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DEVICES AND METHODS FOR MICROREACTOR FLUID DISTRIBUTION

PRIORITY

[0001] This application claims priority to European Patent Application number 08305873.5, filed November 28, 2008, titled “Devices and Methods For Microreactor Fluid Distribution” and European Patent Application number 09305384.1, filed April 30, 2009, titled “Devices and Methods For Microreactor Fluid Distribution”

BACKGROUND

[0002] This application relates to devices and methods for fluid distribution within a microreactor, and more particularly to devices and methods for providing desired flows of both process fluids and thermal control fluids, particularly in microreactors employing microstructures comprising glass, ceramic, and glass-ceramic.

SUMMARY

[0003] According to one aspect of the invention, a microreactor (10) includes a plurality of interconnected microstructures (14, 50, 40) arranged in m process units (102) with the process units (102) configured to be operable together in parallel. Each of the m process units (102) has a number n of respective process fluid inlets (104), wherein a number y of the n respective process fluid inlets (104) are connected individually to respective non-manifolded fluid pumps (20A, 20B, 20C, 20D; 22A, 22B, 22C, 22D; 24A, 24B, 24C, 24D), and wherein a number n minus y of the n respective process fluid inlets (104) are connected to a respective manifolded fluid pump (20, 22, 24, 26, 28, 30) via a manifold (80), wherein y is an integer from 1 to n-1 inclusive.

[0004] Additional variations and features of the present invention are described below in connection with the figures, of which:

BRIEF DESCRIPTION OF THE DRAWINGS

[0005] Figure 1 is cross section of a microstructure 14 in the form of a layered microfluidic device 210;

- [0006] Figure 2 is another cross section of the microstructure 14 of Figure 1;
- [0007] Figure 3 is a perspective view of another instance of a microstructure 14 in the form of a honeycomb-body based unitary microfluidic device 312.
- [0008] Figure 4 is a cross-sectional view of a microstructure 14 in the form of a honeycomb body microfluidic device 312 similar to that of Figure 3, with fluid connections;
- [0009] Figure 5 is a perspective view of a microstructure 14 including three unitary microstructures in the form of multiple multilayer microfluidic devices 210;
- [0010] Figure 6 is a perspective view of a hybrid or combination microstructure 14 including two multilayer microfluidic devices 210 and one honeycomb-body based microfluidic device 312;
- [0011] Figure 7 is a schematic diagram of a microreactor 10 comprising multiple microstructures 14;
- [0012] Figure 8 is a schematic diagram of another microreactor 10 comprising multiple microstructures 14;
- [0013] Figure 9 is a schematic diagram of the microreactor 10 of Figure 7, with both thermal control fluid and process fluid fluidic connections shown;
- [0014] Figure 10 is a schematic diagram of a microreactor or portion of a microreactor having two process units 102 and having a manifold 60 in the path of thermal control fluid H according to an aspect of the present invention;
- [0015] Figure 11 is a schematic diagram of a microreactor or portion of a microreactor according to another aspect of the present invention and including four process units 102 arranged in parallel;
- [0016] Figure 12 is a schematic diagram of a microreactor or portion of a microreactor according to another aspect of the present invention according to which a different one of the process fluids is forced by non-manifolded pumps, relative to the embodiment of Figure 11;
- [0017] Figure 13 is a schematic diagram of a microreactor or portion of a microreactor according to yet another aspect of the present invention according to which more than one of the process fluids is forced by non-manifolded pumps;
- [0018] Figure 14 is a partial schematic diagram of a microreactor or portion of a

microreactor according to still another aspect of the present invention;

[0019] Figure 15 is a schematic diagram of a microreactor or portion of a microreactor according to yet another aspect of the present invention according to which flow from one or both of non-manifolded pumps and manifolded pumps may be monitored and/or feedback controlled.

DETAILED DESCRIPTION

[0020] Whenever possible, the same reference numerals will be used throughout the drawings to refer to the same or like parts. Features described as desirable are preferred but optional, representative of variations of the invention.

[0021] Within this document, “unitary microstructure” refers to single-piece or otherwise generally permanently assembled microfluidic devices having internal passages with a characteristic cross-sectional dimension in the few-millimeter to sub-millimeter range. Unitary microstructures may include, for instance, devices similar to and including those disclosed and described in Patent No. US7007709 entitled “A Microfluidic Device and Manufacture Thereof,” whether made by the method therein disclosed or other methods. Unitary microstructures may also include devices similar and including those disclosed and described in Publication No. WO2008/121390 entitled “Extruded Body Devices and Methods for Fluid Processing,” whether made by the methods disclosed or by other methods. “Microstructure” refers to both unitary and other microstructures and to combinations of microstructures joined or interconnected in close proximity, treated or treatable as a unit for fluid distribution. “Microreactor” refers to a device for performing chemical or physical processes or combinations thereof, the device including, in the context of this document, two or more microstructures with associated fluid connections arranged in one or more production units. “Production unit” refers to a combination of microstructures with associated fluid connections arranged to as to be capable of performing a desired reaction or process along a single primary path along or through the microstructures, and not along multiple parallel primary paths through multiple microstructures in parallel. “Flow balance” or “flow balancing” relates to achieving any particular desired flow ratio between or among multiple fluid feeds, and not merely to equal flows.

[0022] Figure 1 is cross section of one instance of a microstructure 14 in the form of a unitary microstructure or unitary multilayer microfluidic device 210 which may be used with the present invention. The microfluidic device 210 may be comprised of multiple substrates 220, generally at least four as shown at the top of the figure, but more may be included if desired, up to “k” total, as labeled at the left edge of Figure 1. Between each adjacent pair of the multiple substrates 220, a layer 230 of the device 210 is defined, such that multiple layers 230 are present, generally at least three, and optionally more, with up to k-1 total layers, as labeled at the right edge of Figure 1. The substrates 220 are joined to each other and supported relative to one another by walls 234 (for ease of viewing, not all labeled), some of which are cut by the cross section of the figure, as indicated by the cross-hatching. Inlet and outlet holes 264, 265 which may extend through one or more of the substrates 220, provide external access to a thermal control fluid path 240 defined in or through one or more of the layers 230, in this case through the two layers 232 of the layers 230. Alternative access routes, such as by holes or gaps (not shown) through walls 234, may be used in place of or in addition to holes 264, if desired.

[0023] Figure 2 is another cross section of the microstructure 14 or microfluidic device 210 of Figure 1, taken in a plane different from but parallel to that of Figure 1. In the cross section of Figure 2 may be seen inlet and outlet holes 282, 283 which provide access through substrates 220 to a process fluid path 250 defined through one or more of the layers 230 of the device, in this case through the one layer 231. The process fluid path 250 may include one or more additional inlet ports or holes 282 (in a cross section not shown in Figures 1 and 2), such that two or more process fluids can be contacted and/or mixed and/or reacted together within the process fluid path 250. More than one outlet port or hole 283 may also be included on the output end of the process fluid path 250, such that a process fluid may be divided upon exiting the device 210, if desired.

[0024] Various materials and methods may be used to form the microstructures 14 or microfluidic devices 210 of the type shown in Figures 1 and 2, including methods that produce walls and substrates simultaneously as one piece. Additional methods include, for instance, those disclosed and described in Patent Publication No. EP1964817, entitled “Method for Making Microfluidic Devices and Devices Produced Thereof,” and in Patent Publication No. US2007/0154666, entitled “Powder Injection Molding of Glass and

Glass-Ceramics.”

[0025] Figure 3 is a perspective view of another instance of a microstructure 14 that may be used in the context of the present invention, in the form of a honeycomb-body based unitary microfluidic device 312.

[0026] The microfluidic device 312 comprises a honeycomb body 320. The body 320 has cells 323 extending in parallel in a common direction from a first end 332 of the body 320 to a second end 334, divided by walls 382. The cells 323 include a first plurality of cells 322 open at both ends of the body and a second plurality of cells 324 closed at one or both ends of the body by one or more plugs 326 or by a more or less continuous plugging material 326 disposed at or near the end of the body and optionally at least partly within the cells 324, or by other suitable means. The second plurality of cells 324 (the closed cells) contain, at least in part, one or more passages 328 extending through the body 320. The passage 328 may have a serpentine shape when considered in a plane perpendicular to the common direction of the cells 323, as shown in Figure 3, but other passage shapes may also be used. More than one passage 328 per body 20 may also be used, if desired.

[0027] Figure 4 is a cross-sectional view of a honeycomb body microstructure 14 in the form of a microfluidic device 312 similar to that of Figure 3, but with a type of fluid connection also shown. In Figure 4, a fluid housing 340 supports the honeycomb body 320 via seals 342. A passage 348, typically used for a thermal control fluid, is formed in parallel through all the open channels 322 of the body 320, in cooperation with the housing 340. Passage 328 in the body 320 is accessed via conduits 360 through seals 343. As seen in the cross-section of Figure 4, the path or passage 328 in the body 320 may also be serpentine in a plane parallel to the common direction of the cells 323, but other passage shapes may also be used.

[0028] The honeycomb body 320 is desirably formed of an extruded glass, glass-ceramic, or ceramic material for durability and chemical inertness. Alumina ceramic is generally preferred as having good strength, good inertness, and higher thermal conductivity than glass and some ceramics. Greater detail concerning general materials and fabrication procedures developed by the present inventor and/or colleagues of the present inventor may be found in the above-referenced PCT Publication No. WO

2008/121390.

[0029] Unitary microstructures such as those shown in Figures 1-4 may also be combined to form hybrid or combination microstructures as shown in Figures 5 and 6. Figure 5 shows a microstructure 14 including three unitary microstructures in the form of multilayer microfluidic devices 210, connected together physically and fluidically by any suitable means. Figure 6 shows a hybrid or combination microstructure 14 including two multilayer microfluidic devices 210 and one honeycomb-body based microfluidic device 312.

[0030] As is understood in the field of microreaction technology, for many desirable applications of microreactor technology the production rate achievable in a single production unit, having a single primary path in or through a given set of microstructures, may be insufficient for commercial needs. This may be the case even where the microstructures in question utilize what is known as “internal numbering up” or internal parallelism in flow passages. For this reason, it is desirable to operate multiple production units of microstructures in parallel, that is, to use what is sometimes called “external numbering up.”

[0031] An example of a mounting and interconnection system for fluidic microstructures, developed by the present inventors and/or their associates, may be found in Patent Publication No. EP1854543, assigned to the assignee of the present application. Such a system any other appropriate means may be employed to form various microreactor configurations by connecting microstructures in series and in parallel and in combinations of series and parallel arrangements.

[0032] For many processes, achieving external numbering up by replicating every part of a production unit, including multiple pumps for feeding multiple streams of process and thermal control fluids to each production unit, is not sufficiently economical. This may be appreciated from the microreactors 10 shown in Figures 7-9, each of which represents an instance of a microreactor 10 comprised of an interconnected network 12 of microstructures 14 together forming a single process unit 102 or a portion of a single process unit 102.

[0033] Schematic diagrams of two arrangements of a microreactor 10, among essentially infinite possible arrangements, are shown in Figures 7 and 8, in the form of an

interconnected network 12 of microstructures 14. Each microstructure 14 typically, though not necessarily, includes both process fluid passages or paths and thermal control or thermal control fluid passages or paths therein, and is thus provided with one or more process fluid feeds and typically one (but possibly more) thermal control fluid feeds. In Figures 7 and 8, only process fluid feeds, the feeds of process fluids A-F, are shown. Thermal control fluid feeds are omitted from Figures 7 and 8 for ease of viewing.

[0034] Microstructures 14 may take the form of microstructures 40 having two or more process fluid inputs, such as mixing or contacting microstructures, and microstructures 50 having only one process fluid input, such as thermal control or dwell time or catalysis microstructures, or any of various other microstructures having various combinations of process fluid inputs and outputs. In the embodiment shown in Figure 7, process fluid A is pumped by pump 20, and process fluid B is pumped by pump 22, directly into the first microstructure 40 where the fluids are combined and mixed. Process fluid C is pumped by pump 24 through microstructure 50 where the fluid is pre-heated or pre-cooled before entering the second microstructure 40 to be combined and mixed with the mixture or the product of mixing fluids A and B. Successive process fluids D, E and F are added similarly by pumps 26, 28 and 30, and the resulting fluid product is delivered at output O.

[0035] The microreactor of Figure 8 is identical to that of Figure 7 and may operate similarly, except that the microreactor is arranged such that after the addition and initial combination and mixing of each of the process fluids D, E, and F, the process fluid stream passes through a respective thermal microstructure 50, which provides additional dwell time and thermal control capability.

[0036] Figure 9 shows the microreactor 10 of Figure 7, but with thermal control fluid feeds added. Two or more thermal control fluids may be used. In this embodiment, two thermal control fluids G and H are used, allowing two different temperatures to be approached or maintained in the respective associated portions of the microreactor 10. Thermal control fluid G is fed by pump 32 through microstructure 50 and out to fluid return RG, where the fluid may be recycled back through the same loop, if desired, after any necessary heating or cooling. Thermal control fluid H is fed by a pump 34, but is fed via a manifold 60 with branches 62 into the five microstructures 40 in parallel. A collection manifold 70 collects and returns the thermal control fluid H at fluid return RH.

Such parallel feeding of thermal control fluid is desirable, where possible, from efficiency, cost, and reliability considerations.

[0037] Where thermal fluid is fed in parallel, as by pump 34 in Figure 9, each microstructure 40 so fed should receive the needed rate of flow of thermal control fluid. Inadequate thermal fluid flow can lead to poor reaction control or even out-of-control conditions.

[0038] The microreactor 10 of Figure 9 constitutes only a single process unit 102—that is, a microreactor having a single principal process path in or through multiple microstructures—a process fluid path along which microstructures are not employed in parallel to form multiple principal process paths. In the microreactor of Figure 9, a single process unit 102 has six process fluid feeds A-F and two thermal control fluid feeds G and H. Depending on the reaction to be performed, more process fluid feeds, more thermal control fluid feeds, and/or a more complicated network 12 of microstructures 14 may be required.

[0039] From Figure 9 (and from Figure 8, which is shown with thermal control fluid feeds omitted), it may be appreciated that a microreactor 10 consisting of only a single process unit 102 can be fairly complex. Nonetheless, to meet high production throughputs that may be required, multiple process units 102 are desirably operated in parallel. While replicating the entire process unit 102 in parallel is possible, various fluid connection and fluid handling components, pumps in particular, add to the cost, and replicating the eight pumps of Figure 9 across multiple process units may be prohibitively expensive for many processes. Accordingly, it is desirable, to the degree possible, to operate multiple process units 102 in parallel from a single pump for each feed.

[0040] To this end, where multiple process units 102 are used, the thermal control fluid feed may be manifolded across multiple process units if desired, in addition to being manifolded across multiple microstructures 40, 50 within each process unit, as shown in the embodiment of Figure 10.

[0041] The microreactor 10 of Figure 10 includes two process units 102, labeled 1 and 2, configured for operation in parallel. Again, process fluid feeds are omitted for ease of viewing. The microreactor 10 includes two thermal control fluid pumps 32, 34 and in this case each are connected via a respective thermal control fluid manifold 60, one of which

further includes sub-manifolds 60A and 60B. The manifolds 60 (and sub-manifolds 60A, 60B) each provide thermal control fluid to two or more of the plurality of interconnected microstructures 40, 50. The thermal control fluid sub-manifolds 60A and 60B each include branches 62.

[0042] The thermal control passage or path or passage internal to the individual microstructures 40 and 50—such as path or passage 240 in the microstructure of Figures 1 and 2, or path or passage 348 in the microstructure of Figures 3 and 4, and combinations of such paths or passages in the microstructures of Figures 5 and 6—desirably has relatively low flow resistance, allowing for relatively high flow rates of thermal control fluid in a given microreactor.

[0043] Although flow resistance is desirably low, layer(s) 232 are also desirably of low height 233, generally in the range of 0.2 to 3 mm, desirably in the range of 0.2 to 1.5 mm, more desirably in the range of 0.5 to 1.0 mm, such that any boundary layers formed during thermal fluid flow are thin, preserving good thermal performance. Desirable low flow resistance may be achieved in significant part by the outlet hole 265 of Figures 1 and 2 having a diameter in the range of 1 to 10 mm, desirably 2 to 5 mm or more desirably 3 to 5 mm. The process fluid path 250 also is not large, desirably having a passage or path height 235 in the range of 0.1 to 2 mm, with the process fluid path 250 lying within a generally planar volume or layer 231. The thermal control fluid layer 232 may have an inlet hole 264 having a diameter in the same range as the outlet 265.

[0044] Where heat transfer rate must be maximized, the height 233 of the thermal fluid passages (the height of layers 232) should be kept small, such as in the range of 0.5-1.0 mm, for instance. Where heat transfer rate is not as critical, the height 233 can be increased for lower flow resistance in path 240 in the layers 232. Regardless of whether some flexibility in the height 233 is available, input and output port diameters are increased relative to previous work with this type of microstructure, thus providing the desired benefit of lower flow resistance even where high heat transfer rates are required.

[0045] Despite the relatively large diameters ports or holes 264, 265, as disclosed herein, the input and output ports or holes 264, 265 experience no significant increase, or even a slight decrease of stress, relative to previous devices with smaller apertures, thus providing at least the same pressure resistance performance as previously achieved. This

has been demonstrated by experiments and by finite element modeling. Such enlarged diameters for input and output ports or holes may also be applied, if desired, in the process fluid path, that is, input and output ports or holes 282 and 283 may also desirably in the size range of from 1 to 10mm in diameter, desirably 2 to 5 mm or more desirably 3 to 5 mm, allowing decreased flow resistance with at least the same pressure resistance within the process fluid path 250.

[0046] In a microreactor like that of Figure 10, addition to decreasing the number of pumps required for thermal control fluid, it is also desirable to decrease the number of pumps required for process fluids. Because of the sensitivity of many reactions to small changes in stoichiometry, fluid balancing for process fluids can be critical.

[0047] Figure 11 shows another embodiment of a microreactor 10 according to the present invention. The microreactor 10 of Figure 11 includes four process units 102 arranged in parallel and labeled 1-4. Only process fluid feed lines are shown. Thermal fluid feed lines are omitted for ease of viewing.

[0048] In the embodiment of Figure 11, the process fluid feeds B-F are all pumped by a respective manifolded pump 22-30 connected across the four process units 102. Fluid balance is preserved to significant degree by having one process fluid, process fluid A in this case, pumped by non-manifolded pumps 20A-20D, one for each process unit 102. By forcing one of the process fluid flows to flow at ideal rates, and by using low-restriction manifolds 80, downstream variations within each process unit 102 are suppressed. Desirably, the very first or head-end process fluid, process fluid A in the figures, is the one that is forced, as in this case, or is at least one of those that is forced, as in Figure 13 described below. In other words, it is desirable that a process fluid inlet (104) individually connected to respective non-manifolded fluid pumps is the inlet (104) for the head-end process fluid A.

[0049] As an alternative to the embodiment of Figure 11, a different one of the process fluids may be forced by non-manifolded pumps, as shown in Figure 12. For example, a particularly low-flow-rate process fluid flow may be forced, or that fluid flow may be forced which produces the greatest variation of reaction performance or which otherwise has the greatest effect on the desired results. In the case that fluid B has a lower flow requirement than fluid A, for example, then the microreactor 10 of Figure 12 could

desirably be used to provide strict control of the introduction of fluid B. In the reactor of Figure 12, so employed, a process fluid inlet (104) individually connected to respective non-manifolded fluid pumps is the inlet (104) for the process fluid B, desirably having a flow requirement less than that of fluid A. The fluid B inlet connected to non-manifolded pumps may be the only inlet so connected, or, as another alternative, two or more of the process fluids may be forced, as shown in the microreactor 10 of Figure 13. In that microreactor 10, process fluids A (the head-end fluid) and B (a lower flow fluid, in the case of one desirable alternative) are both forced by respective non-manifolded pumps 20A-20D and 22A-22D. Other combinations are possible, of course.

[0050] Figure 14 shows a partial schematic diagram of a microreactor 10 according to the present invention including m total process units 102. The microreactor 10 comprises a plurality of interconnected microstructures 14 arranged in m process units 102 (which appear as rows in the figure as labeled at left) with the process units 102 configured to be operable together in parallel, each of the m process units having a number n of respective process fluid inlets 104 (which are arranged in the figure as columns labeled at the top). Note that although the diagram is in rows and columns, this arrangement need have little to do with the actual physical layout of component according to the present invention. For example, the process units 102 need not be linear or single-branched or arranged in rows. What matters is that the relationships herein described, and understood with the aid of the Figure, hold. For each process unit 102, a number y of the n respective process fluid inlets 104 are connected individually to a respective non-manifolded fluid pump (not shown for ease of viewing). In this specific case, three of the process fluid inlets, those for process fluids A, B, and C at the left of Figure 14, are connected individually to a non-manifolded pump (20A-20D for A, not shown for B and C). A number $n-y$ of the n respective process fluid inlets 104—at least two at the right of the figure in this case, for process fluids E and F—are connected to a respective manifolded fluid pump 28, 30 via a manifold 80, wherein y may be an integer from 1 to $n-1$ inclusive. Desirably, the flow resistance, from a respective manifolded fluid pump along the associated manifold 80 to an associated microstructure 14, is smaller than the flow resistance of an associated process fluid path 150 through the associated microstructure(s) 14, or in other words, it is desirable that the manifold 80 be a low resistance manifold relative to the associated

microstructure(s) 14. It is also desirable to minimize the number of individual pumps, so y is desirably only 1 or 2, and only as high as required to adequately control the desired reaction to be performed. The net result is that microstructures, including microstructures comprising glass, glass-ceramic and ceramic materials, may be used to perform highly complex and sensitive reactions in an externally-numbered-up microreactor, without requiring individual feed lines and pumps for every feed to every microstructure.

[0051] Figure 15 is a schematic diagram of a microreactor or portion of a microreactor according to yet another aspect of the present invention according to flow from one or both of non-manifolded pumps and/or manifolded pumps may be monitored and/or feedback controlled. Where strictly passive flow splitting for flows from the manifolded pumps is insufficient to maintain the required flow balance, one or more flow monitors 142 of suitable type may be employed to monitor the outputs of one or more the manifolded pumps. These may include, for example, a positive displacement flowmeter 144 or, desirably, a rotameter 146. The meter output may be monitored by an operator who may adjust a manual valve 162 to tune the flow balance of the microreactor.

Alternatively, a control system computer, factory production control system, microprocessor or the like 110 may receive flow information via flow-information links 140, and may employ the information received in adjusting automatically controlled valves 164 via valve-control links 160. The control system computer, factory production control system, microprocessor or the like 110 may also receive various inputs from individual microstructures or sensors associated therewith, via process-information links 150, and may also automatically adjust the flow rate of the non-manifolded pumps such as pump 20D, via pump-control link 170. It is understood that such links need not be hard-wired.

[0052] The methods of use and/or the devices disclosed herein are generally useful in performing any process that involves mixing, separation, extraction, crystallization, precipitation, or otherwise processing fluids or mixtures of fluids, including multiphase mixtures of fluids—and including fluids or mixtures of fluids including multiphase mixtures of fluids that also contain solids—within a microstructure. The processing may include a physical process, a chemical reaction defined as a process that results in the interconversion of organic, inorganic, or both organic and inorganic species, a

biochemical process, or any other form of processing. The following non-limiting list of reactions may be performed with the disclosed methods and/or devices: oxidation; reduction; substitution; elimination; addition; ligand exchange; metal exchange; and ion exchange. More specifically, reactions of any of the following non-limiting list may be performed with the disclosed methods and/or devices: polymerisation; alkylation; dealkylation; nitration; peroxidation; sulfoxidation; epoxidation; ammoxidation; hydrogenation; dehydrogenation; organometallic reactions; precious metal chemistry/homogeneous catalyst reactions; carbonylation; thiocarbonylation; alkoxylation; halogenation; dehydrohalogenation; dehalogenation; hydroformylation; carboxylation; decarboxylation; amination; arylation; peptide coupling; aldol condensation; cyclocondensation; dehydrocyclization; esterification; amidation; heterocyclic synthesis; dehydration; alcoholysis; hydrolysis; ammonolysis; etherification; enzymatic synthesis; ketalization; saponification; isomerisation; quaternization; formylation; phase transfer reactions; silylations; nitrile synthesis; phosphorylation; ozonolysis; azide chemistry; metathesis; hydrosilylation; coupling reactions; and enzymatic reactions.

What is claimed is:

1. A microreactor (10) comprising a plurality of interconnected microstructures (14, 50, 40) arranged in m process units (102), said process units (102) configured to be operable together in parallel, each of the m process units (102) having a number n of respective process fluid inlets (104), wherein a number y of the n respective process fluid inlets (104) are connected individually to respective non-manifolded fluid pumps (20A, 20B, 20C, 20D; 22A, 22B, 22C, 22D; 24A, 24B, 24C, 24D), and wherein a number n-y of the n respective process fluid inlets (104) are connected to a respective manifolded fluid pump (20, 22, 24, 26, 28, 30) via a manifold (80), wherein y is an integer from 1 to n-1 inclusive.
2. The microreactor (10) according to claim 1 wherein the flow resistance, from a respective manifolded fluid pump (104) along the associated manifold (80) to an associated microstructure (14, 40, 50) is smaller than the flow resistance of an associated process fluid path (250, 328) through the associated microstructure (14, 40, 50).
3. The microreactor (10) according to either of claims 1 and 2, wherein the microreactor (10) comprises at least one thermal control fluid pump (32, 34) connected via a thermal control fluid manifold (60, 60A, 60B) to two or more of the plurality of interconnected microstructures (14, 40, 50).
4. The microreactor according to claim 3 wherein the two or more of the plurality of interconnected microstructures (14, 40, 50) include a thermal control fluid outlet hole (265) having a diameter in the range of 1 to 10mm.
5. The microreactor according to claim 4 wherein the two or more of the plurality of interconnected microstructures (14, 40, 50) include a thermal control fluid outlet hole (265) having a diameter in the range of 2 to 5mm.
6. The microreactor according to either claim 4 or claim 5 wherein the two or more

of the plurality of interconnected microstructures (14, 40, 50) include a thermal control fluid inlet hole (264) having a diameter in the range of 2 to 5mm.

7. The microreactor according to any of claims 1-6 wherein the microstructures (14, 40, 50) comprise at least one of glass, ceramic, and glass ceramic.
8. The microreactor according to any of claims 1-7 wherein the microstructures (14, 40, 50) include at least one multilayer microfluidic device (210).
9. The microreactor according to any of claims 1-8 wherein the microstructures (14, 40, 50) include at least one honeycomb-body based microfluidic device (312).
10. The microreactor according to any of claims 1-9 wherein y is 2.
11. The microreactor according to any of claims 1-9 wherein y is 1.
12. The microreactor according to any of claims 1-11 wherein a process fluid inlet (104) individually connected to respective non-manifolded fluid pumps (20A, 20B, 20C, 20D; 22A, 22B, 22C, 22D; 24A, 24B, 24C, 24D) is the inlet (104) for a head-end fluid (A).
13. The microreactor according to claim 1-11 wherein a process fluid inlet (104) individually connected to respective non-manifolded fluid pumps (20A, 20B, 20C, 20D; 22A, 22B, 22C, 22D; 24A, 24B, 24C, 24D) is the inlet (104) for a fluid (B) having a lower flow requirement than the inlet (104) for a head-end fluid (A).
14. The microreactor according to any of claims 1-13 further comprising one or more flow meters (142, 144, 146) for monitoring flow rates in the outputs of a respective manifolded fluid pump (20, 22, 24, 26, 28, 30).
15. A method of tuning the flow balance of a microreactor comprising the steps of:

providing a microreactor according to any of claims 1-14, the microreactor further comprising one or more flow meters 142 and one or more manual valves 162;

monitoring the one or more flow meters 142; and

adjusting the one or more manual valves 162 to tune the flow balance of the microreactor.

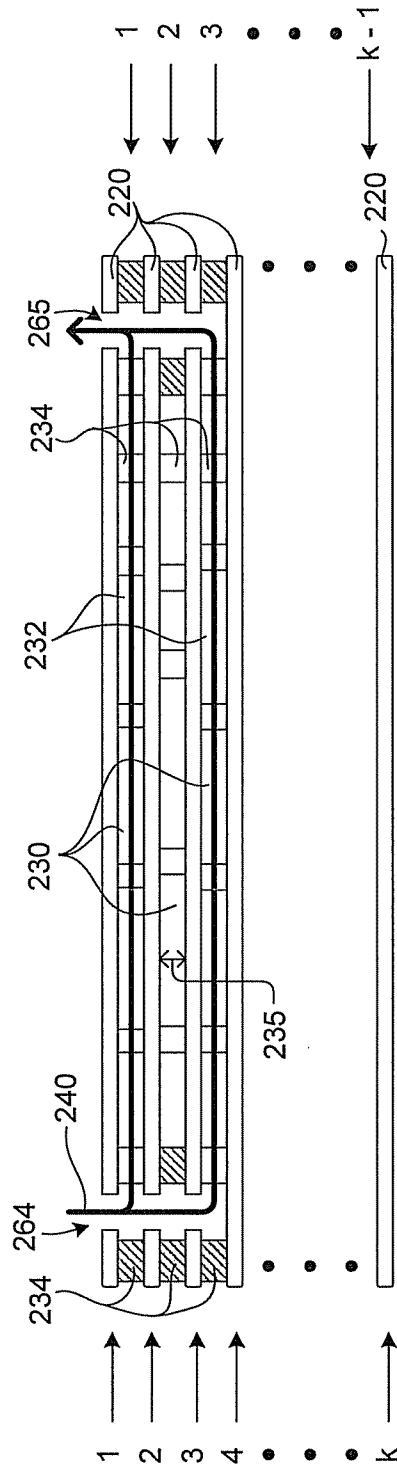


Figure 1

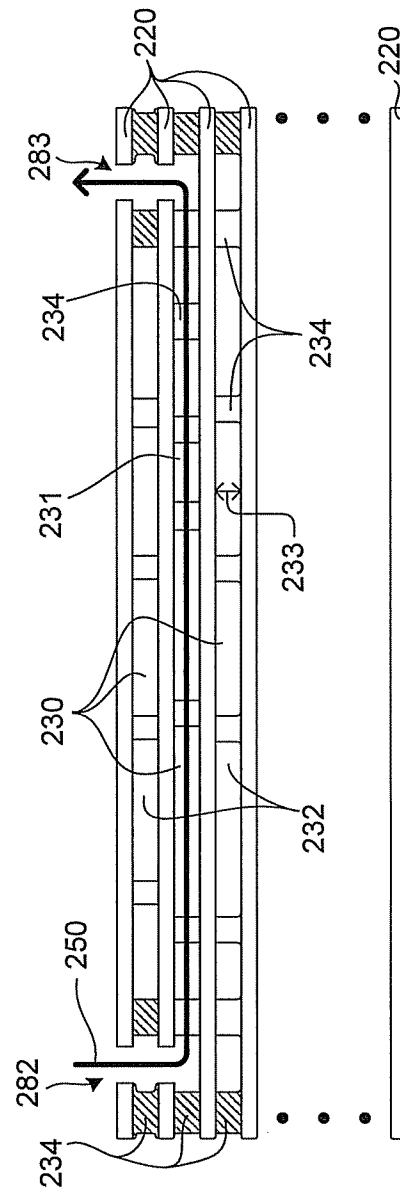


Figure 2

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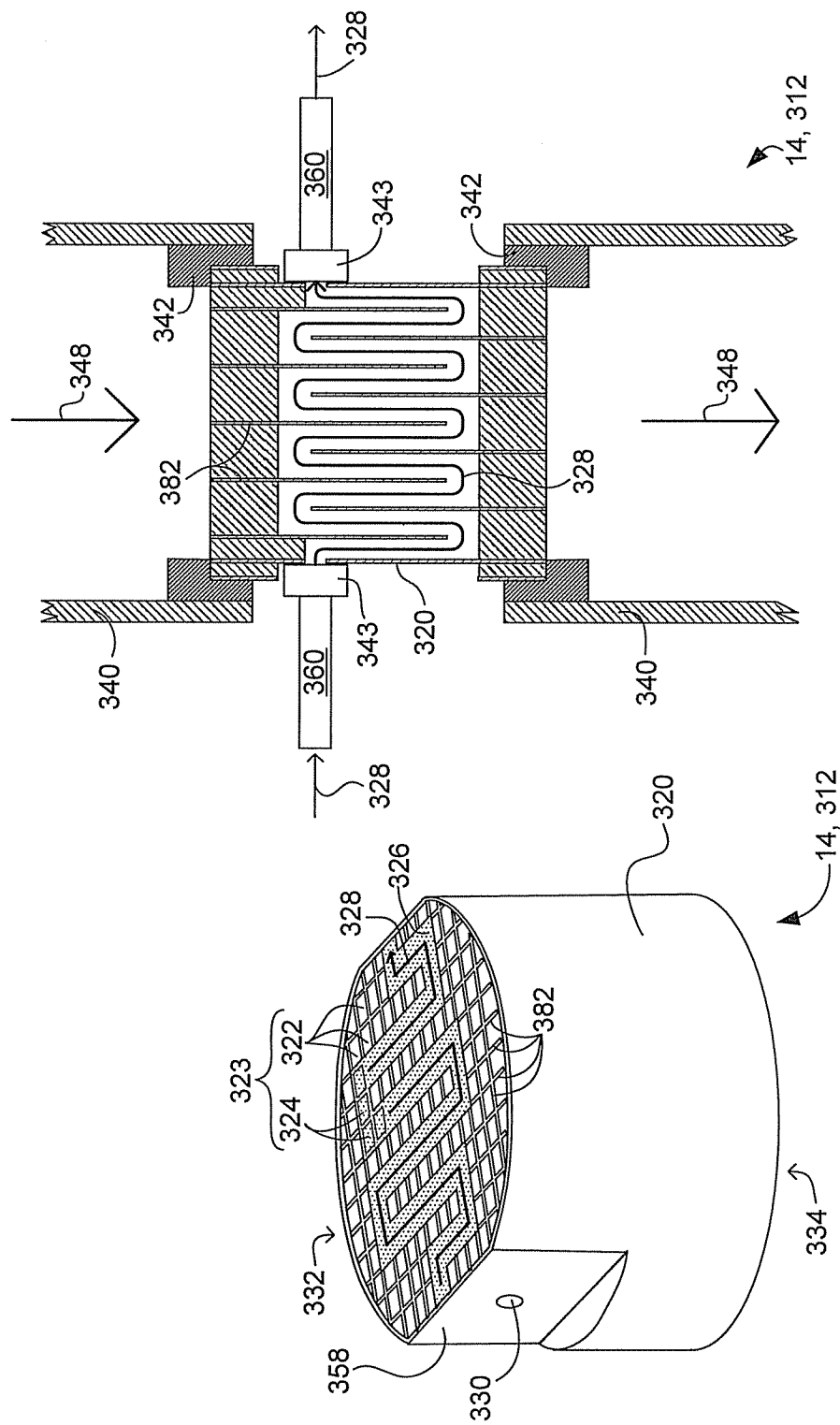


Figure 4

Figure 3

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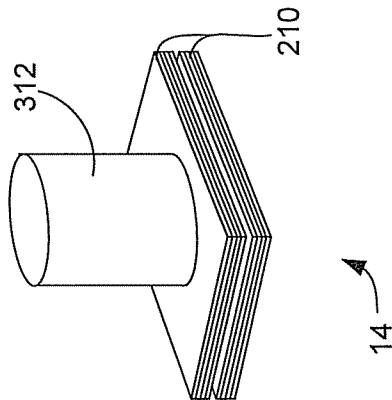


Figure 6

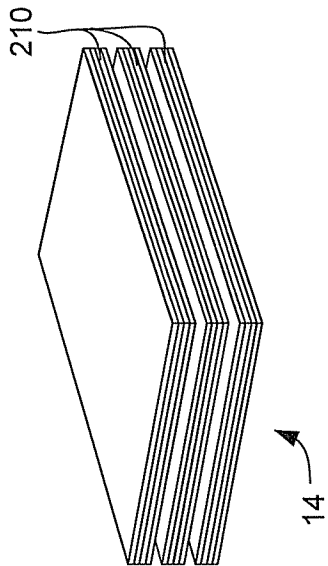


Figure 5

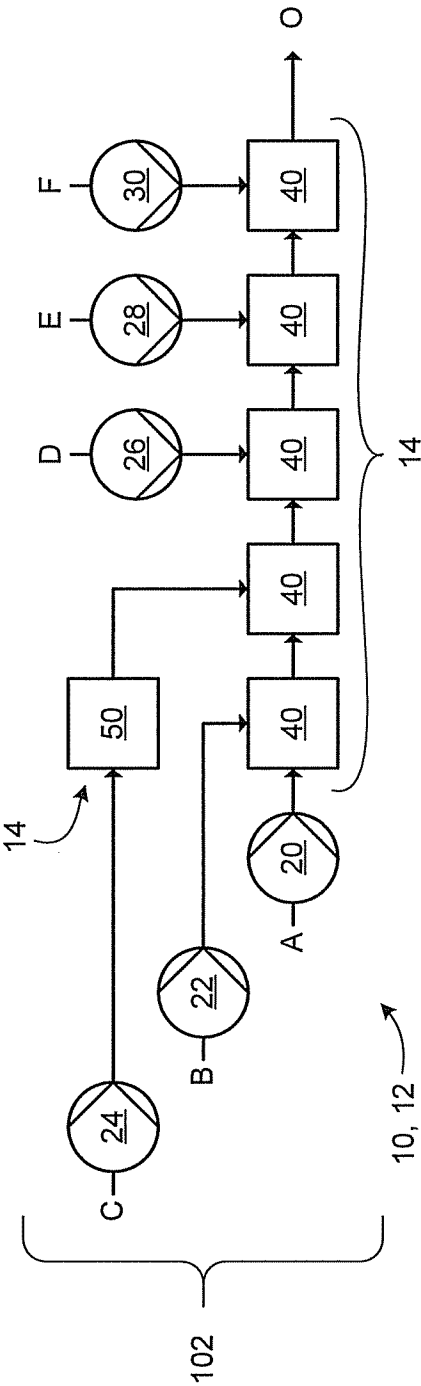


Figure 7

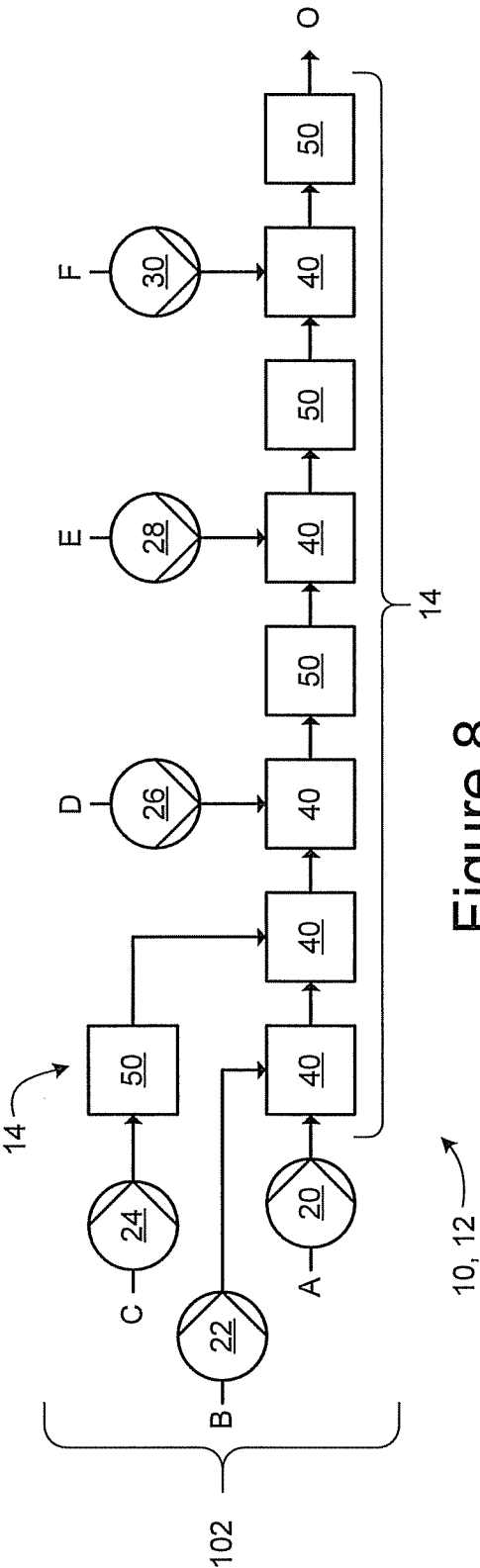


Figure 8

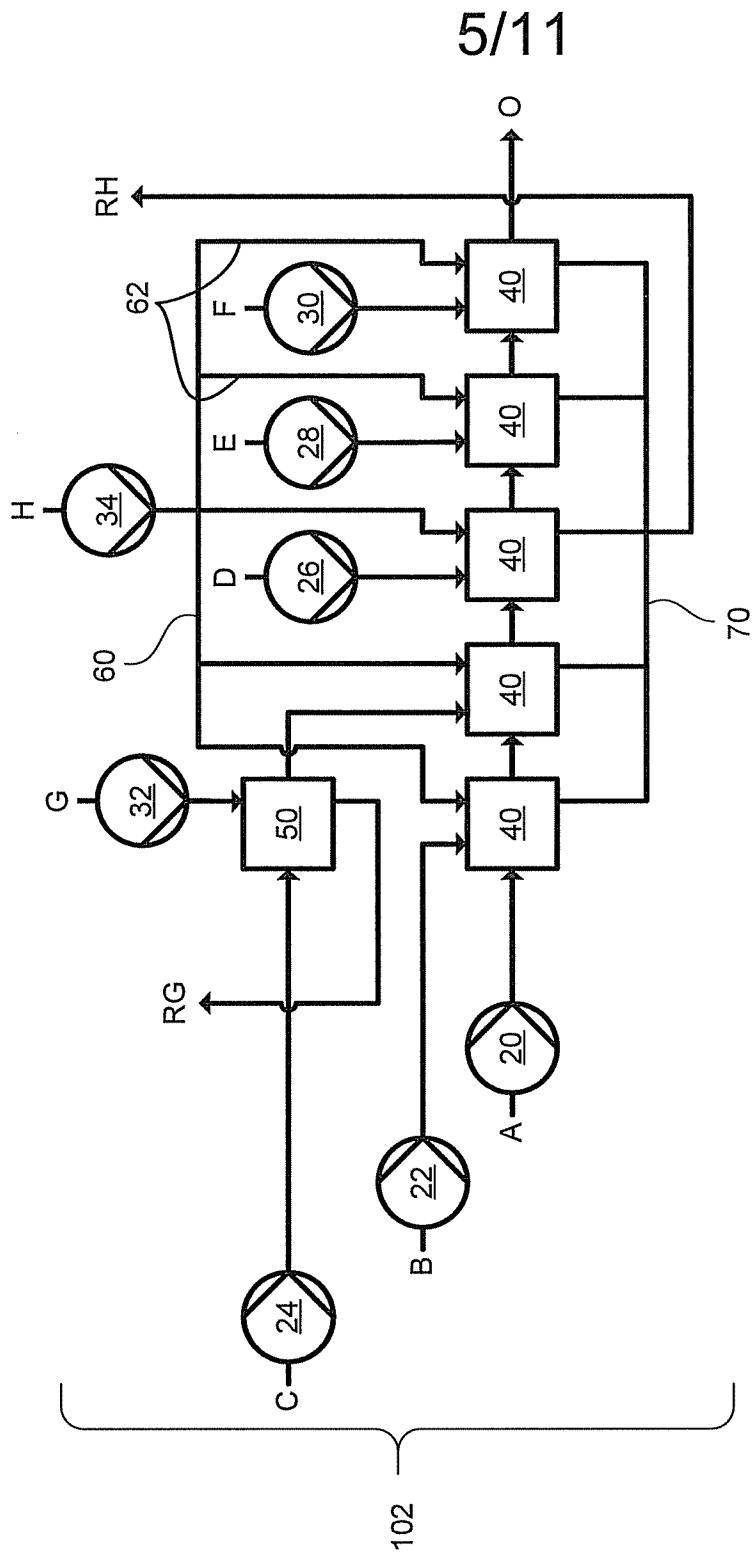


Figure 9

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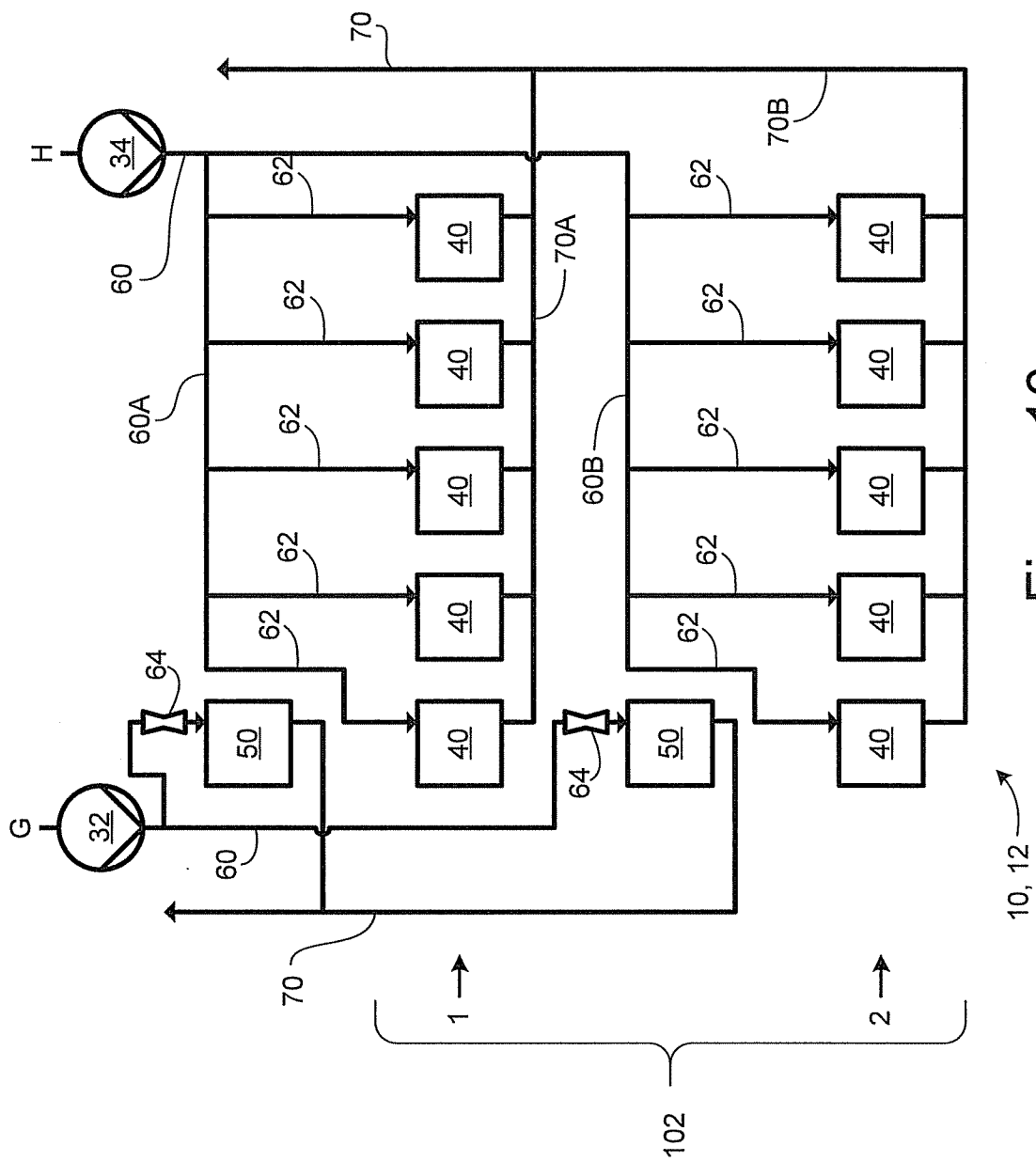


Figure 10

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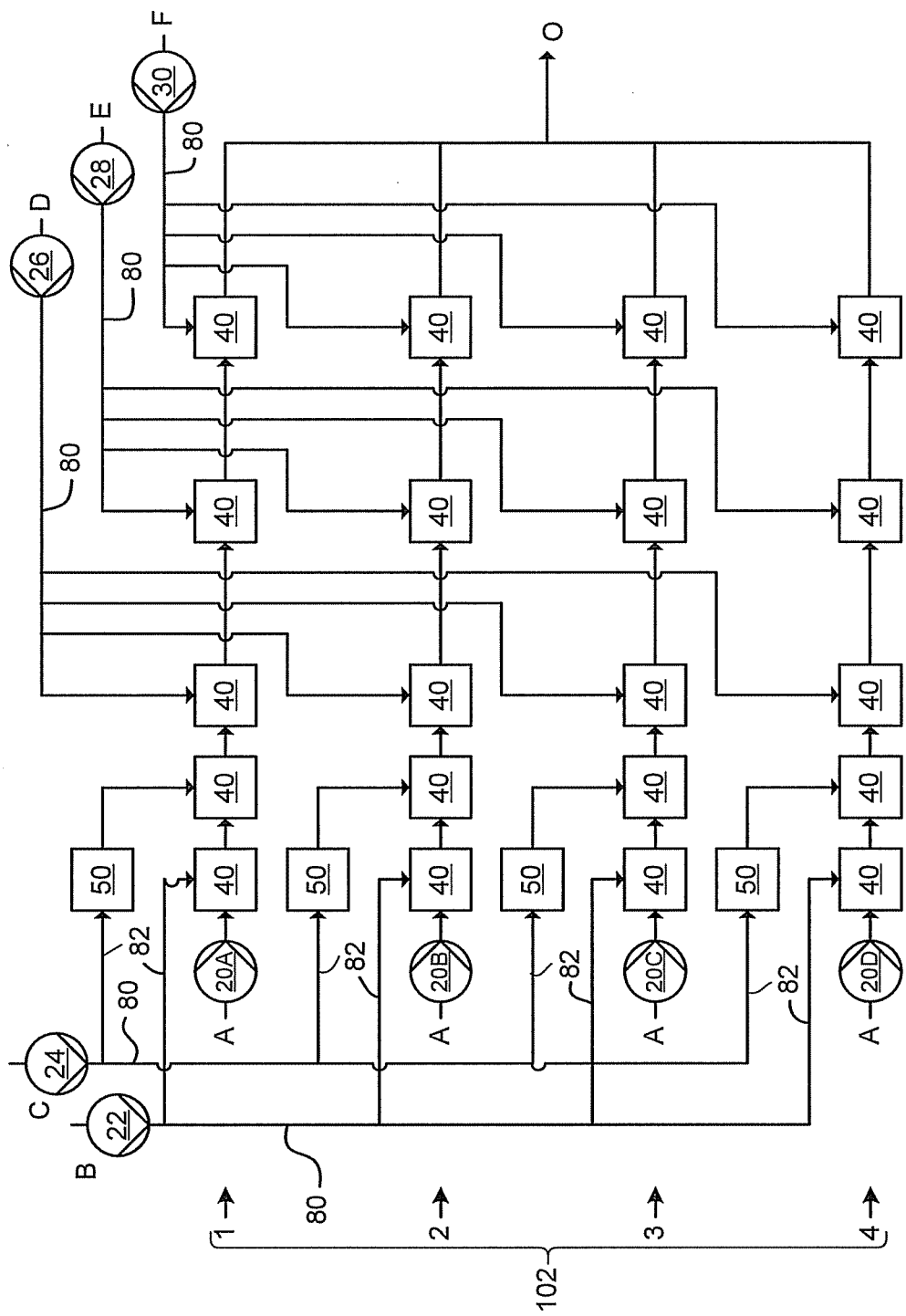
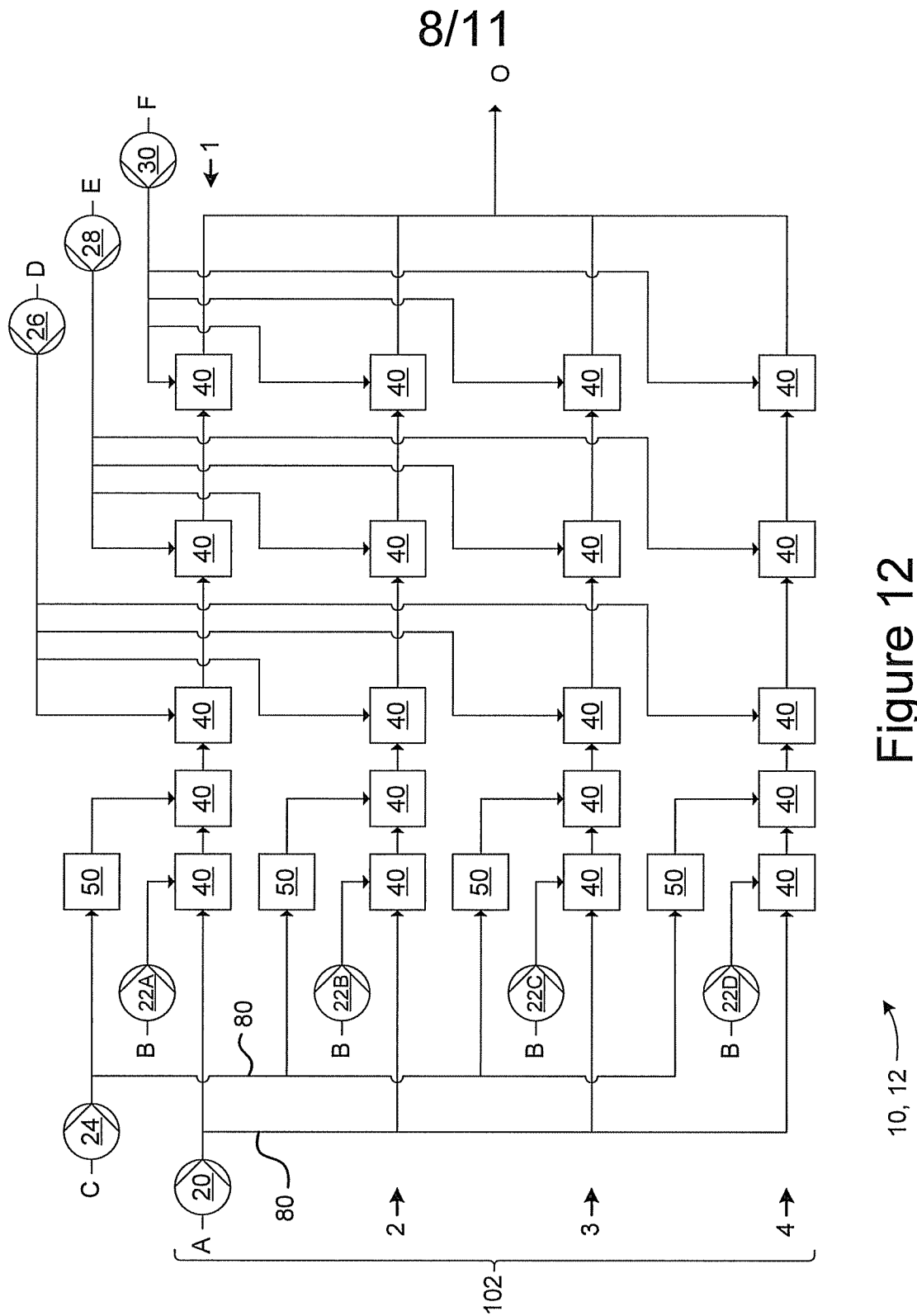


Figure 11

10, 12



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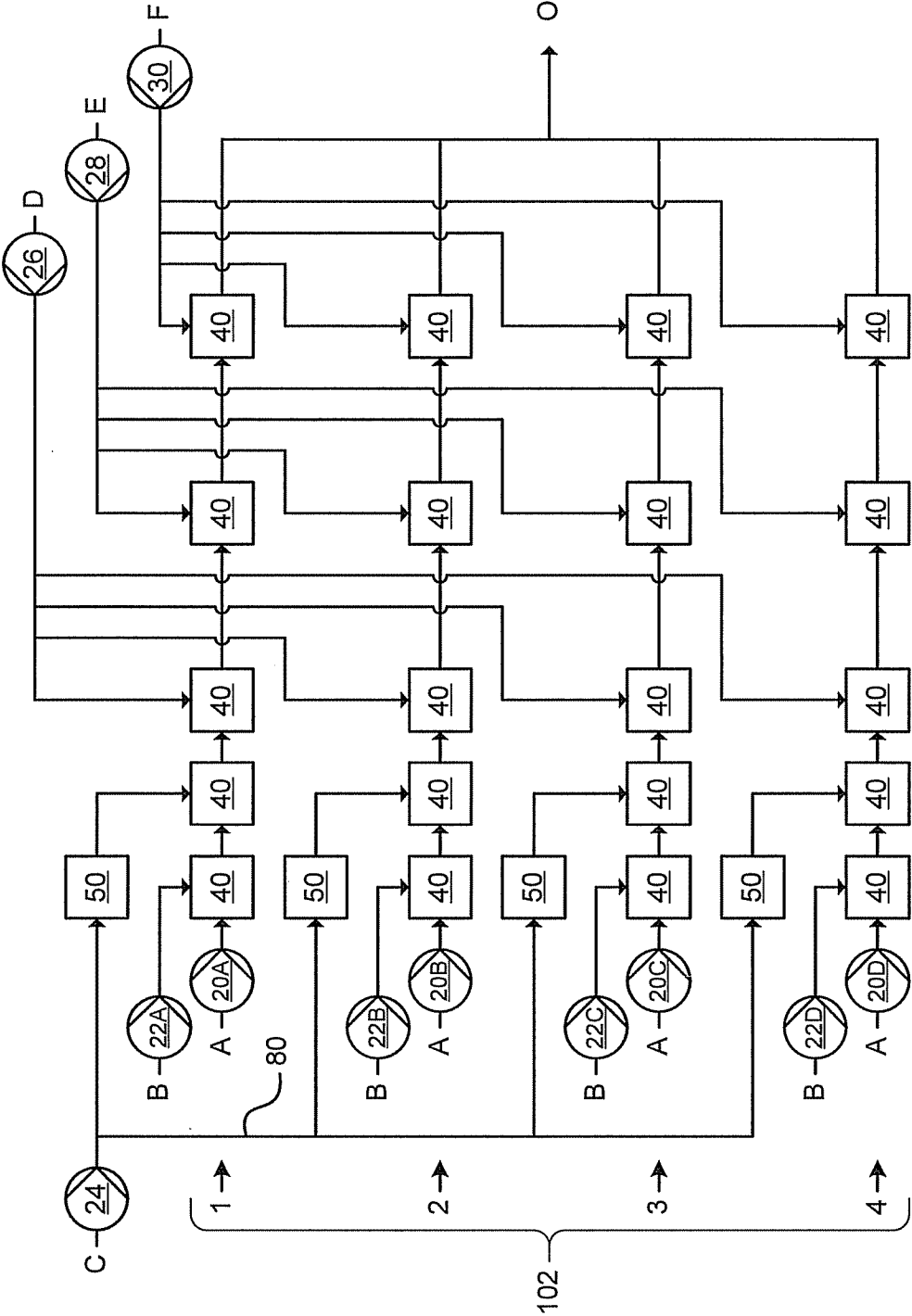


Figure 13

10, 12

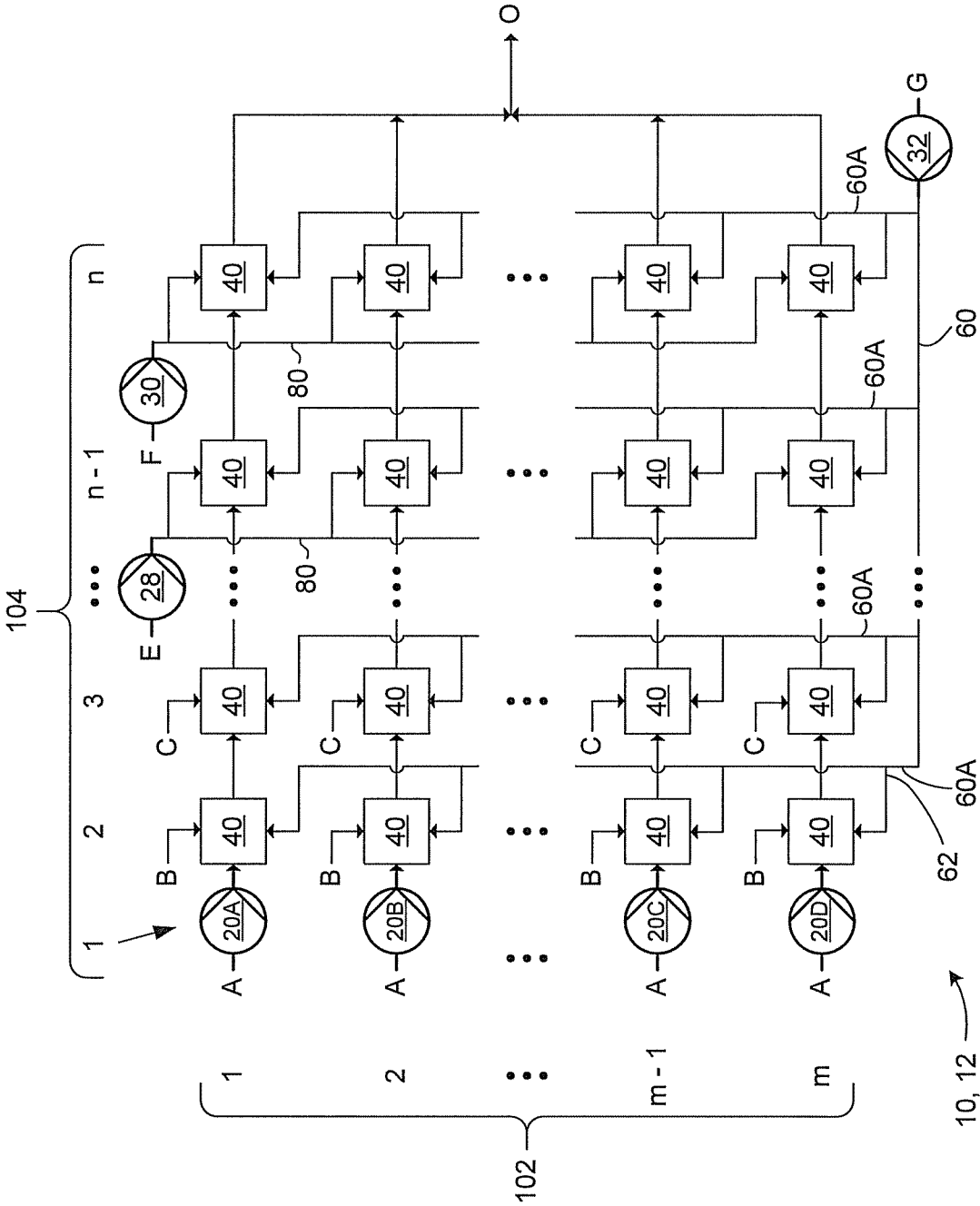


Figure 14

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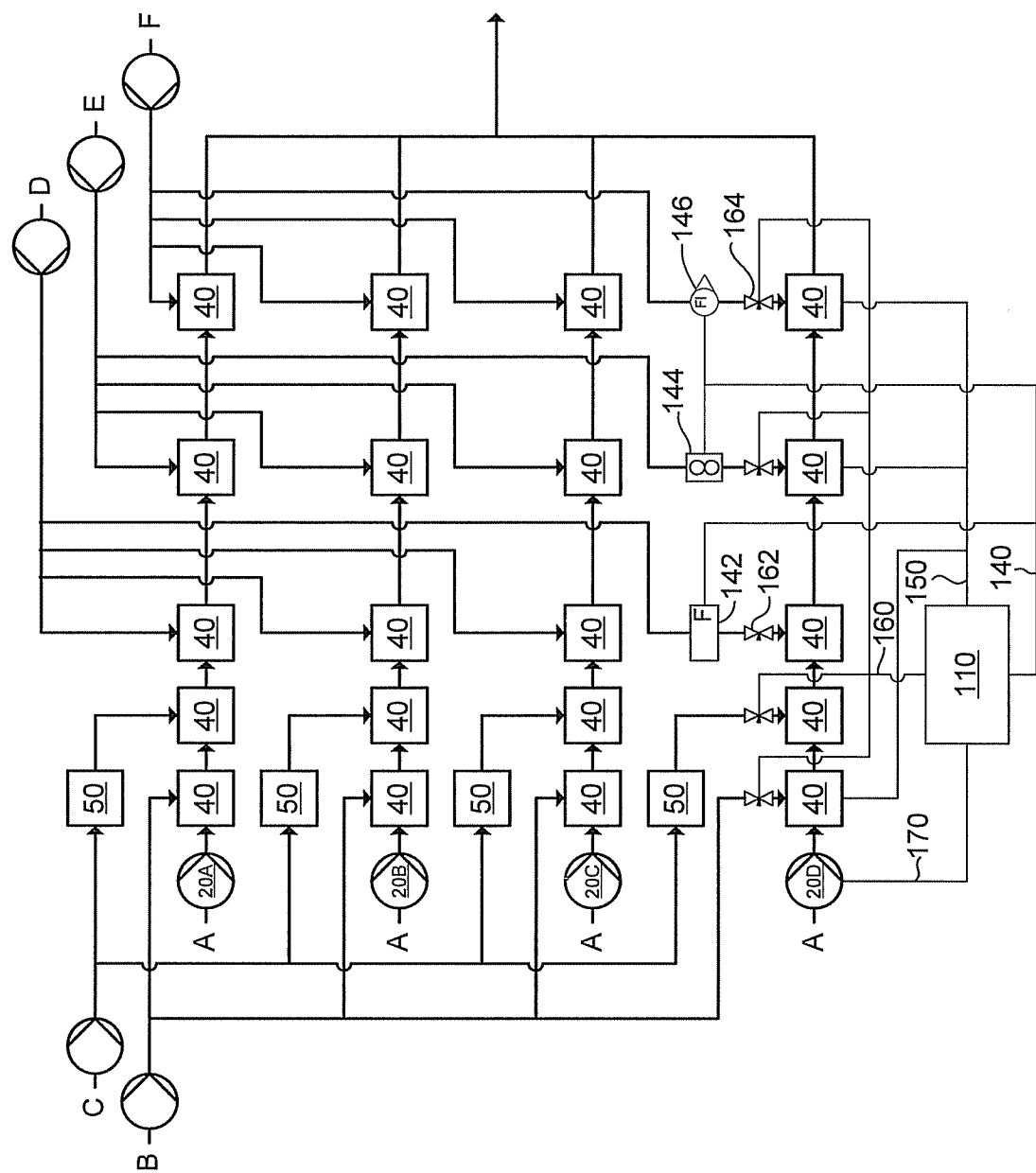


Figure 15

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US 09/65650

A. CLASSIFICATION OF SUBJECT MATTER

IPC(8) - C07C 17/23; B01L 3/00 (2010.01)

USPC - 422/130; 137/884; 422/102

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)

USPC: 422/130; 137/884; 422/102

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

USPC: 422/130; 137/884; 422/102 (text search)

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

Electronic Databases Searched: USPTO WEST (PGPUB, EPAB, JPAB, USPT), Google. Search Terms Used: microreactor\$, thermal control, manifold, outlet, inlet, interconnect\$, series or parallel, reactor, process unit, fluid pump

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2004/0136878 A1 (Meier et al.) 15 July 2005 (15.07.2005), abstract; figure 1, 6 and 10C; para [0078]-[0085]; [0094]; [0120]	1-6
Y	EP 1854536 A1 (Barthe et al.) 14 November 2007 (14.11.2007), entire document especially, figure 1, 15; abstrct; para [0024]-[0026]; [0073]	1-6
A	Elena Daniela Lavric "thermal performance of coming glass microstructures", ECI International Conference on Heat Transfer and Fluid Flow in Microscale, Whistler, 21-26 September 2008 entire document retrieved from http://www.corning.com/uploadedFiles/Corporate/ww/R_+ _D/Our_Innovation_Library/2008_Corning_Research/docs/NTR105406.pdf on 11 January 2009	1-6
A	US 2004/0136873 A1 (Meier et al.) 15 July 2004 (15.07.2004), entire document	1-6

☐ Further documents are listed in the continuation of Box C.

* Special categories of cited documents:

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

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

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

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

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

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

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

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

"&" document member of the same patent family

Date of the actual completion of the international search

06 January 2010 (06.01.2010)

Date of mailing of the international search report

03 FEB 2010

Name and mailing address of the ISA/US

Mail Stop PCT, Attn: ISA/US, Commissioner for Patents
P.O. Box 1450, Alexandria, Virginia 22313-1450

Facsimile No. 571-273-3201

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Lee W. Young

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PCT OSP: 571-272-7774

INTERNATIONAL SEARCH REPORT

International application No.

PCT/US 09/65650

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

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

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

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

3. ☒ Claims Nos.: 7-15
because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a).

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

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

1. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.
2. ☐ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.
3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:

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

Remark on Protest

- ☐ The additional search fees were accompanied by the applicant's protest and, where applicable, the payment of a protest fee.
- ☐ The additional search fees were accompanied by the applicant's protest but the applicable protest fee was not paid within the time limit specified in the invitation.
- ☐ No protest accompanied the payment of additional search fees.