US 20130186109A1

(19) United States

(12) Patent Application Publication

Atrey et al.

(10) Pub. No.: US 2013/0186109 A1

(43) Pub. Date: Jul. 25, 2013

(54) COUNTER FLOW HEAT EXCHANGER FOR A MINIATURE JOULE-THOMSON CRYOCOOLER

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(21) Appl. No.: **13/812,838**

(22) PCT Filed: **Jul. 22, 2011**

(86) PCT No.: **PCT/IN11/00488**

§ 371 (c)(1), (2), (4) Date: **Apr. 5, 2013**

(30) **Foreign Application Priority Data**

Jul. 27, 2010 (IN) 2133/MUM/2010

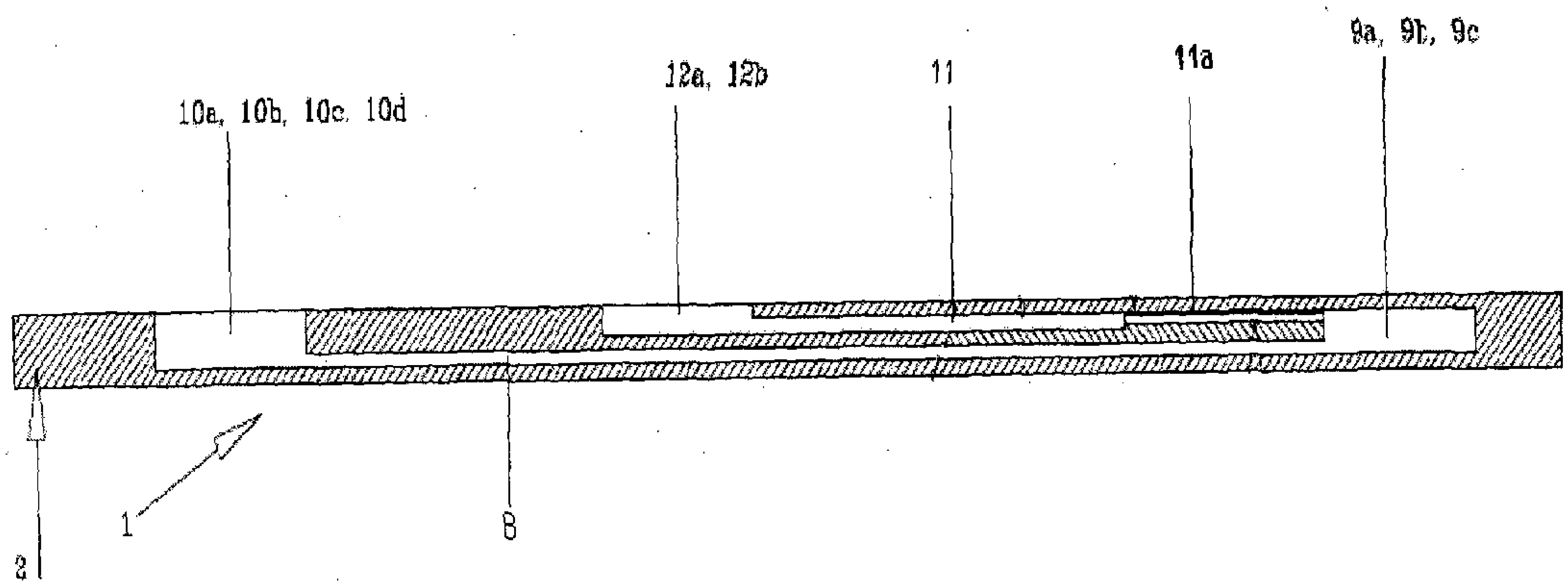
Publication Classification

(51) **Int. Cl.**
F28F 3/08 (2006.01)

(52) **U.S. Cl.**
CPC ***F28F 3/08*** (2013.01)
USPC **62/6**; 165/165; 29/890.035

(57) **ABSTRACT**

A counter flow heat exchanger comprising a body formed of stacked, fused, ceramic sheets. The sheets comprising: a bottom sheet, a second sheet, a third sheet, a fourth sheet and a top sheet. The sheets have punched holes such that when the sheets are aligned there is an inlet hole spanning from the top sheet to the fourth sheet, an outlet hole spanning from the top sheet to the second sheet, and an inflow hole spanning from the fourth sheet to the second sheet. Within the second sheet, a low pressure flow channel connects the outlet hole with the inflow hole. Within the fourth sheet, the inlet hole flows into a high pressure flow channel which flows into a narrow flow path which then empties into the inflow hole. The high pressure flow channel is aligned with the low pressure flow channel to allow for heat exchange.



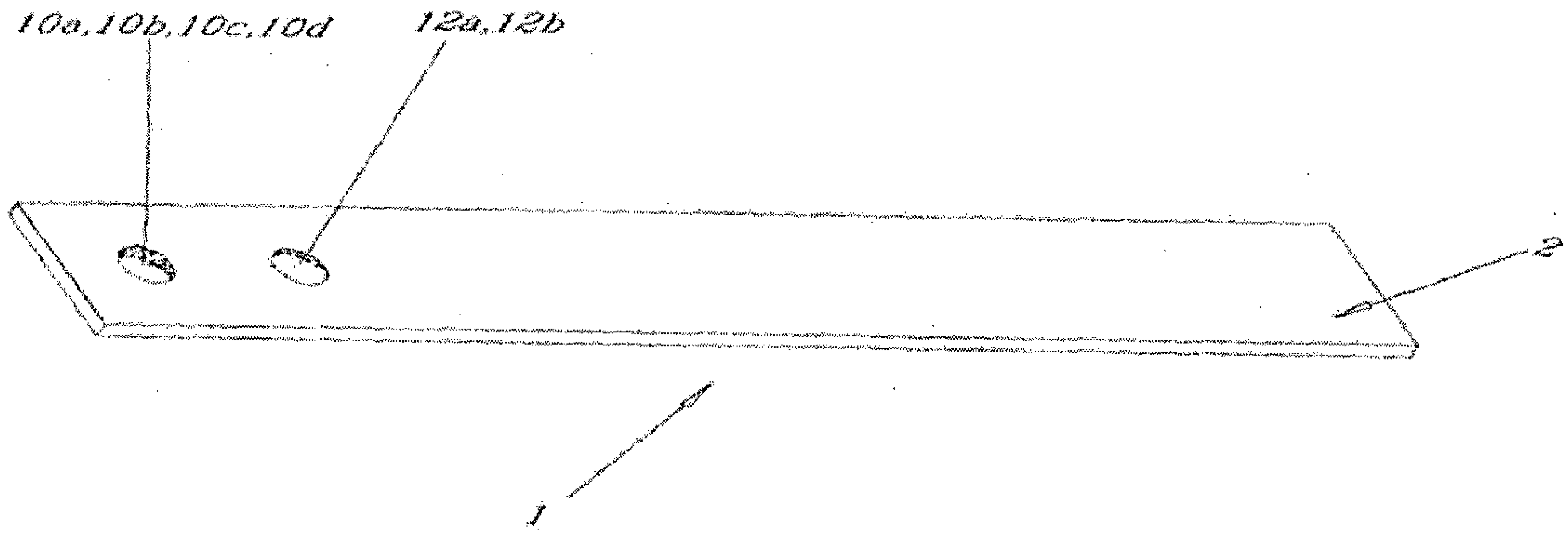

10a,10b,10c,10d
12a,12b
2
1

Fig 1

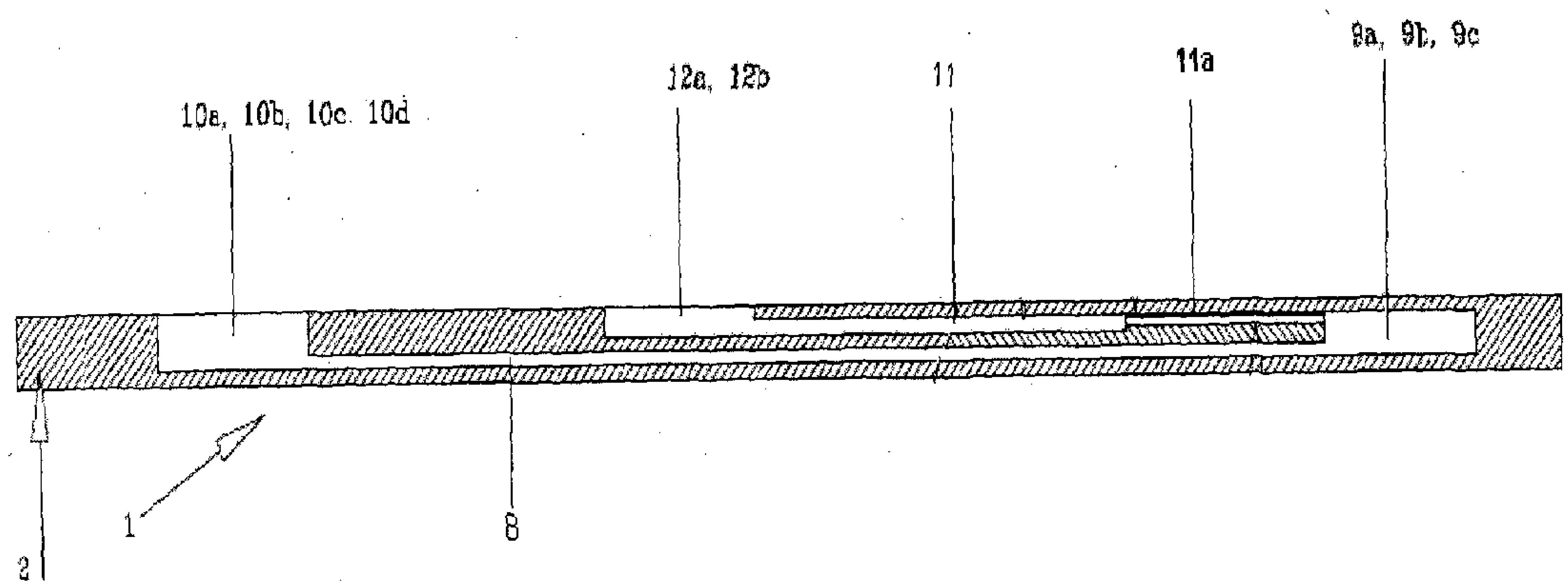

10a, 10b, 10c. 10d
12a, 12b
11
11a
9a, 9b, 9c
2
1
8

Fig 2

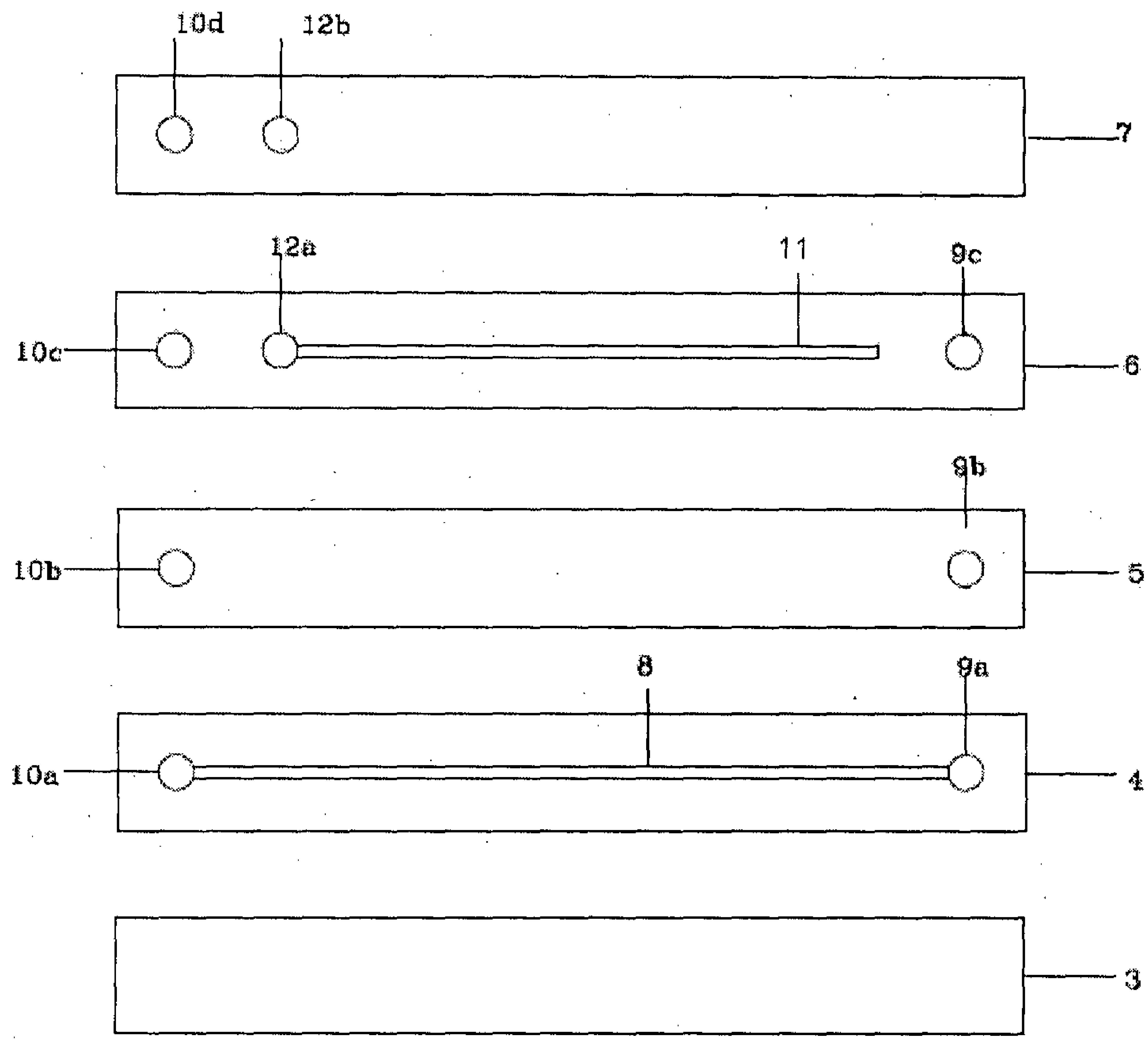


Fig 3

COUNTER FLOW HEAT EXCHANGER FOR A MINIATURE JOULE-THOMSON CRYOCOOLER

FIELD OF THE INVENTION

[0001] This invention relates to a counter flow heat exchanger for a miniature Joule-Thomson cryocooler.

[0002] The invention also relates to a method of manufacturing the counter flow heat exchanger and a miniature Joule-Thomson cryocooler comprising the counter flow heat exchanger.

BACKGROUND OF THE INVENTION

[0003] Joule-Thomson cryocoolers are cryogenic refrigerators that are used to create cryogenic cooling ie cooling at extremely low temperatures, typically temperatures lower than 120K (Kelvin) at atmospheric pressure. Large Joule Thomson cryocoolers are, for example, used for cryogeneic cooling of large devices like infrared detectors or super conductors or for cooling or liquefaction of gases. Miniature Joule-Thomson cryocoolers are generally used for cryogenic cooling of small areas requiring limited cooling effect, where weight and volumes are critical requirements, for examples miniature electronic devices like chips, microsensors or cryogenic probes for microsurgeries to improve the performance efficiency and life thereof. It is very important that such devices are cooled below their critical temperatures in order to ensure their efficient performance over a long period of time.

[0004] A miniature Joule-Thomson cryocooler comprises a counter flow heat exchanger (micro heat exchanger) having a high pressure channel and a low pressure channel. A narrow flow path (constricted flow path) is provided in continuity with the high pressure channel and opening into an inflow hole communicating with the low pressure channel. A micro inlet hole is provided at the inlet end of the high pressure channel and a micro outlet hole is provided at the outlet end of the low pressure channel. A cryogen like nitrogen or helium at high pressure flows through the high pressure channel and expands and cools down in the inflow hole providing an expansion zone. While flowing through the expansion zone, the cryogen absorbs the heat of the device in contact with the heat exchanger so as to cool down the device to cryogenic temperatures. While flowing back through the low pressure channel of the heat exchanger, the cryogen further absorbs heat from the high pressure channel side of the heat exchanger which is at a higher temperature. In an open-cycle Joule-Thomson cryocooler, the cryogen at low pressure is vented out to the atmosphere, whereas in a closed-cycle Joule-Thomson cryocooler, the cryogen at low pressure is recompressed and sent back to the heat exchanger.

[0005] A generally used counter flow heat exchanger comprises a body formed of three glass wafers (Pyrex glass wafers) stacked one above another and fused together using the very large scale integration (VLSI) technology. Patterns of protective material on the wafers are cut to size with lithography and the high pressure channel and low pressure channel are formed by chemical etching. The inlet and outlet holes and inflow hole are formed by powder blasting. Prior to cutting the devices to size, several pretreatments of the wafers like anodic bonding are also carried out. [Lerou, P.P.P.M. (Low Temp. Div., Univ. of Twente, Enschede, Netherlands); Venhorst, G. C. F.; Berends, C. F.; Veenstra, T. T.; Blom, M.; Burger, J. F.; ter Brake, H. J. M.; Rogalla, H. "Fabrication of a micro cryogenic cold stage using MEMS-technology," *Journal of Micromechanics and Microengineering,* v 16, n 10, p 1919-25, October 2006]. Because of the large number of steps and pretreatments, the method of manufacture of the heat exchanger is complicated and time consuming and is expensive. Further because of the large scale integration, miniaturization of the heat exchanger and integration of the heat exchanger into the electronic devices or the other devices for cooling thereof is rather difficult. The cooling efficiency of the heat exchanger depends on the pressure withstanding capability thereof. The higher the pressure withstanding capability in small volumes, the better the cooling efficiency. Glass wafer based heat exchangers have limited mechanical strength. Therefore, the cooling efficiency of such heater exchanger is also limited. Low temperature cofired ceramics are generally used for packaging of integrated circuits, micro-electro mechanical systems (MEMS), electronic circuits embedded with MEMS or microsensors or as substrates comprising fluidics channels.

OBJECTS OF THE INVENTION

[0006] An object of the invention is to provide a counter flow heat exchanger for a miniature Joule-Thompson cryocooler, which heat exchanger is simple in construction, easy and convenient to manufacture and is cost effective.

[0007] Another object of the invention is to provide a counter flow heat exchanger for a miniature Joule-Thompson cryocooler, which heat exchanger is miniature in size and can be easily integrated into the device to be cooled thereby.

[0008] Another object of the invention is to provide a counter flow heat exchanger for a miniature Joule-Thompson cryocooler, which heat exchanger has increased pressure withstanding capability and increased cooling efficiency.

[0009] Another object of the invention is to provide a method of manufacturing a counter flow heat exchanger for a miniature Joule-Thompson cryocooler, which method is simple, easy and convenient to carry out and is cost effective.

[0010] Another object of the invention is to provide a method of manufacturing a counter flow heat exchanger for a miniature Joule-Thompson cryocooler, which method facilitates miniaturization of the heat exchanger so as to be easily integrated into the device to be cooled by the heat exchanger.

[0011] Another object of the invention is to provide a method of manufacturing a counter flow heat exchanger for a miniature Joule-Thompson cryocooler, which method produces a heat exchanger having increased pressure withstanding capability and increased cooling efficiency.

[0012] Another object of the invention is to provide a miniature Joule-Thompson cryocooler comprising the above counter flow heat exchanger.

DETAILED DESCRIPTION OF THE INVENTION

[0013] According to the invention there is provided a counter flow heat exchanger for a miniature Joule-Thompson cryocooler, the heat exchanger comprising a body formed of a bottom sheet, a second sheet, a third sheet, a fourth sheet and a top sheet, all the sheets being made of low temperature cofired ceramics and stacked one above another and fused together, the second sheet comprising a low pressure flow channel along the length thereof terminating in an inflow hole at one end thereof and in an outlet hole at the other end thereof, the third sheet comprising an inflow hole at one end thereof corresponding to and matching with the inflow hole in the second sheet and an outlet hole at the other end thereof corresponding to and matching with the outlet hole in the second sheet, the fourth sheet comprising a high pressure flow channel along the length thereof, an inflow hole at one end thereof corresponding to and matching with the inflow hole in the third sheet and spaced apart from corresponding one end of the high pressure flow channel, an inlet hole terminating at the inception of the high pressure flow channel and an outlet hole corresponding to and matching with the outlet hole in the third sheet and spaced apart from the inlet hole in the fourth sheet, the top sheet comprising an inlet hole corresponding to and matching with the inlet hole in the fourth sheet and an outlet hole corresponding to and matching with the outlet hole in the fourth sheet and a narrow flow path between the fourth sheet and top sheet communicating with said one end of the high pressure flow channel and the inflow hole in the fourth sheet.

[0014] According to the invention there is also provided a method of manufacturing a counter flow heat exchanger for a miniature Joule-Thompson cryocooler, the heat exchanger comprising a body formed of a bottom sheet, a second sheet, a third sheet, a fourth sheet and a top sheet, all the sheets being made of low temperature cofired ceramics and stacked one above another and fused together, the method comprising punching a low pressure flow channel along the length of the second sheet with an inflow hole at one end thereof and an outlet hole at the other end thereof, punching an inflow hole and an outlet hole in the third sheet corresponding to and matching with the inflow hole and the outlet hole in the second sheet respectively, punching a high pressure flow channel along the length of the fourth sheet, punching an inflow hole at one end of the fourth-sheet corresponding to and matching with the inflow hole in the third sheet and in spaced apart relationship with one end of the high pressure flow channel, punching an inlet hole at the other end of the high pressure flow channel and punching an outlet hole in the fourth sheet corresponding to and matching with the outlet hole in the third sheet and spaced apart from the inlet hole in the fourth sheet, punching an inlet hole and an outlet hole in the top sheet corresponding to and matching with the inlet hole and outlet hole in the fourth sheet respectively, filling the low pressure flow channel, high pressure flow channel, inflow holes, inlet holes and outlet holes with a sacrificial material and forming thin layer of a sacrificial material between the inflow hole and corresponding said one end of the high pressure flow channel in the fourth sheet, stacking the sheets one above another, cutting the sheets to size, compacting the sheets and fusing the sheets together by sintering at 30 to 900° C. with simultaneous formation of a narrow flow path in the fourth sheet and top sheet between the inflow hole in the fourth sheet and corresponding said one end of the high pressure flow channel in the fourth sheet.

[0015] According to the invention there is also provided a miniature Joule-Thomson cryocooler comprising the counter flow heat exchanger described above. The Joule-Thomson cryocooler is a closed cycle Joule-Thomson cryocooler or an open cycle Joule-Thomson cryocooler. Preferably the sheets are ‘green tape 951’ of Dupont Microcircuit Materials, USA.

[0016] The following is a detailed description of the invention with reference to the accompanying drawings, in which:

[0017] FIG. **1** is an isometric view of the counter flow heat exchanger for a miniature Joule-Thomson cryocooler according to an embodiment of the invention;

[0018] FIG. **2** is a crosssection of the heat exchanger of FIG. **1**; and

[0019] FIG. **3** is an exploded view of the heat exchanger of FIG. **1**.

[0020] The counter flow heat exchanger **1** as illustrated in FIGS. **1** to **3** of the accompanying drawings comprises a body **2** formed of a bottom sheet **3**, a second sheet **4**, a third sheet **5**, a fourth sheet **6** and a top sheet **7** stacked one above another and fused together. All the sheets are made of low temperature cofired ceramics. The second sheet is formed with a low pressure flow channel **8** along the length thereof and an inflow hole **9***a* at one end thereof and an outlet hole **10***a* at the other end thereof. The third sheet is formed with an inflow hole **9***b* and an outlet hole **10***b* at opposite ends thereof corresponding to and matching with the inflow hole and outlet hole in the second sheet, respectively. The fourth sheet is formed with a high pressure flow channel **11** along the length thereof. An inflow hole **9***c* is formed at one end of the fourth sheet corresponding to and matching with the inflow hole in the third sheet and in spaced apart relationship with corresponding one end of the high pressure flow channel. The fourth sheet is also formed with an inlet hole **12***a* at the inception of the high pressure flow channel and an outlet hole **10***c* in spaced apart relationship with the inlet hole **12***a* and corresponding to and matching with the outlet hole in the third sheet. The top sheet is formed with an inlet hole **12***b* and an outlet hole **10***d* corresponding to and matching with the inlet hole and outlet hole in the fourth sheet, respectively. The low pressure flow channel, high pressure flow channel, inlet holes, outlet holes and inflow holes are all preferably made by punching in a punching machine. The low and high pressure channels and all the inlet holes, outlet holes and inflow holes are filled with a sacrificial material (not shown). A thin layer of a sacrificial material (not shown) is laid between the inflow hole **9***c* and corresponding one end of the high pressure flow channel **11** in the fourth sheet. The sheets are stacked one above another with the inlet holes aligned with each other, the inflow holes aligned with one another and the outlet holes aligned with one another and the low and high pressure channels are aligned with each other. The sheets are cut to size preferably in a shearing machine and compacted preferably by isostatic compression. The heat exchanger body is sintered by firing at a temperature 30 to 900° C., preferably in an electric furnace. After sintering, the heat exchanger is allowed to cool down to ambient temperature. During firing, the sacrificial material burns out and the inlet holes, outlet holes and inflow holes and the low and high pressure channels remain in tact. Due to the thin sacrificial layer between the inflow hole **9***c* and corresponding one end of the high pressure flow channel in the fourth sheet, a narrow or constricted flow path **11***a* is formed in the fourth and top sheets between the inflow hole **9***c* and corresponding one end of the high pressure flow channel. The sacrificial material is, preferably, carbon paste. During operation of the heat exchanger, a cryogen like nitrogen or helium at high pressure enters the high pressure flow channel via the inlet holes in the top and fourth sheets. The cryogen at high pressure flows into the low pressure flow channel via the narrow flow path between the top and fourth sheets and the inflow holes in the fourth, third and second sheets. Due to the constriction provided by the narrow flow path, the cryogen expands and cools down the device (not shown) in contact therewith. The cryogen absorbs the heat of the device while flowing through the expansion zone provided by the inflow holes and while flowing through the low pressure flow channel. The cryogen flows out through the outlet holes in the second, third, fourth and top sheets and while doing so, the cryogen also picks up the heat from the high pressure channel side of the heat exchanger which is at a higher temperature. In the case of an open cycle Joule-Thompson cryocooler, the cryogen is vented out to the atmosphere through the outlet holes in the second, third, fourth and top sheets. In the case of a closed cycle Joule-Thompson cryocooler, the cryogen enters a compressor (not shown) and is recompressed in the compressor and sent back to the heat exchanger.

[0021] According to the invention fabrication of the heat exchanger is simple, easy and convenient to carry out. Time for fabrication of heat exchanger is reduced and fabrication does not require any pretreatment of the sheets. As a result of all this, the heat exchanger is also cost effective. Because of the use of the low temperature cofired ceramic sheets, it has been possible to miniaturize the heat exchanger. Due to miniaturization, the heat exchanger can be easily integrated into the device to be cooled thereby. Also, the overall size of the heat exchanger is reduced and overall size of the device to be cooled by the heat exchanger is reduced. Ceramic has high pressure withstanding capability. Therefore, the pressure withstanding capability of the heat exchanger is increased and the cooling efficiency of the heat exchanger is increased. Because of the benefits and advantages of the heat exchanger of the invention as explained above, a miniature Joule Thomson cryocooler comprising the heat exchanger also obviously will have similar benefits and advantages.

[0022] A typical heat exchanger of the invention was fabricated using five low temperature cofired ceramics sheets of 'green tape 951, containing particles of 0.7 to 5 μm of Al_2O_3, SiO_2, PbO, CaO, B_2O_3, K_2O, TiO_2 and BaO distributed in the polymer matrix. Each of the sheets was 200 μm thick and 101 mm×101 mm size. The length, width and depth of the low pressure flow channel were 64 mm×1 mm×0.2 mm, respectively. The length, width and depth of the high pressure flow channel were 51 mm×1 mm×0.2 mm, respectively: The length, width and depth of the narrow flow path were 4 mm×1 mm 0.015 mm, respectively. The diameter of each of the inlet holes was 3 mm. The diameter of each of the outlet holes was 3 mm. The diameter of each of the inflow holes was 3 mm. The thickness of the sacrificial layer between the inflow hole and corresponding one end of the high pressure flow channel was 20 μm. The heat exchanger was sintered upto a temperature of 900° C. during a period of 171 minutes. Simulation study showed that nitrogen gas compressed to 80 bar pressure gave a cooling effect of 65 mw and that the pressure withstanding capability of the heat exchanger was 105 bar.

1. A counter flow heat exchanger for a miniature Joule-Thompson cryocooler, the heat exchanger comprising a body formed of a bottom sheet, a second sheet, a third sheet, a fourth sheet and a top sheet, all the sheets being made of low temperature cofired ceramics and stacked one above another and fused together, the second sheet comprising a low pressure flow channel along the length thereof terminating in an inflow hole at one end thereof and in an outlet hole at the other end thereof, the third sheet comprising an inflow hole at one end thereof corresponding to and matching with the inflow hole in the second sheet and an outlet hole at the other end thereof corresponding to and matching with the outlet hole in the second sheet, the fourth sheet comprising a high pressure flow channel along the length thereof, an inflow hole at one end thereof corresponding to and matching with the inflow hole in the third sheet and spaced apart from corresponding one end of the high pressure flow channel, an inlet hole terminating at the inception of the high pressure flow channel and an outlet hole corresponding to and matching with the outlet hole in the third sheet and spaced apart from the inlet hole in the fourth sheet, the top sheet comprising an inlet hole corresponding to and matching with the inlet hole in the fourth sheet and an outlet hole corresponding to and matching with the outlet hole in the fourth sheet and a narrow flow path between the fourth sheet and top sheet communicating with said one end of the high pressure flow channel and the inflow hole in the fourth sheet.

2. The heat exchanger as claimed in claim **1**, wherein the sheets are 'green tape 951'.

3. A method of manufacturing a counter flow heat exchanger for a miniature Joule-Thompson cryocooler, the heat exchanger comprising a body formed of a bottom sheet, a second sheet, a third sheet, a fourth sheet and a top sheet, all the sheets being made of low temperature cofired ceramics and stacked one above another and fused together, the method comprising punching a low pressure flow channel along the length of the second sheet with an inflow hole at one end thereof and an outlet hole at the other end thereof, punching an inflow hole and an outlet hole in the third sheet corresponding to and matching with the inflow hole and the outlet hole in the second sheet respectively, punching a high pressure flow channel along the length of the fourth sheet, punching an inflow hole at one end of the fourth sheet corresponding to and matching with the inflow hole in the third sheet and in spaced apart relationship with one end of the high pressure flow channel, punching an inlet hole at the other end of the high pressure flow channel and punching an outlet hole in the fourth sheet corresponding to and matching with the outlet hole in the third sheet and spaced apart from the inlet hole in the fourth sheet, punching an inlet hole and an outlet hole in the top sheet corresponding to and matching with the inlet hole and outlet hole in the fourth sheet respectively, filling the low pressure flow channel, high pressure flow channel, inflow holes, inlet holes and outlet holes with a sacrificial material and forming thin layer of a sacrificial material between the inflow hole and corresponding said one end of the high pressure flow channel in the fourth sheet, stacking the sheets one above another, cutting the sheets to size, compacting the sheets and fusing the sheets together by sintering at 30 to 900° C. with simultaneous formation of a narrow flow path in the fourth sheet and top sheet between the inflow hole in the fourth sheet and corresponding said one end of the high pressure flow channel in the fourth sheet.

4. The method as claimed in claim **3**, wherein the sheets are cut to size in a shearing machine.

5. The method as claimed in claim **3**, wherein the sheets are compacted by isostatic compression.

6. The method as claimed in claim **3**, wherein the sacrificial material comprises carbon paste.

7. The method as claimed in claim **3**, wherein the sheets are 'green tape 951'.

8. A miniature Joule-Thompson cryocooler comprising a counter flow heat exchanger as claimed in claim **1**.

9. The cryocooler as claimed in claim **8**, which is a closed cycle miniature Joule-Thompson cryocooler.

10. The cryocooler as claimed in claim **8**, which is an open cycle miniature Joule-Thompson cryocooler.

11. The method as claimed in claim **4**, wherein the sheets are compacted by isostatic compression.

12. The method as claimed in claim **4**, wherein the sacrificial material comprises carbon paste.

13. The method as claimed in claim **5**, wherein the sacrificial material comprises carbon paste.

14. The method as claimed in claim **4**, wherein the sheets are 'green tape 951'.

15. The method as claimed in claim **5**, wherein the sheets are 'green tape 951'.

16. The method as claimed in claim **6**, wherein the sheets are 'green tape 951'.

17. A miniature Joule-Thompson cryocooler comprising a counter flow heat exchanger as claimed in claim **2**.

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