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(54) **FLOW RATE MODULE AND INTEGRATED FLOW RESTRICTOR**

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(52) **U.S. Cl.** **73/202.5; 73/204.21; 73/861.52;**
73/861.61

(58) **Field of Search** 73/861.52, 861.69,
73/52, 63, 202.5, 204.21

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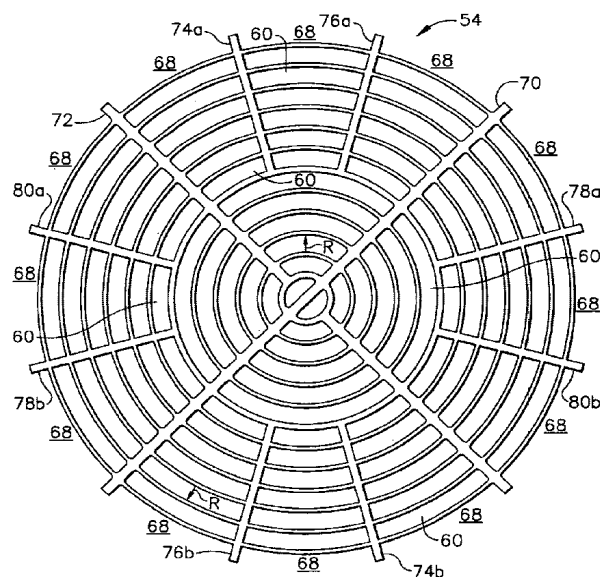
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(57) **ABSTRACT**

An integrated module is provided for measuring a flow rate of a fluid, whether gaseous or liquid, with a flow restrictor comprising a plurality of orifices adapted to a flow channel of the integrated module and a sensor mounted to measure a property of the fluid at said flow restrictor corresponding to the flow rate. The integrated module provided may be used in numerous flow systems, such as reactors, ventilators and respirators, and has the benefit of better laminarization of the flow as well as better calibration between the flow sensor and the flow restrictor for more accurate flow measurements.

34 Claims, 9 Drawing Sheets



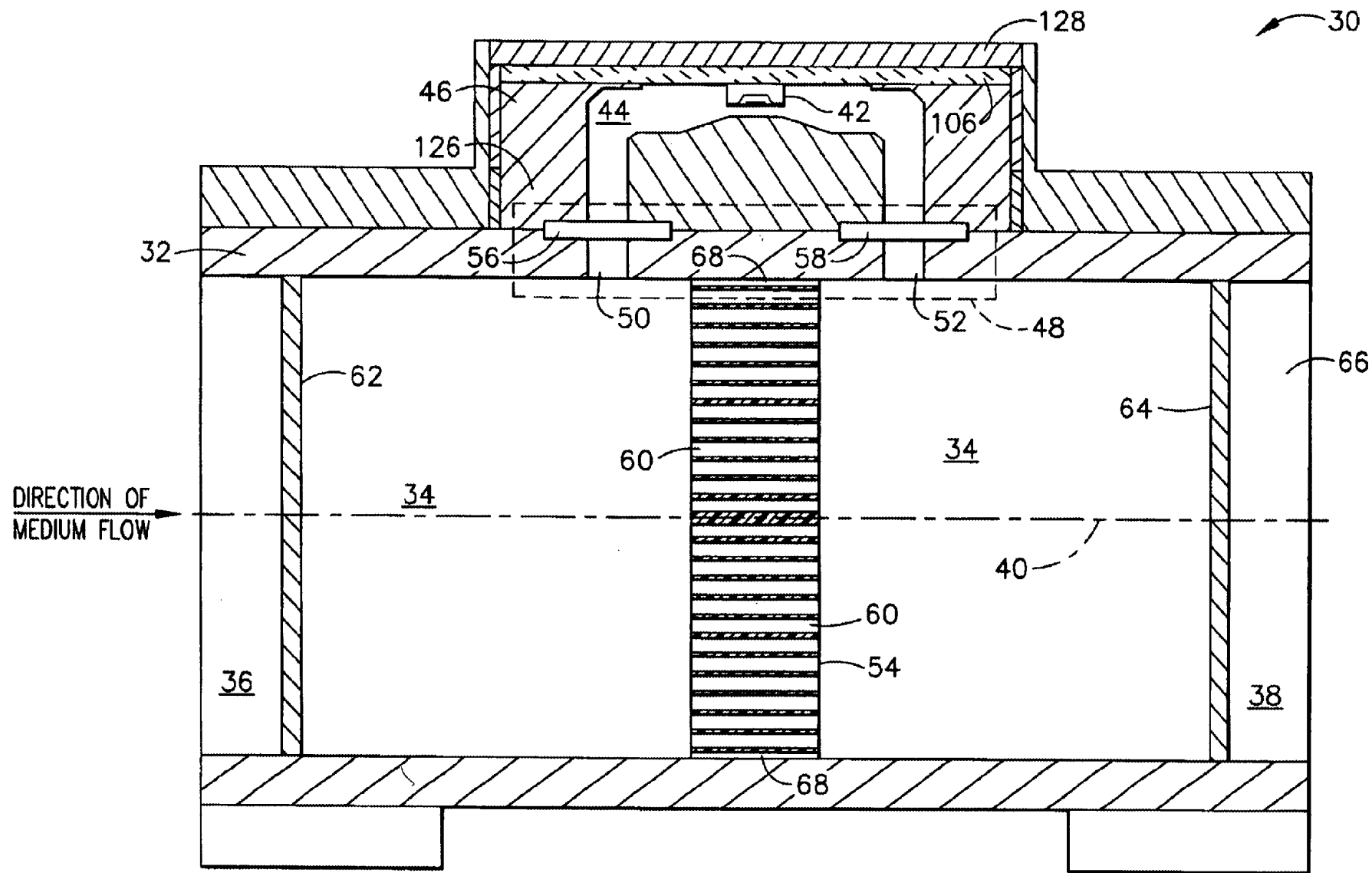
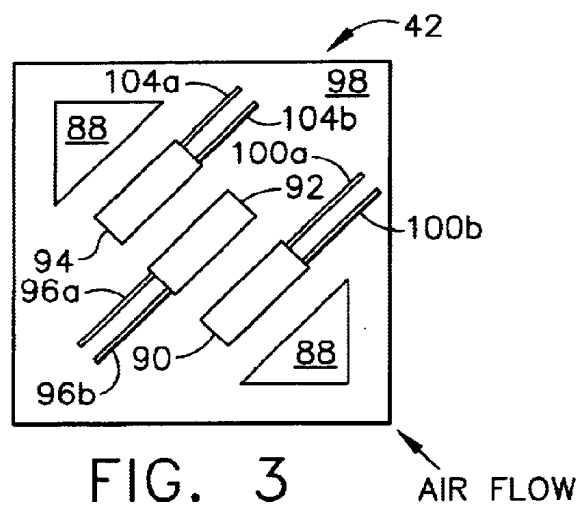
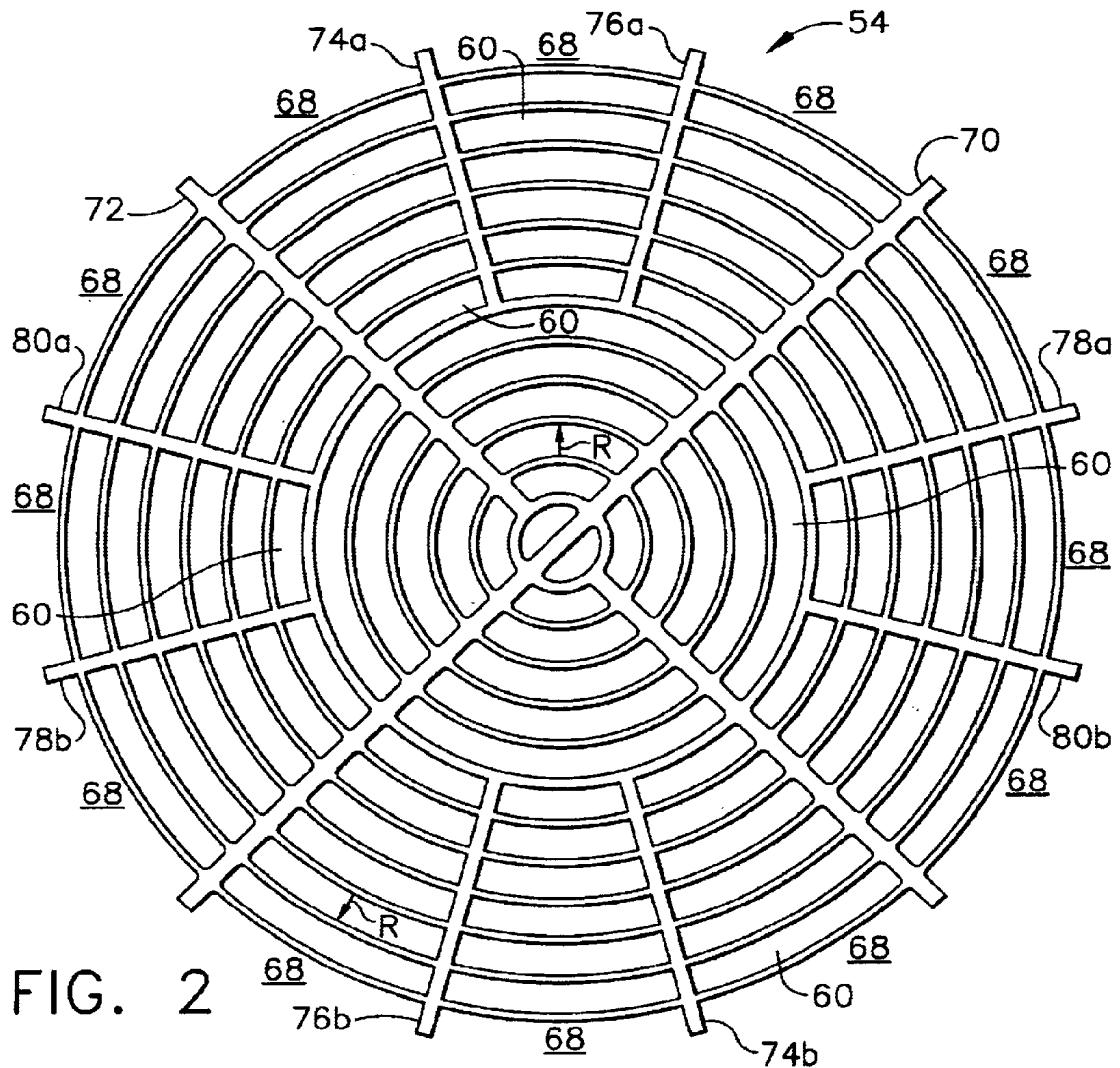


FIG. 1



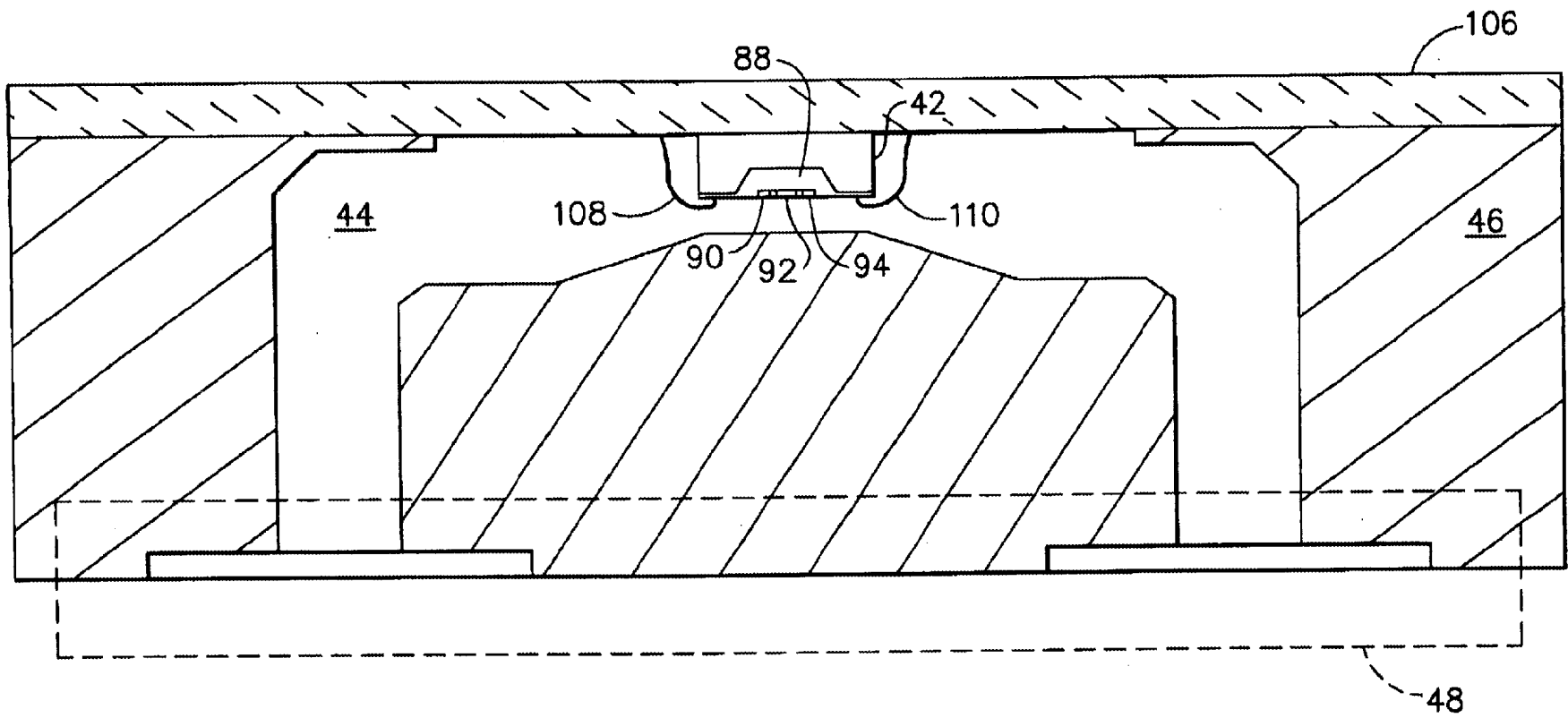
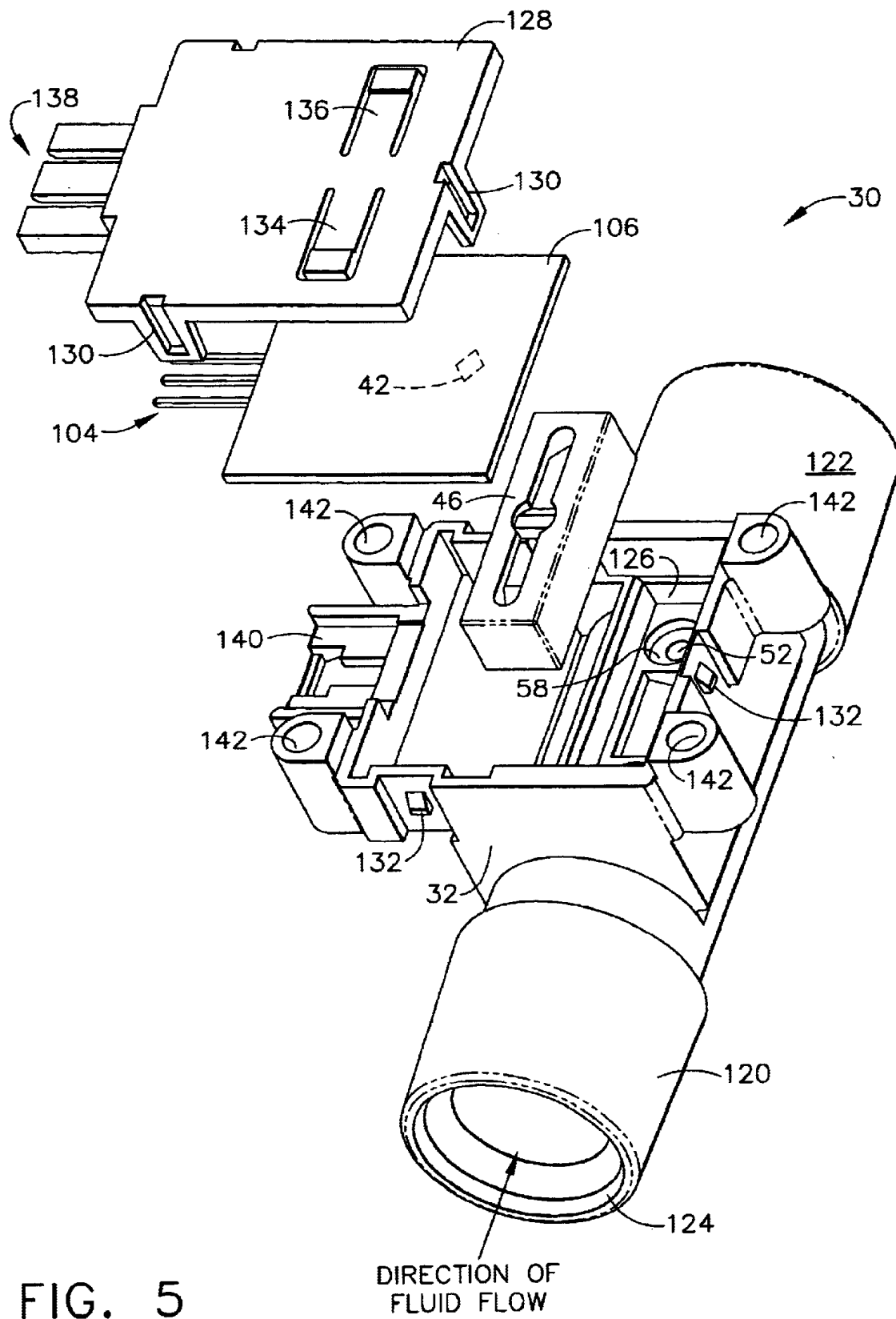


FIG. 4



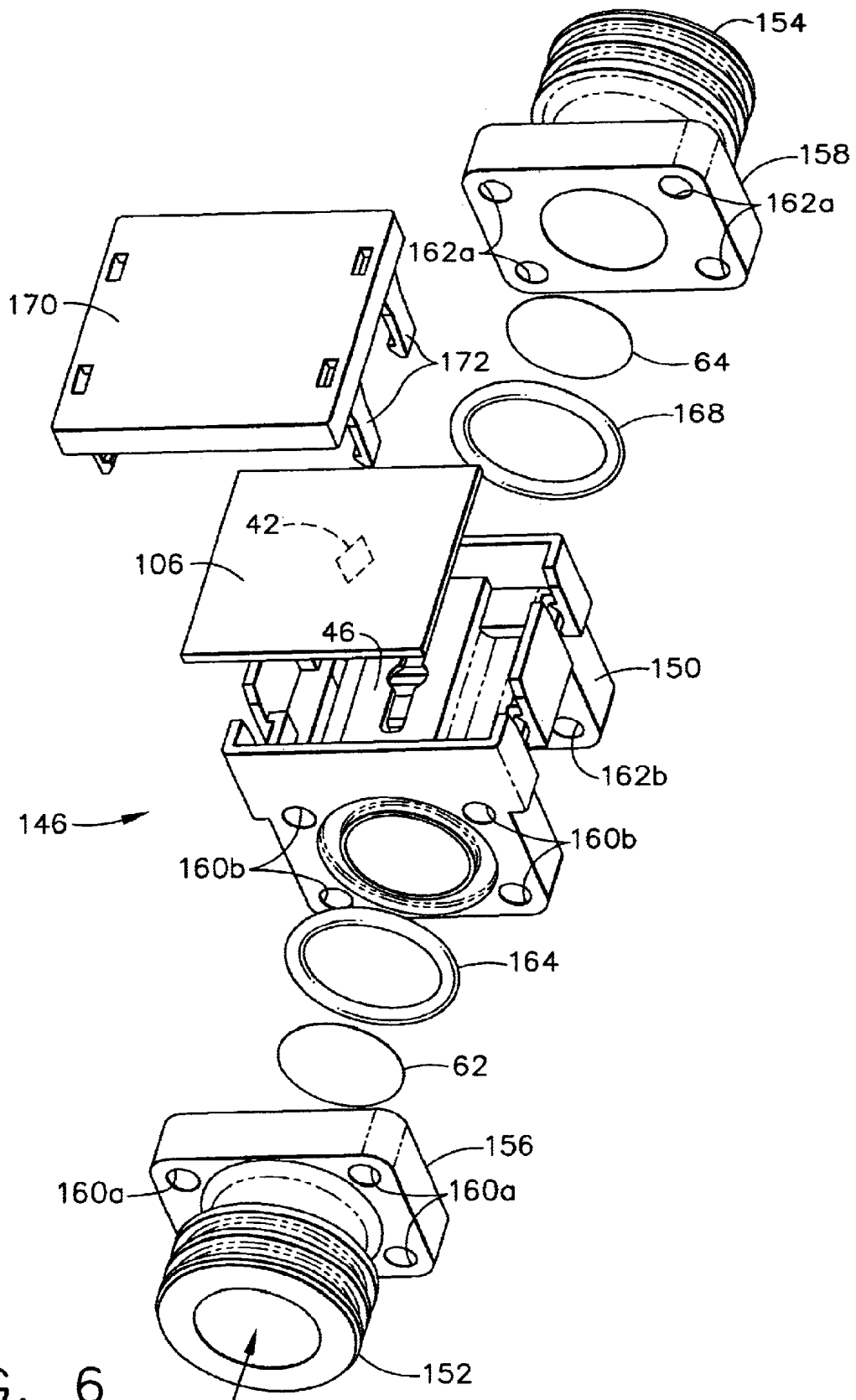


FIG. 6

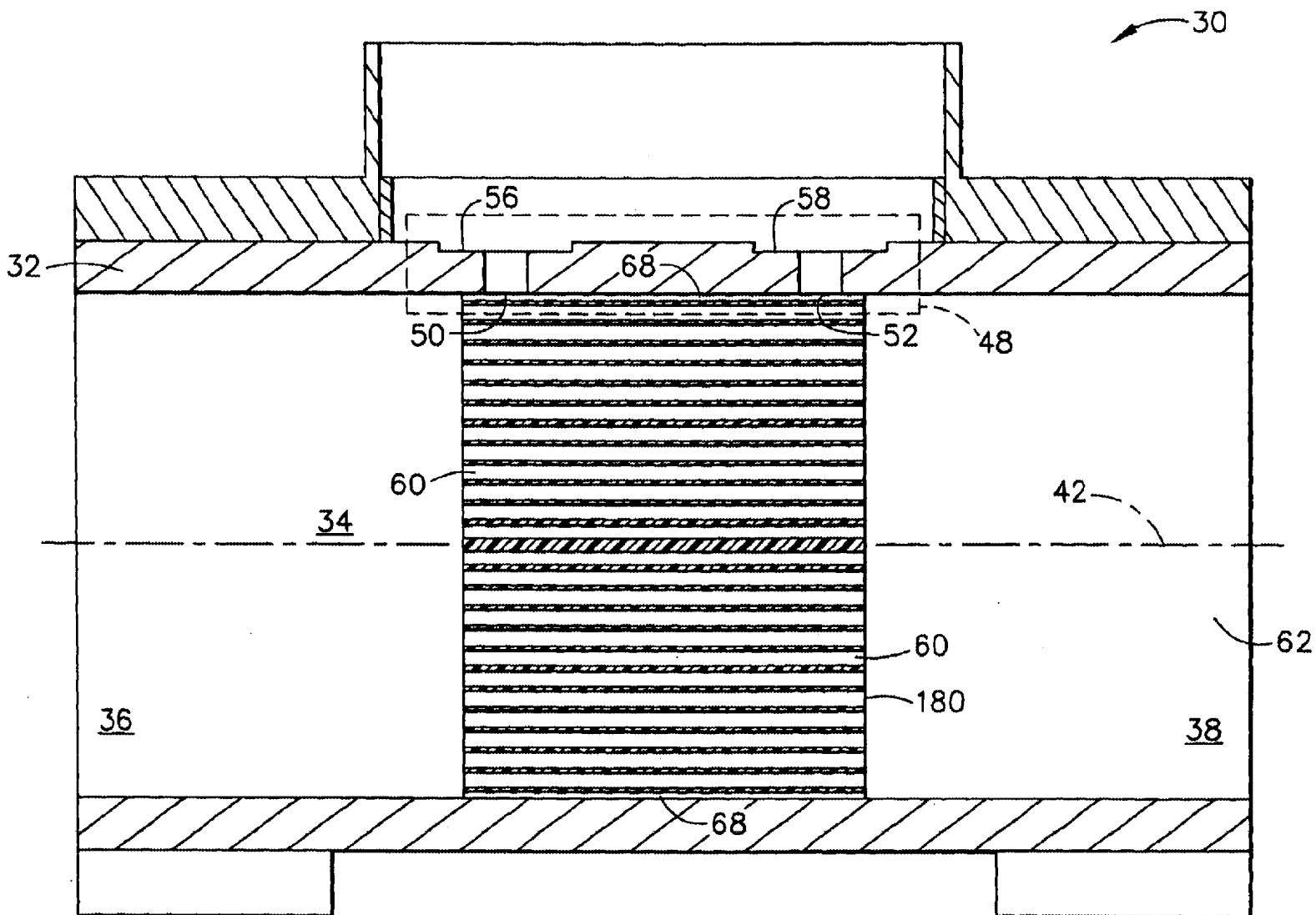


FIG. 8

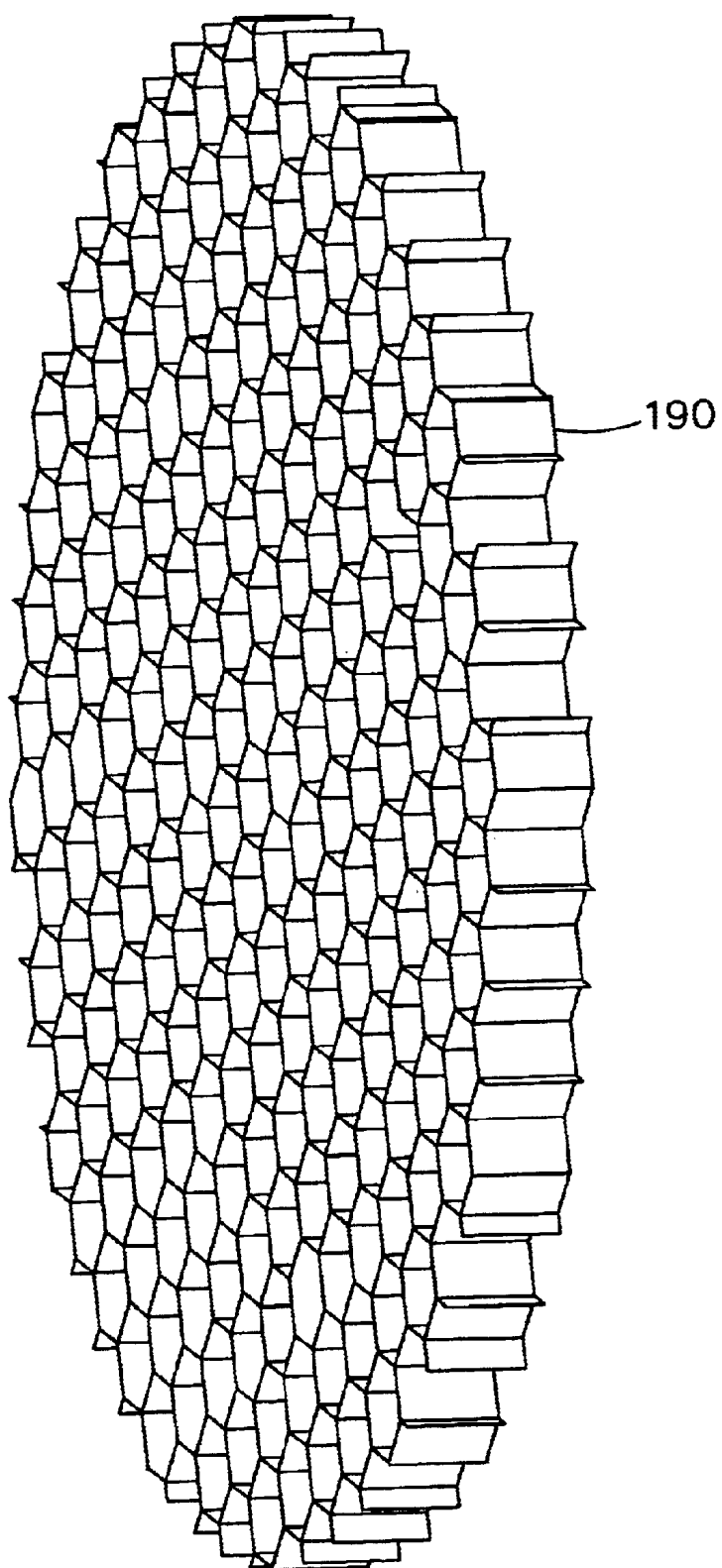


FIG. 9

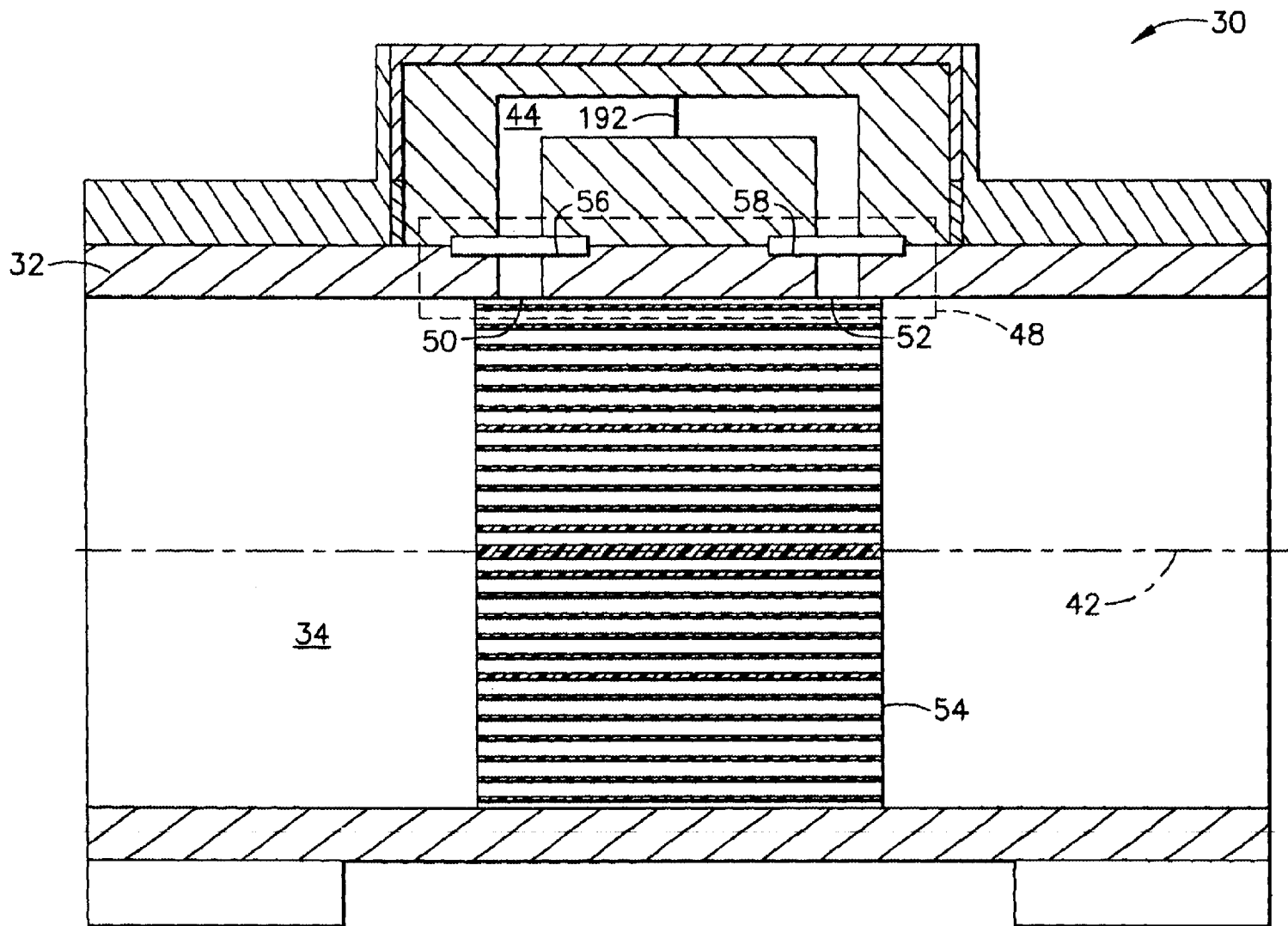


FIG. 10

FLOW RATE MODULE AND INTEGRATED FLOW RESTRICTOR

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates generally to flow sensors and, more particularly, to a flow sensor with an integrated flow restrictor.

2. Description of Related Technology

Flow rate control mechanisms are used in a variety of flow systems as a means for controlling the amount of fluid, gaseous or liquid, traveling through the system. In large-scale processing systems, for example, flow control may be used to affect chemical reactions by ensuring that proper feed stocks, such as catalysts and reacting agents, enter a processing unit at a desired rate of flow. Additionally, flow control mechanisms may be used to regulate flow rates in systems such as ventilators and respirators where, for example, it may be desirable to maintain a sufficient flow of breathable air or provide sufficient anesthetizing gas to a patient in preparation for surgery.

Typically, flow rate control occurs through the use of control circuitry responsive to measurements obtained from carefully placed flow sensors. One such flow sensor is a thermal anemometer with a conductive wire extending radially across a flow channel and known as a hot-wire anemometer. These anemometers are connected to constant current sources which cause the temperature of the wire to increase proportionally with an increase in current. In operation, as a fluid flows through the flow channel and, thus, past the anemometer, the wire cools due to convection effects. This cooling affects the resistance of the wire, which is measured and used to derive the flow rate of the fluid. Another form of thermal anemometer flow sensor is a microstructure sensor, either a microbridge, micro-membrane, or microbrick, disposed at a wall of a flow channel. In this form, the sensors ostensibly measures the flow rate by sampling the fluid along the wall of the flow channel. In either application, the thermal anemometer flow sensor is disposed in the flow channel for measuring rate of flow.

There are numerous drawbacks to these and other known flow sensors. One drawback is that the proportional relationship upon which these sensors operate, i.e., that the conductive wire or element will cool linearly with increases in the flow rate of the fluid due to forced convection, does not hold at high flow velocities where the sensors become saturated. This saturation can occur over a range from 10 m/s to above 300 m/s depending on the microstructure sensor, for example. As a result, in high flow regions, measured resistance of an anemometer, or other sensor, no longer correlates to an accurate value of the flow rate. Furthermore, because these sensors reside in the main flow channel, they are susceptible to physical damage and contamination.

In addition to these drawbacks, known flow sensors are susceptible to mis-measurement due to turbulent flow effects, i.e., non-uniformity in flow velocity and pressure, both of which exist to some degree in all flow systems. Furthermore, conventional hot-wire anemometers have a slow time response and therefore do not produce accurate flow rate values upon abrupt changes in flow velocity. In addition, they require high input power to keep the entire length of wire at an elevated temperature at zero flow.

In contrast, wall-mounted thermal microstructures may have a relatively fast time response, but offer little advantage

over the hot-wire anemometers because their response times are too fast, producing flow rate values that fluctuate with turbulence conditions instead of averaging out the noise associated with such turbulence. Therefore, as the flow rate of the fluid increases, turbulence increases and the wall-mounted thermal microstructure will produce increasingly erratic measurements in response thereto.

An indirect flow sensor measuring technique that measures flow rate from a sensor positioned outside of the flow channel and improves upon some of the drawbacks of the foregoing, has been designed. In one form, ΔP pressure sensors measure a pressure drop across a flow restrictor, which acts as a diameter reducing element in the flow channel thereby creating a difference in pressure between an entrance end and an exit end of the flow restrictor. These flow restrictors have been in either honeycomb-patterned or porous metal plate flow restrictors. The pressure sensors are disposed in dead-end channels to measure the pressure drop due to the flow restrictor, with this pressure drop being proportional to the flow rate of the fluid. In other forms, the indirect flow mechanism can use a translucent tube disposed near the flow channel with a free-moving ball or indicator that rises and falls with varying flow rate conditions in the flow channel, or a rotameter, such as a small turbine or fan, that operates as would a windmill measuring wind rate.

Though they offer some improvements over sensors disposed directly in the flow channel, all of these indirect flow sensors are hampered by calibration problems. An indirect flow sensor may be calibrated to work generally with certain types of restrictors, e.g., honeycomb restrictors, but imprecise restrictor geometry results in variations in pressure and, therefore, variations in measured flow rate. And, furthermore, the sensors are not calibrated for use with other types of restrictors.

In addition to these deficiencies of indirect flow sensors, known flow restrictors further hamper flow measuring mechanisms because they do not produce uniform, laminarizing flow of the fluid. Non-uniformities in the cross-sectional area and position of the orifices in known flow restrictors result in such non-uniform flow, an example of which occurs in a honeycomb restrictor where orifices abutting the outer wall of the flow channel are truncated to conform the restrictor to circular shape of the wall. Moreover, non-linear correlations between pressure and flow rate result from this non-uniformity, especially at higher flow rates.

Therefore, to overcome the foregoing shortcomings, it is desirable to have a flow sensor and integrated flow restrictor that reduces calibration errors and that is adapted to reduce the flow rate measurement errors created by turbulence effects at the outer edges of the flow channel and to do so at an affordable cost.

SUMMARY OF THE INVENTION

In accordance with an aspect of the invention, an integrated module for measuring a flow rate of a fluid in a flow system has a housing that defines a flow channel through which a portion of the fluid flows and a flow restrictor, with an entrance end and an exit end, disposed in the flow channel. The flow restrictor comprises a plurality of orifices adapted to the flow channel to produce substantially uniform flow across the flow channel at the exit end.

In accordance with another aspect of the invention, a module for measuring a flow rate of a fluid in a flow system is provided with a flow restrictor disposed in a flow channel; a flow sensor disposed in a sensing channel communicating

with the flow channel via a sensing tap with an inlet end and an outlet end such that the flow restrictor creates a pressure drop across the sensing channel allowing a portion of the fluid in the flow channel to flow into the sensing channel; and a housing wherein the flow restrictor, the flow sensor, and the sensing channel are integrally formed.

In accordance with yet another aspect of the invention, a flow restrictor, for use in a flow channel, comprises a plurality of orifices adapted to the flow channel to produce a substantially uniform flow across the flow channel at an exit end of the flow restrictor.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a cross-sectional view of an integrated module in accordance with the invention, wherein a flow restrictor, flow sensor, and housing are shown.

FIG. 2 is a front view of the flow restrictor in the preferred embodiment of the invention.

FIG. 3 is a top view of an exemplary flow sensor that may be used in the invention.

FIG. 4 is a cross-sectional view of the flow sensor of FIG. 3 with an integrated flow tube disposed thereon in accordance with an embodiment of the invention.

FIG. 5 is a trimetric view of a pre-assembled molded integrated module in accordance with a first embodiment of the invention in which the module is formed of a singular structure.

FIG. 6 is a trimetric view of a pre-assembled integrated module in accordance with a second embodiment of the invention in which the module is formed of adapters for connecting to an existing flow system.

FIG. 7 is a cross-sectional view of the housing of FIG. 1 employing extension tubes to allow the module to be used with high flow rates.

FIG. 8 is a cross-sectional view of an integrated module with a flow restrictor extending beyond an inlet and an outlet tap of the sensing tap of the flow channel according to a third embodiment of the invention that may be implemented in a similar manner to the first and second embodiments.

FIG. 9 is a trimetric view of an inlet or outlet screen of FIG. 1 showing a honeycomb patterned structure.

FIG. 10 is a cross-sectional view of a variation of any of the embodiments shown in FIGS. 5-8 in which a pressure sensor is disposed in a channel communicating with a flow channel of the integrated module.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

An integrated module 30 for use in a flow system to measure the rate of flow of a fluid therein is provided in FIG. 1. As will be apparent from the following description, the integrated module 30 may be used in numerous flow systems in which flow rate measurement is necessary, such as in a ventilator or a respirator. Further, the integrated module 30 is an improvement over the prior art addressing one or more of the problems thereof, as described above, including having a flow channel with an integrated flow restrictor and flow rate sensor that allows for calibrated flow rate measurements.

The integrated module 30 comprises a housing 32 defining a flow channel 34 into which an entering fluid may flow from a flow system via an inlet end 36, with the fluid exiting the flow channel 34 at an outlet end 38. The flow channel 34 preferably has a cross-sectional shape and size compatible

with that of existing flow systems, such as to fit a 22 mm conical connector as used in ventilators and respirators and which allows approximately 200 L/min of flow rate for the entering fluid. Other diameters and varying diameters may be used. However, to ensure that the integrated module 30 is calibrated to measure an accurate flow rate of the fluid and to maintain the flow rate at the outlet end 38 at substantially the same rate as at the inlet end 36, the flow channel 34 is designed to have substantially the same cross-sectional shape and size throughout a length running along an axis 40.

The integrated module 30 has a flow sensor 42 disposed in a bypass sensing channel 44 parallel to the flow channel 34. The sensor 42 is preferably a microbridge sensor as exemplarily shown in FIG. 3 and discussed below. In operation, as the fluid flows through the flow channel 34 in the direction indicated, a portion of the fluid flows through the sensing channel 44 so that the flow sensor 42 can measure the flow rate of the fluid in the flow channel 34 indirectly without being exposed to the damage or fluctuating conditions existing in typical flow channels. In FIG. 1, the sensing channel 44 is formed by disposing a flow tube 46 over a sensing tap 48 in the flow channel 34, communicating therewith, that allows a portion of the entering fluid to flow into the sensing channel 44. Typically, the flow rate of the fluid in the sensing channel 44 will be a fraction of the flow rate of the fluid in the flow channel 34.

The sensing tap 48 of the embodiment in FIG. 1 is formed from an inlet tap 50 and an outlet tap 52 shaped with a circular cross-sectional shape, disposed on opposing sides of an entrance end (closest to the inlet end 36) and an exit end (closest to the outlet end 38) of a flow restrictor 54. The circular inlet and outlet taps 50, 52 terminate at mounting indentations 56, 58, respectively, which are fitted to receive O-rings for sealably mounting the flow tube 46 to the sensing tap 48 to reduce leakage of the tapped portion of the fluid. Though the sensing tap 48 is shown with two taps 50, 52, other numbers of taps could be used and other methods of communicating flow from the channel 34 to channel 44 may be used. And, such other methods are considered within the scope of the invention.

The flow restrictor 54 creates a pressure drop across the inlet 50 and outlet 52 of the sensing channel which facilitates fluid flow into the sensing channel 44. This pressure drop, or pressure differential, is dependent on restrictor geometry and increases with flow rate. Furthermore, the fluid in the flow channel will have an increasingly turbulent flow as the flow rate of the fluid increases, i.e., an increasing non-uniform pressure and velocity across a given plane orthogonal to the direction of flow. In response, the flow restrictor 54, in addition to creating a pressure drop, straightens and laminarizes the flow in the flow channel 34, thereby reducing turbulence. The flow restrictor 54 reduces turbulence by forcing the fluid to flow through a series of equally spaced orifices 60. The pressure drop across the flow restrictor 54 is also dependent on the size and uniformity of these orifices 60. To further straighten and laminarize the fluid flow in the flow channel 34, two optional screens, an inlet screen 62 and an outlet screen 64 formed preferably of a honeycomb-patterned structure like those currently available, may be positioned upstream and downstream of the flow restrictor 54, respectively.

With the flow restrictor 54 of FIG. 2, for example, the orifices 60 are circular and concentrically spaced about the axis 40, which extends normal to FIG. 2. Due to the large number of orifices 60 in the flow restrictor 54, only a few are provided with reference numerals in FIG. 2. Each orifice 60 has a radial distance, R, of approximately 0.085 inches. In

the preferred form, the orifices **60** are circular to adapt the flow restrictor **54** to the shape of the flow channel **34**. This shape matching results in more uniform reduction of turbulence across the entire flow channel **34**. Nevertheless, other geometries of orifices adapted to arbitrary cross-sectional shapes of the flow channel **34** and extending substantially parallel to the axis **40** therein may be employed. These could have a uniform repeating pattern of orifices of substantially identical hydraulic diameter throughout or a partially-repeating pattern in which orifices are symmetrically aligned about the axis **40** with other orifices of substantially the same hydraulic diameter. Other variations will be obvious from the disclosure.

The flow restrictor **54** is made from a material strong enough to withstand high flow rates of over 6000 L/min, and can be formed from multiple pieces affixed together or from a single molded structure. It is desirable to have the flow restrictor **54** formed of a temperature resistant material of high modulus of elasticity. Furthermore, for use in applications such as anesthetizing apparatus where high concentrations of potentially damaging chemicals are used or in medical applications generally where potentially damaging cleaning agents are used, the flow restrictor **54** should be made from a material that is also chemically resistant. In addition, the flow restrictor **54** requires thin walls to minimize turbulence. To this end, the flow restrictor **54** is preferably made of a nylon 6/6 resin, e.g., RTP 201™ resin available from RTP Corporation of Illinois. Nylon resins are processible by injection molding, foam molding or extrusion techniques and demonstrate minimal creep defects under high load. Therefore, the use of this resin allows the flow restrictor **54** to be easily manufactured and to achieve very long useful lifetimes under heavy load conditions. In particular, nylon resins have proven more manufacturable than other materials because of their ability to uniformly fill all intricate details of the mold used to form the flow restrictor **54** and/or integrated module **30**, before hardening into the final structure. The RTP 201™ resin with 10% glass fill has a tensile strength of approximately 14,000 psi and an elastic modulus of approximately 700,000 psi. Those of ordinary skill in the art will appreciate that other similar materials can be used to form the flow restrictor **54**. For example, a polyetherimide resin such as an Ultem® 2210 resin with 20% glass by weight, available from General Electric Co., could be used. This polyetherimide resin forms a material more amorphous than semi-crystalline plastics which produce non-uniform shrinkage in the mold causing slightly warped structures. In addition, the flow restrictor **54** may be formed of various metals, plastics, resins, ceramics, or liquid crystal polymers (LCPS) which exhibit similar properties as those provided above.

As discussed above, the orifices **60** of the flow restrictor **54** have been shaped to match the curvature of an outer wall **66** of the flow channel **34**. By utilizing the shape of the outer wall to create orifices of substantially the same circular shape, the flow restrictor **54** is adapted to the flow channel to reduce the non-uniform velocity effects present at the outer walls with previously known flow restrictors. Each orifice **60** is disposed concentrically with each other, with the outer wall **66**, and with the axis **40**. Moreover, the flow restrictor **54** has outer orifices **68** which are partially formed by the flow channel wall **66** (FIG. 1) and are uniform in shape and concentric with orifices **60**. Two main support rods **70**, **72** extend radially across the flow restrictor **54** to support the same and to give points of contact for affixing the flow restrictor **54** rigidly into the flow channel **34**, if necessary.

Alternatively, and preferably, the flow restrictor **54** can be formed integrally with the housing **32** and outer wall **66** by using a single casting mold for the entire structure. In this form, the integrated module **30** could be entirely formed of a moldable nylon resin or the other materials referenced above. In fact, the integrated module **30** is preferably formed entirely of a nylon resin. The use of this material also gives the outer wall **66** sufficient smoothness to allow the fluid to travel through the flow channel **34** with a reduced amount of turbulence.

In addition to the two main support rods **70**, **72**, numerous support pairs formed of two smaller support rods aligned radially with one another are used (shown as pairs **74a**, **74b**, **76a**, **76b**, **78a**, **78b**, and **80a**, **80b**). The support pairs **74a**, **74b** through **80a**, **80b** provide additional support to the flow restrictor **54** preventing those portions of the orifices **60** between the main support rods from moving during high flow rate usage, whereas without such support pairs, the flow restrictor **54** could move, or rattle, resulting in less reduction in turbulence of the fluid and more noise measured by the sensor **42**. Thus, this rigidity reduces noise in the system thereby allowing the use of a higher sensitivity sensor **42**. The support pairs are formed of these smaller support rods **74a**, **74b** through **80a**, **80b**, in such a way as to form identical, mirrored orifices on each side of the axis **40** along a given radial distance, with uniformity in orifice structure and diameter being important to laminarizing the flow fluid. That is, by using the main support rods **70**, **72** and support pairs **74a**, **74b** through **80a**, **80b** in this symmetrical way, any orifice **60** will be symmetric with an identical orifice **60** of equal hydraulic diameter. As is known, when the width of an opening is much greater than the distance (r) across the opening, the hydraulic diameter is approximately equal to $2r$. The symmetrical and uniform hydraulic diameters of the orifices **60**, **68** create uniform flow velocity at the exit end **38**.

The flow rate sensor **42** is shown in FIG. 3 for exemplary purposes only because, as will be appreciated by persons of ordinary skill in the art, many types of flow sensors may be used in addition to those shown by Bohrer in U.S. Pat. No. 4,478,076 and Johnson et al. in U.S. Pat. No. 4,651,564 including optical flow sensors, orifice-based ΔP sensors, and pitot tubes. With the thermal microstructure form of sensor **42** being only exemplary, the operation of the flow rate sensor **42** will only be generally described below.

As a microbridge structure, the sensor **42** comprises a microchannel **88** that defines an air space into which some of the fluid flowing into the sensing channel **44** will flow, in the direction indicated. The fluid will flow across an upstream sensor **90**, a heater **92**, and a downstream sensor **94**. In principle, the heater **92** is heated to approximately 160° C. above ambient temperature via the application of a current to a conductive wire or pattern through two heater leads **96a**, **96b**. Under no flow conditions, the upstream sensor **90** and the downstream sensor **94** would both read the same temperature due to the heater **92**, i.e., both sensors would have the same measured resistance values because both are equally-spaced from the heater **92**. The resistance values of the sensors **90**, **94** are measured from the application of a constant current to a conductive wire or pattern forming the sensors **90**, **94**. As the fluid enters the flow channel **34**, a portion thereof enters the sensing channel **44** with an even smaller portion thereof enters the microchannel **88** (FIG. 4), creating a flow path across the top and bottom surfaces of the heater **92** and sensors **90**, **94**. Convection from the flow of the fluid moves heat produced by the heater **92** away from the upstream sensor **90** and towards the

downstream sensor **94**, resulting in a reduction of temperature of the former and an increase in temperature in the latter. The change in temperatures produces a corresponding change in the resistance values of each sensor, with the upstream sensor **90** seeing a lower temperature therefore lower resistance and the downstream sensor **94** seeing higher temperature therefore a higher resistance. The difference between the resistance values for the two sensors **90, 94** is measured by circuitry (not shown) and used to determine the flow rate of the fluid in the sensing channel **44** from which the flow rate of the fluid in channel **34** can be determined.

The entire sensor **42** may be formed on a silicon, or other insulating semiconductor, substrate **98** upon which sits heater leads **96a, 96b**, upstream sensor leads **100a, 100b**, and downstream sensor leads **104a, 104b** for connecting to control or biasing circuitry (not shown) through wire leads like the exemplary three-wire lead **104** of FIG. **5**, with input, output, and ground leads that are used to control the heating and sensing functions of the sensor **42**.

The sensor **42** is integrated with the flow channel **34** containing the flow restrictor **54** by affixably mounting the sensor **42** onto the housing **32** to form the sensing channel **44**. Preferably, the sensor **42** is first adhesively mounted to a substrate base **106**, supporting the lead **104** and providing a wire-bond connection thereto, which is then adhesively mounted to the flow tube **46** creating the structure of FIG. **4**. The substrate **106** can be formed of an alumina ceramic, for example. An epoxy is used for the adhesive mounting. Wire bonds **108, 110** extending from the sensor **42** are attached to conductive pads on the substrate **106** before the substrate is mounted to a top opening in the flow tube **46** (FIG. **5**). These wire bonds **108, 110** connect directly to the wire leads **104** via the conductive pads depending on the design of the sensor **42** and substrate **106**.

The flow tube **46** is compatible with attachment to the sensing tap **48** for forming an air tight sensing channel parallel to the flow channel. The flow tube **46** can be made of a nylon resin, ceramic or other above-mentioned materials. By epoxying the flow tube **46** to the substrate **106**, the microchannel **88** will be exposed to receive a portion of the fluid that flows into the sensing channel **44**. An advantage of affixing the flow tube **46** directly to the substrate **106** before mounting it onto the housing **32** is that the combined structure can be more easily attached to the integrated module **30** in an aligned position with the more sensitive alignment of the microchannel **88** having already occurred. This method also helps protect the wire bonds **108, 110** during assembly.

As stated above, the integrated module **30** is designed to be installed into existing flow systems, and to facilitate this installation in one embodiment the integrated module **30** is formed of a housing with molded inlet and outlet mounts **120, 122** as shown in FIG. **5**. The inlet and outlet mounts **120, 122** are preferably 22 mm conical connectors which are easily adapted for use in a flow system. The entire structure, i.e., including the housing **32**, the inlet mount **120**, and the outlet mount **122**, can be formed of the nylon resin or other materials referenced above. Alternatively, the conical mounts **120, 122** can be replaced by threaded screw mounts or rubber O-ring connections to sealably connect with an existing flow system. Furthermore, the inlet and outlet mounts **120, 122** can have a screen recess space **124** for optionally placing the upstream inlet screen **62** and a downstream outlet screen **64** of FIG. **1**.

The integrated module **30** of FIG. **5** is further depicted with a rectangularly shaped sensing tap recess **126** into

which the flow tube **46** will be sealed, with the recess **126** extending from the inlet end **50** (not shown) to the outlet end **52** of the sensing tap **48**. The mounting indentation **58** for the outlet end **52** is also depicted and, along with the mounting indentation **56** for the inlet end **50**, is sized to receive rubber O-rings for sealably attaching the flow tube **46** to the recess **126**.

A cover **128**, disposed against the rear side of the substrate **106** opposite the sensor **42** (shown in phantom), protects the sensor **42** from environmental effects and clamps the sensor **42** and flow tube **46** against the sensing tap **48** of the housing **32**. Clamping is achieved primarily in two ways. First, notches **130** on the cover **128** are disposed to snap in place over pegs **132** of the housing **32**. Second, the cover **128** has two oppositely disposed, horseshoe-shaped tabs **134, 136** that are flexible in a spring-like manner. As the cover **128** is snapped into place over the pegs **132**, the two tabs **134, 136** will contact the top surface of the substrate **106** and thereby protrude slightly upward while applying a restraining downward force onto the substrate **106**. The cover **128** can be made from similar resins as the other components. Additionally, the cover **128** also has an upper connection portion **138** which forms an electrical receptacle with a lower connection portion **140** of the housing **32**, both of which house the wire lead **104** when the cover is snapped in place to form an electrical receptacle for connecting the lead **104** to external circuitry.

An alternative embodiment of an integrated module **146** is shown in FIG. **6**, wherein a housing **150** defining the flow channel **34** is formed with an inlet mount **152** and an outlet mount **154** which are attached to adaptors **156, 158**, respectively. Thus, the housing **150**, inlet mount **152**, and outlet mount **154** are not formed of a single molded structure like that of the embodiment in FIG. **5**. The integrated module **146** uses the sensor **42**. The embodiment of FIG. **6**, however, shows an alternative means of mounting the sensor, whereby the flow tube **46** is affixed to the housing **150** before the substrate **106** is epoxied to the flow tube **46**. The mounting steps of FIG. **5** could also be used.

The integrated module **146** requires less manufacturing expense; is packaged in a smaller form; and allows the customer greater versatility in mounting than the embodiment of FIG. **5**. For example, a customer may prefer that the mounts **152** and **154** take the form of rubber O-rings which can be placed into adaptors **156, 158** or tapered threaded screw mounts, either of various sizes. Alternatively, the customer could choose to clamp the module **146** to a manifold.

Screw mounting through holes **160a, 160b** and **162a, 162b** may be used to attach the adaptors **156, 158**, respectively, to the housing **150** at the manufacturing facility. An epoxy, heat-stake, or other method may also be used instead. Further, O-rings **164, 168** may be used to form a better contact between the adaptors **156, 158** and the housing **150**. Optional screens **62, 64** may be placed on either an inlet end or an outlet end of the flow channel **34**, or both. Moreover, the adaptors **156, 158** have industry standard end connections that can receive standard 22 mm conical connectors (ISO 5356), such as those used in ventilators and respirators. A cover **170** is similar to that of the cover **128** except that notches **172** are used to fasten the cover **170** in place. And while it is not shown, the cover **170** could have tabs similar to those of FIG. **5**.

In any of the previous embodiments, the flow channel **34** can be used to pass fluid of very high flow rates. For example, flow rate above 5,500 L/min can be achieved with

a 3 inch diameter flow channel. It may be desirable, under high flow operating conditions however, to deploy extensions to the inlet end **50** and outlet end **52** of the sensing tap **48**. In FIG. 7 exemplary extensions are shown as narrow hollow tubes **174, 176**, respectively. These tubes **174, 176** magnify the pressure differential across the sensing channel **44** and further restrict the flow entering the sensing channel to prevent damage and reduce noise that could result from high flow rates. The tubes **174, 176** have a hollow core with a diameter approximately equal to that of the ends **50, 52** and are aligned to extend the same distance into the channel **34** from each respective end.

An advantage of the embodiments depicted in FIGS. 5–7 is that the sensor **42** can be calibrated to produce accurate flow rate measurements for a given flow restrictor. To calibrate the integrated module **30** or **146**, first, testing is performed at no flow conditions to measure the null output of the sensor **42**. The gain stage feedback resistor of a gain amplifier (not shown but disposed on control circuitry connected to either the sensor **42** or the substrate **98**) is trimmed until the sensor output is at a predetermined voltage, such as 1V. Second, a fluid flowing at a known flow rate such as 200 L/min is passed through the flow channel **34** producing a voltage output from the sensor **42**. The gain stage of the sensor **42** is further trimmed at this operating output to a predetermined voltage, such as 6V. In this way, the sensor is calibrated to produce output voltages over a defined range compatible with the functional voltage input ranges of any connecting circuitry. Furthermore, by calibrating the output range in this manner, sensitive flow sensors may be used thus allowing the flow rate of gases to be readily measured.

While in the preferred embodiment the flow restrictor **54** is that of FIG. 2, in any of the embodiments of FIGS. 5–7 other known flow restrictors, such as a orifice-based flow restrictor or a honeycomb flow restrictor, can be used. However, these flow restrictors may create pressure drops across the sensing channel but are not adapted for use with a particular flow channel in that they do not reduce turbulence uniformly across the entire flow channel **34**, as occurs with the concentrically orificed flow restrictor **54**.

In addition, in any of the above embodiments a flow restrictor **180**, which is identical to the flow restrictor **54** but longer, may extend beyond the inlet end **50** and outlet end **52** of the sensing tap **48** as shown in FIG. 8. In such an embodiment, the sensor **42** (not shown) measures the flow rate based on the pressure drop between the inlet end **50** and the outlet end **52** of the sensing channel **44**. Though these two ends **50, 52** are not disposed outside of the flow restrictor **180**, there will be a pressure drop between the two (as well as a laminarizing of the flow), from which the sensor **42** can measure flow rate. Pressure drop, i.e., pressure differential, is created in primarily three ways by a flow restrictor. First, a pressure drop is created as the fluid enters the restrictor. Second, a further pressure drop is created as the fluid exits the restrictor. Third, a still further pressure drop occurs as the fluid is flowing through the flow restrictor. In the embodiment of FIG. 1, the sensor **42** measures flow rate based upon a pressure drop across the sensing channel **44** from all three factors because the inlet tap **50** and outlet tap **52** are disposed on opposite sides of the flow restrictor **54**. Whereas, with the longer flow restrictor **180**, the sensor **42** will measure a flow rate based upon a smaller pressure drop that includes the drop in pressure due to the first and third factors described above, because the flow restrictor **180** extends beyond the taps **50, 52**. An advantage of using this longer flow restrictor arrangement, is that a longer flow

restrictor produces a more laminar flow with less noise measured by the sensor **42**.

As shown by example in FIGS. 1, 5 and 6, the inlet screen **62** and the outlet screen **64** may be used to further straighten and laminarize the flow as well as reduce the Reynold's number in the flow channel **34**. The inlet and outlet screens **62, 64** may be any type of flow laminarizer, including a honeycomb-patterned screen **190** (FIG. 9), a woven polyester, or a structure similar to the flow restrictors **54 180**.

In the foregoing embodiments, a flow sensor in the form of a thermal microstructure is used. Alternatively as shown in FIG. 10, a differential pressure (ΔP) sensor **192** can be deployed in the channel **44** for measuring the pressure of the flowing fluid. The pressure differential created by the flow restrictor **54** between the inlet **50** and the outlet **52** is measured by the sensor **192** from which a flow rate of the fluid can be derived. The sensor **192** is positioned across the sensing channel **44**, thus precluding the flow of fluid across the channel **44**.

Those of ordinary skill in the art will appreciate that, although the teachings of the invention have been illustrated in connection with certain embodiments, there is no intent to limit the invention to such embodiments. On the contrary, the intention of this patent is to cover all modifications and embodiments fairly falling within the scope of the appended claims either literally or under the doctrine of equivalents.

What we claim is:

1. A uniform flow apparatus comprising:

a housing having a wall that defines a flow channel through which fluid flows, wherein the flow channel has a central axis; and

a flow restrictor, with an entrance end and an exit end, disposed in the flow channel, wherein the flow restrictor comprises a plurality of orifices following a contour of the flow channel, wherein the orifices are distributed uniformly along a line extending from the central axis to the wall, and wherein the orifices produce a substantially uniform flow across the flow channel at the exit end.

2. An apparatus comprising:

a housing that defines a flow channel through which fluid flows; and,

a flow restrictor, wherein the flow restrictor has an entrance end and an exit end and is disposed in the flow channel, wherein the flow restrictor comprises at least three orifices distributed in parallel along a line extending perpendicularly from a longitudinal axis of the flow channel, and wherein each of the orifices has a shape about the longitudinal axis matching a shape of the flow channel so as to produce a substantially uniform flow across the flow channel at the exit end.

3. The apparatus of claim 2, wherein the flow channel has an outer wall of circular cross-sectional shape, and wherein the orifices are circular orifices aligned concentrically about the longitudinal axis.

4. The apparatus of claim 3, wherein the flow restrictor further comprises a plurality of support pairs formed of two supports aligned radially on opposing sides of the longitudinal axis and disposed to define pairs of circular orifices of substantially identical shape and radial position.

5. The apparatus of claim 4, wherein at least one of the orifices has substantially similar hydraulic diameter to at least one other of the orifices.

6. The apparatus of claim 2, wherein the flow restrictor is formed of a resin.

7. The apparatus of claim 6, wherein the resin is a nylon resin.

11

8. The apparatus of claim 2, wherein the housing comprises an inlet end with an inlet mount and an outlet end with an outlet mount, and wherein the inlet mount and the outlet mount are adapted for coupling the apparatus to a flow system.

9. The apparatus of claim 8, wherein the housing and the inlet mount and the outlet mount are singularly formed in a molded structure.

10. The apparatus of claim 8, wherein the inlet mount is affixably mounted to the inlet end and wherein the outlet mount is affixably mounted to the outlet end.

11. The apparatus of claim 2, wherein the housing includes at least one sensing tap into which a portion of the fluid flows, wherein said apparatus further comprises a sensor mounted to the sensing tap, and wherein the sensor measures a property of the fluid corresponding to a flow rate.

12. The apparatus of claim 11, wherein the sensor is affixably mounted to the housing to form a substantially fluid-tight seal with the sensing tap.

13. The apparatus of claim 11, wherein the sensing tap has an inlet end and an outlet end, and wherein the sensor is mounted to the sensing tap to define a sensing channel.

14. The apparatus of claim 13, wherein the flow restrictor is disposed in the flow channel such that the sensing inlet and the sensing outlet are disposed on opposite, non-adjacent sides of the entrance end and the exit end.

15. The apparatus of claim 13, wherein the flow restrictor is disposed in the flow channel such that the sensing inlet and the sensing outlet are disposed between opposite, non-adjacent sides of the entrance end and the exit end.

16. The apparatus of claim 11, wherein the sensor is mounted to the sensing tap through a flow tube affixably mounted to the sensor and to the sensing tap, wherein the sensing tap has an inlet end and an outlet end, and wherein the flow tube defines a sensing channel between the sensing inlet and the sensing outlet.

17. The apparatus of claim 11, wherein the sensor comprises a thermal microstructure sensor.

18. The apparatus of claim 11, wherein the sensor comprises a pressure sensor.

19. The apparatus of claim 11, wherein the sensing tap has an inlet and an outlet end, and wherein the sensor is a flow sensor mounted to the sensing tap to define a sensing channel between the sensing tap inlet and the sensing tap outlet.

20. The apparatus of claim 2, wherein the housing comprises a turbulence reducing inlet screen disposed upstream of the flow channel and a turbulence reducing outlet screen disposed downstream of the flow channel.

21. The apparatus of claim 20, wherein the inlet screen and the outlet screen each comprises a honeycomb-patterned laminarizing structure.

12

22. The apparatus of claim 2, wherein the flow channel has an outer wall of circular cross-sectional shape, and wherein the orifices are circular orifices.

23. A module for measuring a flow rate of a fluid in a flow system, the module comprising:

a flow restrictor disposed in a flow channel, wherein the flow restrictor creates a pressure drop;

a sensing channel having an inlet and an outlet, wherein the inlet and the outlet communicate with the flow channel such that the pressure drop forces a portion of a fluid in the flow channel to flow through the sensing channel;

a flow sensor disposed in the sensing channel, wherein the flow sensor senses the flow of fluid through the sensing channel; and,

a housing fastened to the flow channel and containing the flow sensor and the sensing channel.

24. The module of claim 23, further comprising an inlet mount and an outlet mount, both mounts being adapted for connecting the module to the flow system.

25. The module of claim 23, wherein the flow sensor comprises a thermal microstructure sensor.

26. The module of claim 23, wherein the flow restrictor comprises a plurality of orifices adapted to produce a substantially uniform flow across the flow channel.

27. The module of claim 23, wherein the flow restrictor comprises a honeycomb-patterned structure.

28. The module of claim 23 wherein the flow restrictor comprises a plurality of orifices following a contour of the flow channel, wherein the orifices are distributed uniformly along a line extending perpendicularly from the central axis to the wall, and wherein the orifices produce a substantially uniform flow across the flow channel at the exit end.

29. A flow restrictor having a longitudinal axis and comprising n orifices distributed along a line that is perpendicular to the longitudinal axis, wherein the n orifices are parallel to one another, wherein the n orifices have different cross-sectional areas, wherein the n orifices produce a substantially uniform flow across a flow channel, and wherein $n > 2$.

30. The flow restrictor of claim 29, wherein the n orifices comprise n circular orifices.

31. The flow restrictor of claim 29, wherein the n orifices comprise n circular orifices aligned concentrically about the longitudinal axis and extending along the longitudinal axis.

32. The flow restrictor of claim 31, wherein the flow restrictor comprises a plurality of radial supports.

33. The flow restrictor of claim 32, wherein the flow restrictor is formed of a resin or plastic.

34. The flow restrictor of claim 33, wherein the resin comprises a nylon resin.

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