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(54) **SYSTEM AND METHOD FOR THERMAL MANAGEMENT USING DISTRIBUTED SYNTHETIC JET ACTUATORS**

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(57) **ABSTRACT**

One embodiment of the device comprises a device for thermal management. More particularly, one embodiment comprises a synthetic jet actuator (**60**) and a tube (**61**). The synthetic jet actuator (**60**), though not required, typically comprises a housing (**47**) defining an internal chamber (**45**) and having an orifice (**46**) in a wall (**44**) of the housing (**47**). The synthetic jet actuator (**60**) typically also comprises a flexible diaphragm (**42**) forming a portion of the housing (**47**). The tube (**61**) of this exemplary embodiment typically comprises a proximal end (**64**) and a distal end (**65**), the proximal end (**64**) being positioned adjacent to the synthetic jet actuator (**60**). In this embodiment, operation of the synthetic jet actuator (**60**) causes a synthetic jet stream (**52**) to form at the distal end (**65**) of the tube (**61**).

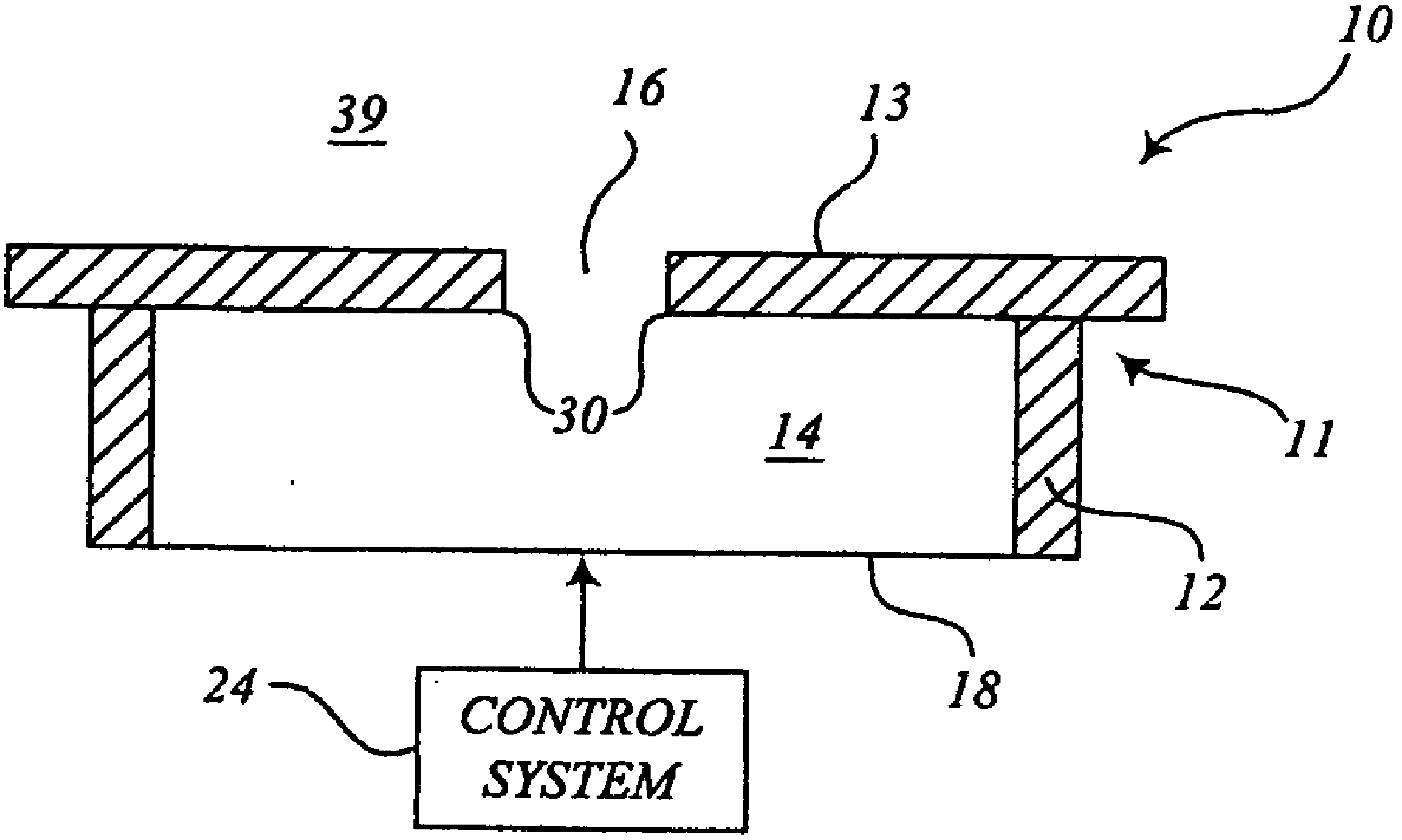


FIG. 1A

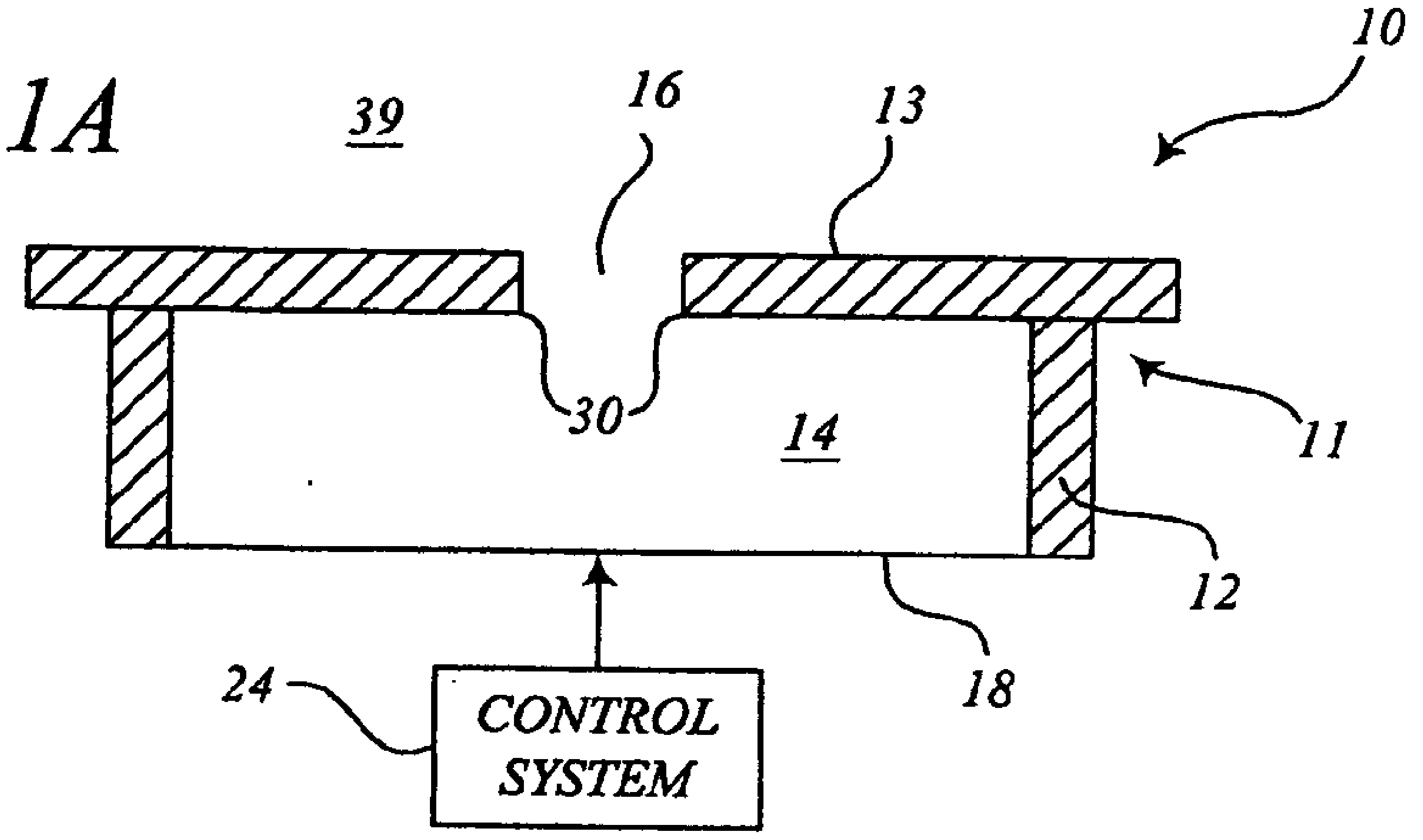


FIG. 1B

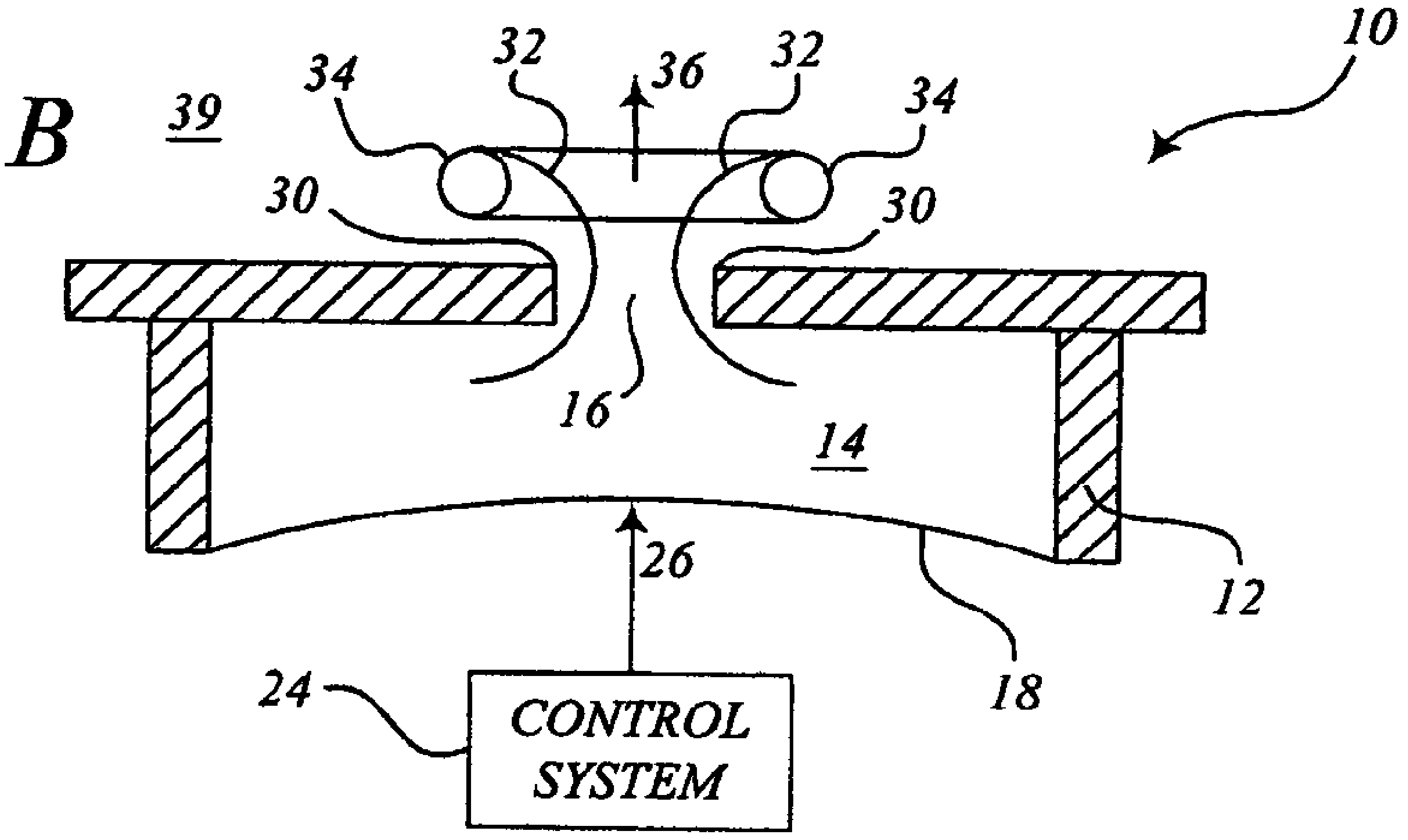
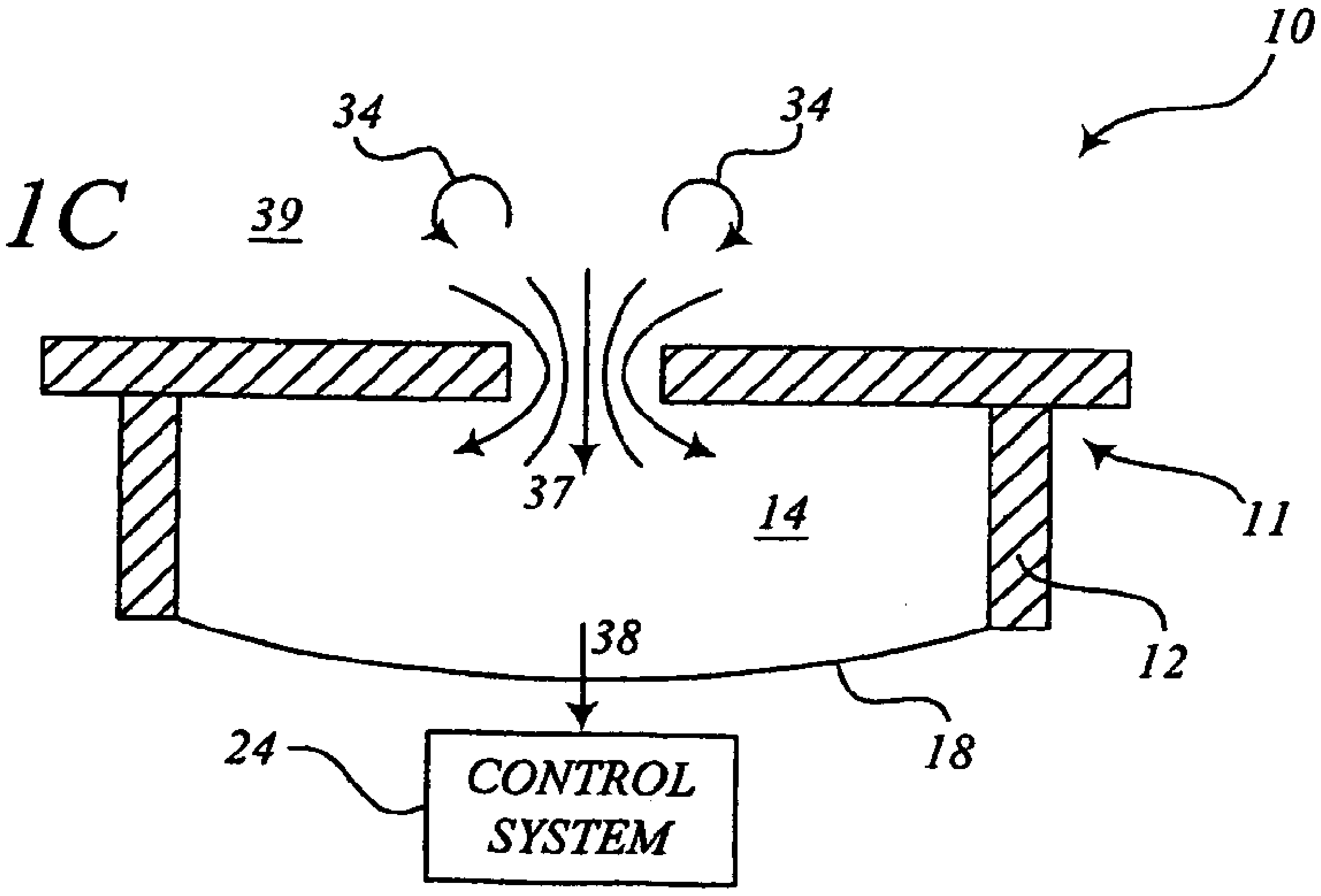
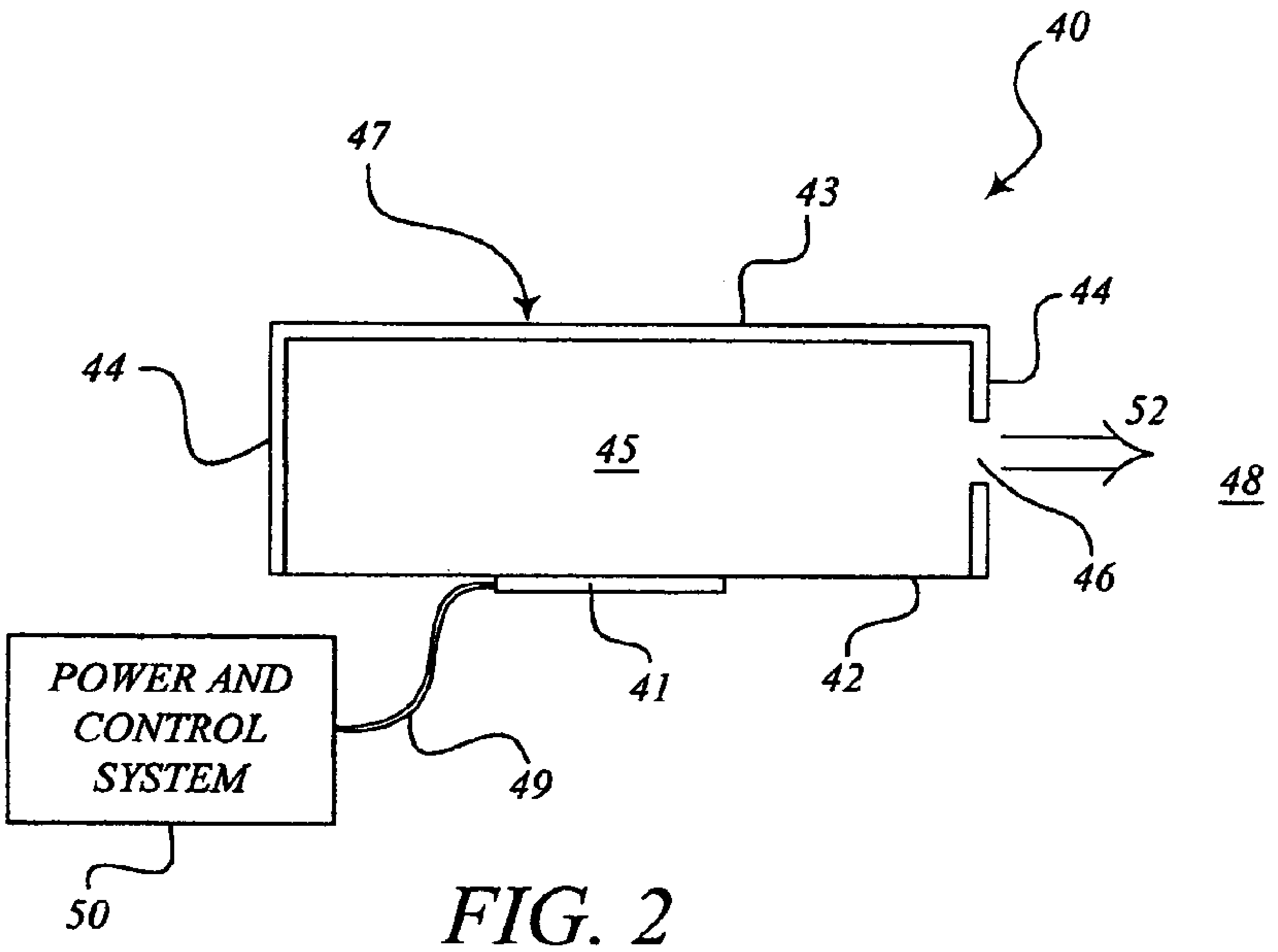


FIG. 1C

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47
43
44
44
45
52
48
46
POWER AND CONTROL SYSTEM
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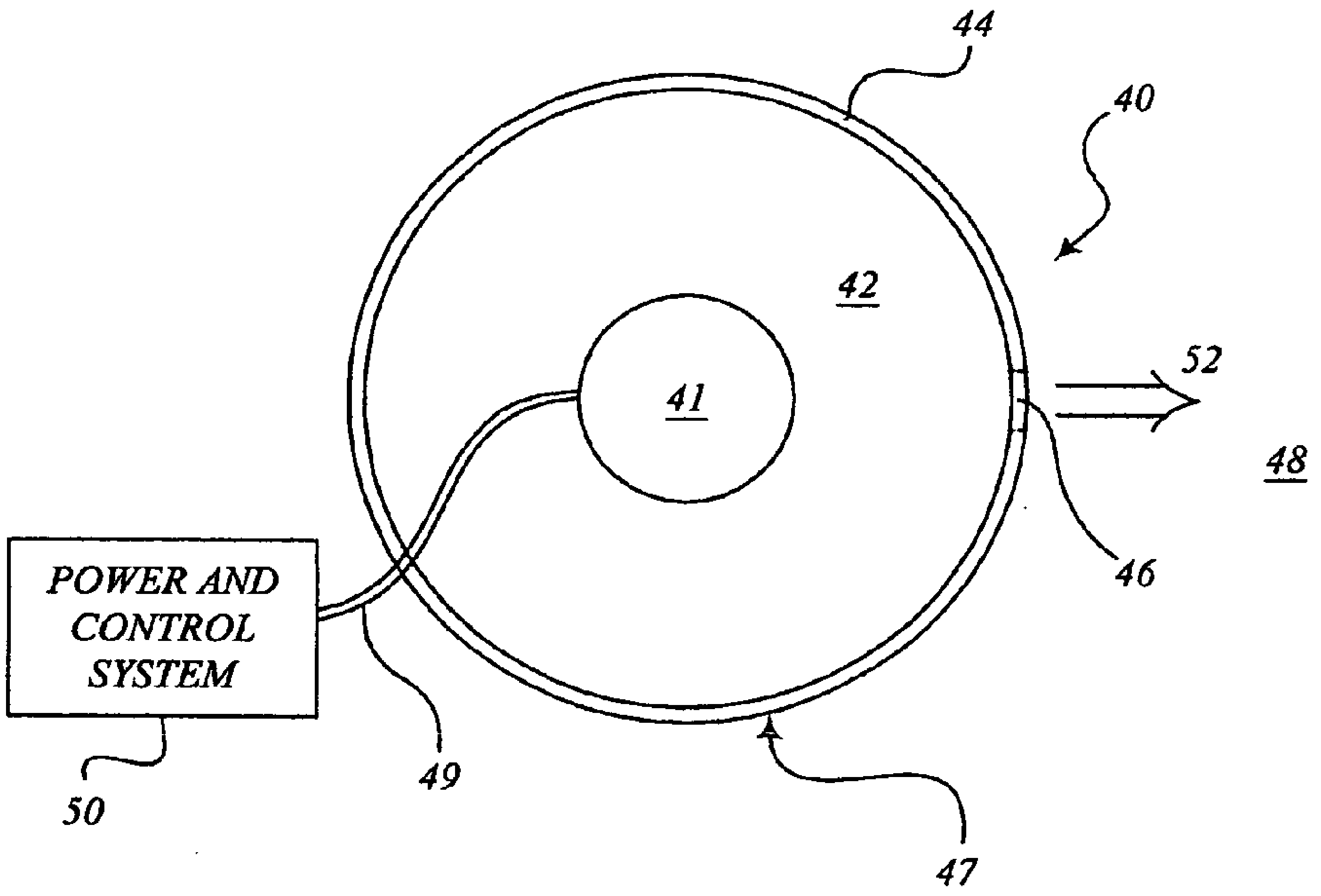
42
49
50

FIG. 2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POWER AND CONTROL SYSTEM
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FIG. 3

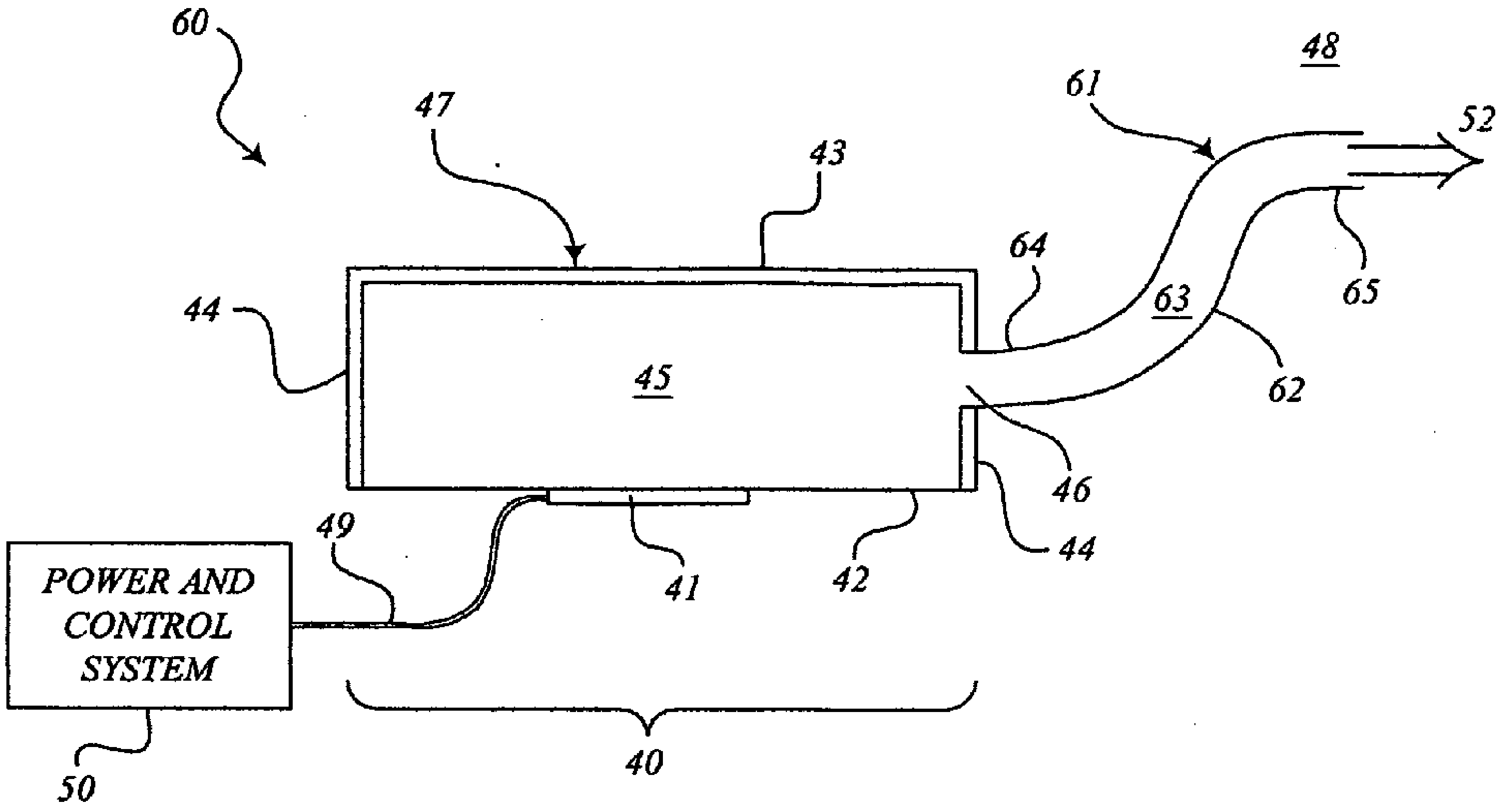


FIG. 4A

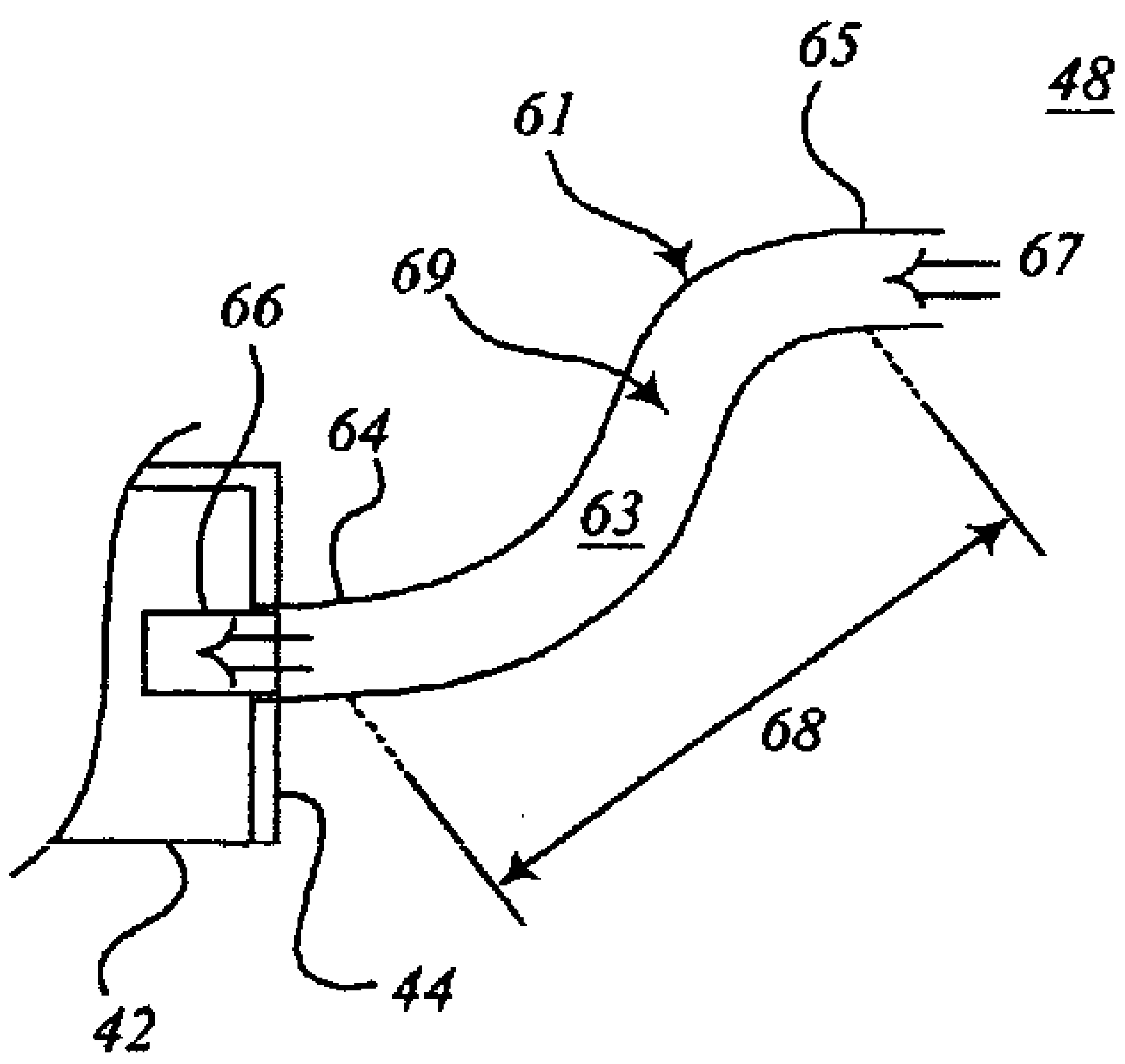


FIG. 4B

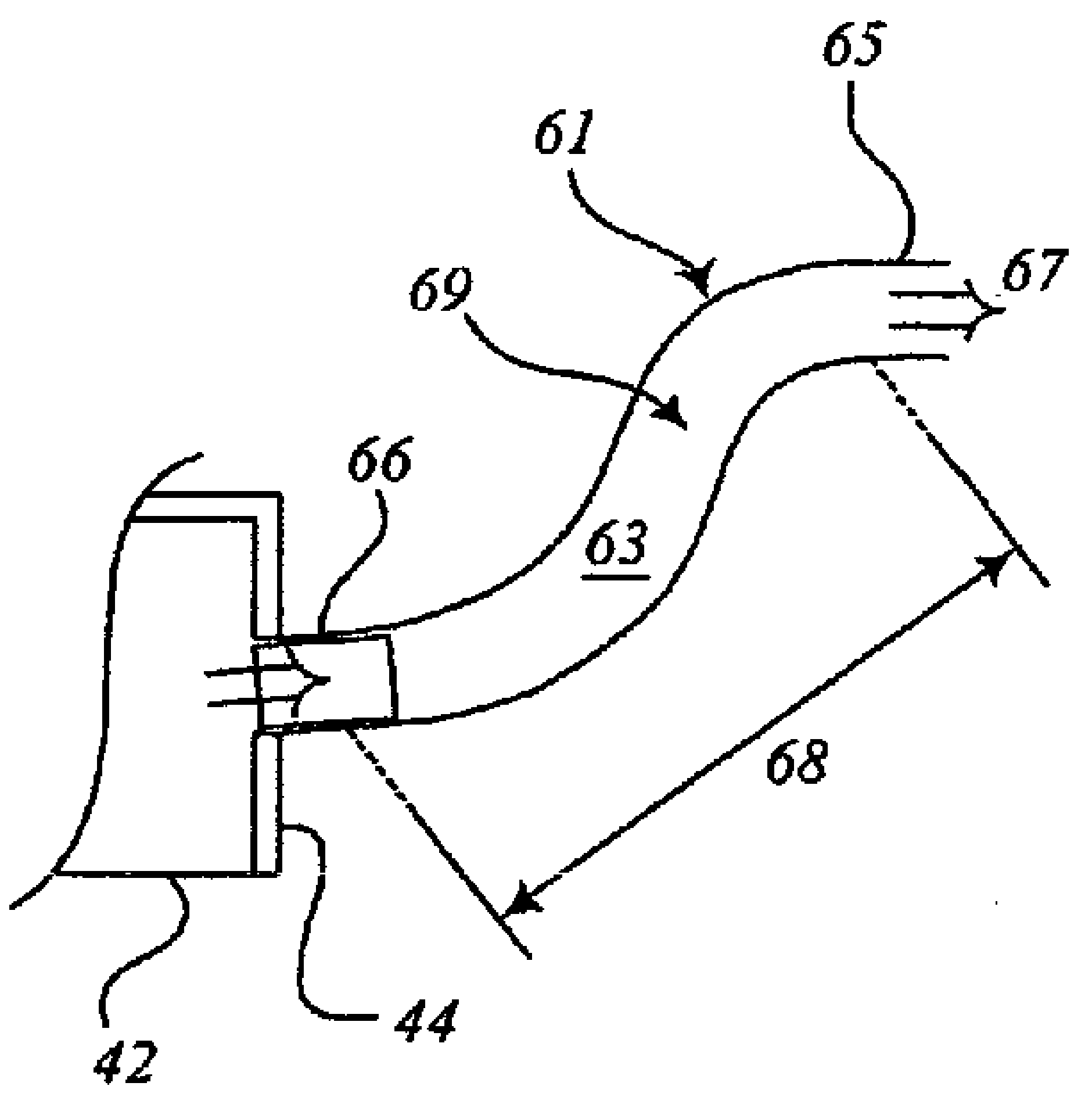
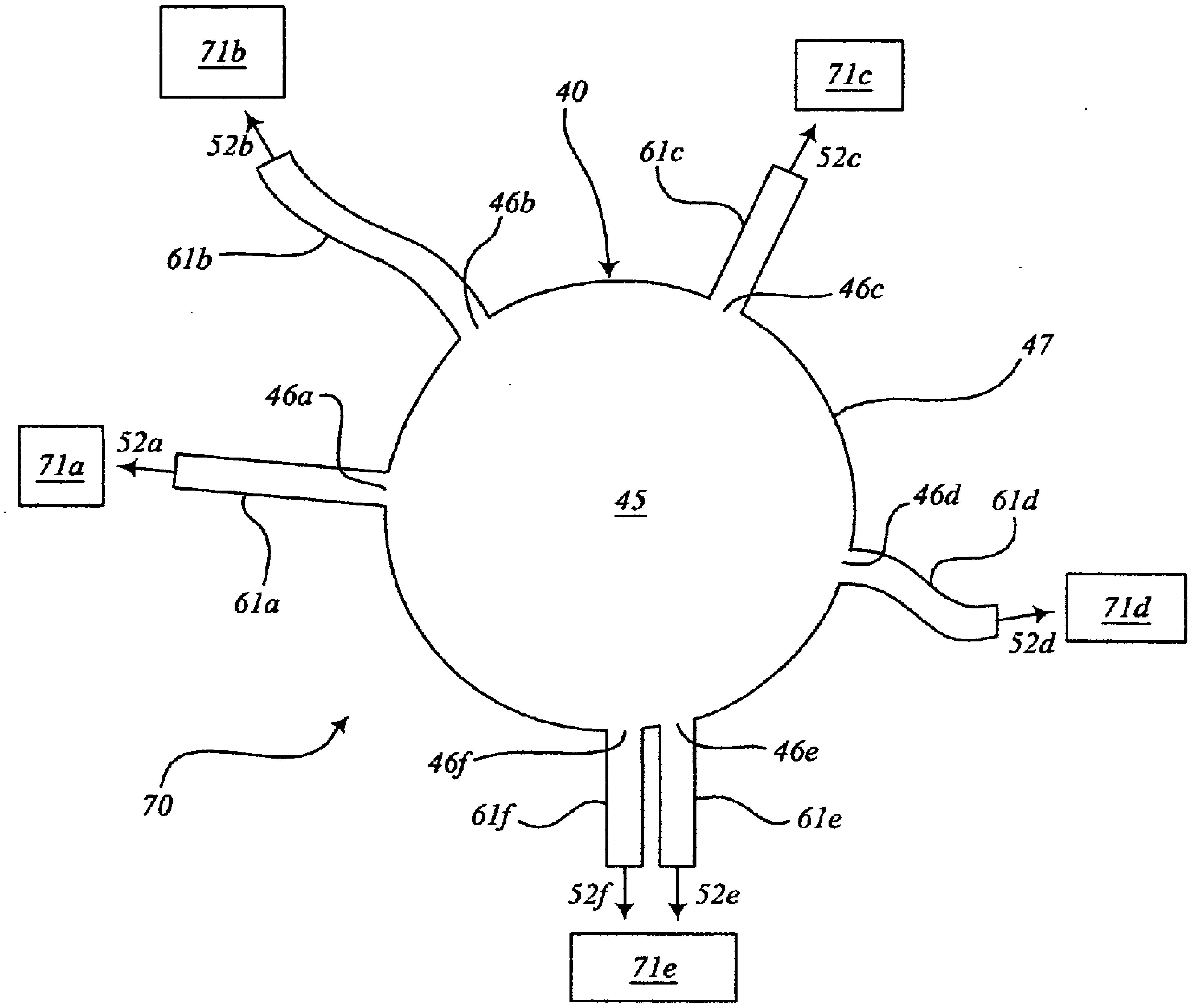


FIG. 4C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61b
46b
40
71c
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52c
46c
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46a
52a
71a
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71e

FIG. 5

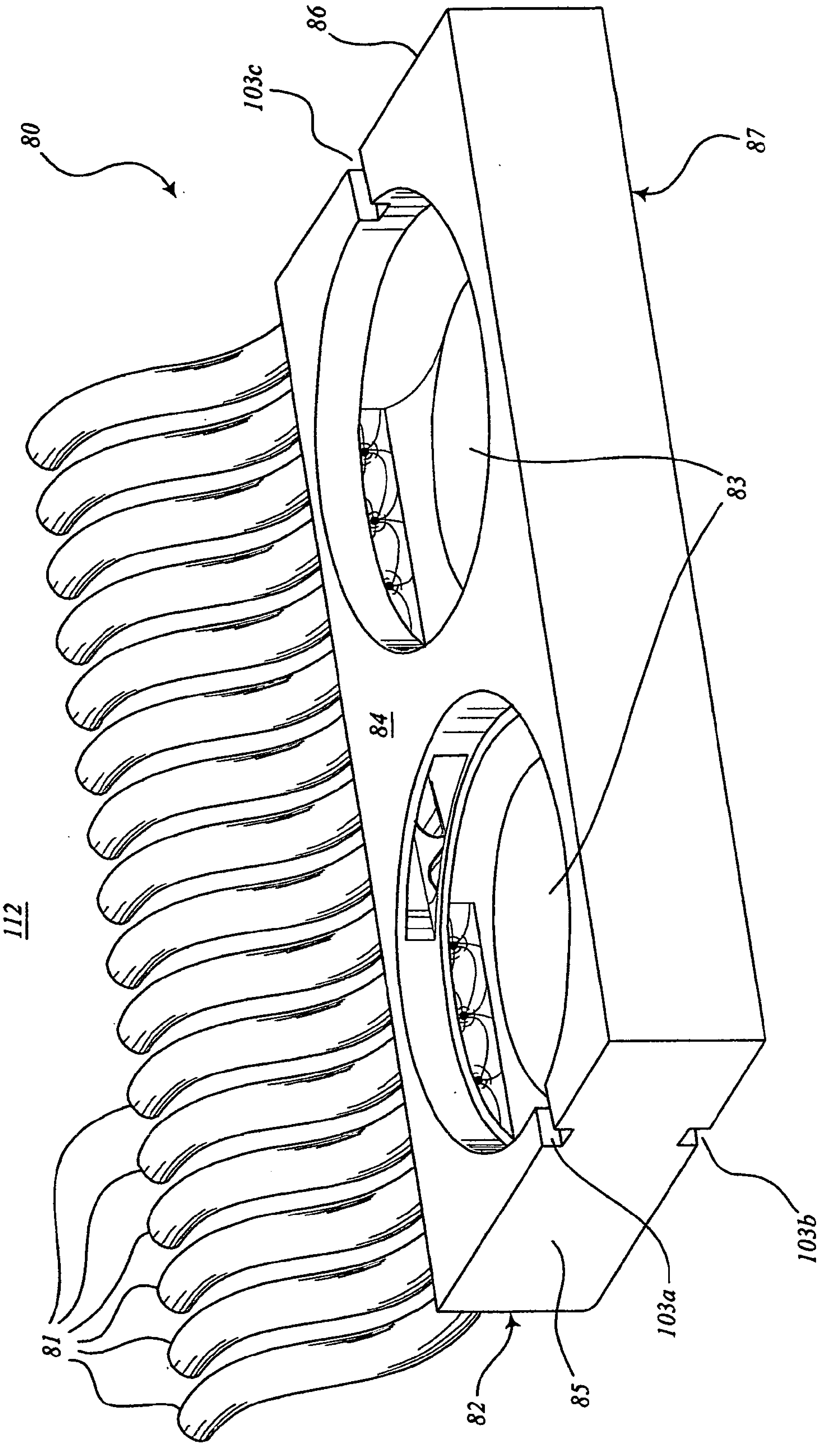

FIG. 6

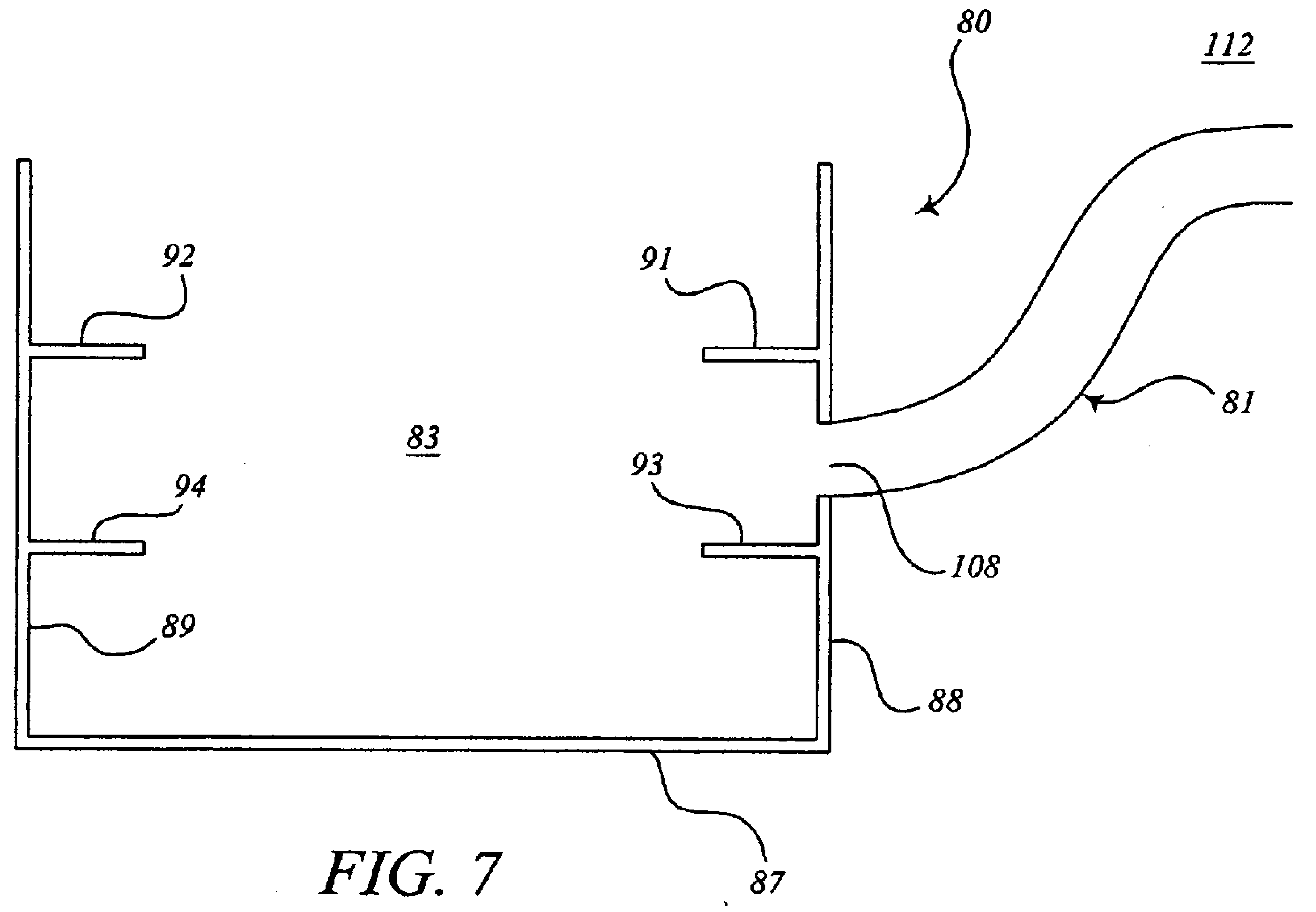
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FIG. 7

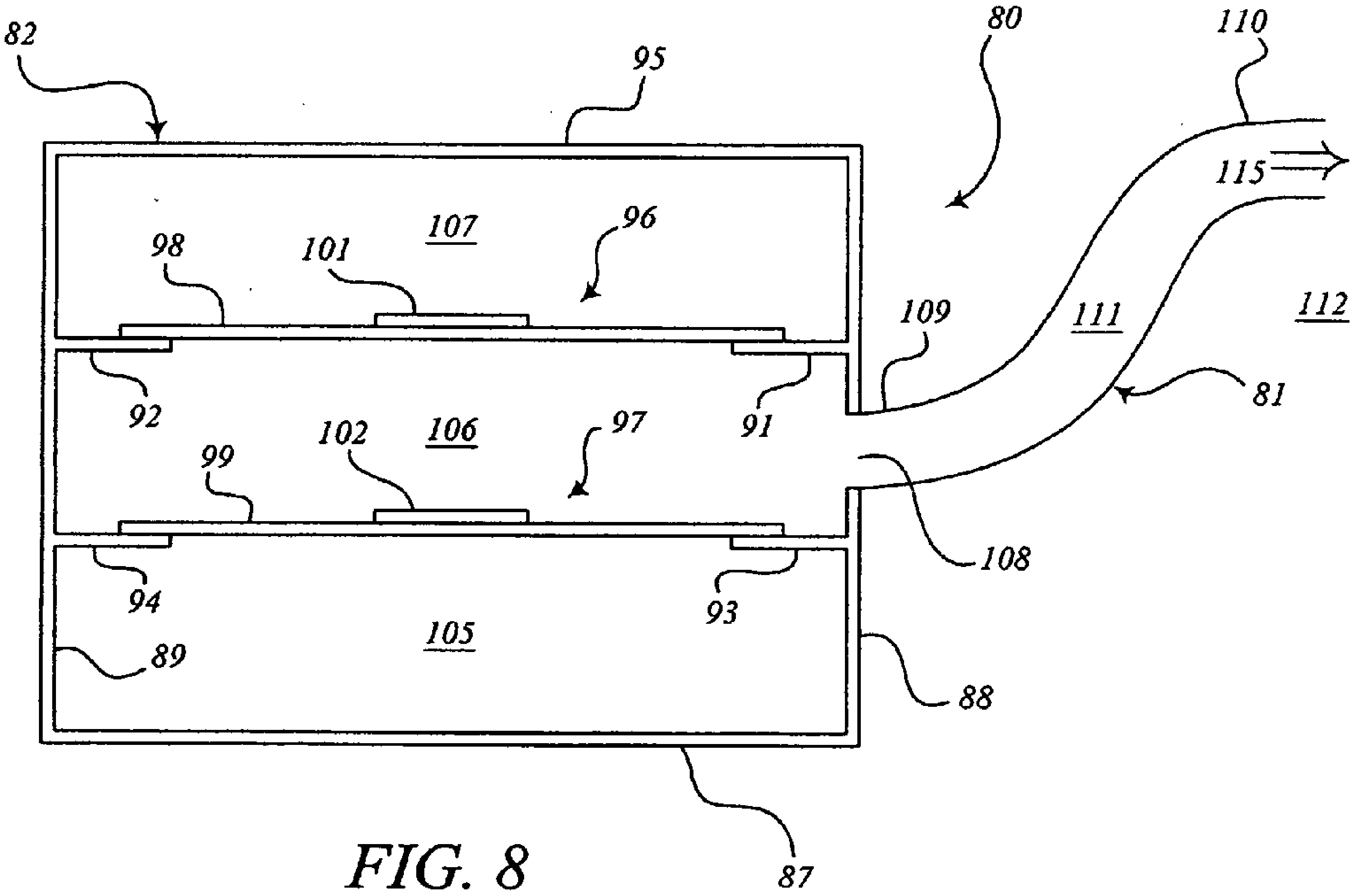
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FIG. 8

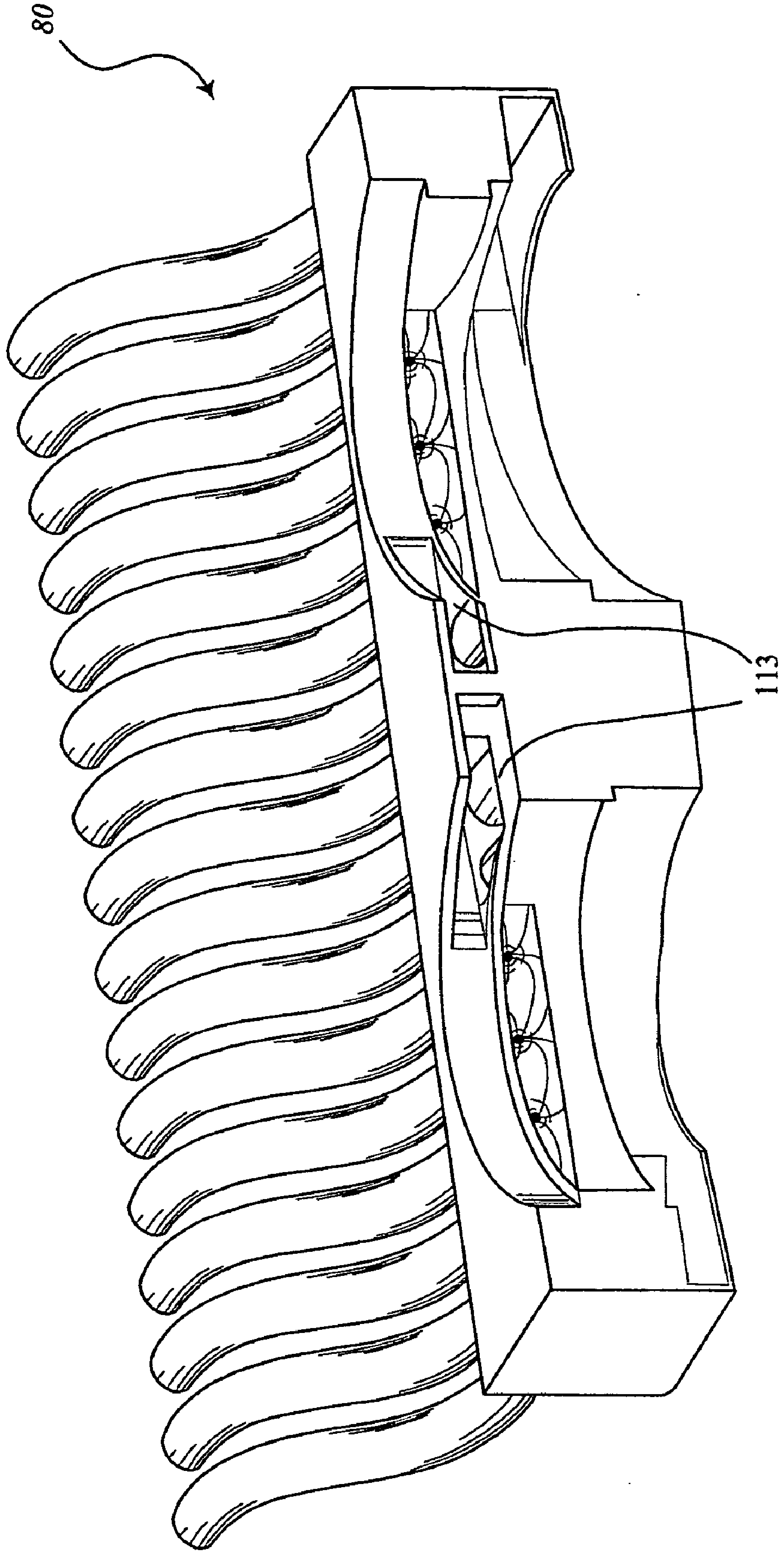

FIG. 9

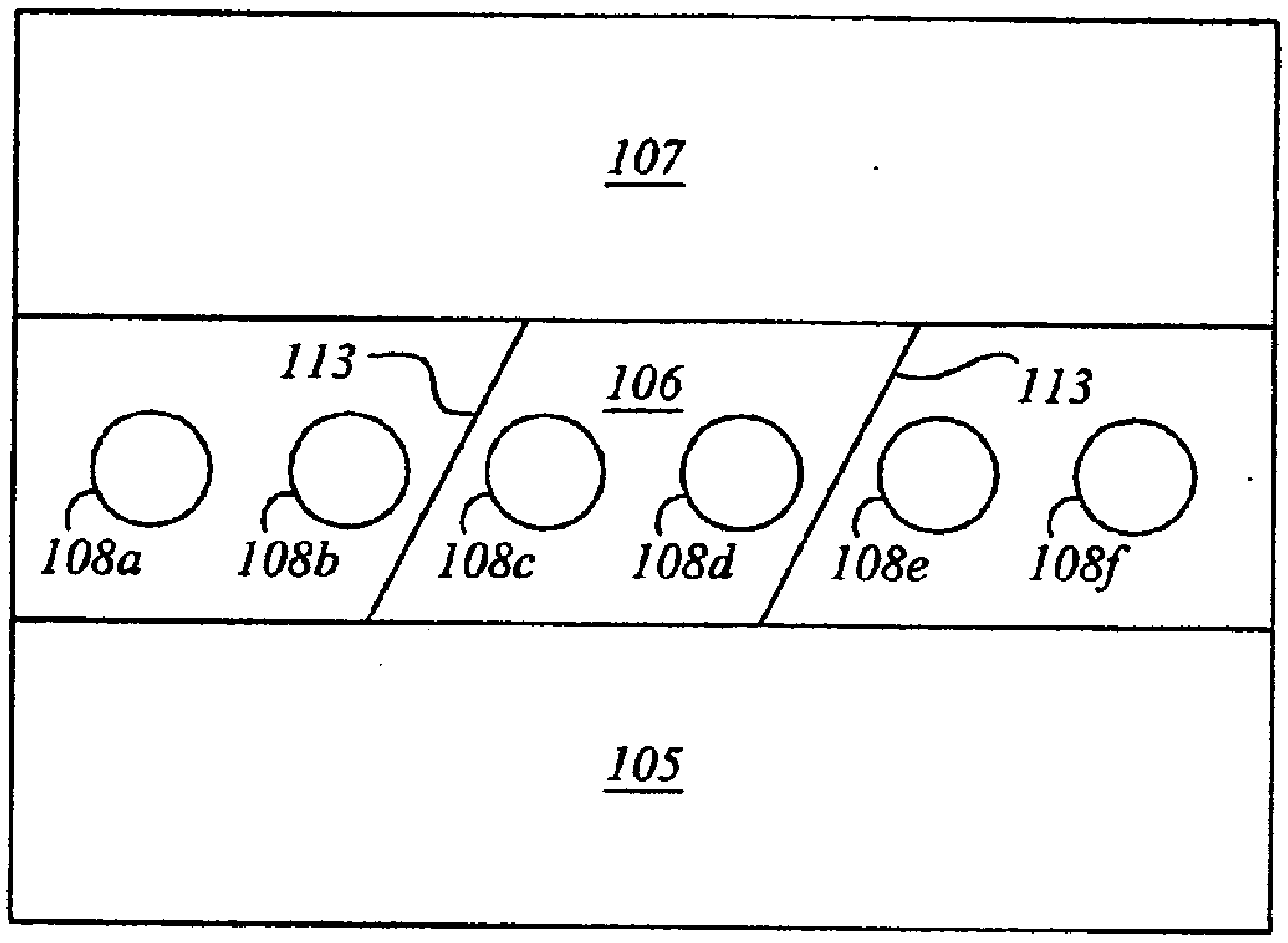

FIG. 10

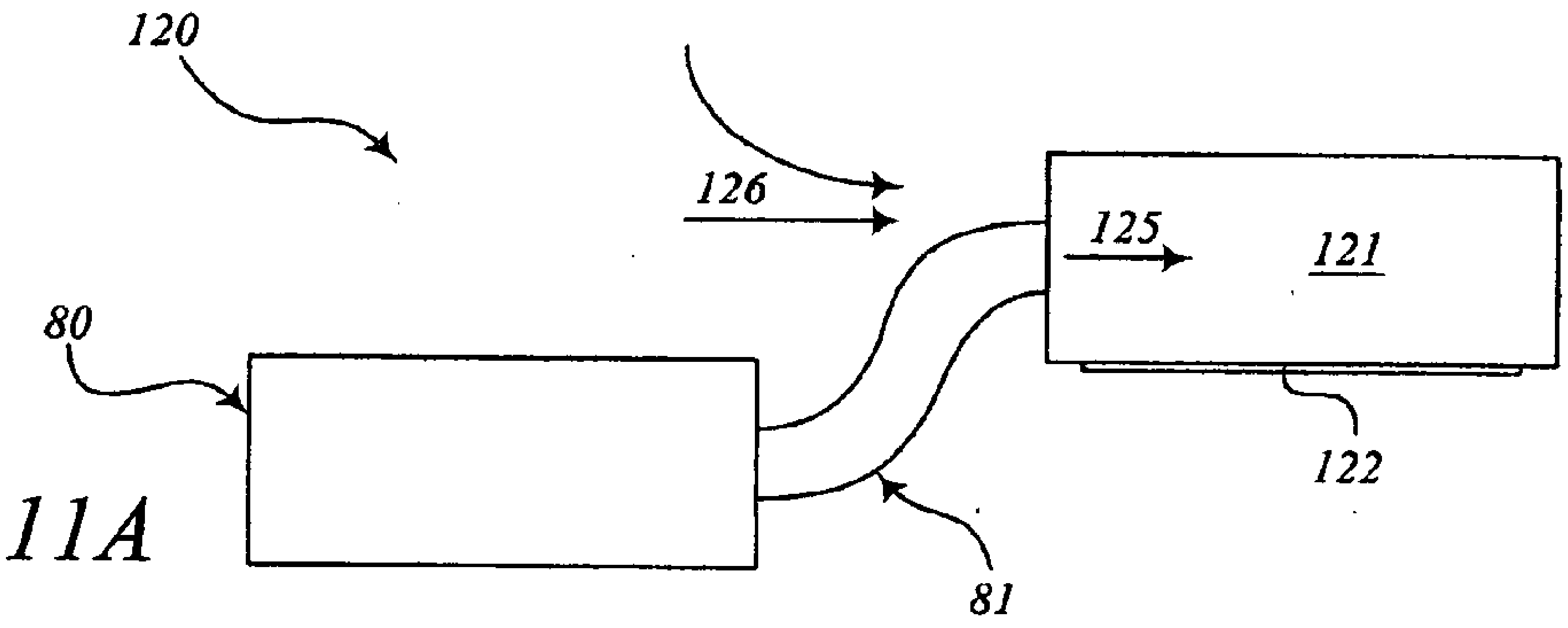

FIG. 11A

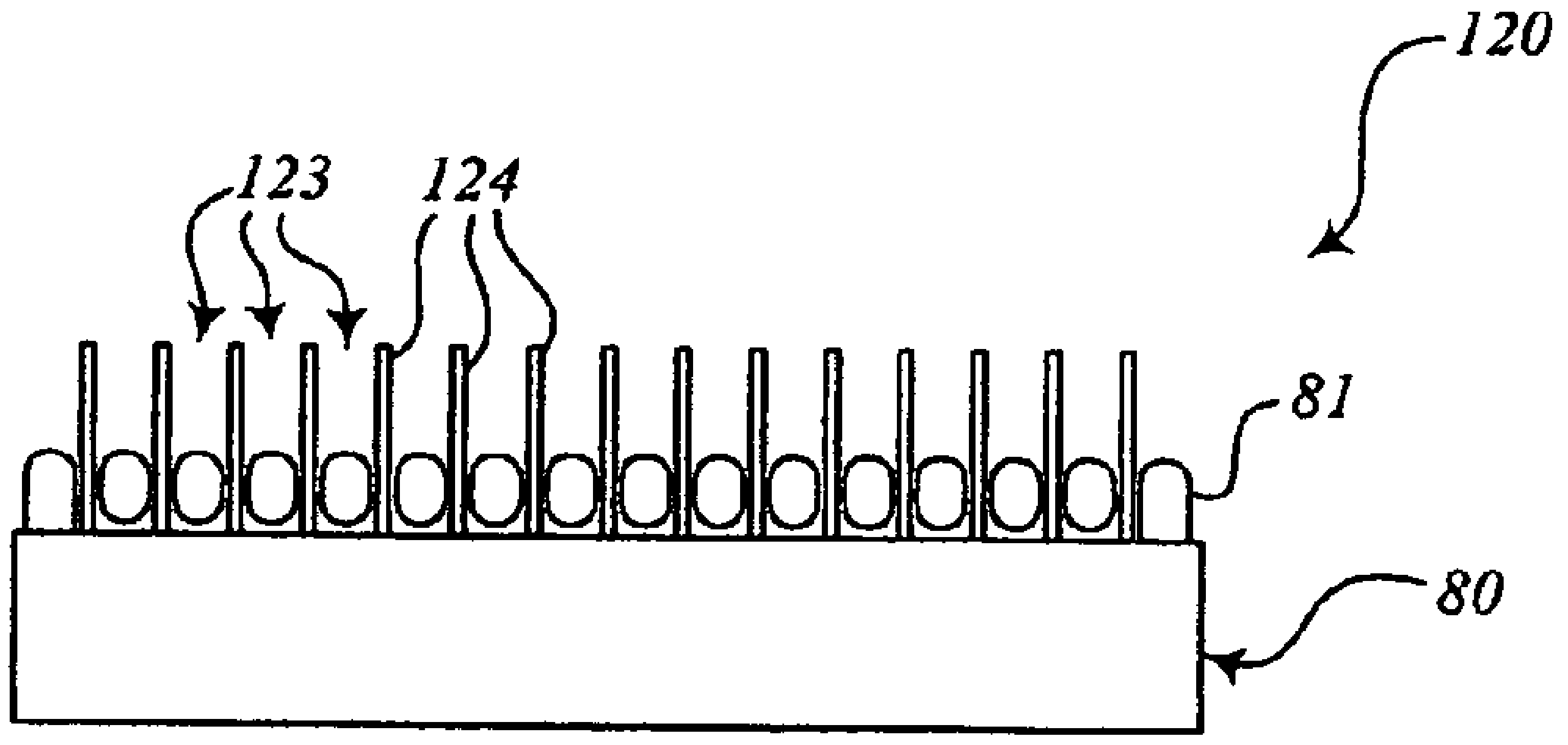

FIG. 11B

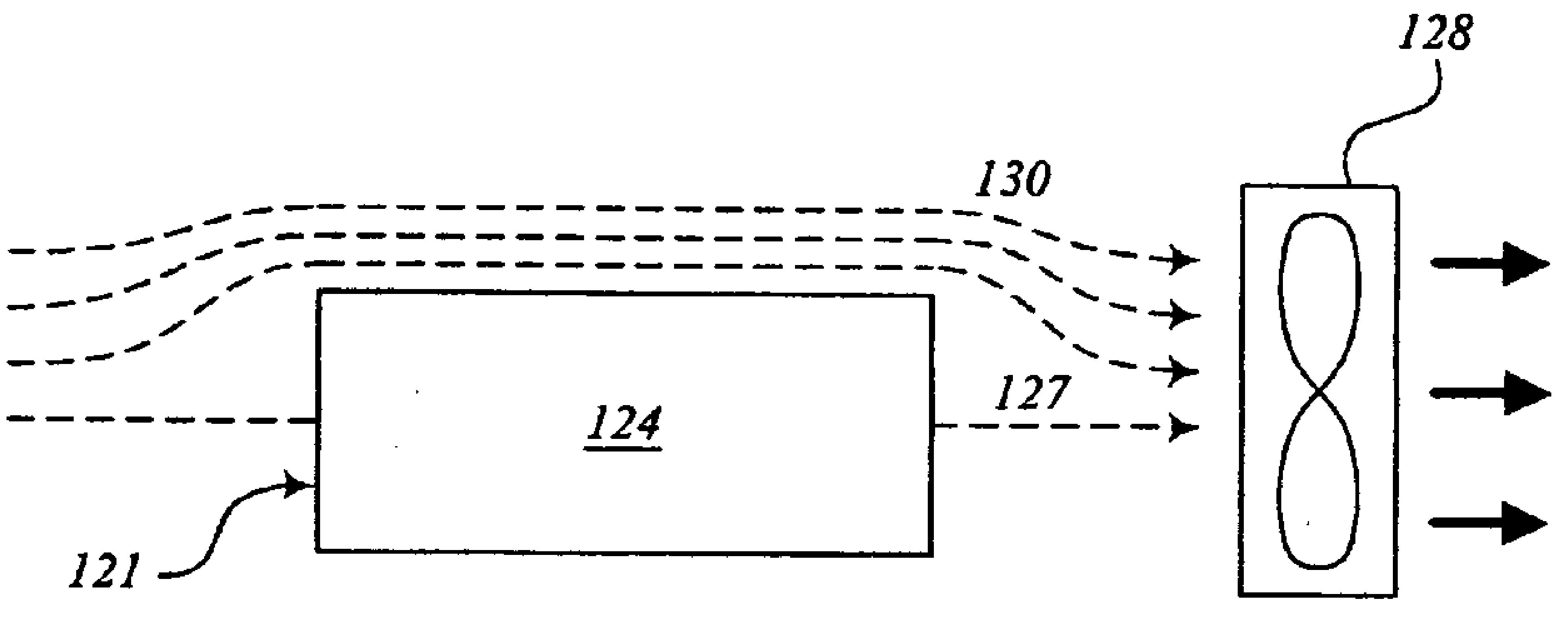

FIG. 12A

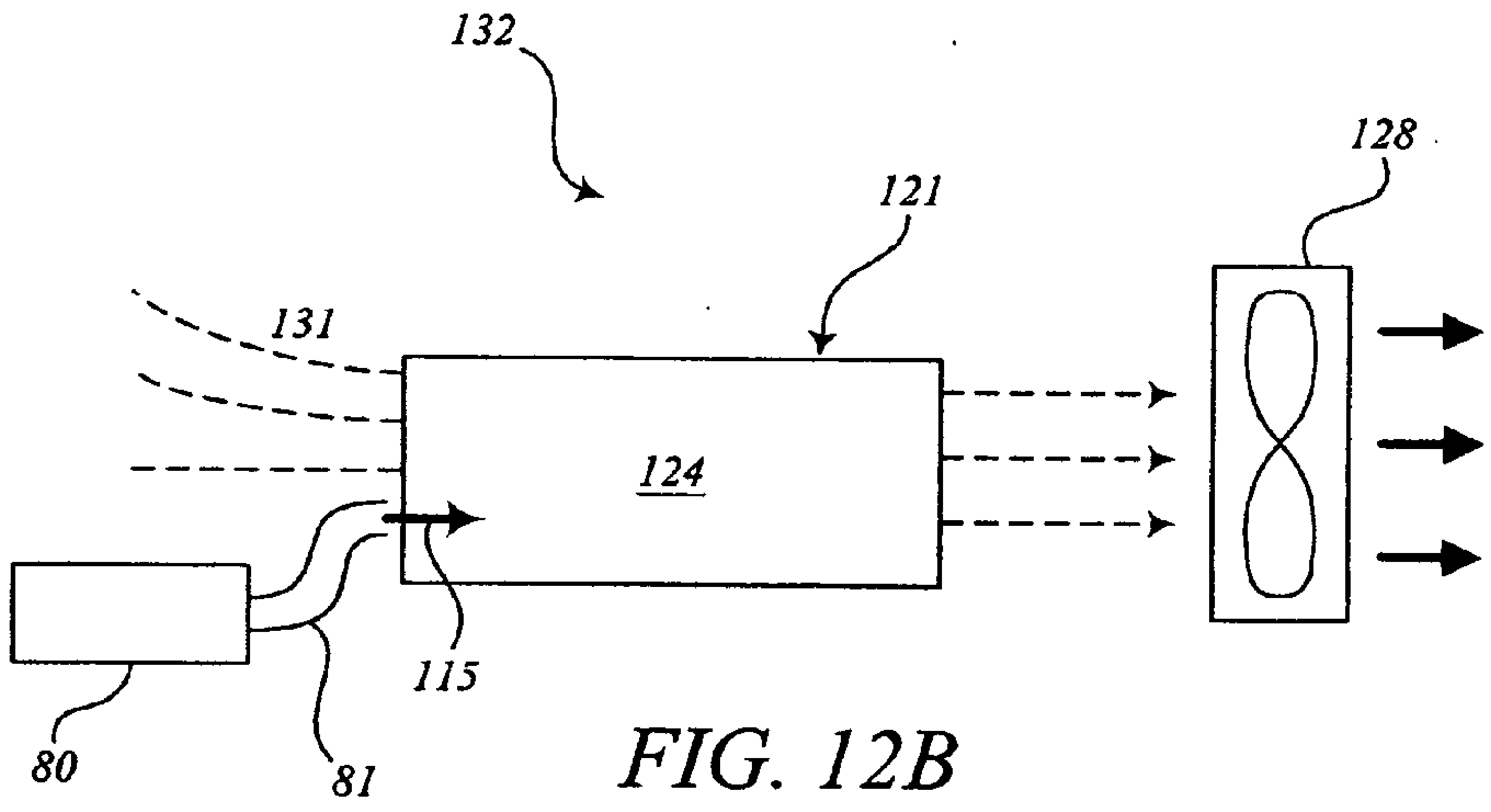

FIG. 12B

SYSTEM AND METHOD FOR THERMAL MANAGEMENT USING DISTRIBUTED SYNTHETIC JET ACTUATORS

TECHNICAL FIELD

[0001] The present invention is generally related to thermal management technology and, more particularly, is related to a system and method for cooling heat-producing bodies or components using distributed synthetic jet actuators.

BACKGROUND OF THE INVENTION

[0002] Cooling of heat-producing bodies is a concern in many different technologies. Particularly in microprocessors, the rise in heat dissipation levels accompanied by a shrinking thermal budget has resulted in the need for new cooling solutions beyond conventional thermal management techniques. Moreover, there is a greatly increased demand for effective thermal management strategies to be used within small handheld devices, such as portable digital assistants (PDA's), mobile phones, portable CD players, and similar consumer products. Indeed, thermal management is a major challenge in the design and packaging of state-of-the-art integrated circuits in single-chip and multi-chip modules.

[0003] Traditionally, the need for cooling large microelectronic devices has been met by using forced convection air cooling techniques. Forced convection can be implemented either with or without heat sinks. Conventionally, fans are employed to provide either global cooling or local cooling.

[0004] Fans are capable of supplying ample volume flow rate, but there are several distinct disadvantages to using a fan. Fans are relatively inefficient in terms of the heat removed for a given volume flow rate. In addition, the use of fans to globally or locally cool a heated environment often results in electromagnetic interference and noise generated by the magnetic-based fan motor. Use of a fan also requires a relatively large number of moving parts in order to have any success in cooling a heated body or microelectronic component. For this or other reasons, fans may be hindered by long-term reliability.

[0005] Mobile applications introduce the added complication of space constraints that might be difficult to achieve with fans, while at the same time increased thermal management requirements have necessitated larger fans driving higher flow rates. Since the power dissipation requirements have necessitated placing fans directly on the heat sink in some instances, the associated noise levels due to the flow-structure interaction have become an additional concern.

[0006] In some instances, as in handhelds like portable digital assistants ("PDAs"), cell phones, etc., the need for thermal management has been met by employing a strategy of spreading the heat produced through the use of heat spreaders to the outer shell of the handheld. Subsequently, the heat generated is dissipated though the outer shell, or skin, of the device via natural convection.

[0007] While these approaches are common, they offer certain drawbacks that will be exacerbated as new products that produce even more heat are developed. The difficulty with the heat spreading strategy is simply that it is often ineffective at removing adequate quantities of heat. Additionally, the heat dissipated may result in raising the temperature of the casing of the handheld device, which is not desirable from a consumer use ergonomic standpoint.

[0008] In an effort to remedy some of the limitations of previous cooling techniques, the use of synthetic or "zero-net-mass-flux" jet actuators in thermal management has been explored. For example, U.S. Pat. No. 6,123,145 discusses the use of synthetic jet actuators for use in cooling. U.S. Pat. No. 6,123,145 is hereby incorporated by reference in its entirety, as if fully set forth herein. Unlike conventional jets, synthetic jet actuators require no mass addition to the system, and thus provide a compact way of efficiently directing airflow across a heated surface. Because the jet streams are generated entirely from the ambient fluid, they can be conveniently integrated without the need for complex plumbing.

[0009] As a further example of the development of thermal management techniques with synthetic jet actuators, Glezer and Mahalingam developed an apparatus and device for channel cooling. This apparatus and method is described in U.S. Pat. No. 6,588,497, which is hereby incorporated by reference in its entirety, as if fully set forth herein.

[0010] While the techniques described in the afore-mentioned U.S. patents solve some of the limitations in the industry, there is an ever-increasing need for improving even the aforementioned techniques. For example, there is a need for a more effective, efficient, or compact synthetic jet actuator. It is desirable to have a more compact cooling device. On the other hand, there is also a need to distribute the cooling flow to far-reaching parts of a heated environment.

[0011] Thus, a heretoforeunaddressed need exists in the industry to address the aforementioned deficiencies and inadequacies.

SUMMARY OF THE INVENTION

[0012] Embodiments of the present invention provide a device for thermal management in various environments. More specifically, the present embodiments include devices for cooling an area or device through the use of synthetic jet actuators in a distributed cooling apparatus.

[0013] Briefly described, in architecture, one embodiment of the device, among others, can be implemented as a device for thermal management comprising a synthetic jet actuator and a channel. The channel of this exemplary embodiment typically comprises a proximal end and a distal end, the proximal end being positioned adjacent to the synthetic jet actuator. Operation of the synthetic jet actuator preferably causes a synthetic jet stream to form at the distal end of the channel. Of course, the synthetic jet stream may also form at the proximal end of the channel.

[0014] The synthetic jet actuator of this or other exemplary embodiments, though not required, may comprise a housing defining an internal chamber and having at least one orifice in a wall of the housing. The synthetic jet actuator of this embodiment also preferably comprises a device for changing the volume of the internal chamber, wherein the volume changing device is preferably positioned adjacent to the housing. In some embodiments, the device for changing the volume may actually make up a portion of the synthetic jet actuator housing. For example, the volume changing device of some exemplary embodiments comprises a flexible diaphragm forming a portion of the synthetic jet actuator housing.

[0015] In some exemplary embodiments, the channel is comprised of one or more tubes connected to an external surface of a wall of the synthetic jet actuator housing. In these exemplary embodiments the tube (or tubes) typically encloses at least a portion of a synthetic jet actuator orifice.

[0016] Other systems, methods, features, and advantages of the present invention will be or become apparent to one with skill in the art upon examination of the following drawings and detailed description. It is intended that all such additional systems, methods, features, and advantages be included within this description, be within the scope of the present invention, and be protected by the accompanying claims.

BRIEF DESCRIPTION OF THE DRAWINGS

[0017] Many aspects of the invention can be better understood with reference to the following drawings. The components in the drawings are not necessarily to scale, emphasis instead being placed upon clearly illustrating the principles of the present invention. Moreover, in the drawings, like reference numerals designate corresponding parts throughout the several views.

[0018] **FIG. 1A** is a schematic cross-sectional side view of a first exemplary embodiment zero net mass flux synthetic jet actuator with a control system.

[0019] **FIG. 1B** is a schematic cross-sectional side view of the synthetic jet actuator of **FIG. 1A** depicting the jet as the control system causes the diaphragm to travel inward, toward the orifice.

[0020] **FIG. 1C** is a schematic cross-sectional side view of the synthetic jet actuator of **FIG. 1A** depicting the jet as the control system causes the diaphragm to travel outward, away from the orifice.

[0021] **FIG. 2** is a cross-sectional side view of a second exemplary embodiment of a synthetic jet actuator.

[0022] **FIG. 3** is a bottom view of the second exemplary embodiment of a synthetic jet actuator of **FIG. 2**.

[0023] **FIG. 4A** is a cross-sectional side view of a distributed cooling apparatus.

[0024] **FIG. 4B** is a cross-sectional side view of the tube used in the distributed cooling apparatus of **FIG. 4A** as the tube withdraws fluid from an ambient.

[0025] **FIG. 4C** is a cross-sectional side view of the tube used in the distributed cooling apparatus of **FIG. 4A** as the tube creates a synthetic jet stream of fluid at an exit end of the tube.

[0026] **FIG. 5** is a cross-sectional top view of a distributed cooling apparatus for directing fluid flow to different areas of a heated environment.

[0027] **FIG. 6** is a three-dimensional view of a multiple actuator distributed cooling apparatus.

[0028] **FIG. 7** is a cross-sectional side view of the multiple actuator distributed cooling apparatus of **FIG. 6**, focussing on one of the “plenums” of the multiple actuator distributed cooling apparatus.

[0029] **FIG. 8** is a cross-sectional side view of the multiple actuator distributed cooling apparatus of **FIG. 6**, focussing on one of the “plenums” of the apparatus, where actuators have been installed into the “plenum.”

[0030] **FIG. 9** is a three-dimensional, cut-away view of the multiple actuator distributed cooling apparatus of **FIG. 6**.

[0031] **FIG. 10** is a cut-away schematic rear view of the multiple actuator distributed cooling apparatus of **FIG. 6**.

[0032] **FIG. 11A** is a side view of the multiple actuator distributed cooling apparatus of **FIG. 6** implemented into a cooling system.

[0033] **FIG. 11B** is a front view of the multiple actuator distributed cooling apparatus of **FIG. 6** implemented into a cooling system.

[0034] **FIG. 12A** is a side view of a prior art cooling system.

[0035] **FIG. 12B** is a side view of the cooling system of **FIG. 12A** wherein the multiple actuator distributed cooling apparatus of **FIG. 6** has been implemented into the cooling system.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

I. Synthetic Jet Actuators

[0036] A. Basic Design of a Typical Synthetic Jet Actuator

[0037] **FIG. 1A** depicts an example of a synthetic jet actuator **10** comprising a housing **11** defining and enclosing an internal chamber **14**. The housing **11** and chamber **14** can take virtually any geometric configuration, but for purposes of discussion and understanding, the housing **11** is shown in cross-section in **FIG. 1A** to have a rigid side wall **12**, a rigid front wall **13**, and a rear diaphragm **18** that is flexible to an extent to permit movement of the diaphragm **18** inwardly and outwardly relative to the chamber **14**. The front wall **13** has an orifice **16** of any geometric shape. The orifice diametrically opposes the rear diaphragm **18** and connects the internal chamber **14** to an external environment having ambient fluid **39**.

[0038] The flexible diaphragm **18** may be controlled to move by any suitable control system **24**. For example, the diaphragm **18** may be equipped with a metal layer, and a metal electrode may be disposed adjacent to, but spaced from, the metal layer so that the diaphragm **18** can be moved via an electrical bias imposed between the electrode and the metal layer. Moreover, the generation of the electrical bias can be controlled by any suitable device, for example but not limited to, a computer, logic processor, or signal generator. The control system **24** can cause the diaphragm **18** to move periodically, or modulate in time-harmonic motion, and force fluid in and out of the orifice **16**.

[0039] The operation of the example synthetic jet actuator **10** will now be described with reference to **FIGS. 1B and 1C**. **FIG. 1B** depicts the synthetic jet actuator **10** as the diaphragm **18** is controlled to move inward into the chamber **14**, as depicted by arrow **26**. The chamber **14** has its volume decreased and fluid is ejected through the orifice **16**. As the fluid exits the chamber **14** through the orifice **16**, the flow separates at sharp orifice edges **30** and creates vortex sheets

32 which roll into vortices **34** and begin to move away from the orifice edges **30** in the direction indicated by arrow **36**.

[0040] **FIG. 1C** depicts the synthetic jet actuator **10** as the diaphragm **18** is controlled to move outward with respect to the chamber **14**, as depicted by arrow **38**. The chamber **14** has its volume increased and ambient fluid **39** rushes into the chamber **14** as depicted by the set of arrows **37**. The diaphragm **18** is controlled by the control system **24** so that when the diaphragm **18** moves away from the chamber **14**, the vortices **34** are already removed from the orifice edges **30** and thus are not affected by the ambient fluid **39** being drawn into the chamber **14**. Meanwhile, a jet of ambient fluid **39** is synthesized by the vortices **34** creating strong entrainment of ambient fluid drawn from large distances away from the orifice **16**.

[0041] B. Synthetic Jet Actuator Having a Hybrid Piezoelectric Actuator

[0042] As explained above, the diaphragm **18** of the synthetic jet actuator **10** of the first exemplary embodiment comprises electrical actuation consisting of a metal layer and a metal electrode driven at a specific excitation frequency. This electrical stimulation causes the diaphragm **18** of the synthetic jet actuator **10** to oscillate, thereby modifying the internal volume of the chamber **14** of the synthetic jet actuator **10**.

[0043] Alternatively, as depicted in **FIG. 2**, a synthetic jet actuator **40** could comprise a housing **47** defining a chamber **45**. The chamber volume could be altered by causing a flexible diaphragm **42** to move in time-harmonic motion due to the excitation of the diaphragm **42** by a piezoelectric actuator **41**. **FIG. 2** is a cut-away side view of a synthetic jet actuator **40** having a housing **47** defined by a relatively-rigid circular top wall **43**, a relatively-rigid circular cylindrical side wall **44**, and a flexible diaphragm **42** forming a bottom wall of the actuator **40**. As depicted in the figure, the side wall connects the top wall **43** to the diaphragm **42**. Preferably, the side wall **44** and the top wall **43** are manufactured from a single piece of rigid material, such as plastic. It would, of course, also be possible to construct the walls **43**, **44** from a metallic material, or other suitably-rigid material. Additionally, the material forming the synthetic jet actuator **40** does not necessarily have to be rigid. The material could have some flexibility. One with ordinary skill in the art would readily understand the appropriate material for the synthetic jet actuator **40** based on a particular implementation.

[0044] As noted above, the top wall **43**, the flexible diaphragm **42**, and the side wall **44** form the housing **47** of a synthetic jet actuator **40** and define a chamber **45** having a volume. The housing **47** of this embodiment **40** comprises the shape of a cylindrical element. This configuration is not required, and the particular configuration has been selected in order to drive home the point that a synthetic jet actuator **40** can take almost any overall shape.

[0045] In this embodiment of a synthetic jet actuator **40**, an orifice **46** is formed in a portion of the side wall **44**. The orifice **46** fluidically connects the chamber **45** with an ambient fluid **48**. The particular size and shape of the orifice **46** is not critical to the present exemplary embodiment **40**. By way of example, the orifice **46** could be in the shape of a circular opening, or of a horizontal or vertical slot in the side wall **44**.

[0046] **FIG. 3** is a plan view of the second exemplary embodiment of a synthetic jet actuator **40**, more specifically depicting the piezoelectric actuator **41** and flexible diaphragm **42**. In other words, **FIG. 3** can be thought of as a view of the synthetic jet actuator **40** from the underside, or "bottom" of the actuator **40**. As can be seen from the figure, the diaphragm **42** is attached to the side wall **44**. Preferably, the attachment of the diaphragm **42** to the side wall **44** is accomplished by an adhesive appropriate to the materials used to construct the diaphragm **42** and the side wall **44**. Alternatively, the diaphragm **42** could be attached to the side wall **44** by another attachment mechanism or device. The method of attachment is not critical to the present exemplary embodiment **40**. It is preferred, however, that the selected method of attachment result in a seal between the side wall **44** and the diaphragm **42**.

[0047] The diaphragm **42** is preferably constructed of an elastomer or polymer material. An elastomer or polymer diaphragm **42** is not required in the present embodiment **40**; however, a diaphragm constructed from these materials is preferred. Conventionally, piezoelectric actuators are comprised of a metal diaphragm coupled with a piezoelectric disc. However, it may be advantageous in certain implementations to use a polymeric (like plastic) or elastomeric (like rubber) material for a diaphragm of the piezoelectric actuator. Alternatively, a polymeric or elastomeric diaphragm could be used in combination with a metal diaphragm to produce a hybrid diaphragm.

[0048] An elastomer or polymer can be constructed from a number of specific materials, such as polyisoprene, polyisobutylene, polybutadiene, and/or polyurethanes. For the present embodiment **40**, a diaphragm **42** constructed of an elastomer or polymer material is chosen due to its ability to be stretched and yet bounce back into its original shape without permanent deformation.

[0049] There are at least two advantages to such a modified actuator construction. First, the use of an elastomer or polymer diaphragm generally reduces the natural resonant frequency of the actuator, enabling its preferred use at low frequencies (for example, <200 Hz). This renders the actuator operation relatively soundless. Second, such a construction generally has superior reliability when compared to metal diaphragms that tend to produce larger stresses in the piezoelectric material and the adhesive that typically attaches the piezoelectric material to the metal.

[0050] As noted above, a piezoelectric actuator **41** is attached to the elastomer or polymer diaphragm **42**. The piezoelectric actuator **41** is preferably mounted to the diaphragm **42** by an appropriate adhesive. The piezoelectric actuator **41** is supplied power by electrical wiring **49**. The electrical wiring **49** will not only supply power to the piezoelectric actuator **41**, but will also control operation of the actuator **41**. Specifically, the wiring **49** connects the piezoelectric actuator with a power supply and control system **50** that is preferably separate from the housing **47** of the synthetic jet actuator **40**. Of course, in certain embodiments, the power supply and control system **50** may be mounted on, or even in, the housing **47** of the synthetic jet actuator **40**.

[0051] The power supply and control system causes the piezoelectric actuator **41** to vibrate. The vibration of the piezoelectric actuator **41** causes the diaphragm **42** to oscillate in time-harmonic motion. The piezoelectric actuator **41** is preferably caused to vibrate at the resonant frequency of the diaphragm **42**. Of course, the magnitude and frequency of the diaphragm oscillation can be controlled by causing the piezoelectric actuator to operate at different frequencies. One with ordinary skill in the art will readily be able to adjust the vibration of the piezoelectric actuator **41** in order to yield the desired frequency and amplitude of oscillation of the diaphragm **42**.

[0052] As noted above with respect to the first exemplary embodiment **10**, the oscillation of the diaphragm **42** in the second exemplary embodiment **40** causes a synthetic jet stream **52** of fluid to form at the orifice **46** of the actuator **40**. As the diaphragm **42** moves inward with respect to the chamber **45**, the chamber **45** has its volume decreased and fluid is ejected through the orifice **46**. As the fluid exits the chamber **45** through the orifice **46**, the flow separates at orifice edges and creates vortex sheets which roll up into vortices and to move away from the orifice **46**. These vortices entrain the ambient fluid **48** and use this fluid to form a synthetic jet stream **52**.

[0053] Similar to the operation of the first exemplary synthetic jet actuator **10**, when the diaphragm **42** is caused to move outward with respect to the chamber **45**, the chamber **45** has its volume increased. This increase in volume causes a pressure gradient to form at the orifice **46** and ambient fluid **48** rushes into the chamber **45**. Then, as the diaphragm **42** oscillates back into the chamber **45**, the fluid in the chamber **45** is expelled, forming a synthetic jet stream **52** as described above.

III. Distributed Cooling Apparatus

A. FIRST EXAMPLE

Single Actuator Device

[0054] The synthetic jet actuators **10**, **40** described above can be used in a number of different embodiments. However, one specific adaptation of the synthetic jet actuators **10**, **40** is for what may be referred to as distributed cooling applications. A distributed cooling application is a situation that may call for a single synthetic jet actuator to provide a cooling synthetic jet stream to multiple locations. Alternatively, a distributed cooling application may call for a synthetic jet actuator to supply cooling fluid flow to a single location that is somewhat remote from the location of the actuator. Although not limiting examples, these two examples are common distributed cooling applications.

[0055] **FIG. 4A** depicts one embodiment of a distributed cooling synthetic jet actuator **60**. For ease of explanation, the exemplary embodiment of a distributed cooling synthetic jet actuator **60** has been designed as a modified form of the second exemplary embodiment **40**. As such, the distributed cooling synthetic jet actuator **60** comprises a housing **47** defining an internal chamber **45**. The housing **47** and chamber **45** can take virtually any geometric configuration, but for purposes of discussion and understanding, the housing **47** is shown in cross-section in **FIG. 4A** to have a rigid side wall **44**, a rigid top wall **43**, and a diaphragm **42** that is flexible to an extent to permit movement of the diaphragm **42** inwardly and outwardly relative to the chamber **45**. A portion of the side wall **44** forms an orifice **46**. As above, the orifice **46** can have any geometric shape.

[0056] As with the exemplary embodiment **40** above, the distributed cooling synthetic jet actuator **60** also comprises a power supply and control system **50** connected to a piezoelectric actuator **41** on the diaphragm **42** by electrical wiring **49**. As above, the power supply and control system **50** may be remote from the actuator **60**, or may be attached to the housing **47** or in the housing **47** for example.

[0057] The exemplary distributed cooling apparatus **60** further comprises a channel, or a tube, **61**. The tube **61** may be of similar cross-sectional shape as that of the orifice **46**. However, it may also be desirable to have the cross-sectional shape of the tube **61** very different from the shape of the orifice **46**. For example, the use of a different cross-sectional shape may permit more effective directing of any flow emitting from the tube **61**. The tube **61** is formed of a preferably rigid shell **62** enclosing an inner area **63**. The tube **61** further comprises a proximal, or attachment end **64** and a distal, or open end **65**. The tube **61** is preferably constructed from a plastic material such that the tube **61** will be relatively-rigid, but still lightweight. Alternatively, the tubing **61** could be constructed from a flexible material having the ability to be formed into a shape and hold that shape. In **FIG. 4A**, the tube **61** is formed into a generally serpentine shape. The shape of the tube **61** is not important to the principles of the present invention, and the particular shape depicted has been chosen only to illustrate the principles of the present exemplary embodiment **60**.

[0058] As shown in the figure, the tube **61** is preferably attached to the side wall **44** of the synthetic jet actuator **60** such that the actuator orifice is fluidically coupled to the interior region **63** of the tubing **61**. In the preferred configuration, the tubing **61** has an internal diameter equal to or greater than the diameter of the orifice **46**. Thus, the orifice **46** does not communicate directly with the ambient environment **48**, or in other words, the tube **61** completely covers the orifice **46**. Although the tube **61** is referred to as "attached" to the side wall **44**, it should be understood that the housing **47** and tube **61** can be created from a single piece of material.

[0059] As will be explained in more detail below, during operation, vortices form at the edges of the tubing exit end **65**. These vortices roll up and move away from the exit of the tube **61**. These vortices entrain ambient fluid **48** forming a fluidic jet **52** at the exit **65** of the tube **61**. In essence, the use of tubing **61** permits a jet of fluid **52** to eject from the tubing **61**, away from the actuator itself. Basically, the synthetic jet of fluid that would be emitted from the orifice **46** of the synthetic jet actuator, if no tube **61** was present, is emitted instead from the exit end **65** of the tube **61**. This feature of the present embodiment **60** permits a designer of a cooling system to position the synthetic jet actuator **40** at any convenient location, but still direct the fluid flow **52** to a relatively-distant location by simply directing the tube **61** to this desired location.

[0060] For example, the actuator **40** could be positioned a distance away from the area to be cooled, such as in a centralized location. The tubing **61** could be shaped to direct flow through the fins of a heat sink. The fact that the synthetic jet actuator is not near the heat sink will generally increase the flow through the heat sink fins. Indeed, if the actuator is positioned at the entrance of a fin channel, the flow through the fin channel may be impeded by the presence of the actuator housing. This is not an issue with distributed cooling.

[0061] As noted above, the tubing **61** could either be pre-formed or flexible. If flexible, the designer could place the device **40** and then shape tube **61** as desired. This may be very beneficial for retrofit applications. However, in the most common embodiment, the tube **61** will be relatively-rigid such that the design of the overall cooling system can be fine-tuned prior to installation.

[0062] As noted above, the shape or dimensions of the tube **61** is not critical to the present exemplary embodiment **60**. However, the length and/or shape of the tube **61** may affect the performance of the distributed cooling synthetic jet actuator **60**. To better explain this point, resort should be made to the operation of the distributed cooling apparatus **60**.

[0063] The operation of the synthetic jet actuator **40** in the distributed cooling apparatus **60** is similar to the operation of the synthetic jet actuator in the second exemplary embodiment described above. Specifically, the piezoelectric actuator **41** is caused to vibrate at an appropriate frequency, preferably the resonant frequency of the diaphragm **42**. This vibration causes the diaphragm **42** to oscillate in time-harmonic motion. As the diaphragm **42** moves inward relative to the internal chamber **45**, the volume of the chamber **45** is reduced, the pressure in the chamber **45** increases, creating a pressure gradient at the orifice **46**, and fluid is ejected from the orifice **46** of the synthetic jet actuator **40**. Because there is no ambient fluid to entrain at the orifice **46**, the flow exiting the orifice **46** is generally pulsating in nature, generally reflecting the frequency of the diaphragm **42** driven by the piezoelectric actuator **41**. This fluidic pulse moves into an interior region **63** of the tube **61** attached to the orifice **46**. As the diaphragm **42** is moved outward with respect to the chamber **45**, fluid is drawn into the synthetic jet actuator chamber **45** from the tube interior **63**. Then, as the diaphragm **42** continues its time-harmonic oscillation and moves back into the chamber **45**, fluid is again ejected from the chamber **45** into the tube interior **63**.

[0064] **FIGS. 4B and 4C** depict the fluidic interaction within the interior **63** of the tube **61** during operation of the synthetic jet actuator **40** of the distributed cooling apparatus **60**. When the fluid from the synthetic jet actuator chamber **45** enters the interior **63** of the tube **61**, the entering fluid acts like a "virtual piston"**66**. The pulse of fluid **66** entering the interior **63** of the tube **61** compresses the fluid in the tube interior **63**, which in turn, causes fluid **67** to be expelled from the exit end **65** of the tube **61**. When the diaphragm **42** moves outward from the synthetic jet actuator chamber **45**, the "virtual piston"**66** moves out from the interior **63** of the tube **61**, withdrawing fluid from the tube interior **63** into the chamber **45**, thereby lowering the pressure in the tube **61**. This lower pressure in the tube **61** creates a pressure gradient at the tube exit end **65**, thereby drawing fluid from the ambient **48** into the tube **61**. Again, the fluid at the tube attachment end **64** acts as a "virtual piston"**66**, operating in time-harmonic oscillation.

[0065] The central portion **68** of the tube **61** acts like another synthetic jet actuator "chamber"**69** bounded by the walls **62** of the tube **61**. The fluid at the orifice **46** of the synthetic jet actuator **40** bounds this "chamber"**69** and acts as a virtual piston **66** to this virtual synthetic jet actuator "chamber"**69**. The fluid exiting and entering the orifice **46**, acting as a piston **66**, creates a flow of fluid **67** emitting from the exit end **65** of the tube **61**. The fluid **67** exiting the tube **61** creates vortices at the exit **65** of the tube **61**. These vortices roll up and move away from the tube exit **65**. As the vortices form and move away, these vortices entrain the ambient fluid **48** in order to form a synthetic jet stream **67** at the exit **65** of the tube **61**.

[0066] Depending on the length of the tube **61**, the operation of the diaphragm **42** of the synthetic jet actuator **40** could be specifically tuned to create the virtual synthetic jet actuator in the tube **61**. As is apparent from the discussion above, and as will be recognized by one of ordinary skill in the art, the operation of the diaphragm **42** should preferably be tuned such that the frequency of the air pulses **66** emitting from the orifice **46** of the synthetic jet actuator **40** are emitted at a resonant frequency of the tube **61**. The tube **61**, in essence, acts as a type of Helmholtz resonator and can be operated in like manner. The attachment end **64** of the tube **61** acts as the closed end of a typical Helmholtz resonator, and also as the exciting force to the resonator.

[0067] One of ordinary skill in the art can compute the resonant frequency of the tube **61** if the dimensions of the tube **61** are known. Then, the frequency and amplitude of the diaphragm **42** oscillation can be computed so that the pulses **66** emitted from the synthetic jet actuator **40** orifice **46** will excite the tube **61** at a resonant frequency. Of course, this could all be controlled automatically by an appropriate control system **50**.

[0068] In another exemplary configuration of a distributed cooling synthetic jet actuator **70**, the synthetic jet actuator **40** is configured to drive a number of tubes. Such a configuration is depicted in **FIG. 5**. **FIG. 5** is a cut-away top view of a distributed cooling synthetic jet actuator. As shown, the synthetic jet actuator housing **47** of the actuator **70** preferably has multiple orifices **46***a*, **46***b*, **46***c*, **46***d*, **46***e*, **46***f*. On the exterior of the housing **47** are attached a number of tubes **61***a*, **61***b*, **61***c*, **61***d*, **61***e*, **61***f* such that these tubes **61***a*, **61***b*, **61***c*, **61***d*, **61***e*, **61***f* correspond to each of the orifices **46***a*, **46***b*, **46***c*, **46***d*, **46***e*, **46***f*. The tubes **61***a*, **61***b*, **61***c*, **61***d*, **61***e*, **61***f* could all be configured to direct fluid flow at the same area, or in the preferred application, are formed such as to direct synthetic jet streams **52***a*, **52***b*, **52***c*, **52***d*, **52***e*, **52***f* at separate heated areas or objects **71***a*, **71***b*, **71***c*, **71***d*, **71***e*.

[0069] In another embodiment of the distributed cooling apparatus, it may be desirable to have a ready means of attaching the synthetic jet actuator module to another surface. For example, if the distributed cooling apparatus will be used in a retrofit application, there may not be a ready method of attachment. In such a situation, it may be desirable to have the top wall **43** of the synthetic jet actuator **40** configured such as to readily adhere to a surface. The synthetic jet actuator **40** could be manufactured so as to "stick-on" to a surface. This can be accomplished by applying double sided tape, foam with adhesive on both sides, or the like.

B. SECOND EXAMPLE

Multiple Actuator Device

[0070] In some implementations of a distributed cooling apparatus, it may be desirable to generate multiple synthetic jet streams. As noted above, a single synthetic jet actuator **40** may drive multiple tubes, and thereby generate multiple, distributed synthetic jet streams of fluid. This, of course, is not the only possible implementation of a multiple synthetic jet distributed cooling apparatus. Another exemplary embodiment may comprise multiple synthetic jet actuators driving multiple tubes, and thereby emitting multiple synthetic jet streams. The tubes of such an embodiment may be directed to different areas, different heat sink channels, or all to the same location.

[0071] An exemplary embodiment of a multiple actuator distributed cooling apparatus **80** is depicted in **FIG. 6**. This apparatus **80** generally comprises a plurality of tubes **81** emerging from a generally rectangularly cubic housing **82**. The housing **82** has two "plenums"**83** formed into the housing **82** such that these two plenums **83** descend from a top surface **84** of the housing **82**. The two plenums **83** are spaced from the side walls **85**, **86** of the housing **82**, and do not preferably reach all the way to the bottom surface **87** of the housing **82**.

[0072] A cross-sectional side view of the multiple actuator distributed cooling apparatus **80** is depicted in **FIG. 7**. One of the plenums **83** of the housing **82** is depicted as bound by the bottom surface **87**, a front wall **88**, and a rear wall **89** of the apparatus **82**. The front wall **88** and the rear wall **89** each form a pair of upper platforms **91**, **92** and a pair of lower platforms **93**, **94**. These platforms **91**, **92**, **93**, **94** are preferably formed from the same material as the walls **88**, **89**, and not merely adhered to the walls **88**, **89**. Of course, this is not a required feature of the multiple actuator distributed cooling apparatus **80**. In addition, a top wall **95** (depicted in **FIG. 8**) may be installed on the device **80** in order to seal the plenums **83**.

[0073] **FIG. 8** shows the device of **FIG. 7** after having two actuators **96**, **97** positioned in the plenum **83** and a top wall **95** installed over the plenum **83**. As depicted in the figure, a first actuator **96** rests on the upper platforms **91**, **92** and a second actuator **97** rests on the lower platforms **93**, **94**. These two actuators **96**, **97** preferably comprise a flexible diaphragm **98**, **99** having a piezoelectric actuator **101**, **102** mounted to the flexible diaphragm **98**, **99**. The preferred actuator **96**, **97** is the elastomeric or polymeric actuator described above with regard to the exemplary embodiment **40**. See **FIG. 2**. Other actuators could be used with the apparatus **80** described herein. However, the elastomeric/polymeric actuators are preferred for their low profile design, robust actuation, and inexpensive cost.

[0074] Power and control is supplied to the actuators **96**, **97** by electrical wiring (not depicted). These wires typically enter the housing **82** through four small channels **103***a*, **103***b*, **103***c* (only three are depicted in **FIG. 6**) cut into both the upper and lower side walls **85**, **86** of the housing **82**. In fact, it is anticipated that the entire control electronics (not depicted) can be positioned in these channels **103***a*, **103***b*, **103***c*. Then, only power will preferably be supplied to these channels **103***a*, **103***b*, **103***c* and the control hardware they contain.

[0075] The actuators **96**, **97** are preferably secured to the platforms **91**, **92**, **93**, **94** in the apparatus housing **82**. This is preferably accomplished by using a type of adhesive. As the material of the diaphragm **98**, **99** is preferred to be an elastomer or polymer, and the preferred material of the housing **82** is a plastic, one of ordinary skill in the art will readily be able to select an appropriate adhesive, or other attachment mechanism.

[0076] Once the actuators **96**, **97** are secured in the internal portion of the apparatus housing **82**, the apparatus plenums **83** are essentially divided into three parts. The positioning of the actuators **96**, **97** forms three separate chambers that generate three separate, but related, synthetic jet actuators. A first, or bottom, chamber **105** is bounded by the housing bottom wall **87**, the housing front wall **88**, the housing back wall **89**, and the second actuator **97**. The second chamber **106** is bounded by the first actuator **96**, the front wall **88**, the back wall **89**, and the second actuator **97**. The third, or top, chamber **107** is bounded by the first actuator **96**, the front wall **88**, the back wall **89**, and the top wall **95**.

[0077] Recall that the above implementation of a distributed cooling apparatus **60** (**FIG. 4A**) had a single orifice **46** leading from a chamber **45** to a single tube **61**. However, in the present exemplary embodiment **80**, each chamber **105**, **106**, **107** has one or more orifices **108**. In the exemplary embodiment **80**, each chamber **105**, **106**, **107** has two orifices fashioned into the front wall **88** of the apparatus housing **82**. Each orifice is further fluidically connected to one of the tubes **81** emerging from the front wall **88** of the housing **82**. Of course, it is not necessary that each chamber **105**, **106**, **107** have two orifices **108** and tubes **81**. The present exemplary embodiment **80** will also work if there are more or less than two orifices **108** and tubes **81**, or if there are different numbers for each chamber **105**, **106**, **107**.

[0078] The tubes **81** are preferably attached to the housing **82** in generally the same horizontal plane, as depicted in **FIG. 6**. For this reason, **FIGS. 7 and 8** appear to only show one tube **81** (and one orifice **108**) attached to the housing **82** at approximately a mid-point of the housing front wall **88**. The tubes **81** comprise an attachment end **109**, attached to the housing front wall **88**, and a fluid exit end **110**, fluidically connecting a tube interior **111** to an ambient fluid **112**.

[0079] Because the tubes **81** are preferably all attached to the housing **82** in the same horizontal plane, and the chambers **105**, **106**, **107** are not in the same horizontal plane, contoured passageways **113** are preferably used to fluidically connect each chamber **105**, **106**, **107** to the orifices **108** and tubes **81** served by that particular synthetic jet actuator.

[0080] These ported passageways **113** are depicted in the cut-away sectional view of **FIG. 9**. Furthermore, **FIG. 10** depicts a cut-away view of the three chambers **105**, **106**, **107** and the orifices **108***a-f* each chamber **105**, **106**, **107** services. By way of example, in **FIG. 10**, the first chamber **105** has two orifices **108***e*, **108***f*; the second chamber **106** has two orifices **108***c*, **108***d*; and the third chamber **107** has two orifices **108***a*, **108***b*. As can also be seen from **FIGS. 9 and 10**, the three chambers **105**, **106**, **107** in the housing **82** are not necessarily rectangular in cross-section, but rather, are oddly-shaped so as to direct fluid to the various tubes **81** serviced by each chamber **105**, **106**, **107**.

[0081] Of course, in an alternative embodiment, the tubes **81** are not necessarily attached to the housing **82** in the same horizontal plane. For example, the tubes **81** to be serviced by each chamber **105**, **106**, **107** could be directly connected to the chamber **105**, **106**, **107**. Then, the chambers **105**, **106**, **107** could be fashioned such that they have generally-rectangular cross-sections.

[0082] The operation of the exemplary multiple actuator distributed cooling apparatus **80** will now be described, with specific discussion of one of the "plenums"**83**. It should be understood that the operation of the other "plenum"**83** will be similar. In operation, the two diaphragms **98**, **99** are caused to oscillate in time-harmonic motion by the control systems (not depicted) controlling each piezoelectric actuator **101**, **102** on each diaphragm **98**, **99**. The diaphragms **98**, **99** are preferably actuated such that the two diaphragms **98**, **99** oscillate out of phase with one-another.

[0083] As the two actuators **96**, **97** move toward one-another, the volume of the second chamber **106** is reduced, and the volumes of the top chamber **107** and bottom chamber **105** are increased. Therefore, the second chamber **106** pushes fluid from the chamber **106** into the interior **111** of the tubes **81** connected to this chamber **106**. Recall from the discussion relative to the single actuator exemplary embodiment **60** above, this pushing of fluid into the tube interior **111** acts like a "virtual piston" of fluid. See the description relating to **FIGS. 4B and 4C** above for an explanation of this process. This virtual piston moves into the interior **111** of the tubes **81**, compressing the fluid in the tube interior **111**, and thus causing a synthetic jet stream of fluid **115** to form at the exit end **110** of the tubes **81** connected to this second chamber **106**.

[0084] The top chamber **107** and bottom chamber **105** undergo the opposite effect. Specifically, as the two diaphragms **98**, **99** move toward one-another, both the top and bottom chambers **107**, **105** pull fluid in from the interior **111** of the tubes **81** connected to these chambers **107**, **105**. This moves the "virtual piston" of fluid into the top and bottom chambers **107**, **105**, thereby causing the exit end **110** of the tubes **81** connected to these chambers **107**, **105** to draw fluid in from the ambient **112**.

[0085] As the diaphragms **98**, **99** oscillate away from one-another, the second chamber's volume increases and fluid is pulled into the tubes **81** connected to this chamber **106** from the ambient **112**. Of course, the volumes of the top and bottom chambers **107**, **105** are similarly reduced. This causes a synthetic jet stream **115** of fluid to form at the exit ends **110** of the tubes **81** connected to these two chambers **107**, **105**.

[0086] As will be recognized by one of ordinary skill in the art, the principle of operation of the multiple actuator distributed cooling apparatus **80** is very similar to the operation of the basic distributed cooling apparatus **60** described above. For example, the tubes **81** of this embodiment **80** act as Helmholtz resonators in the manner described above with regard to the single actuator distributed cooling apparatus **60**.

[0087] One common implementation **120** of a multiple actuator distributed cooling apparatus **80** is depicted in **FIGS. 11A and 11B**. Of course, many other implementations are possible for the apparatus **80**, depending on the thermal management requirements of a system and the configuration of the apparatus **80**. This exemplary implementation **120** is not limiting on the range of implementations for the apparatus **80**. An exemplary implementation is presented merely to better illustrate the features of the present embodiment **80**.

[0088] The exemplary implementation **120** involves the use of an extruded heat sink **121** for transporting heat away from a heated object **122**. The multiple actuator distributed cooling apparatus **80** is positioned such that each of the tubes **81** in the apparatus **80** are aligned with a series of channels **123** formed with a series of fins **124** of the heat sink **121** such that the flow **125** of the jet passes through the channels **123** between the fins **124**. This jet flow **125**, in turn entrains secondary cool airflow **126** that is forced into the channels **123** of the heat sink **121**.

[0089] In another utilization **132** of this cooling module **80** the synthetic jet array of tubes **81** is used to reduce a flow bypass **130** in a heat sink **121** cooled by a fan-driven flow **127**. **FIG. 12A** depicts the situation without a synthetic jet actuator **80**. In this embodiment, the fan **128** draws fluid flow **127** though the channels **123** between the fins **124** of a heat sink **121**. However, due to the pressure drop generated by the channels **123** of the heat sink **121** a large portion of the airflow **130** bypasses the heat sink **121**. This is a common problem encountered in several applications like blade servers, telecom racks and the like, where the spacing between the component boards is narrow and there are large banks of fans attempting to drive massive airflow through the heat sink mounted on the hot components.

[0090] In this implementation, as depicted in **FIG. 12B**, a synthetic jet actuator is positioned such that the tubes **81** of the actuator **80** are directed to empty their flow **115** into the channels **123** of the heat sink **121**. Note that because of the distributed nature of the apparatus **80**, the actuator can be positioned below the plane of the heat sink **121**, thereby preventing any interference with the flow. When the actuator **80** is caused to operate, a tangential synthetic jet **115** is directed near the left edge of the heat sink **121**. The fan **128** continues to operate. The low-pressure, high momentum synthetic jet enables a significant entrainment **131** of the airflow **130** that was previously bypassing the heat sink **121**.

[0091] It should be emphasized that the above-described embodiments of the present invention, particularly, any "preferred" embodiments, are merely possible examples of implementations, merely set forth for a clear understanding of the principles of the invention. Many variations and modifications may be made to the above-described embodiment(s) of the invention without departing substantially from the spirit and principles of the invention. All such modifications and variations are intended to be included herein within the scope of this disclosure and the present invention and protected by the following claims.

Therefore, having thus described the invention, at least the following is claimed:

1. A device for thermal management comprising:

a housing defining an internal chamber and having an orifice in a wall of said housing; and

a volume changing device adjacent to said housing, said volume changing device for modifying a volume of said internal chamber;

wherein, when said volume changing device decreases the volume of said internal chamber, fluid within the internal chamber is expelled from the internal chamber through said orifice into an ambient fluid outside the housing;

wherein, when said volume changing device increases the volume of said internal chamber, ambient fluid outside the housing is drawn through said orifice into the internal chamber; and

wherein the fluid being expelled from the internal chamber and the ambient fluid being drawn into the internal chamber provide a cooling effect.

2. The device of claim 1, further comprising a control system for controlling an operation of said volume changing device, wherein said operation of said volume changing device draws a gas from outside the housing into said internal chamber and forces a gas out of said internal chamber.

3. The device of claim 1, wherein said volume changing device comprises a flexible diaphragm forming a portion of said housing.

4. The device of claim 3, wherein said volume changing device further comprises a piezoelectric actuator adhered to said flexible diaphragm.

5. The device of claim 4, wherein said flexible diaphragm comprises an elastomer material.

6. The device of claim 4, wherein said flexible diaphragm comprises a polymer material.

7. The device of claim 1, further comprising a tube connected to an external surface of said wall of said housing, said tube enclosing at least a portion of said orifice;

wherein said tube comprises an attachment end and an open end, said attachment end connected to said housing, and wherein an operation of said volume changing device generates a synthetic jet stream at said open end of said tube.

8. The device of claim 7, wherein said tube generates said synthetic jet stream at a location remote from said housing.

9. The device of claim 7, wherein said tube is sized such that a Helmholtz-type resonance is created in an interior of said tube due to the operation of said volume changing device.

10. The device of claim 7, further comprising a heat sink having fins, wherein said open end of said tube is positioned adjacent to said heat sink such that said synthetic jet stream passes between adjacent ones of the fins.

11. The device of claim 10, further comprising a fan, said fan positioned at one end of said heat sink such that said synthetic jet stream assists said fan by reducing a flow bypass due to a pressure drop of the fins.

12. The device of claim 1, wherein said internal chamber comprises:

a first sub-chamber;

a second sub-chamber adjacent to said first sub-chamber; and

a third sub-chamber adjacent to said second sub-chamber.

13. The device of claim 12, wherein said first sub-chamber and said second sub-chamber are formed from a first common wall, said first common wall contained within said internal chamber of said housing, and said first common wall comprising a first flexible diaphragm.

14. The device of claim 13, wherein said second sub-chamber and said third sub-chamber are formed from a second common wall, said second common wall contained within said internal chamber of said housing, and said second common wall comprising a second flexible diaphragm.

15. The device of claim 14, wherein said orifice further comprises at least one opening in each of said sub-chambers.

16. The device of claim 15, further comprising a pipe adjacent to each said at least one opening, said each pipe enclosing at least a portion of said each opening.

17. The device of claim 16, further comprising:

a first piezoelectric element attached to said first flexible diaphragm; and

a second piezoelectric element attached to said second flexible diaphragm.

18. The device of claim 17, wherein said first and second flexible diaphragms comprise an elastomer material.

19. The device of claim 17, wherein said first and second flexible diaphragms comprise a polymer material.

20. A device for cooling comprising:

a synthetic jet actuator; and

a channel having a proximal end and a distal end, said proximal end adjacent to said synthetic jet actuator;

wherein said synthetic jet actuator causes a first synthetic jet stream of fluid to flow substantially in a first direction through said channel;

wherein said synthetic jet actuator causes a second synthetic jet stream of fluid to flow substantially in a second direction through said channel, the second direction being opposite of the first direction; and

wherein the first and second synthetic jet streams provide a cooling effect.

21. The device of claim 20, wherein said first synthetic jet stream forms at said distal end of said channel.

22. The device of claim 20, wherein said second synthetic jet stream forms at said proximal end of said channel.

23. The device of claim 20, further comprising a control system for controlling an operation of said synthetic jet actuator.

24. The device of claim 20, wherein said synthetic jet actuator comprises:

a housing defining an internal chamber and having an orifice in a wall of said housing;

a volume changing means adjacent to said housing.

25. The device of claim 24, wherein said volume changing means comprises a flexible diaphragm forming a portion of said housing.

26. The device of claim 25, wherein said volume changing means further comprises a piezoelectric actuator adhered to said flexible diaphragm.

27. The device of claim 26, wherein said flexible diaphragm comprises an elastomer material.

28. The device of claim 26, wherein said flexible diaphragm comprises a polymer material.

29. The device of claim 26, wherein said channel is sized such that a Helmholtz-type resonance is created in an interior of said channel due to the operation of said volume changing means.

30. The device of claim 29, wherein said channel comprises a tube.

31. The device of claim 29, further comprising a heat sink having fins, wherein said distal end of said channel is positioned adjacent to said heat sink such that said first synthetic jet stream passes between adjacent ones of said fins.

32. The device of claim 31, further comprising a fan, said fan positioned at one end of said heat sink such that said first synthetic jet stream assists said fan by reducing flow bypass due to pressure drop of said fins.

33. The device of claim 20, wherein said channel comprises a portion of a heat sink.

34. The device of claim 20, wherein said synthetic jet actuator comprises a first synthetic jet actuator, said device further comprising:

a second synthetic jet actuator adjacent to said first synthetic jet actuator and;

a third synthetic jet actuator adjacent to said second synthetic jet actuator.

35. The device of claim 34, wherein said synthetic jet actuators are formed by a common housing, and further wherein said first synthetic jet actuator and said second synthetic jet actuator are formed from a first common wall, and said second synthetic jet actuator and said third synthetic jet actuator are formed from a second common wall.

36. The device of claim 35, wherein said channel comprises a first tube, said device further comprising:

a second tube having a proximal end and a distal end, said proximal end adjacent to said second synthetic jet actuator; and

a third tube having a proximal end and a distal end, said proximal end adjacent to said third synthetic jet actuator.

37. The device of claim 36, wherein said first common wall comprises a first flexible diaphragm, and said second common wall comprises a second flexible diaphragm.

38. The device of claim 37, further comprising:

a first piezoelectric element attached to said first flexible diaphragm; and

a second piezoelectric element attached to said second flexible diaphragm.

39. The device of claim 38, wherein said first and second flexible diaphragms comprise an elastomer material.

40. The device of claim 38, wherein said first and second flexible diaphragms comprise a polymer material.

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