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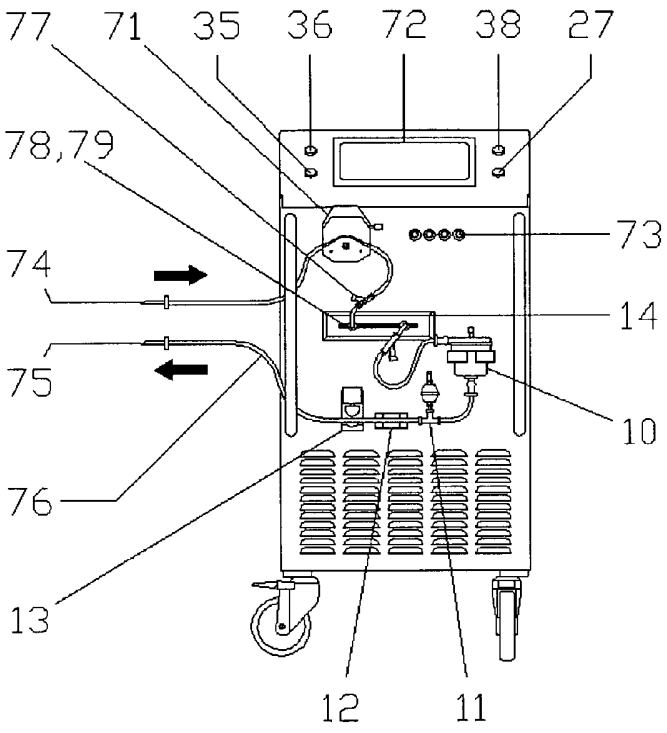
(54) Title: APPARATUS AND METHOD FOR INDUCING RAPID, EXTRACORPOREAL, THERAPEUTIC HYPOTHERMIA



(57) Abstract: Disclosed is an extracorporeal therapeutic hypothermia apparatus and disposable set to rapidly induce and indefinitely maintain a patient in a state of whole body or regional, mild-to-moderate hypothermia by lowering the core body temperature within the range of 30°C to 34°C through continuously cooling and/or warming using extracorporeal blood circulation through a cassette (79) located within a heat exchanger (14). The apparatus can lower the core body temperature to 34°C in ten minutes or less. Its heat exchanger (14) cools the patient's blood and lowers the body's core temperature to the selectable hypothermic level under spontaneous blood circulation (shunt blood flow) via venous or arterial shunts. The apparatus and procedure are performed on a patient in a hospital emergency room or clinic, but it can be configured for use in an ambulance to induce hypothermia at the point of injury. The apparatus maintains mild-to-moderate hypothermia for a selectable period of time as necessary and then heats the blood to return the patient's core temperature to normothermia. The apparatus can also induce hyperthermia at a selectable rate by raising the core body temperature to a desired level by blood circulation through the heat exchanger (14) and maintaining that temperature for a selectable period of time as required.

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APPARATUS AND METHOD FOR INDUCING RAPID, EXTRACORPOREAL, THERAPEUTIC HYPOTHERMIA

BACKGROUND OF THE INVENTION

1. Field of the Invention

[0001] The invention relates to the use of emergency therapeutic hypothermia. In particular, the present invention relates to providing transportable, emergency, cooling capabilities to rapidly induce mild-to-moderate therapeutic hypothermia using extracorporeal circulation to lower and maintain the core body temperature of a patient.

2. Description of Related Art

[0002] Interest in therapeutic hypothermia intervention continues to increase as a result of hypothermia's protective impact during ischemic events. Clinical evidence demonstrates that patients suffering severe brain trauma or ischemia from myocardial infarction or stroke have improved medical outcomes if core temperature is lowered below normal body temperature (37°C). Hypothermia was employed during the 1980s and 1990s in a range of surgical procedures to protect the brain, heart and other vital organs from ischemia, but did not gain broad acceptance as a standard of care for specific applications. Only recently has therapeutic hypothermia generated increased interest based on several significant clinical studies. Therapeutic hypothermia may ultimately become an important therapeutic adjunct in acute stroke, acute myocardial infarction, cardiac arrest, head trauma, and specific surgical procedures requiring neuroprotection.

[0003] Currently, expanded clinical trials for therapeutic hypothermia are ongoing, and broader applications for thermal management devices are anticipated. Based on several early clinical trials, the American Heart Association published a recommendation in June of 2003 that victims of ventricular fibrillation (VF) cardiac arrest may be helped by immediate mild hypothermia. Approximately 300,000 cardiac arrest cases occur in the United States each year and about 75,000 make it to the hospital. Studies are now demonstrating that mild cooling in cardiac arrest cases improve survivals about 15% (up from 40% to 55%), and further cooling of hearts after myocardial infarction and not just arrests/defibrillations, may also be very beneficial.

[0004] In addition to cardiac arrest, multi-center clinical trials for mild hypothermia benefits in stroke treatment are also currently ongoing in the United

States. Annually, there are approximately 500,000 stroke victims in the United States that could benefit from immediate cooling treatments. Also, about 180,000 trauma deaths occur in the United States annually and 50% of these deaths occur within the first few hours, with exsanguination being the common cause. All of these cases could potentially benefit from hypothermia protocols if an emergency apparatus was available that could rapidly induce mild-to-moderate hypothermia.

[0005] Generally, the earlier cooling is initiated, the better the outcome. Hence, an effective apparatus must not only induce hypothermia, it must do so rapidly, on the order of reducing the body's core temperature by 3°C to 7°C in approximately ten minutes. Rapid emergency cooling could ultimately benefit the following conditions: acute myocardial infarction, stroke, traumatic hemorrhagic shock, traumatic brain injury, spinal cord injury, septic shock, neuroprotection, fever control and status epilepticus.

[0006] A variety of methods to induce hypothermia in a patient are known and have been used in the past. One of the earliest methods was to pack the patient in ice to lower the body's core temperature externally. To return the patient to normothermia, hot packs, hot water bottles, etc. are applied externally to the patient or the patient is allowed to warm normally. Using ice for external cooling is too slow to be effective, is cumbersome in application, and may cause frostbite. The most serious problem is the difficulty in controlling the body's core temperature such that hypothermia is induced and maintained, but the core temperature does not drop to dangerously low levels. More recent external methods using heat transfer pads or cooled body wraps, while more simply applied, are no more effective than ice packs, although core temperatures can be more easily maintained at the proper level. An example is provided by U.S. Patent No. 3,007,473, which discloses a device that circulates chilled or heated fluid through a blanket covering the patient. A further example is U.S. Patent No. 6,818,012, which discloses a device that selectively cools or heats a fluid circulating through one or more interconnected patient contact pads. In general, there are a number of problems with external cooling methods, the primary being that it requires two to three hours to reduce the core temperature to the mild-to-moderate range (30°C to 34°C). The body's sluggish response to external

cooling and warming also causes temperature control to be a noteworthy consideration.

[0007] Since external methods of reducing body temperature present difficult problems for effective therapeutic hypothermia, an internal heat exchange process for inducing hypothermia has definite advantages. Extracorporeal cooling has been shown to be an effective and efficient method to rapidly induce mild-to-moderate hypothermia. The generally accepted range of mild-to-moderate hypothermia is 30°C to 34°C. The extracorporeal process of internal heat exchange consists of cooling and rewarming infused blood with a heat exchanger during an extracorporeal process.

[0008] Extracorporeal therapy, in which a human patient's circulating blood is detoured outside of the body, treated, and then returned to the patient, is well known in the art. For example, U.S. Patent No. 3,064,649, which shows an apparatus for controlling blood temperature during intracardiac surgery. The apparatus is inserted in the extracorporeal circulation path provided by a blood oxygenator. The apparatus receives circulating blood from a patient through a conventional oxygenator and routes it to a reusable tubular heat exchanger. From the heat exchanger, the circulating blood is routed to a reusable bubble filter and then back to the patient. A further example is U.S. Patent No. 6,413,233, which shows a perfusion hyper/hypothermia treatment apparatus using computerized controls for treating blood and tissue diseases. In one embodiment, the apparatus extracorporeally pumps blood from a patient through a heat exchanger, with pre- and post- blood conditioners, and then back to the patient. Control of blood temperature includes feedback from sensors coupled to the patient to provide automated monitoring and control of the patient temperature, the cooling/heating system, and the treatment protocol. To heat and cool the blood, the system uses a separate heater and cooler to condition water from a reservoir, circulating through the heat exchanger.

[0009] One shortcoming of prior art is the lack of an apparatus dedicated to emergency hypothermia with the cooling capacity to rapidly reduce core body temperature in conjunction with precise temperature control.

SUMMARY OF THE INVENTION

[0010] The present invention is directed to an apparatus and method to induce rapid hypothermia and subsequent return to normothermia through heat

exchange in the blood during extracorporeal circulation. In particular, the present invention is an apparatus that can rapidly induce mild-to-moderate hypothermia, a core body temperature range of 30°C to 34°C, in approximately ten minutes and can indefinitely maintain the core body temperature within plus or minus 0.5°C.

[0011] Described in its preferred embodiment, the present invention provides a transportable, emergency, cooling apparatus, along with cooling methodologies and clinical applications, to rapidly induce whole body or regional, mild-to-moderate therapeutic hypothermia using extracorporeal blood circulation to lower and maintain the core body temperature of a patient in the range of 30°C to 34°C. The apparatus and procedure are performed on a patient in a hospital emergency room or clinic, but it can be configured for use in an ambulance for induction of hypothermia at the point of injury. The apparatus induces therapeutic levels of mild-to-moderate hypothermia through extracorporeal circulation of the patient's blood through a cassette located within the heat exchanger. The heat exchanger cools the patient's blood and lowers the body's core temperature to the selectable hypothermic level under spontaneous blood circulation (shunt blood flow) via venous or arterial shunts. The apparatus maintains mild-to-moderate hypothermia for a selectable period of time as necessary and then, through the same process, heats the blood to return the patient's core temperature to normothermia. It can also induce hyperthermia at a selectable rate by raising the core body temperature to a desired level by blood circulation through the heat exchanger and maintaining that temperature for a selectable period of time as required. The apparatus is used as therapy in a variety of emergency medical situations such as cardiac arrest, traumatic brain injury, acute stroke, spinal cord injury, during surgical procedures, etc.

[0012] One embodiment of the invention includes a cooling unit; a heating unit; a heat exchanger; a system controller and operator interface with software; a fluid pump; sensors for measuring temperature, flow, and pressure; safety components; and a disposable set.

[0013] Hypothermia is induced in a patient through several access techniques, dependent on the specific situation. The variations in access techniques do not materially affect the device design or configuration. Generally, the induction of mild-to-moderate hypothermia using an extracorporeal heat exchanger circuit

requires blood to be shunted from the patient through a disposable heat exchange cassette located within the heat exchanger and back into the patient, generally via contralateral vascular outflow and inflow connections. A standard venous or arterial outflow catheter, placed in a large peripheral vessel, is connected to the disposable cassette through appropriate medical grade disposable tubing. One end is securely connected to the intravascular catheter while the other end is securely connected to the disposable cassette. Similarly, the tubing for the return flow from the disposable cassette is securely connected to the contralateral peripheral venous or arterial catheter placed in the patient.

[0014] The vascular access approaches for the induction of mild-to-moderate hypothermia require connection to the contralateral peripheral outflow and inflow vascular access catheters. Placement of catheters for vascular access include:

[0015] 1. Femoral veins and/or arteries;

[0016] 2. Jugular veins and/or carotid arteries;

[0017] 3. Sub-clavian veins and arteries;

[0018] 4. Brachial/auxiliary veins and arteries; or

[0019] 5. Other peripheral veins and arteries of adequate size for inflow and outflow catheter diameters.

[0020] Vascular access catheters are not part of the disposable set, but the disposable set does include the connectors for attachment to the catheters. The complete disposable set consists of the heat exchanger cassette, appropriately sized medical grade tubing, connector fittings, bubble trap, blood filter, temperature sensors, and flow sensors. The disposable set is sterilized and heparin-bonded.

[0021] The fluid pump circulates the blood through the heat exchanger at a selectable flow rate while the heat exchanger cools the blood and lowers core body temperature very rapidly to a selectable level to induce therapeutic hypothermia for a short or prolonged period of time. In the warming mode, the pump circulates the blood at a selectable flow rate through the heat exchanger, warming the blood and raising the core body temperature to normothermia or to induce hyperthermia for a short or prolonged period of time. The apparatus uses integrated electronic controls to automatically monitor, control, and maintain the induction of mild-to-moderate hypothermia and the patient's core temperature.

[0022] The combination of elements provided in the described embodiment of the present invention results in an efficient hypothermia induction apparatus using extracorporeal blood circulation to rapidly induce and maintain mild-to-moderate, whole-body or regional, hypothermia in a human patient.

[0023] It is an objective of the invention to provide an extracorporeal hypothermia apparatus which is easily transported between locations, and which is not unduly large or heavy. Accordingly, the extracorporeal hypothermia apparatus described is lightweight, is transportable by vehicle, and can easily be moved between locations by the average adult.

[0024] It is another objective of the invention to provide an extracorporeal hypothermia apparatus which can be located, powered, and operated in an emergency vehicle or in an emergency room of a hospital or clinic, to induce mild-to-moderate hypothermia as soon as possible following an ischemic event or other applicable trauma. Hypothermia should be induced immediately following the trauma because the quicker and the earlier hypothermia is induced, the better the medical outcome. The apparatus may also be used when transporting patients between medical facilities, such as from a clinic to a hospital or from one hospital to another, to continue induction of hypothermia or to maintain a hypothermic state.

[0025] It is another objective of the invention to provide an extracorporeal hypothermia apparatus having a means to lower and maintain the core body temperature of a patient to a selectable temperature within the range of 30°C to 34°C. Accordingly, when the core body temperature is higher than the set point (for instance 32°C), electronic controls activate the cooling unit to cool the circulating blood, and remains activated until the core body temperature lowers to the set point. If the core body temperature is lower than the set point, the heating unit is activated by electronic controls and remains in that state until the core body temperature rises to the set point, thereby providing an apparatus having means for maintaining the core body temperature at a set point within the range of 30°C to 34°C.

[0026] It is another objective of the invention to provide an extracorporeal apparatus having a means to induce hyperthermia by raising and maintaining the core body temperature of a patient to a selectable temperature within the range of 37°C to 42°C.

[0027] It is a further objective of the invention to provide an extracorporeal apparatus having a means to maintain normothermia by maintaining the core body temperature of a patient at 37°C ± 0.5°C.

[0028] It is yet another objective of the invention to provide an extracorporeal hypothermia apparatus capable of providing mild-to-moderate hypothermia in a very rapid manner using extracorporeal blood flow through a heat exchanger. The apparatus can lower core body temperature to 34°C in less than ten minutes.

[0029] It is still another objective of the invention to provide an extracorporeal hypothermia apparatus wherein the user is warned if the patient's core body temperature is not within 0.5°C of the set-point temperature. Accordingly, the extracorporeal hypothermia apparatus has a visual means to communicate warnings to the user.

[0030] Further objectives of the invention will become apparent from consideration of the drawings and the ensuing detailed description of the invention which follows. A person skilled in the art will realize that other embodiments of the invention are possible and that the details of the invention can be modified in a number of respects, all without departing from the inventive concept. Thus, the following drawings and detailed description are to be regarded as illustrative in nature and not restrictive.

BRIEF DESCRIPTION OF THE DRAWINGS

[0031] The features of the invention will be better understood by reference to the accompanying drawings, which illustrate presently preferred embodiments of the invention.

[0032] FIGS. **1a** and **1b** are the front and side views, respectively, of a mild-to-moderate hypothermia apparatus of the present invention;

[0033] FIG. **2** is a layout of the disposable set of the present invention;

[0034] FIG. **3** is a system control block diagram of the present invention;

[0035] FIG. **4** is a schematic of an indirect hot-gas bypass control system of the present invention; and

[0036] FIG. **5** is an exploded front view of the heat exchanger of the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0037] Referring to FIGS. **1-5**, a preferred embodiment of the apparatus is disclosed. The apparatus consists of the extracorporeal hypothermia apparatus

and a disposable infusion set. The best mode of the invention involves rapidly inducing therapeutic mild-to-moderate hypothermia by lowering the core body temperature from 37°C to a range of 34°C to 30°C in ten minutes or less via extracorporeal blood circulation at a flow rate of 0.2 to 1.0 liters/minute. After mild-to-moderate hypothermia is induced, the selected core body temperature, in the range of 34°C to 30°C, can be maintained for an extended period of time as desired. Following treatment with therapeutic mild-to-moderate hypothermia, the apparatus returns the patient's core temperature to normothermia at a selectable rate by raising the core body temperature under shunt blood circulation through the heat exchanger. The apparatus is also capable of inducing hyperthermia by raising core body temperature from 37°C up to 42°C at a selectable rate of 0.1 to 1°C/hour via blood circulation at a flow rate of 0.2 to 1.0 liters/minute.

[0038] FIGS. **1a** and **1b** show the front and side views, respectively, of the extracorporeal hypothermia device. At a flow rate of 0.2 to 1.0 liters/minute, a fluid pump assembly **71** circulates the patient's blood received through silicon tubing **76** connected to a venous or arterial catheter with a connector **74**, through a thin heat exchange cassette **79** (secondary heat exchanger) inserted in a primary heat exchanger **14** (evaporator) where heat exchange takes place by conduction. Existing heat exchangers intended for cooling and heating blood are not capable of lowering the core body temperature with the speed required for effective therapeutic application of emergency hypothermia. The extracorporeal hypothermia device requires custom designed primary heat exchanger **14** and heat exchange cassette **79** to satisfy performance requirements. A vapor-compression refrigeration unit **15** with a compressor **16** and a condenser **17** cools or heats the primary heat exchanger **14** and thereby conditions the circulating blood. The circulating blood exits the heat exchange cassette **79,** through a silicon tube **76** and a fitting **78**, into a bubble trap/filter **10** to remove air bubbles, and a pressure isolator **11** used to isolate the blood from the pressure sensor. The circulating blood exits the pressure isolator **11** into a bubble detector **12** and a tubing occluder **13**, back to the patient through a connector **75** connecting a venous or arterial catheter to the silicon tubing **76**. If the bubble detector **12** detects bubbles in the flow of blood, the tubing occluder **13** is activated by the system controls to stop the flow of blood through the apparatus.

[0039] FIG. **2** shows the disposable infusion set which is sterilized, heparin bonded, and consists of a length of medical grade silicon standard tubing **76**, connectors **74** and **75** for connecting to standard venous or arterial catheters, myocardial temperature probes (not shown) for monitoring inflow and outflow blood temperatures, injection ports **77** for inserting myocardial temperature probes, connection fittings **78** for connecting to a heat exchange cassette **79**, a bubble trap/filter **10** to remove air bubbles from the circulating blood, and a pressure isolator **11** used to isolate the blood from a pressure sensor.

[0040] FIG. **3** shows the system block diagram with a power inlet **59** where a detachable 20 amp hospital grade power cord connects the extracorporeal hypothermia device to an electrical outlet, a 20 amp two-pole circuit breaker **60** that also serves as a power switch, and a standard serial COM connector **58** for providing communication means and data upload to a computer, all accessible on the rear panel of the apparatus. Also mounted on the rear panel is an AC fan **64** providing forced ambient air to cool the interior of the apparatus. A toroidal isolation power transformer **61** provides 120 volts AC to the compressor and heaters, and a medical grade switching power supply **62** provides 12 volts DC to the 12V/5V DC/DC converter and a regulator **63** which supplies 5 volts DC and 3.3 volts DC to the electronics, to the pump motor, to the occluder solenoid, and to a 12V/24V DC/DC converter **55,** which supplies 24 volts DC to a stepper motor current monitor **34**.

[0041] The operator interface on the front panel of the apparatus contains multiple connectors **73** for connecting to multiple temperature probes (not shown), with at least two (2) temperature probes used for sensing patient temperatures, at least one (1) for sensing blood inflow temperature (to the patient), and at least one (1) for sensing blood outflow temperature (from the patient). Other operator interface components include, but are not limited to: a pressure isolator port **80** for connecting the pressure isolator **11** to a pressure sensor **46**; the ultrasonic bubble detector **12**; a red push-button emergency switch **35**; access to a pump head **39**; access to the primary heat exchanger **14**; a graphics LCD touch-screen **72** for graphical user interface; a red LED power-on indicator **36**; a green LED ready indicator **37** that indicates the device is ready for a procedure; and a yellow LED alert indicator **38** that is illuminated whenever a fault or alert is detected and a message is displayed.

[0042] The compressor **16** of the refrigeration unit **15** is turned on and off by a compressor solid-state relay (SSR) **27** under control of a system controller/ processor **57**. The bypass valve of the refrigeration system is opened from 0-100% by a bypass valve stepper motor driver **33**, also under control of the system controller/processor **57**. Heaters **24** are controlled by a heater SSR **25**, a solid-state relay driven by a pulse-width modulation (PWM) circuit **26**, to provide 0-100% of heating power under control of the system controller/processor **57**. A thermistor, an evaporator temperature sensor **29**, is embedded in a top inner heat exchanger plate **66**, and, after amplification by an evaporator thermistor amplifier **30**, is routed to an analog-to-digital converter (ADC), multiplexed input ADC 2 **53**, for the purpose of monitoring the temperature of the primary heat exchanger **14**. Similarly, another thermistor, internal temperature sensor **31**, is interfaced to an internal thermistor amplifier **32** and routed to a multiplexed input ADC 2 **53** for monitoring temperature inside the apparatus. The pump motor/pump head **39** is driven by a pump motor driver **40** under control of the system controller/processor **57** using pulse-width modulation to set the speed of the motor and the flow rate from 0-100%, if an emergency electronics circuit **45** has not been activated. Measurement of blood flow is accomplished by a pump speed encoder **47**, an encoder wheel and an opto-isolator attached to the back shaft of the pump motor. The combination generates pulses of frequency proportional to pump speed and, by extension, to the blood flow rate. The output of the encoder is fed into flow electronics **48** for conditioning and shaping, and then to the system controller/processor **57** for measurement.

[0043] The tubing occluder **13** is driven by an occluder driver **42** under control of the emergency electronics circuit **45** and is commanded primarily by the bubble detector **12**, or the emergency switch **35**, or the blood inflow temperature out-of-range signal, IF OR, from optical isolation **51**, and secondarily by the system controller/processor **57** (only during testing). The emergency electronics circuit **45** reacts directly to a signal from the bubble detector **12**, or the emergency switch **35,** or the IF OR signal from optical isolation **51** while the system controller/processor **57** is flagged. The system controller/processor **57** has the means to disable the bubble detector **12** during priming of the tubing and to enable it for a therapeutic procedure, and also has the means to reset the emergency electronics circuit **45** after a stop event generated by a bubble

detection or a closure of the stop switch. The pressure sensor and electronics **46** provide an analog signal, proportional to pressure detected on the output side of the pump **71,** that is fed to multiplexed ADC 2 **53**.

[0044] A patient temperature electronics **49** contain four thermistor amplifiers. The four temperature signals plus two internal voltages (for diagnostics) are fed to multiplexed input ADC 1 **50** for monitoring. Electrical isolation is required for this section and is accomplished by the optical isolators in optical isolation **51** and by a DC/DC converter/regulator **44**. The DC currents of the occluder solenoid, pump motor, and bypass valve stepper motor are monitored for diagnostics by an occluder current monitor **43**, a pump current monitor **41**, and stepper motor current monitor **34**. Multiplexed input ADC 3 **54** reads the current-related voltages of these three elements for monitoring and fault detection. These three elements also provide individual circuit fusing. A coil in the magnetic AC current pick-up **28** reads the combined AC current drawn by the compressor and the heaters and sends a DC equivalent to multiplexed input ADC 3 **54**. Scaled down versions of the supply voltages 24 VDC, 12 VDC, and 5 VDC are routed by a voltage divider **56** to multiplexed ADC 2 **53** for diagnostic monitoring.

[0045] The system controller/processor **57** executes a digital PID algorithm contained in the embedded software for controlling the temperature. For initial cooling, a bypass valve **18** is fully closed to allow the fastest rate of cooling. The PID algorithm controls are initially based on the temperature of the blood delivered to the patient (patient inflow), provided from the patient temperature electronics **49**, stabilizing it to a preselected temperature. When the patient's core body temperature, also from the patient temperature electronics **49**, drops within 0.5°C of the selected hypothermic temperature set point, the PID algorithm switches to using the core body temperature as a basis for controls, stabilizing it to the hypothermia set point. In response, the bypass valve **18** opens up a fixed amount, dependent on the patient's hypothermic temperature set point, to reduce the heating power required of the heaters **24** for maintaining a stable core body temperature.

[0046] When warming the patient, the bypass valve **18** is 80% open to provide a small measure of cooling for maintaining a tight tolerance of the targeted temperature. The PID algorithm controls are initially based on the temperature of the blood delivered to the patient (patient inflow), provided from the patient

temperature electronics **49**, stabilizing it to a preselected temperature. When the patient's core body temperature rises to within 0.5°C of the normothermic or selected hyperthermic temperature set point, the PID algorithm switches to using the core body temperature as a basis for controls, stabilizing it to the normothermic or hyperthermic set point.

[0047] The process of changing feedback temperatures used as a basis for PID algorithm controls during cooling and warming prevents large deviations in blood temperature and possible damage to the blood that would result if the PID algorithm operated exclusively on the patient's core body temperature.

[0048] FIG. **4** shows the indirect hot-gas bypass control system that controls the temperature of the circulating blood. Cooling and warming of the extracorporeally circulating blood is accomplished by heat exchange in the heat exchanger (evaporator) between the patient's blood inside the heat exchange cassette **79** and the plates of the heat exchanger **14**.

[0049] A mechanical vapor-compression refrigeration unit **15** provides cooling to the plates of the heat exchanger **14**. An indirect hot-gas bypass system is used to raise the temperature of the heat exchanger. This method uses a controllable valve on the high-pressure side of the refrigeration unit to bypass the condenser to an injection point between a thermal expansion valve **22** and the heat exchanger **14**. In the high demand mode, the hot-gas discharge bypass valve **18** remains closed and the refrigeration system supplies full cooling output to the heat exchanger **14**. If less cooling is required, the system controller continuously opens the bypass valve **18**, allowing hot gas to flow through the bypass valve to the heat exchanger **14** where it mixes with the cooled liquid refrigerant. As the liquid refrigerant evaporates, the vaporization temperature rises, thus reducing the amount of cooling delivered to the heat exchanger **14**. The pumping action of the compressor **16** draws vapor from the heat exchanger **14**, reducing the pressure in the heat exchanger **14**, and causing the liquid particles to evaporate. As the liquid particles evaporate, the heat exchanger **14** is cooled. Both the liquid and vapor refrigerant tend to extract heat from warmer objects. The ability of the liquid to absorb heat as it vaporizes is very high in comparison to that of the vapor and the evaporation of the liquid refrigerant would soon remove the entire refrigerant from the heat exchanger if it were not replaced. The replacement of the liquid refrigerant is controlled by the thermal

expansion valve **22** which acts as a restrictor to the flow of the liquid refrigerant in the liquid line. Its function is to change the high-pressure, sub-cooled liquid refrigerant to low-pressure, low-temperature liquid particles, which will continue the cycle by absorbing heat. The refrigerant low-pressure vapor, drawn from the heat exchanger **14** by the compressor **16**, in turn is compressed to a high-pressure vapor, which is forced into the condenser **17**. In the condenser **17**, the high-pressure vapor condenses to a liquid under high pressure and gives up heat to the ambient atmosphere. The high pressure created by the compressor **16** forces the condensed liquid refrigerant through a receiver **19** to the thermal expansion valve **22**, defining a complete refrigeration cycle with a simple and reliable indirect hot-gas bypass control system. A drier **20**, or liquid line dehydrator, protects the thermal expansion valve by filtering and removing water and dirt from the flow of liquid refrigerant which may clog the pressure orifice by particle and/or ice formation. Water and dirt enter the system through initial manufacturing, servicing, and/or addition of refrigerant. The drier **20** is located in the liquid line between the condenser **17** and thermal expansion valve **22**, where velocities are generally low. A sight glass **21**, located in the liquid line downstream of the drier **20**, provides a visual indication of the state of refrigerant before entering the thermal expansion valve **22**. In addition to a small window for viewing the flow of liquid refrigerant, the sight glass **21** may contain a moisture indicator for visually determining when the refrigerant's water content is excessive. A few small bubbles appearing in the sight glass window is considered normal; however, excess bubbles indicate the presence of refrigerant vapor due to an excessive pressure drop across the drier **20**, little or no sub-cooling, or insufficient quantity of refrigerant. The indirect bypass control system is simple and reliable.

[0050] FIG. **5** shows an exploded front view of the primary heat exchanger of the hypothermia apparatus, corresponding to the evaporator of a typical refrigeration unit. Because the temperature of the circulating blood must be rapidly lowered and precisely controlled, the refrigeration unit's evaporator cooling coils are serpentinely embedded directly between heat exchanger inner plates **66** and the heat exchanger outer plates **65** of the heat exchanger **14**. The circulating blood flows through the heat exchange cassette **79** fully inserted in the heat exchanger **14** so it is closely sandwiched between two insertion plates **68**.

As the blood flows through the cassette **79** in a serpentine route, heat exchange occurs between the heat exchanger **14** and the blood. A means to precisely control the temperature of the heat exchanger, and hence the blood, requires the capacity to both cool and heat. The hot-gas discharge bypass valve **18** can provide heat and raise the temperature of heat exchanger **14**, but rapid response to temperature fluctuations and precise control of the core body temperature requires an additional heat source. The additional heating capacity supplied to the heat exchanger **14** is accomplished by AC resistive foil heating elements **67** sandwiched between the inner plates **66** and the insertion plates **68**. The heat exchanger inner plates **66** and insertion plates **68** are constructed of aluminum while the outer plates **65** are constructed of polypropylene to reduce the evaporator mass of the heat exchanger **14** for a faster thermal response and to provide insulation. The heating elements **67** and the refrigeration unit **15** may operate simultaneously, heating and cooling the heat exchanger at the same time. Due to the requirements for precise temperature control, the heat exchanger **14** must respond in a very short time. Simultaneous heating and cooling of the heat exchanger **14** is more responsive for adjusting small temperature fluctuations in the core body temperature than just using the hot-gas discharge bypass valve **18**, which opens and closes by means of a stepper motor and is slower effecting a temperature increase in the heat exchanger **14**.

[0051] Although the present invention has been described with reference to a preferred embodiment, further modifications and improvements will be apparent to one skilled in the art based on the present teachings without departing from the spirit and scope of the present invention as defined herein and in the following claims.

What is claimed is:

1. An extracorporeal therapeutic hypothermia apparatus to rapidly induce and indefinitely maintain a patient in a state of whole body or regional, mild-to-moderate hypothermia by continuously cooling and/or warming the patient's blood, said extracorporeal hypothermia apparatus comprising:

a first connector means for removing a circulating flow of blood from a patient;

a second connector means for returning said circulating flow of blood to said patient; and

a flow circuit connected between said first connector means and said second connector means, said flow circuit including

a fluid pump assembly for moving blood through said flow circuit;

a cooling means for lowering the temperature of said circulating flow of blood so as to lower the patient's core body temperature;

a heating means for raising the temperature of said circulating flow of blood so as to lower the patient's core body temperature;

a heat exchanger for removing or adding thermal energy to said circulating flow of blood;

a heat exchange cassette for mounting in the heat exchanger through which flows said circulating flow of blood for the removal or addition of thermal energy;

a pressure isolator to isolate said circulating flow of blood from the pressure sensor;

a bubble trap/filter to remove air bubbles from the circulating blood;

a bubble detector to detect unsafe bubbles in said circulating flow of blood;

a tubing occluder to stop said circulating flow of blood in an emergency or unsafe condition; and

a disposable set consisting of all components, tubing, and sensors that contact the blood or the patient.

2. The extracorporeal hypothermia apparatus as recited in claim 1, wherein the apparatus is easily transported between locations by an average adult and is transportable by emergency vehicle.

3. The extracorporeal hypothermia apparatus as recited in claim 2, wherein the apparatus can be located, powered, and operated in an emergency vehicle or an emergency room of a hospital or clinic.

4. The extracorporeal hypothermia apparatus as recited in claim 1, wherein the apparatus can lower and maintain a patient's core body temperature to the range of 30°C to 34°C.

5. The extracorporeal hypothermia apparatus as recited in claim 4, wherein the apparatus can rapidly induce mild-to-moderate hypothermia by lowering a patient's core body temperature to 34°C in ten minutes or less.

6. The extracorporeal hypothermia apparatus as recited in claim 1, wherein the apparatus can maintain normothermia in a patient by regulating the core body temperature at 37°C ± 0.5°C.

7. The extracorporeal hypothermia apparatus as recited in claim 1, wherein the apparatus can induce and maintain therapeutic hyperthermia in a patient by raising the core body temperature to a selectable temperature within the range of 37°C to 42°C.

8. The extracorporeal hypothermia apparatus as recited in claim 1, wherein said cooling means is a vapor-compression refrigeration unit whose evaporator cooling coils are serpentinely embedded in said heat exchanger.

9. The extracorporeal hypothermia apparatus as recited in claim 1, wherein said heating means is a indirect hot-gas bypass system for raising the temperature of said heat exchanger.

10. The extracorporeal hypothermia apparatus as recited in claim 1, wherein AC resistive heating elements are embedded in the heat exchanger to provide more precise temperature control.

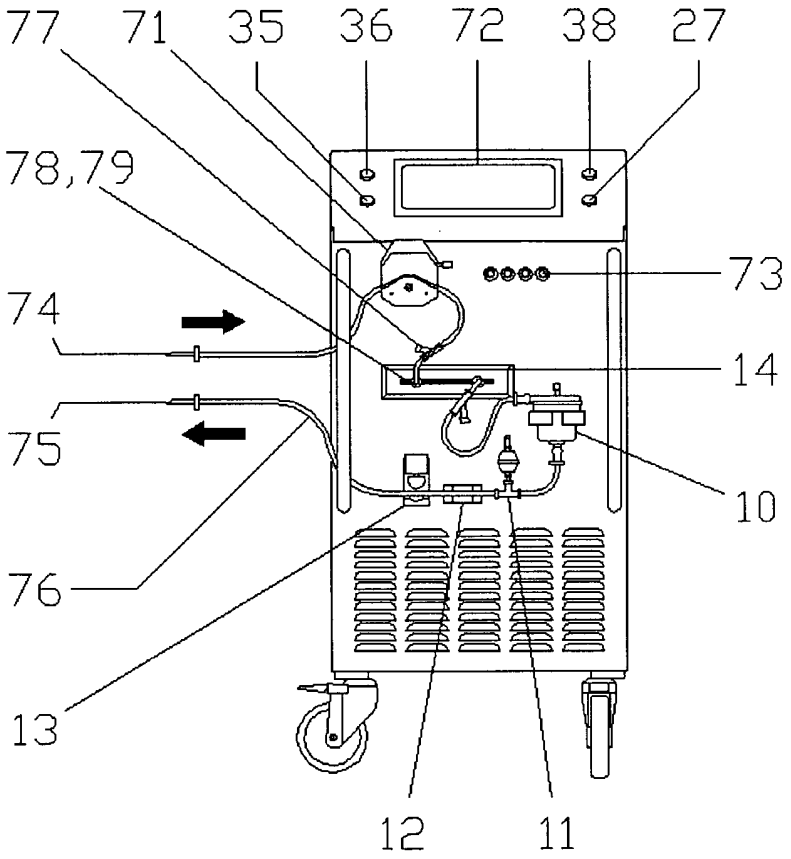


Fig. 1a

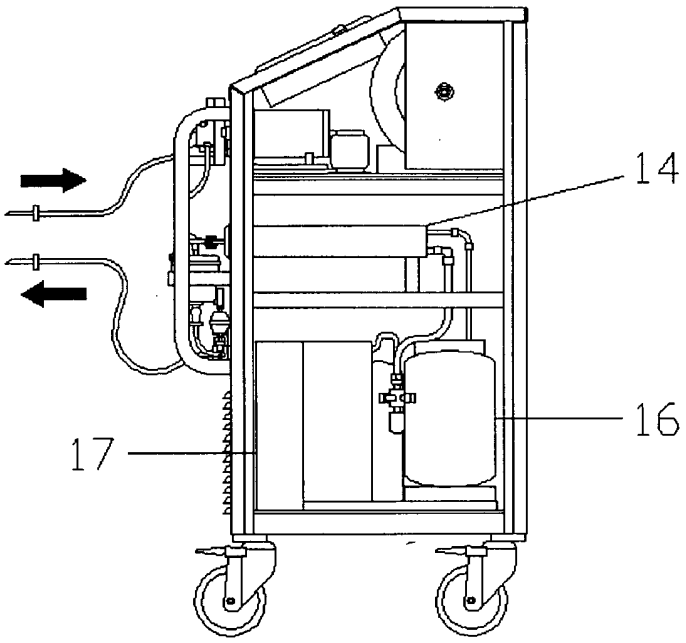


Fig. 1b

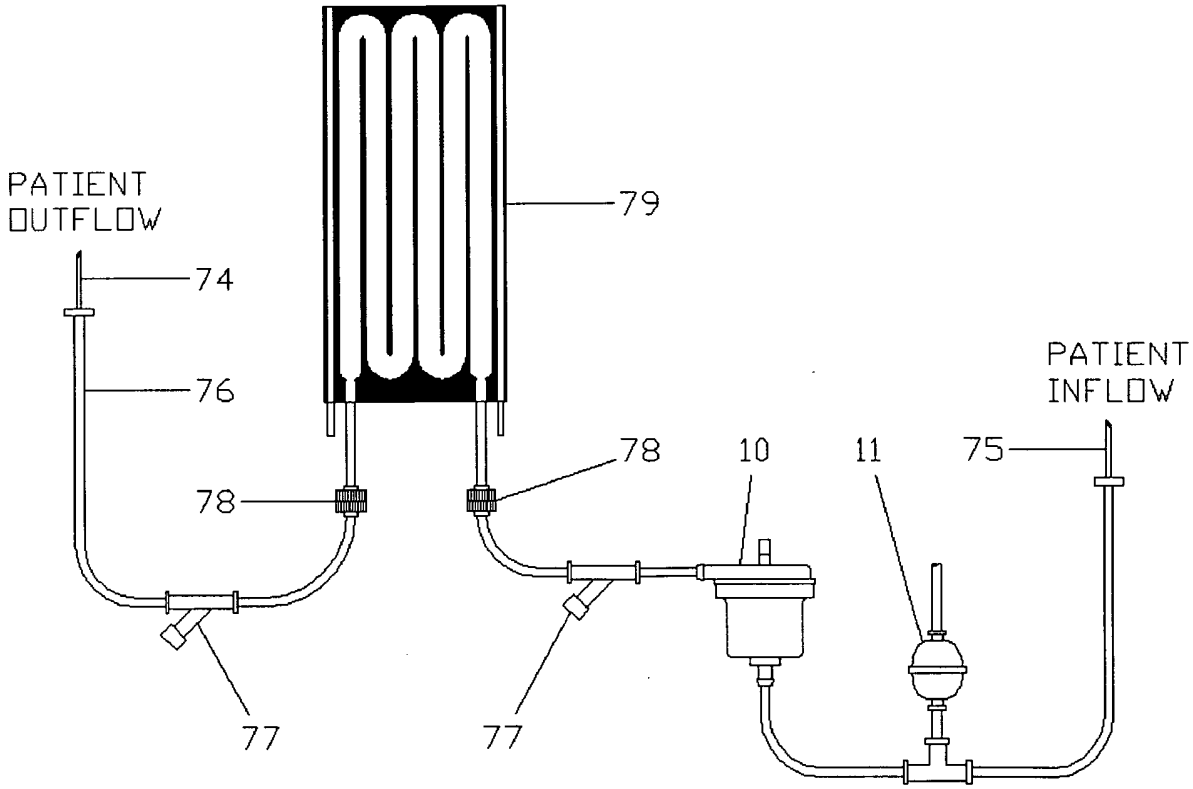
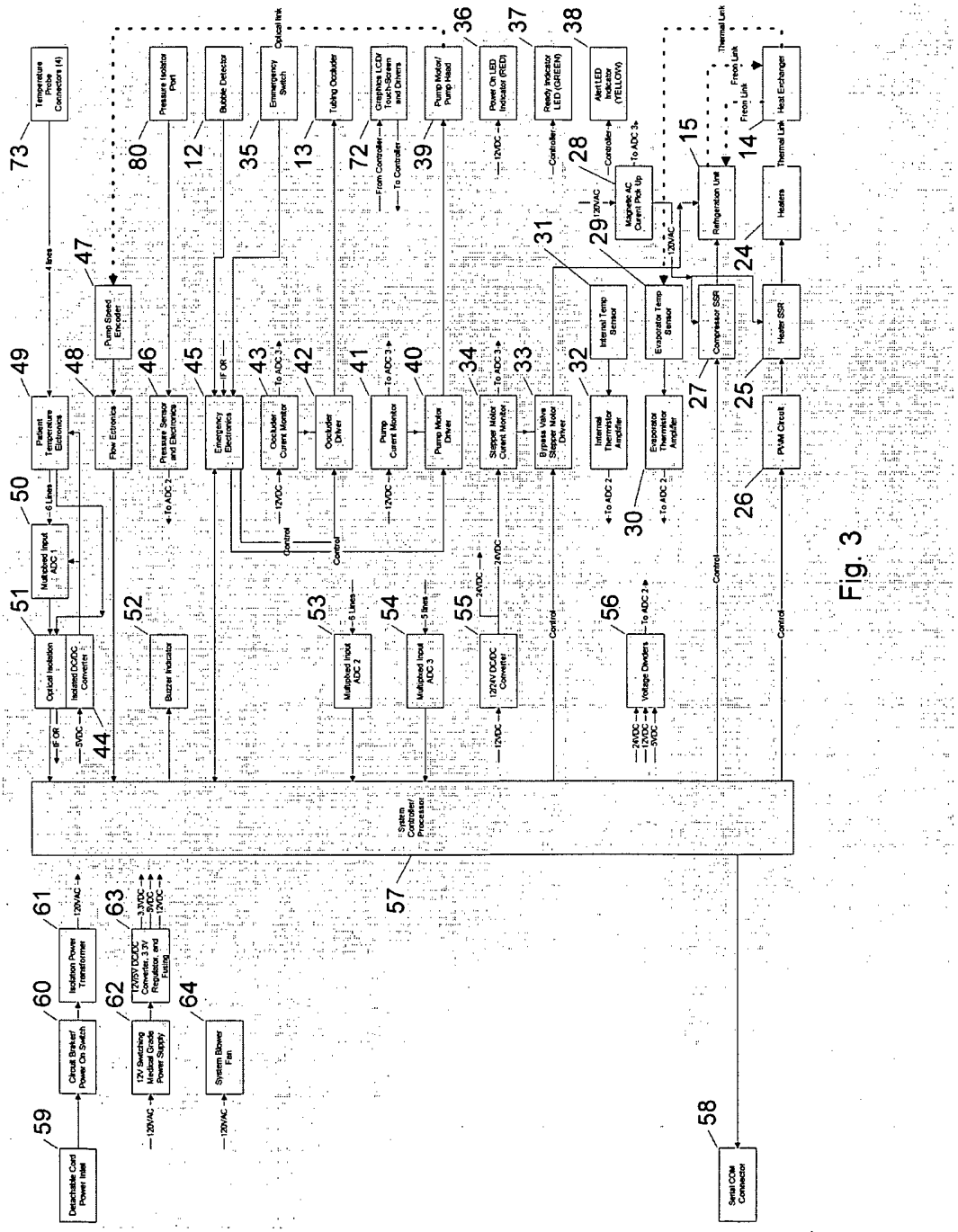


Fig. 2


Temperature Probe Connectors (4)
Pressure Isolator Port
Bubble Detector
Emergency Switch
Occluding Occluder
Graphical LCD Touch-Screen and Drivers
Pump Motor/ Pump Head
Power On LED Indicator (RED)
Ready Indicator LED (GREEN)
Alert LED Indicator (YELLOW)
Thermal Link
Freon Link
Heat Exchanger
Optical Ink
Pump Speed Encoder
Patient Temperature Electronics
Flow Electronics
Pressure Sensor and Electronics
Emergency Electronics
Occluder Current Monitor
Occluder Driver
Pump Current Monitor
Pump Motor Driver
Stepper Motor Current Monitor
Bypass Valve Stepper Motor Driver
Internal Thermistor Amplifier
Evaporator Thermistor Amplifier
Internal Temp Sensor
Evaporator Temp Sensor
Compressor SSR
Heater SSR
Heaters
PWM Circuit
Refrigeration Unit
Magnetic AC Current Pick Up
Multiplexed Input ADC 1
Multiplexed Input ADC 2
Multiplexed Input ADC 3
Optical Isolation
Isolated DC/DC Converter
Buzzer Indicator
12V DC/DC Converter
Voltage Dividers
System Controller/ Processor
Isolation Power Transformer
12V/5V DC/DC Converter, 3.3V Regulator, and Fusing
Circuit Breaker/ Power On Switch
12V Switching Medical Grade Power Supply
System Blower Fan
Detachable Cord Power Inlet
Serial COM Connector
Fig. 3

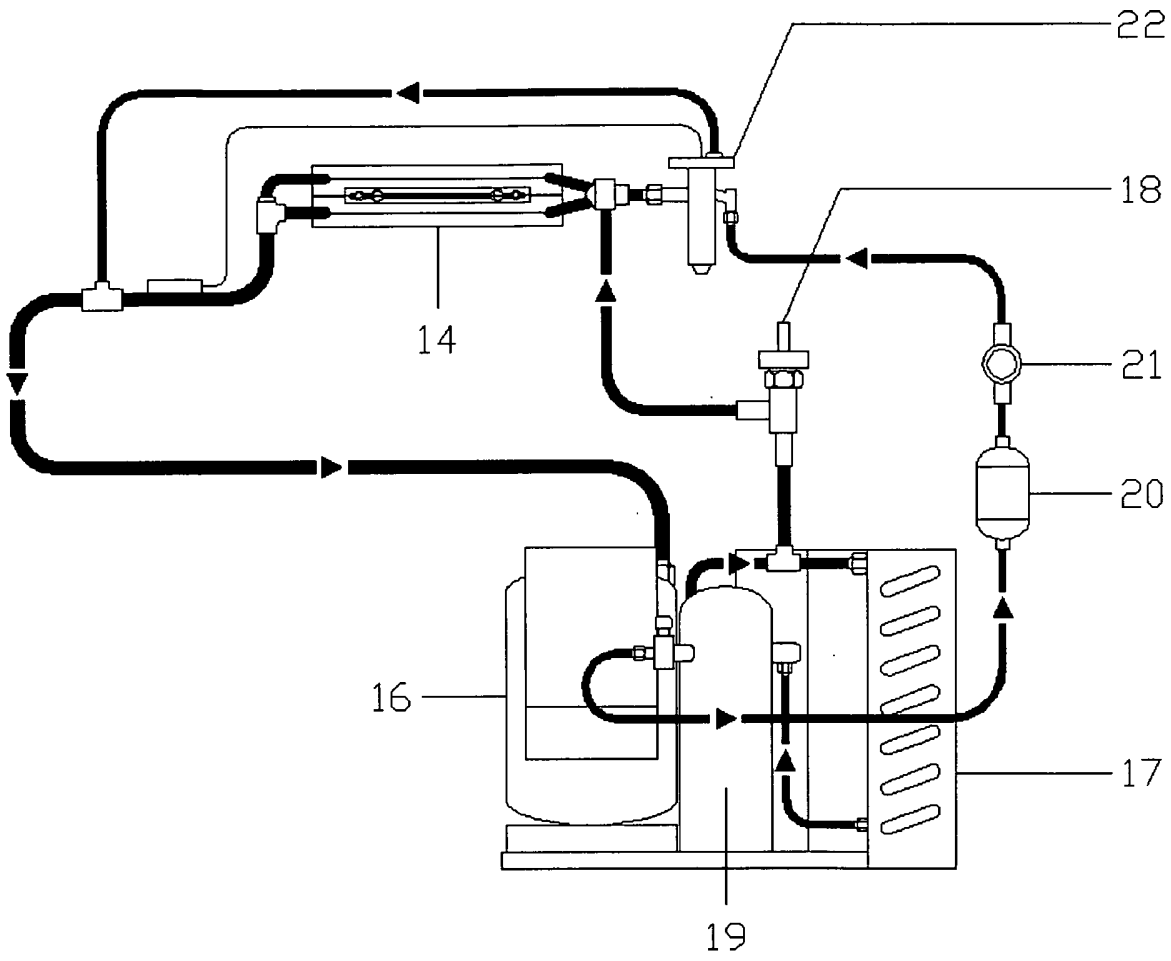


Fig. 4

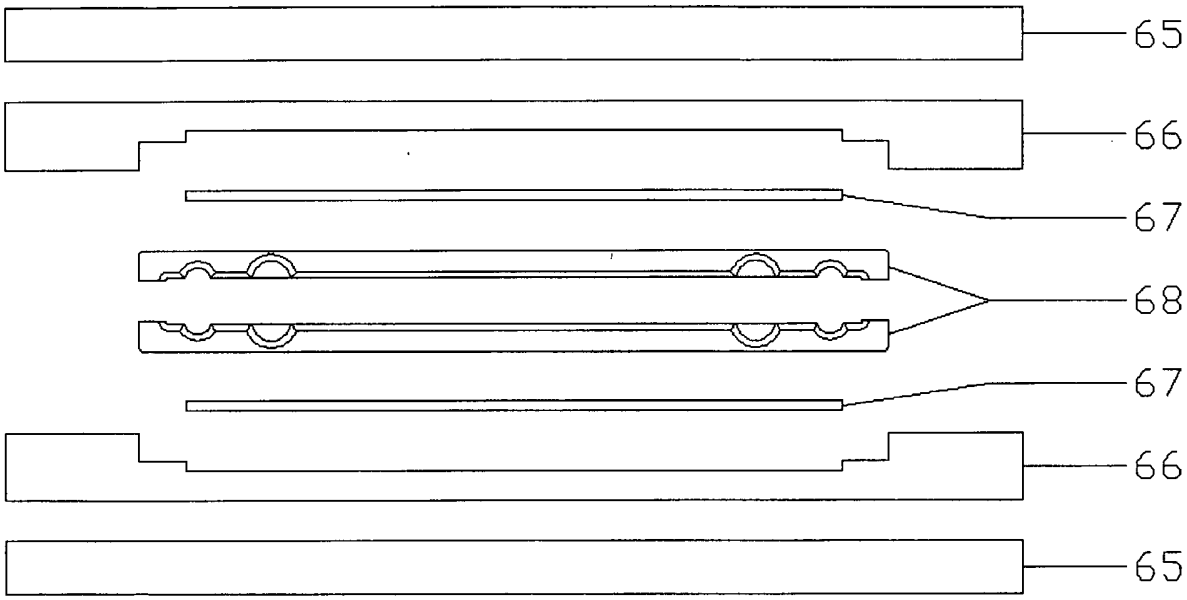


Fig. 5