's walls

- 14 -

are relatively far and the eruption mechanism is weak, and the effect of the baroclinic torque may be sufficient.

To this end, the inventors have found that a ratio between the hydraulic diameters of the orifice and the channel plays a role both in the continuous formation of the vortex ring and in their interaction with the walls providing efficient convection. The inventors have found that at a ratio of about $D/d \approx 1.5$ (hydraulic diameter d of the orifice is about 66% of the hydraulic diameter D of the channel) the generation of the vortex ring is continuous (forming a steady state) and the convection is efficient, providing effective heat transfer from/to the walls.

Thus, by appropriately determining the diameters of the channel D , and the orifice d , to achieve an appropriate ratio between them, e.g. and providing a high subsonic compressible flow, the size and the generation frequency of the vortex rings can be controlled. As indicated above, the disconnection of the vortex rings from the orifice is obtained by the baroclinic production of counter-vorticity and the development of a nonlinear global interaction with the walls.

Table 1 below compares several simulation results for various orifice and channel diameters exemplifying the performance of the technique of the present invention.

Table 1:

$D_{orifice}$ [mm]	D_{pipe} [mm]	Flow Rate [liter/min]	Heat Flux [Watt/cm ²]	Thermal Efficiency [%]	Nu	Nu/Nu_s	Δp [Pa]	COP
0.2	0.3	0.20	6.60	23	6.50	2.0	9000	0.90
0.3	0.45	0.32	9.00	20	13.3	1.6	5200	2.20
0.3	0.45	0.47	16.7	25	24.8	2.5	11000	1.30
0.4	0.6	0.42	9.20	22	18.4	1.9	3140	3.70
0.4	0.6	0.56	14.2	20	28.0	2.6	5800	2.45

The **Table 1** presents the Nusselt number Nu defined by the ratio between heat transfer by convection and by conduction measuring the heat that can be dissipated under similar conditions, and a ratio between the Nusselt number of a heat exchange unit according to the invention and the resulting Nusselt number of a channel of the same hydraulic diameter without an orifice Nu_s . The Nusselt number is defined as $Nu = hD_{channel}/k$, where $D_{channel}$ is the hydraulic diameter of the channel, k is the heat conductivity and h is the heat transfer coefficient defined as $h = Q/A(T_{wall} - T_{inlet})$. Where

- 15 -

Q is the heat extracted from a channel with a wetted area A and T_{wall} and T_{inlet} are the wall and inlet temperatures respectively.

The above **Table 1** also presents the heat flux and the required air flow rate in the case of a single layer of channels placed next to one another on a surface of 1cm^2 forming together a heat exchange device as will be described more specifically further below. The thermal efficiency, η , of one channel is defined as $\eta = Q / \dot{m} C_p (T_{wall} - T_{inlet})$, where $\dot{m}$ is the air mass flow rate and C_p is the specific

heat coefficient. An efficiency of more than 20% is obtained although the channel is very short, in the example the length is 6mm.

Reference is made to **Fig. 4** comparing Nusselt number (i.e. heat exchange efficiency) for the heat exchange unit of the invention (comprising channel(s) with orifice(s)) for different ratios between the channel's hydraulic diameter and the orifice hydraulic diameter, for three values of orifice diameter. As indicated above, the Nusselt number compares the amount of heat transferred by convection relative to the amount of heat transferred by conduction. As shown in the figure, for various diameters of the orifice, the most efficient heat transfer is achieved at a ratio of 1.5 between the channel and the orifice diameters. However, as can also be seen from the figure, the heat exchange unit of the present invention provides for efficient heat transfer by convection also for ratios from 1.3 to 1.6.

The performance of the heat exchange unit according to the present invention as compared to standard microchannels-based systems are illustrated in **Fig. 5** which shows a comparison between the Nusselt number achieved by the above described unit of the invention with respect to a standard microchannel utilizing substantially laminar flow. The heat exchange performance parameter values (Nusselt number, Nu) are presented with respect to the flow rate Q [liter/minute]. As shown, the advantages of the technique of the present invention are significant, and at a flow rate of $Q=0.43$ [liter/minute] (leading to $Re=2000$ in the unit of the invention) the technique of the invention is almost 2.5 more efficient than the standard channel.

The thermal efficiency for the unit of the invention relative to the standard heat exchange channel is illustrated in **Fig. 6** for the flow rate of $Q=0.43$ [liter/min]. The figure shows the thermal efficiency as a function of the geometrical parameter of the channel expressed by a ratio between the channel's length and diameter. The thermal efficiency shown herein is defined by the actual temperature difference

- 16 -

between the inlet fluid and the outlet fluid divided by the temperature difference of the fluid at the walls (in this example 40°C) which is the maximum temperature yield that can occur in the fluid. As shown, the thermal efficiency of the heat exchange unit of the invention increases significantly as the channel's length increases, displaying
 5 values up to 38%, while standard channels show linear increase of thermal efficiency with respect to the length, reaching only up to 24%.

It should be noted that the higher values of thermal efficiency shown by the unit of the invention are associated with the convection mechanism caused by the eruptions of fluid from the periphery of the channel. This eruption is highly effective
 10 even far away from the orifice (as shown in Figs. 3A-3G). While the boundary layer of the standard channel is getting thicker along the channel, increasing the resistance for the heat transfer through it.

Fig. 7 shows a comparison of a single layer of heat exchange unit of the invention relative to the standard channels. The figure shows the dependence of heat
 15 flux per contact area (q_{mean}) on the flow rate, where several corresponding coefficients of performance (COP) are indicated by labels for equal heat fluxes of both cases. The COP is defined as the total extracted heat transfer divided by the invested power required for the generation of the flow $COP = q_{mean} / (Q \cdot \Delta P)$, where Q and ΔP are the volume flow rate and the pressure drop in the channel, respectively. As shown, the
 20 technique of the present invention provides for higher heat flux for similar or smaller flow rates.

As indicated above, one or more of the basic heat exchange units **10** shown in Fig. 1 may be combined together to form a heat exchange device. **Fig. 8** exemplifies such heat exchange device **100** including a plurality (ten in the present not limiting
 25 example) of heat exchange units configured as described above and being aligned one next to the other to form a basic heat sink unit. The adjacent microchannels **20** are channels made within (embedded) or placed on a bulk material, preferably made of metal(s) having high heat conductivity, and configured to direct heat exchange fluid (e.g. air or other coolants) to provide heat exchange to a target element. The heat
 30 exchange device is to be attached to the target element or placed in direct contact therewith, e.g. utilizing a thermally conductive spread between the device **100** and the target element. In this example, the microchannels **20** are arranged in a single layer close to the surface of the bulk material to be in touch with the target element. The microchannels **20** (or at least some of them) are formed with orifices **30** of smaller

- 17 -

diameter located near the inlets region **45** of the respective channels **20**. The heat exchange unit **100** may be of a typical size of 3×6.5×0.65mm (L×W×H), however it should be noted that the size depends on the number of basic units of the device and may differ to provide heat exchange to target elements of different dimensions.

5 The heat exchange device according to the present invention may also include channels (microchannels) arranged in a number of layers within a bulk material forming a heat sink. Reference is made to **Fig. 9**, showing another configuration of a heat exchange device **100** made of a bulk material (e.g. Copper, Aluminum, Stainless Steel or any other heat conductive material) including multiple layers (for example ten
10 layers) of microchannels **20** in it, where each layer includes a plurality (e.g. twenty) basic units (microchannels) **20**. The microchannels (or at least some of them) are configured with one or more orifices (not specifically shown here) as described above to thereby provide flow of heat exchange fluid while generating plurality of vortex rings within the channel **20** and thus increase the heat exchange performance. It
15 should be noted that several such blocks can be placed on the surface of a heat source (target element), as will be described further below with reference to Fig. 10.

As indicated above, the heat exchange device **100** is configured as a heat sink made of a material composition having reasonable or high heat transfer properties (heat conductivity and heat capacity coefficients). Preferred materials may be copper,
20 stainless steel or aluminum, but other materials can be also used. Some embodiments may utilize a Silicon based heat exchange device which offers compatibility with micromachining and micro fabrication techniques widely used in the semiconductor producing processes in the electronics industries.

As described above, one of the most effective heat exchange fluids which may
25 be used in the invention is air (or other gas based heat exchange fluids) providing sufficient thermal properties and compressible flow. It should be noted that an important parameter affecting the efficiency of the heat exchange device is a sufficient supply of air into the inlet(s) and effective evacuation of the air from the outlet(s) directly into the surroundings (or alternatively evacuation through an
30 exhaust- manifold) after exchanging heat with the target element.

Reference is made to **Fig. 10** exemplifying a heat exchange device **200** including a plurality of heat sinks **100** configured as exemplified in **Fig. 9** and including an air directing system **150** for supply and evacuation of the heat exchange

- 18 -

fluid. The heat exchange device **200** of this specific but not limiting example includes six blocks **100** (heat sinks) each including 10 layers of 30 microchannels per layer placed on a thermally conductive surface **180** and **160** to be brought in contact with a target element. Every two adjacent blocks **100** face each other so that the inlet region of cold air is the same for two adjacent blocks. The same applies for the hot-air exit region on the opposite side of the blocks **100**. Air is directed into the device **200** with the appropriate gauge pressure through a manifold **120** into the inlet reservoir **150**. The air/coolant flows through the orificed-microchannels transferring heat from the walls as described above. This is while the hot air, in the non-limiting example of cooling system, flows out of the blocks **100** into the isle between two adjacent blocks and subsequently to the outlet **140** of the device and out to the surroundings. To this end, the air, or any other coolant which may be used, can be directed into and out of the device utilizing conventional techniques, for example by one or more fans, however other arrangements of air supply and evacuation may be used.

The heat exchange device **200** exemplified above may be configured with various size and geometry appropriate for efficient attachment to the corresponding target element (e.g. CPU, GPU, Laser cavity or any other heat source, or alternatively a target to be cooled). For example, the device may have a dimension of approximately $26 \times 32 \times 10 \text{ mm}$ and in such physical dimension it is expected to dissipate $2.5 \text{ Watt}/^{\circ}\text{C}$ or $0.4 \text{ Watt}/\text{cm}^2 \cdot ^{\circ}\text{C}$ or $0.4 \text{ Watt}/\text{cm}^3 \cdot ^{\circ}\text{C}$ in accordance with the surface area being in touch with the target element. It should be noted that conventional full size ($80 \times 80 \times 64 \text{ mm}$ without the fan) air-based heat sinks for today's CPUs (for example, the *Alpha L90C-64NT* heat sink) dissipate $5 \text{ Watt}/^{\circ}\text{C}$ or $0.08 \text{ Watt}/\text{cm}^2 \cdot ^{\circ}\text{C}$ or $0.012 \text{ Watt}/\text{cm}^3 \cdot ^{\circ}\text{C}$. Thus, for a given volume, the device of the present invention dissipates about 30 times more heat than the commercially available, conventional air-cooled fin heat sinks.

It should be noted that the heat exchange device of the invention may be controlled to adapt to varying operating conditions, for example, increasing or decreasing the flow to provide high heat dissipation when needed and reducing noise or energy consumption when less heat needs to be dissipated. To this end, the heat exchange device may be associated with a flow generating unit (e.g. one or more blowers/fans) configured to provide inlet flow and/or to evacuate outlet flow. Additionally, the flow generating unit may include a control unit configured for

- 19 -

managing operation thereof. It should be noted, although not specifically illustrated, that the control unit may include an inlet pressure sensor, cold and hot air temperature sensors, and one or more sensors for detecting the temperature of the target element. The control unit can control the flow by increasing/reducing blower speed or by any
5 other technique for varying the inlet or outlet pressure in accordance with the measured temperatures.

The inventors have found that a train of vortex rings can be generated by a continuous inflow in compressible subsonic air flow through an appropriately configured orifice with adjacent channels' walls. The unsteady propagating vortices
10 enhance substantially the heat transfer capabilities even in the case of low Reynolds number flows (e.g. in small scale system) where conventional heat sinks perform poorly. This allows obtaining high heat transfer in small scale employing air (or other gases) without the need to revert to liquids. The heat-sink based on the present invention have at least one order of magnitude less volume, reaching a value of
15 $0.4\text{Watt}/\text{cm}^3\cdot^{\circ}\text{C}$ (and beyond), a value more than 30 times higher than in conventional air based fin solutions, thus allowing the extension of air-cooling beyond present limits. The use of gases has a huge advantage over the use of liquids in simplifying the heat exchanger, substantially increasing reliability and decreasing maintenance costs, resulting in cheaper systems and better return on investment.

Numerous variations can be made to this basic unit **10** as exemplified in Fig. 1. Two such modifications are exemplified in **Figs. 11A-11B**. For example, a longer channel may be configured by providing multiple orifices arranged in a spaced-apart relationship along the channel with a distance between them being selected to allow generation of vortex ring from each of the orifices. **Fig. 11A** shows a basic unit **10**
25 including a microchannel **20** configured with three orifices **30** located along the channel forming a row of vortex rings' generation regions along the channel. The orifices **30** may be located at a distance selected to be higher than a lifetime distance of the generated vortex rings. This configuration provides continuous generation of vortex rings along the channel length where otherwise the vortex rings would die out
30 while propagating. **Fig. 11B** exemplifies a U-shaped channel unit **10** including a U-shaped channel (microchannel) **20** configured with an orifice **30** in each of its arms. Such microchannel unit **10** may be used for increasing the effective length of the channel while providing heat exchange to a target element having relatively short

- 20 -

contact surface along at least one of its surfaces. This configuration of the microchannels provides for a heat exchange device with "cross-channels" such that the inlet and outlet of the fluid are on the same surface (separated by a manifold to keep hot and cold fluid unmixed). The heat exchange device as described above, or
5 one or more channels/microchannels thereof may be integrated as channels passing through, or as separate layers, into electronic circuit architectures, being located between layers of heat generating components to effectively remove heat and resolve hot-spot regions.

It should also be noted that the technique of the present invention may utilize
10 liquid based heat exchange fluid and is not limited to air or other gasses. However, it should be noted that compressible flow of the fluid is preferred although incompressible flow may also be used.

Thus the present invention provides a novel technique for heat exchange utilizing flow of appropriate fluid in the vicinity of a target element/structure to be
15 heated/cooled. The technique of the invention preferably utilizes laminar and compressible (subsonic) flow through one or more channels while providing continuous generation of vortex rings along the flow. The vortex rings provide mixing of the fluid between the periphery and central regions of the channel and thus increase efficiency of heat exchange by convection. Those skilled in the art will readily
20 appreciate that various modifications and changes can be applied to the embodiments of the invention as hereinbefore described without departing from its scope defined in and by the appended claims.

CLAIMS:

1. A heat exchange device comprising one or more channels having inlet and outlet ports to direct flow of a predetermined fluid to and from said one or more channels, said one or more channels comprising at least one channel having at least one orifice of a predetermined hydraulic diameter, a flow of said predetermined fluid through said orifice and through said channel thereby generating a vortex ring-like fashion of the flow within the channel.
2. The heat exchange device of Claim 1, wherein a hydraulic diameter of said at least one channel is between 100 to 1000 micrometers.
3. The heat exchange device of Claim 1 or 2, wherein a ratio between a hydraulic diameter of said at least one channel and said predetermined hydraulic diameter of said at least one orifice is selected to be between 1.3 to 1.6.
4. The heat exchange device of Claim 3, wherein said ratio between the hydraulic diameter of said at least one channel and said predetermined hydraulic diameter of said at least one orifice in the channel is 1.5.
5. The heat exchange device of any one of the preceding Claims, wherein said one or more channels have a circular or rectangular cross section.
6. The heat exchange device of any one of the preceding Claims, configured to direct compressible flow of a predetermined heat exchange fluid through said at least one channel, passage of said flow through said at least one orifice generating one or more vortex rings thereby providing efficient mixing of fluid portions from periphery of said channel with fluid portions from central region thereof.
7. The heat exchange device of any one of the preceding Claims, wherein said one or more channels are arranged together in one or more layers, at least one of said layers being configured to be in contact with a target element.
8. The heat exchange device of Claim 6, wherein the inlet ports of said one or more channels are arranged to face a predetermined direction for fluid input.
9. The heat exchange device of Claim 7 or 8, comprising a manifold arrangement for directing input heat exchange fluid towards the inlet ports of said one or more channels.
10. The heat exchange device of any one of the preceding claims, wherein said one or more channels are made of a thermally conductive material composition.

- 22 -

11. The heat exchange device of any one of the preceding claims, wherein said one or more channels are made of at least one of the following materials: Copper, Aluminum and Stainless steel.

12. A heat exchange system comprising one or more heat exchange blocks,
5 said heat exchange block comprising a plurality of channels of a predetermined hydraulic diameter, each comprising at least one orifice of a predetermined hydraulic diameter, passage of fluid through said channels and through said orifice therein generating vortex ring downstream of said orifice with respect to a general fluid flow direction through the channel, thereby increasing efficiency of heat exchange by
10 convection of fluid within said channels.

13. A method for use in heat transfer to and from a target element, the method comprising: providing a compressible laminar flow of a fluid through one or more channels being in contact with said target element, and directing said flow through at least one orifice located near an inlet port of said one or more channels, to
15 thereby generate a vortex ring-like flow, providing high-efficiency heat transfer for a relatively small length of said one or more channels.

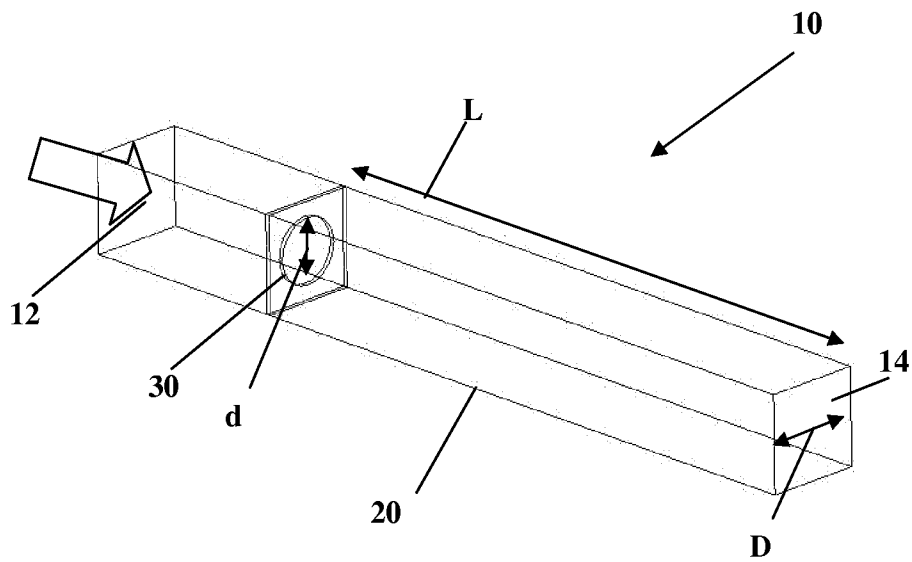


FIG. 1

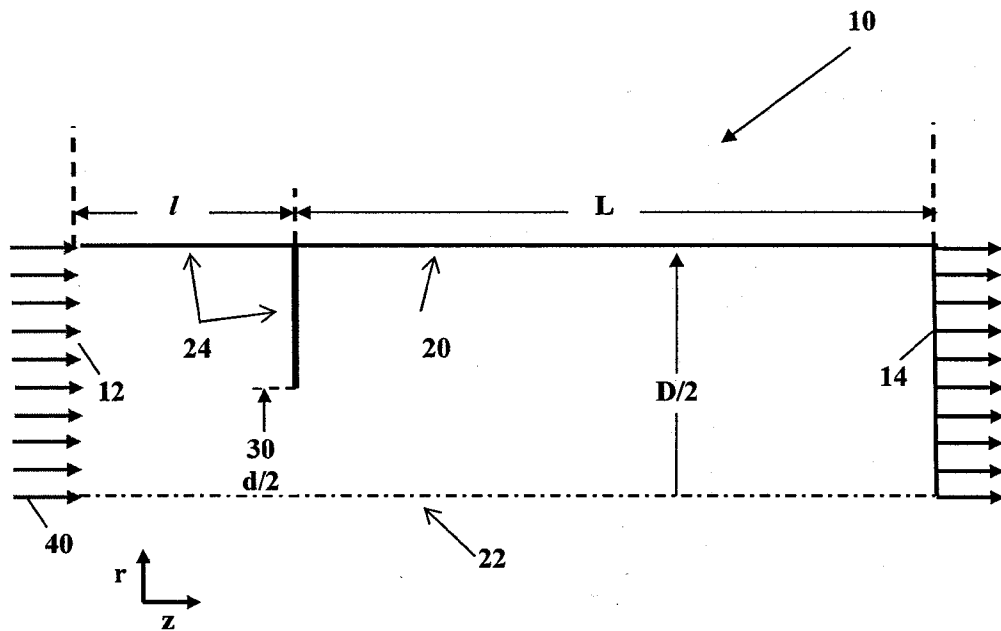


FIG. 2A

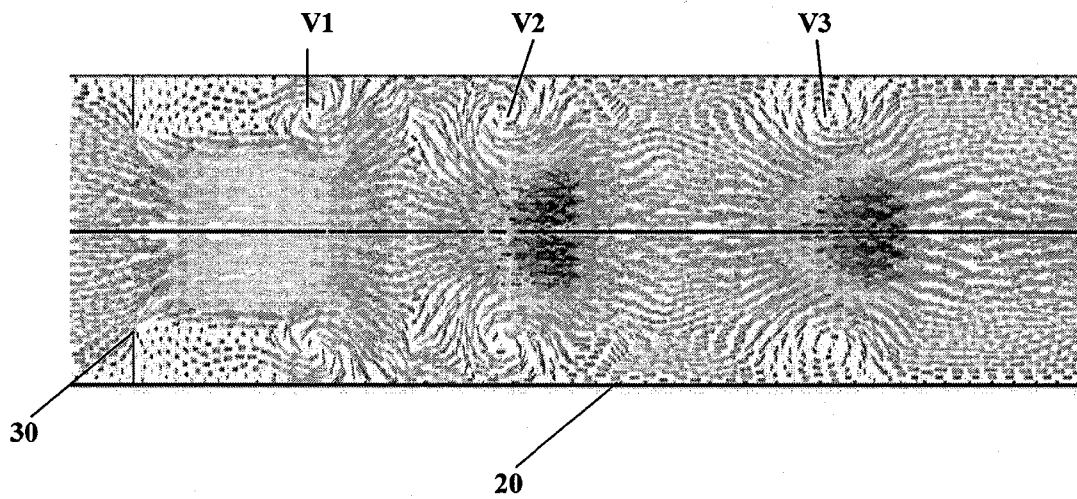


FIG. 2B

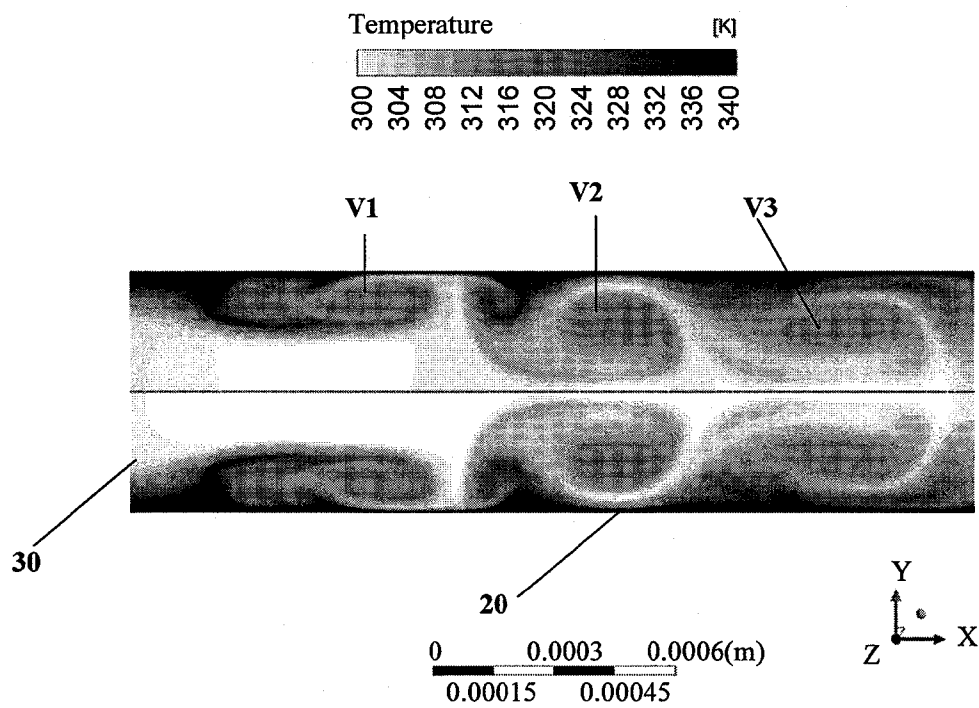


FIG. 2C

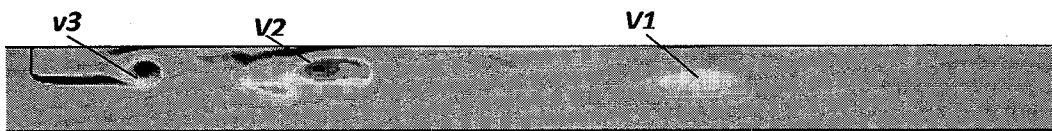


FIG. 3A



FIG. 3B

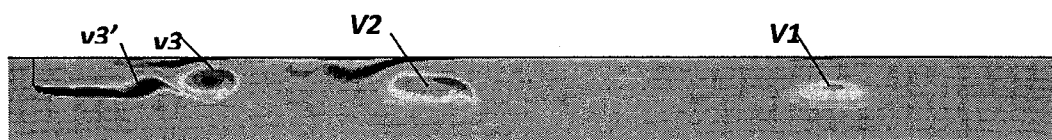


FIG. 3C

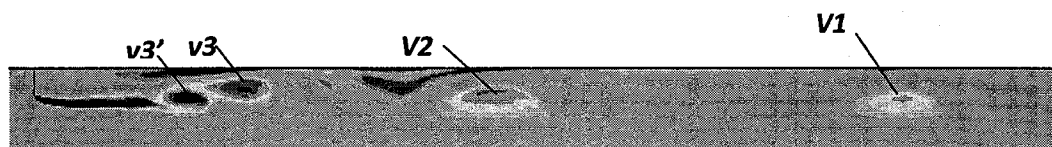


FIG. 3D

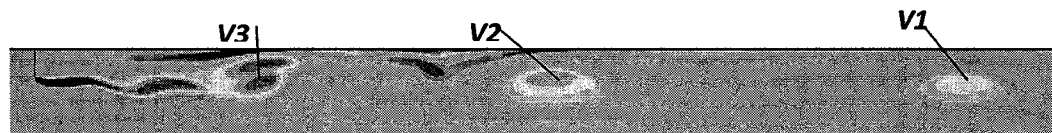


FIG. 3E

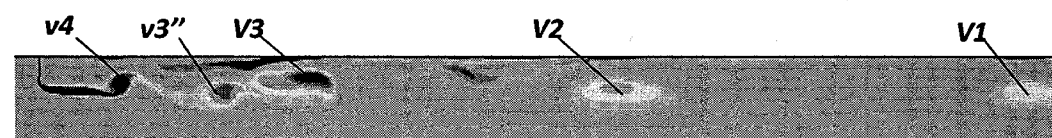


FIG. 3F

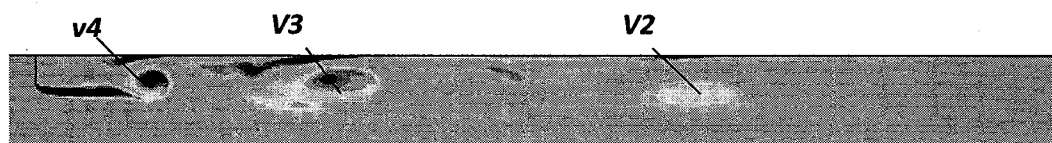


FIG. 3G

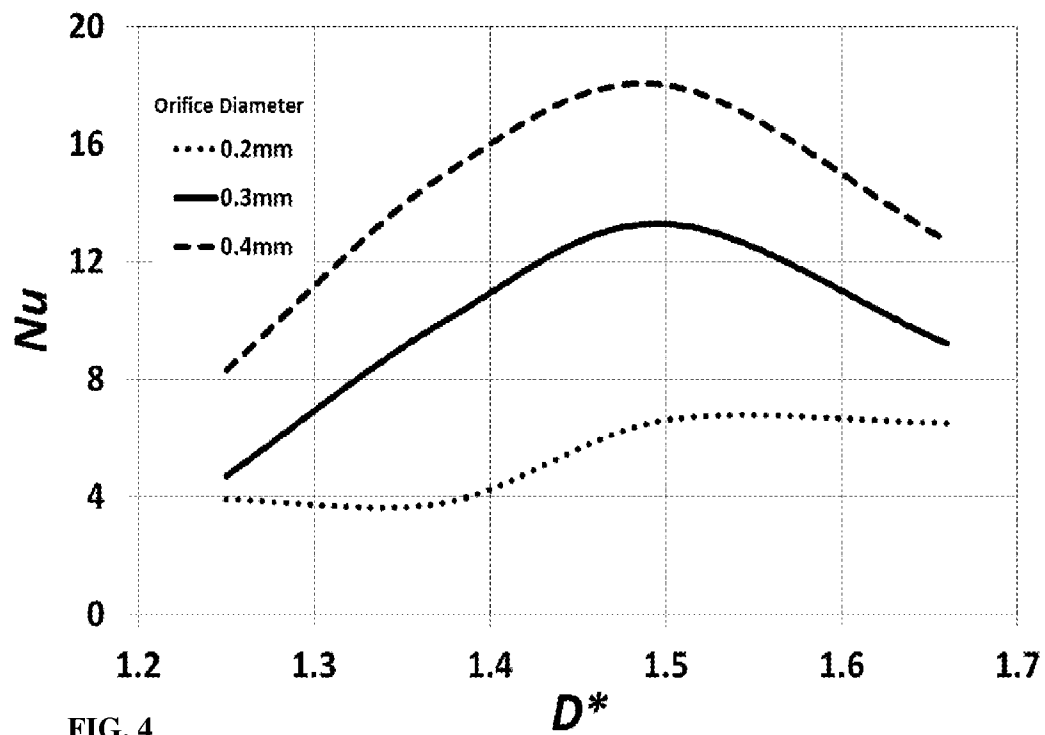


FIG. 4

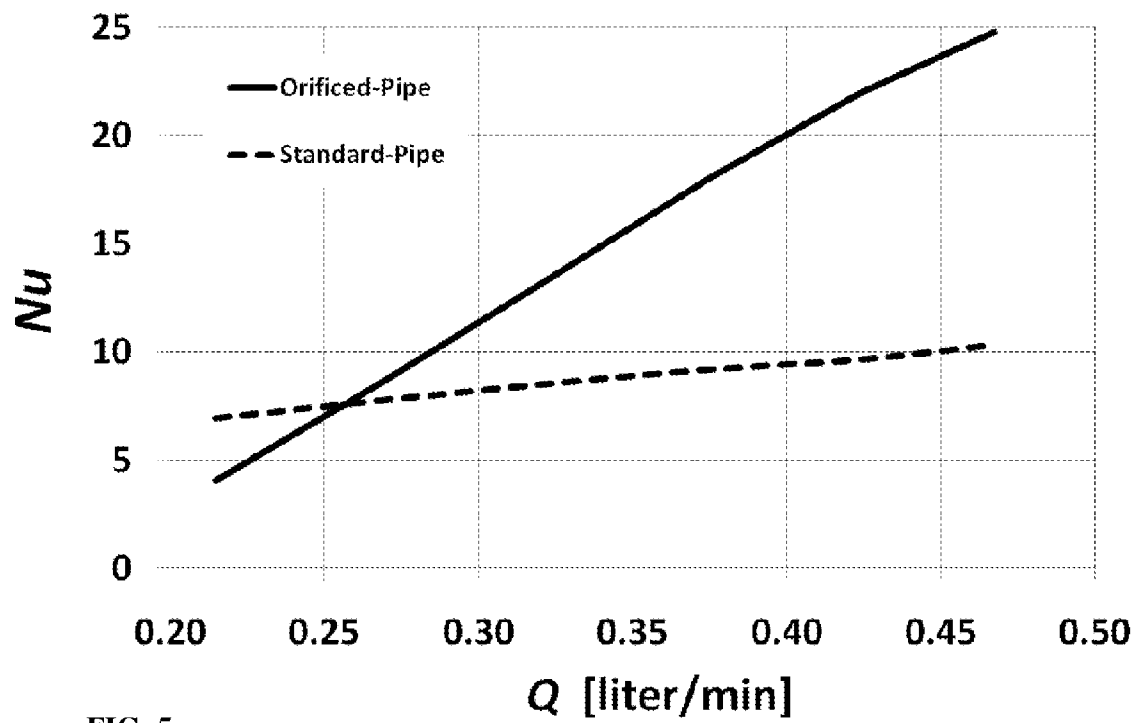


FIG. 5

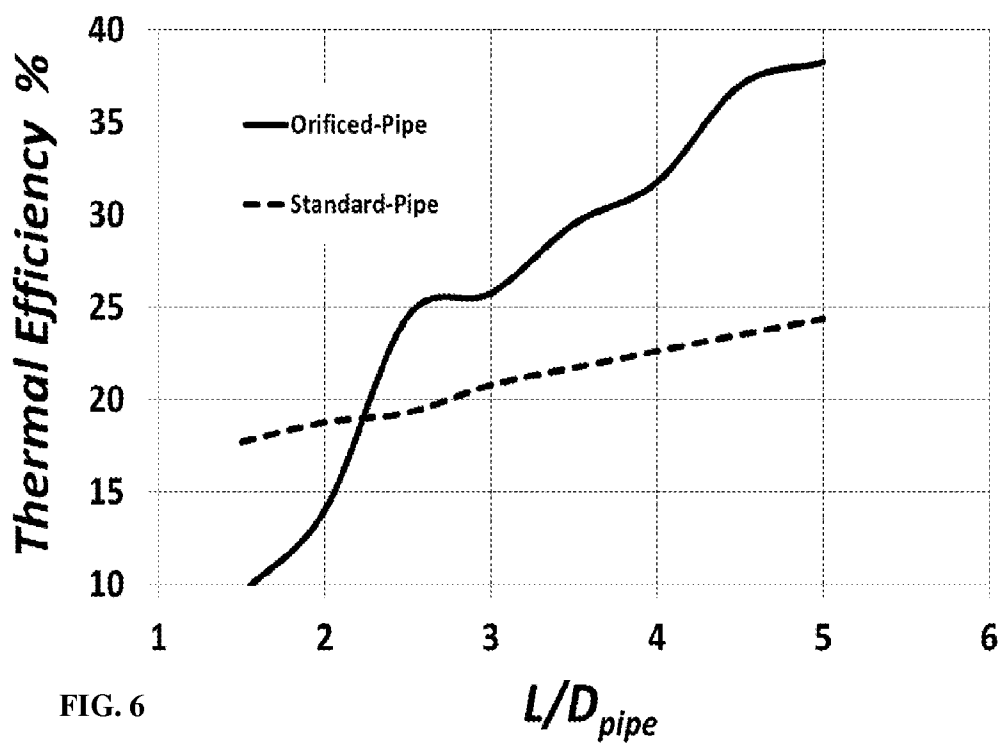


FIG. 6

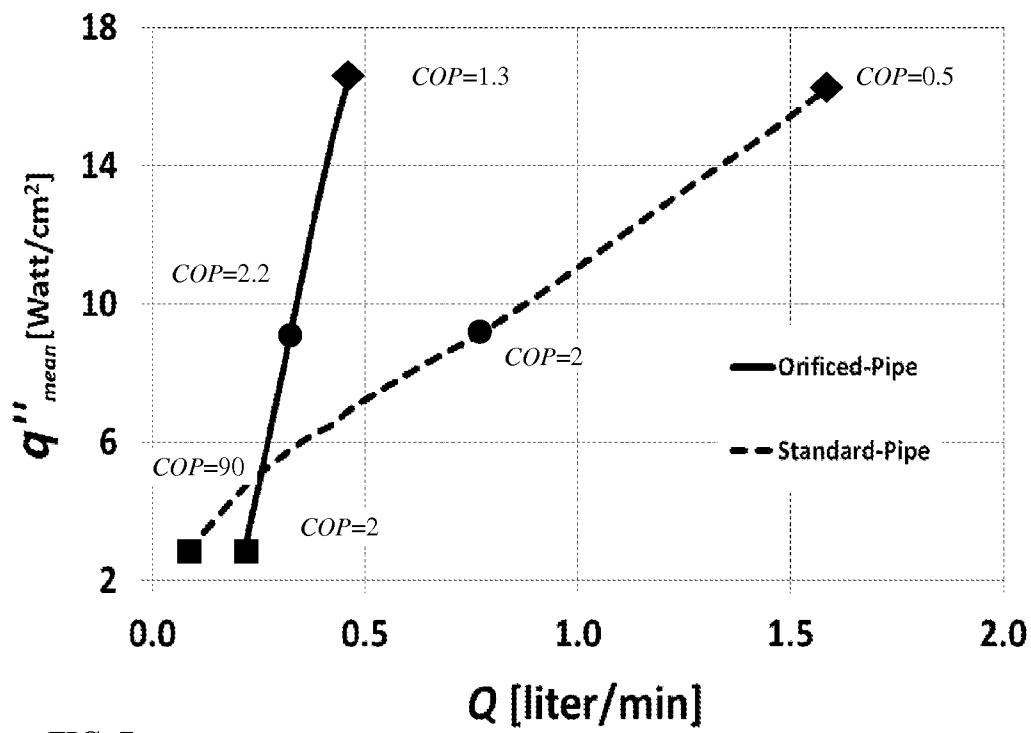


FIG. 7

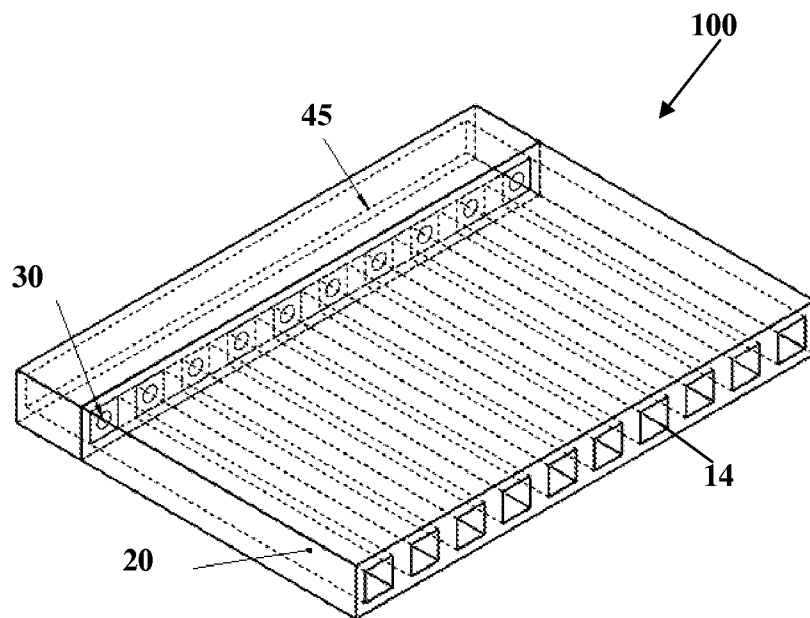


FIG. 8

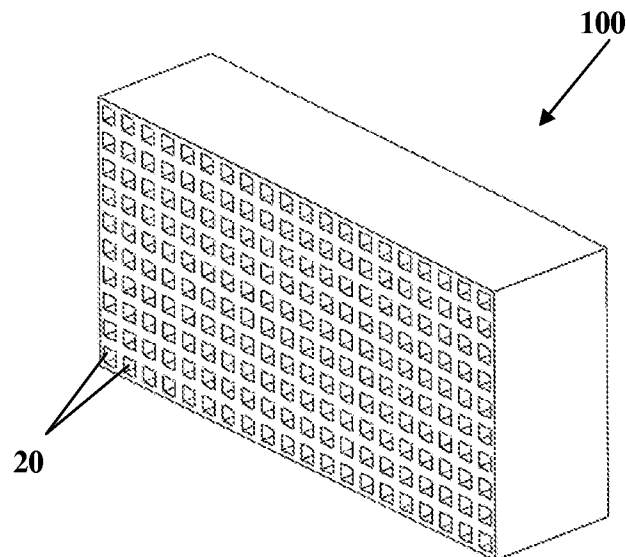


FIG. 9

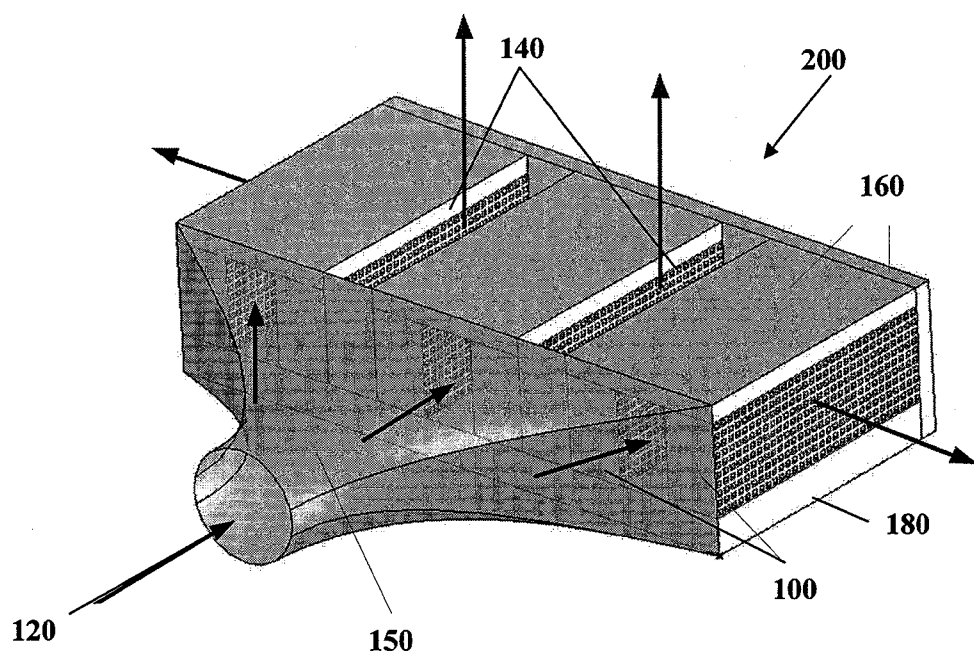


FIG. 10

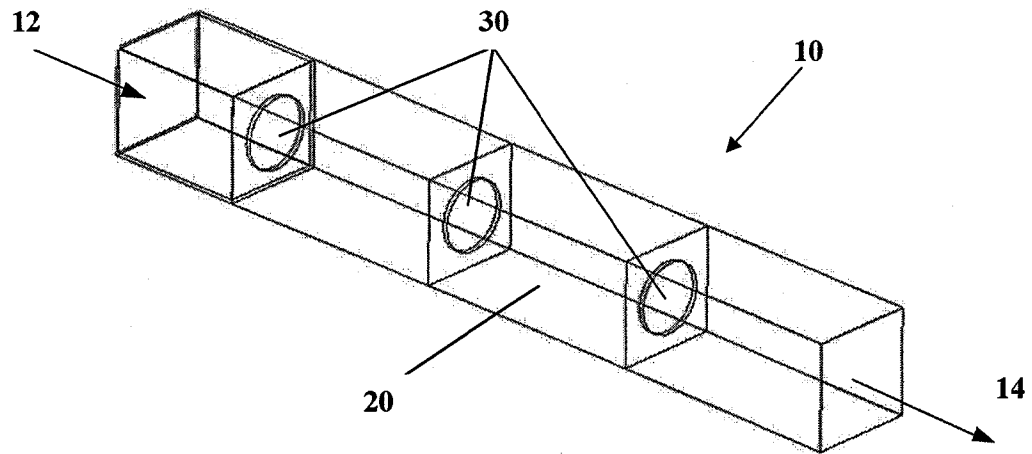


FIG. 11A

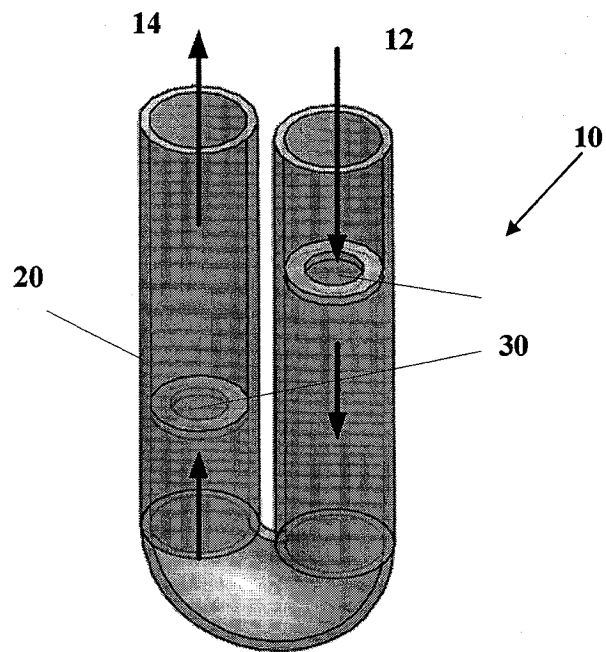


FIG. 11B

INTERNATIONAL SEARCH REPORT

International application No

PCT/IL2012/050187

A. CLASSIFICATION OF SUBJECT MATTER

INV. F28F3/12 F28F13/08 F28F13/12 H01L23/473
ADD.

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)

F28F H01L

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)

EPO-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 2004/184237 A1 (CHANG SHYY-WOEI [TW]) 23 September 2004 (2004-09-23)	1,2,5,6, 12,13
Y	abstract; figures 4,6 -----	9,12
Y	US 2009/236083 A1 (BRAND KARINE [DE] ET AL) 24 September 2009 (2009-09-24) figures 1,5,7,8 -----	9,12
Y	JP 6 120385 A (SUMITOMO LIGHT METAL IND) 28 April 1994 (1994-04-28) figure 4 -----	9,12
X	US 4 075 091 A (BELLHOUSE BRIAN JOHN) 21 February 1978 (1978-02-21) figure 4 -----	1,13



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents :

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"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

24 September 2012

Date of mailing of the international search report

02/10/2012

Name and mailing address of the ISA/

European Patent Office, P.B. 5818 Patentlaan 2
NL - 2280 HV Rijswijk
Tel. (+31-70) 340-2040,
Fax: (+31-70) 340-3016

Authorized officer

Martínez Rico, Celia

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No

PCT/IL2012/050187

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
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