Sept. 28, 1965　　B. L. MESSINGER　　3,208,234

AIR CYCLE REFRIGERATION SYSTEM AND METHOD

Filed March 1, 1963　　4 Sheets-Sheet 1

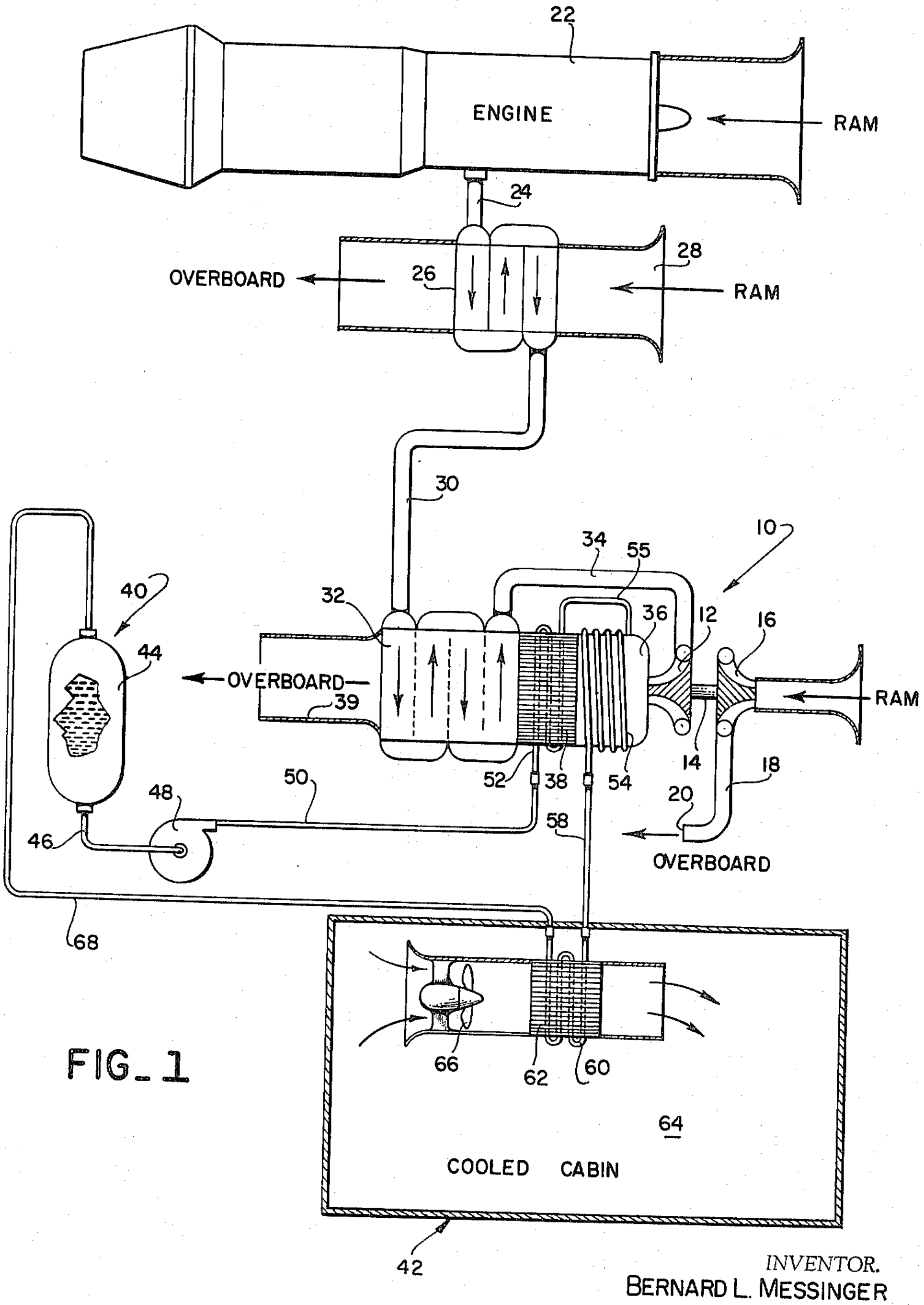

FIG_1

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AIR CYCLE REFRIGERATION SYSTEM AND METHOD

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4 Sheets-Sheet 2

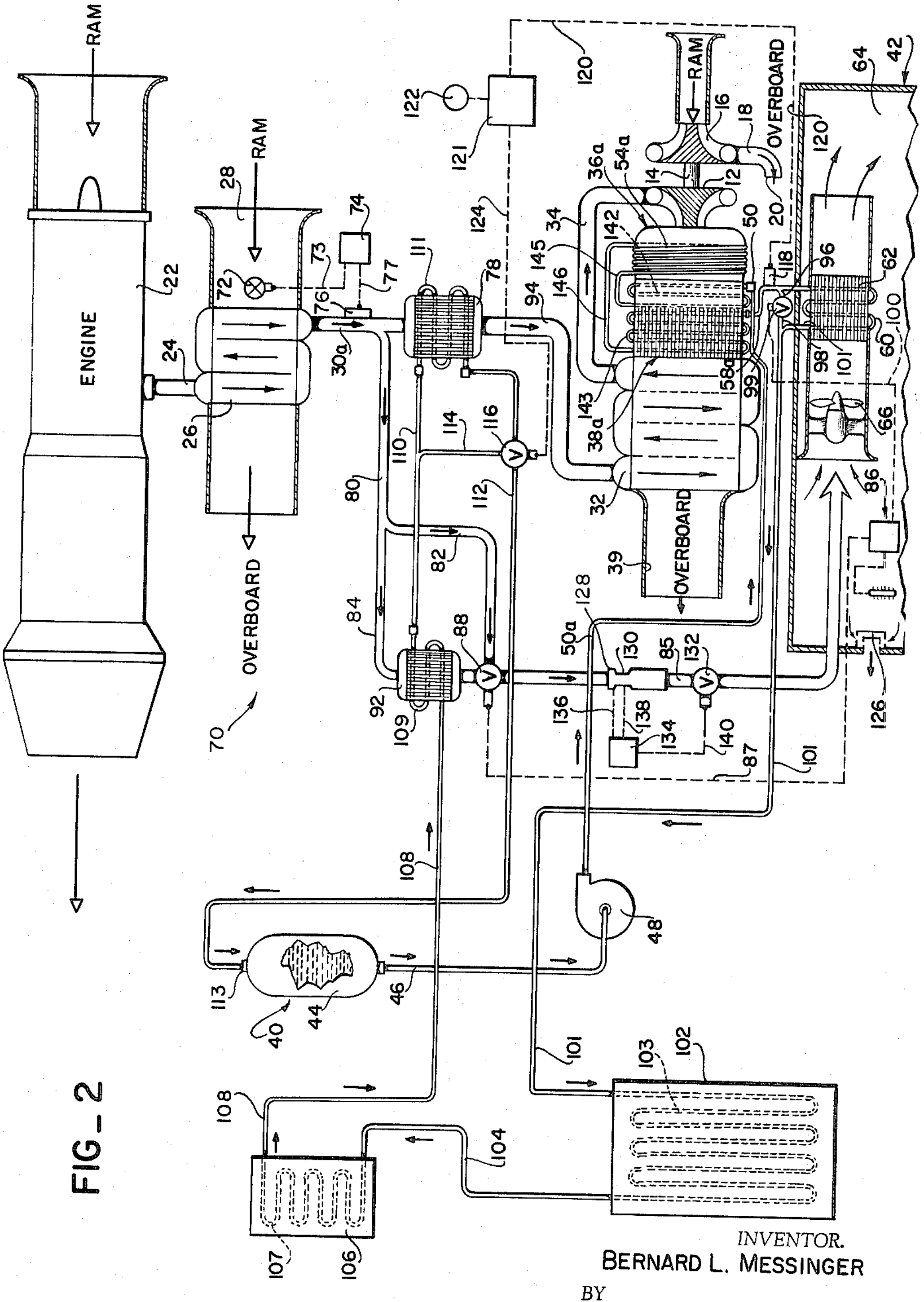

FIG_2

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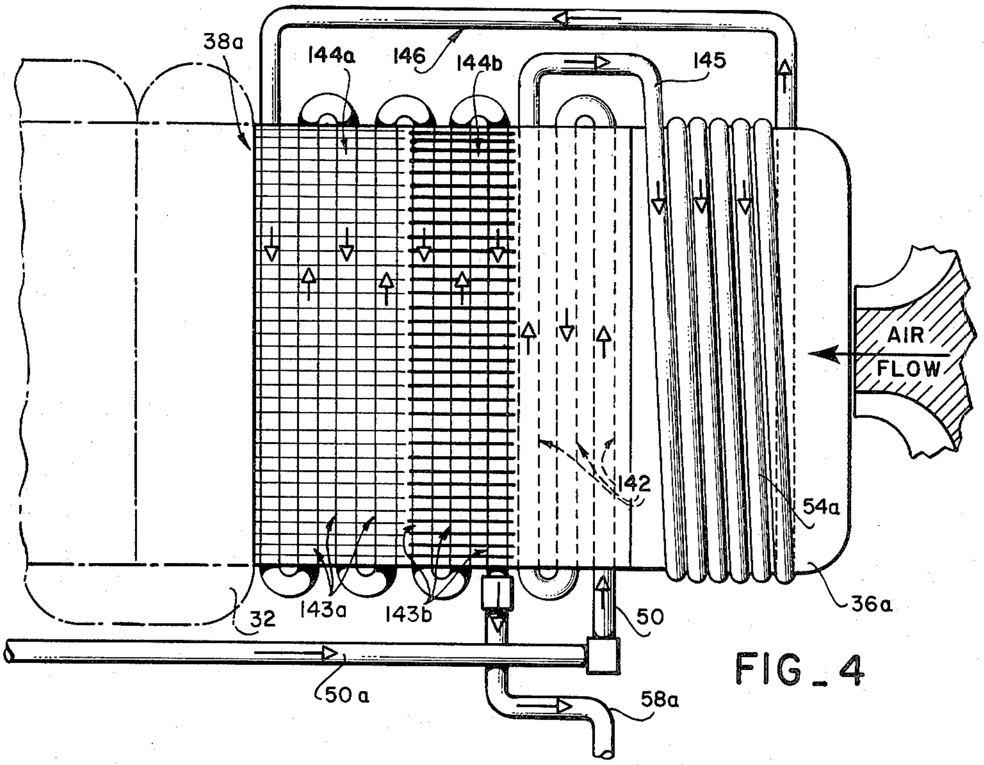

FIG_4

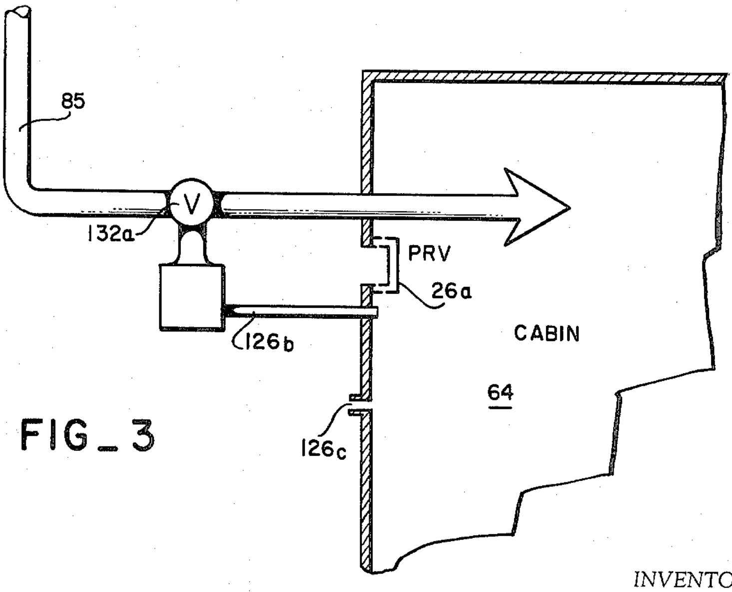

FIG_3

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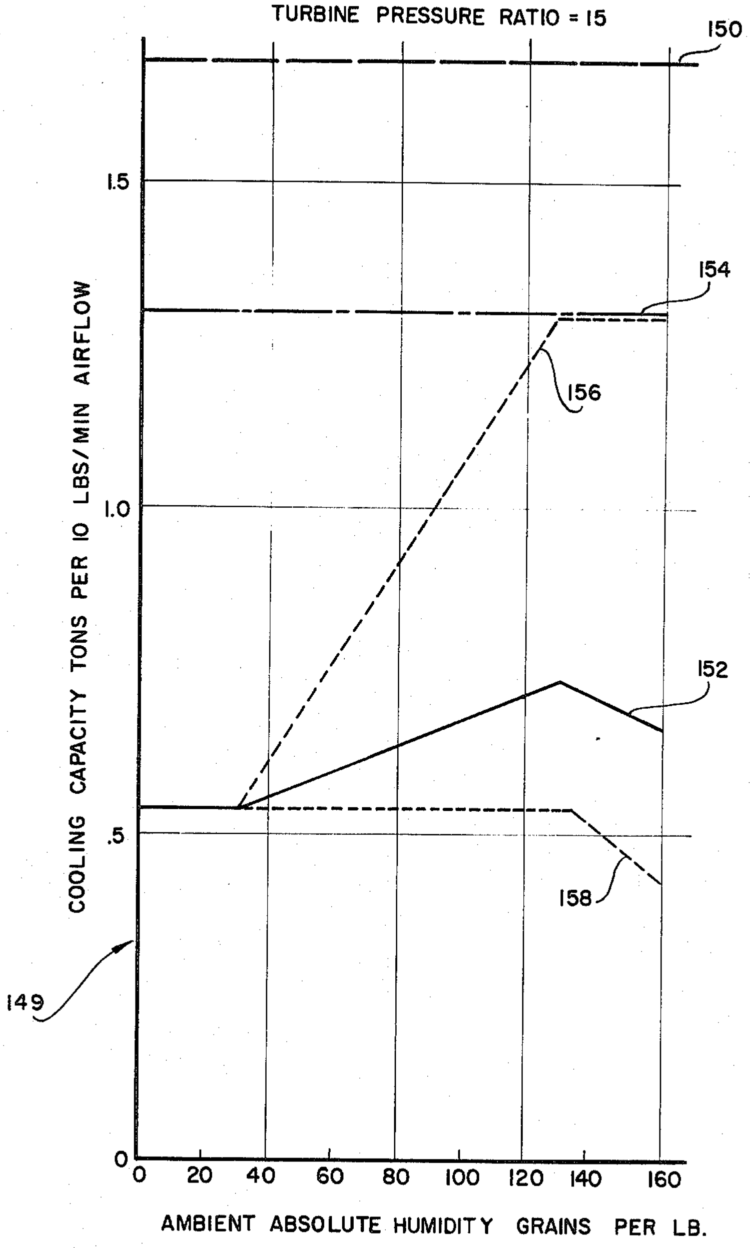

FIG_5

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AIR CYCLE REFRIGERATION SYSTEM AND METHOD

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18 Claims. (Cl. 62—172)

This invention relates to an air cycle refrigeration system and method and more particularly to an indirect air cycle refrigeration system and method for air conditioning aircraft.

Basically, an air cycle refrigeration system produces a cooling effect by extracting work energy from a high pressure air stream by means of an air expansion turbine. This work is then absorbed by some convenient loading device such as a fan or compressor. The result is a considerable reduction in stream temperature at the turbine exit which permits refrigeration of the space to which the air is directed.

While generally satisfactory, these systems do have certain drawbacks. One of the major drawbacks resides in the fact that moisture in the air forms a dense cloud of fog at the turbine discharge and creates downstream visibility and moisture impingement hazards at all temperatures, as well as duct icing and blockage of sub-freezing temperatures. A conventional, and not altogether successful, solution to this fog problem is the application of high pressure-drop filter separator devices at the turbine discharge combined with an above freezing thermostatic limit control. The separator device removes about 75% of the free moisture and discharges it overboard. The latent cooling effect of this amount of separated water represents a net loss capacity to the system. The residual fog which is not caught, but passes on through the separator, must be re-evaporated in order to avoid causing an obstruction to vision.

Another drawback resides in the fact that a residual 20 to 30% of the free moisture, which unavoidably passes through the water separator of an air cycle system, becomes a serious problem in application to electronic equipment cooling. Avionic equipment which is cooled by air forced directly over the surfaces of the equipment components should not be subjected to any entrained moisture. In the case of conventional air cycle cooling and water separator equipment, this can only be accomplished by reheating the water laden separator discharge air to at least the saturation point before permitting it to flow over the avionic component. Such reheating can be achieved by heat transfer or by suitable mixing with recirculated cooling air, although the latter method is not altogether reliable.

The problem of ice prevention in the air cycle system is rather difficult because of the water separator. In particular, a dense filter bag is employed which is extremely susceptible to rapid accumulation of ice and, because of this, icing must be entirely avoided or controlled. One conventional method of controlling the ice formation is to impose a 35° F. minimum temperature limit on the turbine discharge air, which imposes rather severe control accuracy criteria on the system. Another conventional method of handling this problem is to permit a limited build-up of pressure drop which results from the initial ice accumulation on the filter system, and then to prevent it from exceeding this limit by means of a pressure-drop sensitive control which regulates a by-pass system on the turbine. The thermostatic method has a disadvantage of saddling the system with a built in capacity cut-off point which imposes a rather severe penalty to the system unless overridden by some auxiliary control device such as an altitude switch set for an arbitrary altitude above which the effects of moisture can be neglected.

In aircraft, the cooling performance required for certain elements of electronic equipment has become more critical than that required for the comfort of personnel. This is particularly true of high impedance analog computor circuits which are quite sensitive to moisture and temperature variations and are adversely affected by conventional air cycle refrigeration systems.

In view of the foregoing factors and conditions characteristic of air cycle refrigeration systems, it is a primary object of the present invention to provide a new and improved indirect air-cycle refrigeration system not subject to the disadvantages enumerated above employing turbine cooled air to cool a secondary fluid which is then circulated to the refrigerated area, and its cooling effect applied either by a conductive contact with equipment or by circulation through a secondary heat exchanger in the compartment.

Another object of the present invention is to provide an indirect air cycle refrigeration system and method which isolates moisture laden air from the final stage of the cooling process.

Yet another object of the present invention is to provide an indirect air cycle refrigeration system employing a turbine cooled heat exchanger.

A further object of the present invention is to provide an air cycle refrigeration system and method which eliminates the moisture, fog and icing problems which have been troublesome downstream of the turbine exit in conventional air cycle systems used for aircraft.

A still further object of the present invention is to provide a new and improved system and method for air conditioning aircraft.

Yet another object of the present invention is to provide a new and improved air cycle refrigeration system and method which eliminates water separators.

Another object of the present invention is to provide a new and improved air cycle refrigeration system and method which achieves a maximum dry-air-rated performance during high humidity conditions.

Another object of the present invention is to provide a new and improved air-cycle refrigeration system which incorporates a regenerative heat exchange system.

Yet another object of the present invention is to provide a new and improved air-cycle refrigeration system and method for aircraft wherein cooling of personnel and equipment is accomplished by means of a heat exchanger through which an air-cooled, constant density fluid flows.

According to the present invention, equipment and personnel compartments of an aircraft are cooled with an indirect air cycle refrigeration system wherein turbine cooled air is used to cool a secondary fluid which is then circulated to the refrigerated areas. Its cooling effect is applied either by a conductive contact with equipment or by circulation through a secondary heat exchanger in the personnel compartment. The turbine discharges directly through a first heat exchanger to cool the secondary fluid and then flows through a regenerative heat exchanger before being released overboard. A separate, but small, supply of pressurization air is ducted directly into the cabin of the aircraft for pressurizing it. This air quantity is just sufficient to meet the fuselage structural air leakage requirements or the crew ventilation requirements and is pre-cooled by a second heat exchanger through which the cooled, secondary fluid flows. The secondary fluid is a constant density liquid, such as ethylene glycol and water, and is circulated through the first heat exchanger where it leaves an air expansion turbine at a reduced temperature. The secondary fluid is then transferred from the first heat exchanger as a recirculating heat-sink liquid of controlled temperature.

Air is bled from the aircraft engine and is first cooled by ram air in a third or primary heat exchanger and controlled to a minimum temperature of about 225 to 250° F. The major portion of the bleed air, at above ram temperature, is then passed through a fourth heat exchanger in which the recirculated heat-sink liquid is flowing to provide a controllable heat source for maintaining the circulating liquid at a suitable minimum temperature. This prevents ice formation at the first heat exchanger adjacent the turbine discharge when the system heat loads are at a minimum level due to a low speed, low ambient total temperature, or inoperative avionic equipment. A small quantity of bleed air, which is just sufficient to pressurize and heat the crew compartment, is cooled in, or by-passed around, a fifth heat exchanger, which carries the cooled secondary fluid, in response to a signal from the cabin temperature control system.

The major portion of the bleed air flows next to a sixth or regenerative heat exchanger where it is further cooled by air leaving the first heat exchanger before such air flows overboard. The bleed air leaves the sixth heat exchanger and enters the turbine at relatively low temperature and high pressure. Power generated by the turbine is absorbed by a compressor supplied with ambient air (at full ram pressure if at high altitude).

The turbine cooled air leaves the turbine at low pressure and discharges directly into the first heat exchanger to cool the constant density liquid. These two components are necessarily very close-coupled, and it is not permissable to employ elbows or other duct obstructions to intervene between the turbine and the first exchanger. Not only is the location of this first heat exchanger an important feature of the present invention, but also the design of the heat exchange-surface at the air entering face. The tubes and fins are carefully spaced and the fin thickness and conductivity are carefully selected in order to provide for ice-free operation regardless of turbine exit conditions while permitting operation with a constant-density liquid temperature low enough for the system cooling requirements. Thus, downstream of the heat exchanger, the turbine cooled air enters the coolant side of the sixth or regenerative heat exchanger. This component not only increases the system efficiency due to increasing the sensible heat of the air which is rejected overboard, but also evaporates any free moisture which is carried over from the heat exchanger during high humidity conditions. The system thereby benefits from the heat-sink capacity of any water which is re-evaporated and which would otherwise be drained overboard after separation.

The recirculating secondary-liquid coolant loop performs the function of distributing the cooling effect produced by the turbine to the several heat load areas in the flight vehicle. For certain elements of avionic equipment, this is done by means of liquid-cooled, "cold plate" equipment racks. The personnel compartment cabin air is recirculated over the secondary heat exchanger which comprises a suitable finned heat exchanger functioning very much like an evaporator in the conventional vapor cycle system to cool the personnel compartment. Whenever the compartment dewpoint reaches the surface temperature of this heat exchanger, the latter performs the function of removing not only sensible heat of the circulating air, but latent heat as well. Moisture removed in this process is inherently easy to separate and can be disposed of either by an overboard drain or by useful re-evaporation on the external surface of one of the other heat exchangers.

An important additional feature of the present invention is the provision for reducing the minimum liquid coolant temperature in response to a signal from an altitude switch. The altitude for this shift in control point temperature is that altitude above which the quantity of moisture in the air is negligible and therefore would not result in a significant icing problem at the turbine discharge. This reduction in liquid temperature above some arbitrarily selected altitude then permits the attainment of full cooling capacity in the personnel compartments, even though the mass flow rate of fan recirculated air over the cabin heat exchanger is greatly reduced due to lowered cabin density. Over-cooling of critical avionic components is prevented by independent thermostatic controls in the liquid circuit at each major equipment assembly.

Cabin temperatures are controlled by variable bypass of the coolant around the cabin heat exchanger for the cabin cooling regime combined with variable by-pass of the pressurization air around the third of primary heat exchanger during cabin heating. To assure a source of heat for a low speed, low temperature flight, the bleed air is thermostatically controlled at the outlet of the third or primary heat exchanger to some reasonable minimum temperature such as 250° F., or 300° F., which is consistent with maximum cooling performance during high temperature, high speed flights.

Whenever used in this specification, the term "ram air" shall mean ambient air which is compressed by the forward motion of a vehicle.

The features of the present invention which are believed to be novel are set forth with particularity in the appended claims. The present invention, both as to its organization and manner of operation, together with further objects and advantages thereof, may best be understood by reference to the following description, taken in connection with the accompanying drawings, in which:

FIGURE 1 is a schematic view of a first embodiment of an indirect air cycle system of the present invention;

FIGURE 2 is a schematic view of a second embodiment of an indirect air cycle system of the present invention;

FIGURE 3 is a schematic view of a modification of a portion of the system of FIGURE 2;

FIGURE 4 is a plan view of a liquid-to-air heat exchanger employed in the system of FIGURE 2; and

FIGURE 5 is a performance comparison chart of an indirect air cycle system of the present invention and air cycle systems of the prior art.

Referring again to the drawings, and more particularly to FIGURE 1, a simplified indirect air cycle air-conditioning system, generally designated **10**, includes an air expansion turbine **12** which is coupled through a shaft **14** to an air compressor **16**. The compressor **16** is supplied with ambient air, which will be supplied at full ram pressure if at high altitude, and absorbs the power generated by turbine **12**. Compressed air passes through a duct **18** and is dumped overboard through an outlet **20** after it has been compressed by the compressor **16**.

The turbine **12** is a conventional cooling turbine which may have either fixed or variable nozzles and radial inflow rotor blading and is supplied by air bled from an aircraft engine **22** at high pressure and temperature through a pipe **24** into a primary heat exchanger **26**. The primary heat exchanger **26** is cooled by ram air, entering through a duct **28**, to a temperature of about 225° to 300° F. Bleed air passes from the primary heat exchanger **26** through a line **30** into a regenerative heat exchanger **32**. The air next travels through a pipe **34** into the turbine **12**. A cooling effect is produced on the high pressure air stream by the turbine **12** which extracts work which is absorbed by the compressor **16**. The high pressure air is expanded down to a pressure slightly higher than atmospheric and cooled air is discharged from the turbine **12** into a heated transition section or duct **36** connecting the turbine to a glycol-cooling heat exchanger **38** which is coupled directly to the heated transition section **36** without the use of intervening elbows or other duct obstructions, thereby minimizing icing conditions. The downstream side of the glycol-cooling heat exchanger **38** is connected to the coolant side of the regenerative heat exchanger **32** from which discharge air flows overboard through an outlet 39. The regenerative heat exchanger 32 not only increases the system efficiency due to increasing the sensible heat of the air which is rejected overboard, but also re-evaporates any free moisture which is carried over from the glycol-cooling heat exchanger 38 during high humidity conditions. The system thereby benefits from the heat sink capacity of any water which is re-evaporated and which would otherwise be drained overboard after separation.

A recirculating cooling loop, indicated generally as 40, performs the function of distributing the cooling effect produced by the turbine 12 to the several heat load areas in a flight vehicle and includes a tank or reservoir 44 which is filled with a suitable constant-density liquid, such as a low-freezing-point solution of ethylene glycol and water. Coolant from tank 44 passes through a conduit 46 into a pump 48 which pressurizes the coolant and supplies it through a line 50 to the glycol-cooling heat exchanger 38 (hereinafter referred to sometimes as a glycol-cooler). Coolant is circulated through the glycol-cooler 38 by means of tubes 52 which are placed in the flow path from the turbine 12. The discharge end of the tubes 52 is connected by means of a pipe 55 to a coil 54 which encompasses the duct 36 and serves as an anti-icing means for the duct. The discharge end of coil 54 is connected to a line 58 which discharges into the tubes 60 of a finned heat exchanger 62. The finned heat exchanger 62 is located in the personnel compartment or cabin 64 of the air vehicle 42 and includes a fan 66 which recirculates cabin air over the heat exchanger 62 to cool the cabin 64. Whenever the dewpoint in cabin 64 exceeds the surface temperature of the heat exchanger 62, the latter performs the function of removing not only sensible heat of the circulating air, but latent heat as well. Moisture removed in this process is inherently easy to separate and may be disposed of either by an overboard drain, not shown, or by useful re-evaporation on the external surface of the heat exchangers 26 and 32. Coolant is returned from the tubes 60 of heat exchanger 62 to the tank 44 through a line 68.

Referring now to FIGURE 2, a modified indirect air cycle air conditioning system, generally indicated 70, includes most of the same basic components just described in connection with the system of FIGURE 1 and the same numerals will be employed throughout the following description to include these basic units. In system 70, a motor-actuated, butterfly valve 72 is controlled through an electrical lead 73 by a thermostat 74 which senses the temperature of the air being discharged from the primary heat exchanger 26 by means of a sensing element 76 which is attached to the pipe 30*a* and is connected to the thermostat 74 by an electrical lead 77. The valve 72 is placed in duct 28 to control the flow of ambient ram air to the primary heat exchanger 26 so that the temperature of the air leaving heat exchanger 26 will be 250 to 300° F. The major portion of the bleed air from the primary heat exchanger 26 passes through the pipe 30*a* into a small air-to-liquid heat exchanger or reheater 78 which is employed to maintain the constant-density liquid recirculating in system 40 at a suitable minimum temperature (40 to 50° F.) to prevent ice formation on the glycol-cooler 38*a* at the turbine discharge when system heat loads are at a minimum level due to low speed or other factors. A feeder line 80, having a first branch 82 and a second branch 84, is connected to the line 30*a* upstream of the heat exchanger 78 and supplies a small quantity of bleed air through a line 85 to the cabin 64 to pressurize it. A temperature control system 86 is located in cabin 64 and is connected by a lead 87 to a motor operated by-pass valve 88, which is located at the junction of branch line 82 and line 85. If the temperature control system 86 calls for heat, it will position by-pass valve 88 in such a manner that heated air from line 30*a* will pass through feeder 80, branch line 82, by-pass valve 88 and line 85 into the cabin 64. If the cabin temperature control system 86 calls for cooled pressurizing air, the by-pass valve 88 will be positioned by the control system 86 to prevent flow from branch 82 and permit flow from line 30*a* through feeder 80 and branch 84 into a small liquid-cooled heat exchanger 92 which is cooled by coolant flowing system 40. Cooled air then flows from heat exchanger 92 through line 85 into cabin 64.

The major portion of the bleed air flows from the heat exchanger 78 through a line 94 into the regenerative heat exchanger or cooler 32 where it is further cooled by air leaving the glycol-cooler 38*a* before flowing overboard through outlet 39. The bleed air flows from the regenerative heat exchanger 32 through the line 34 into turbine 12 at a relatively low temperature and high pressure. Power generated by the turbine 12 is transmitted through shaft 14 to the compressor 16. The turbine cooled air leaves the turbine 12 at low pressure and discharges directly into the glycol-cooler 38*a* to cool the liquid coolant flowing in coolant loop 40. Coolant flows through banks of bare tubing 142 forming part of the cooler 38*a*, through a coil 54*a* on the surface of duct 36*a* and through banks of finned tubing 143 forming another part of the cooler 38*a*. Coolant leaves the cooler 38*a* through a discharge line 58*a* which includes a branch line 96 connecting the line 58*a* with a line 101 through a line 98 and a thermostatically controlled valve 99. The valve 99 is connected to temperature control system 86 by means of a lead 100 and is positioned thereby to permit a modulated portion of the coolant flowing in line 58*a* to by-pass the heat exchanger 62 when the temperature in cabin 64 reaches a predetermined minimum.

Coolant discharges from tubes 60 of heat exchanger 62 through the line 101 which also carries the flow from line 98, and flows to a cold plate rack 102 which may be employed to cool avionic equipment carried in the flight vehicle 42. The coolant flows through tubes 103 in rack 102 and is discharged therefrom through a line 104 to an equipment cooler or heat exchanger 106 which may also be employed to cool the equipment in the flight vehicle 42. The coolant flows through tubes 107 in heat exchanger 106 and is discharged therefrom through a line 108 into the inlet side of the heat exchanger 92 and then flows through tubes 109 to the discharge side of the heat exchanger 92 which is connected through a line 110 to the inlet side of the coolant reheater 78. The coolant flows through tubes 111 in reheater 78 and is discharged therefrom through a line 112 to the inlet 113 of the reservoir 44.

The reheater 78 may be by-passed with coolant by means of a by-pass line 114 which inter-connects the lines 110 and 112 through a thermostatically controlled valve 116. A sensing element 118 senses the temperature of the coolant in discharge line 58*a* immediately adjacent the glycol-cooler 38*a* and an electrical lead 120 connects the sensor 118 with a thermostatic control 121. An electrical lead 124 connects both the thermostatic control 121 and a barometric switch 122 with the valve 116. Thus, the reheater 78 may be by-passed either at a predetermined altitude or when the temperature of the coolant leaving glycol-cooler 38*a* reaches a predetermined maximum corresponding to operation under a full cooling load. The barometric switch 122 is an important feature of the present invention because it reduces the minimum liquid coolant temperature in response to altitude. The altitude for this shift in control point temperature is that altitude above which the quantity of moisture in the air is negligible and therefore will not result in a significant icing problem at the turbine discharge. This reduction in liquid temperature above a predetermined altitude then permits the attainment of full cooling capacity in cabin 64 even though the mass flow rate of fan-recirculated air over the cabin heat exchanger 62 is greatly reduced due to lowered cabin density.

A conventional cabin pressure regulator 126 is mounted in cabin 64 to control the pressure therein and is coordinated with a flow control device 128 mounted in line 85. The flow control device 128 includes a venturi 130 which controls a pneumatic valve 132 connected thereto through a control box 134. The control box 134 is connected to the venturi 130 by means of lines 136 and 138 and to the valve 132 through a pneumatic line 140. The valve 132 is connected in line 85 to control the flow or air therethrough.

Referring to FIGURE 3, a modified pressure control system is shown wherein the pressure regulator 126 is replaced with a pressure relief valve 126*a* and a pressure-sensing tube 126*b* which are mounted in cabin 64. The pressure-sensing tube 126*b* is connected to an inflow pressure regulator 132*a* which modulates the flow in line 85 in response to a predetermined pressure differential between cabin 64 and ambient atmosphere. The normal structural leakage of cabin 64, represented by orifice 126*c*, determines the quantity of flow of air into and out of the cabin 64. When the pressure in cabin 64 reaches a predetermined minimum, pressure regulator 132*a* receives a signal through tube 126*b* and responds to admit more air into cabin 64 through line 85. When the pressure in cabin 64 reaches a predetermined maximum, regulator 132*a* is repositioned to reduce airflow into cabin 64. Relief valve 126*a* opens if for any reason cabin pressure exceeds a value which is a predetermined amount greater than the maximum control point of pressure regulator 132*a*.

Referring now to FIGURE 4, the glycol-cooler 38*a* and its location are important features of the invention. Careful attention must be given to tube spacing, fin spacing, and fin thickness and conductivity in order to provide for ice-free operation regardless of turbine exit conditions, at the same time permitting operation with coolant-liquid temperatures low enough for system cooling requirements. The cooler 38*a* shown for purposes of illustration, but not of limitation, is connected to duct 36*a* and includes banks of bare tubing 142 and banks of finned tubing 143.

The banks of bare tubing 142 are mounted at the air-entering face of glycol-cooler 38*a* and are stacked vertically in such a manner that they form an anti-icing screen. For extremely severe design icing conditions it may be desirable to provide internally finned and externally bare tubing for this function. The tubing 142 (shown respectively, is arranged for cross-parallel-flow (i.e., fluid flow within the tubing progressing parallel to air flow and flow in individual tubes being perpendicular to air flow) and receives coolant supplied through line 50. Coolant discharges from tubes 142 into the coil 54*a* through a cross connecting line 145. Coolant flows through coil 54*a* to heat duct 36*a* and prevent ice from forming on the walls thereof and discharges through a line 146 into a bank of finned tubing 143*a*. The tubing 143*a* includes relatively thin fins 144*a* which are arranged relatively close together. Another bank of finned tubing 143*b* includes fins 144*b* arranged at approximately the same spacing as fins 144*a* but which are fabricated of somewhat thicker material. The tubing banks 143*a* and 143*b* are arranged for cross-counter flow and may be made of aluminum. The fins 144*a* and 144*b* are made of a high conductivity material such as copper or aluminum.

Coolant flows from reservoir 44 (FIGURE 2) by means of line 46 and pump 48 through a line 50*a* to heat exchanger 38*a* to heat the tubing 142 and prevent the accumulation of ice thereon from the sub-cooled fog laden air leaving turbine 12. From tubing 142 the coolant flows through line 145 into coil 54*a* to heat the walls of duct 36*a* and prevent accumulation of ice thereon. Coil 54*a* then, in effect, extends the glycol-cooler 38*a*. The coolant passes from coil 54*a* through a line 146 into the downstream side of glycol-cooler 38*a* where it enters the bank of finned tubing 143*a* and flows upstream to the other bank of finned tubing 143*b* through which it flows upstream to discharge line 58*a*.

The arrangement of the glycol-cooler 38*a* and the flow pattern herein shown and described yields an above-freezing surface temperature at the air inlet face of cooler 38*a* and a minimum coolant exit temperature in line 58*a* with no icing in the finned banks 143 even though the air from turbine 12 contains condensed liquid water droplets at a sub-freezing temperature.

Referring now to FIGURE 5, the performance advantage of the indirect air-cycle system of the present invention is compared with the performance of conventional, direct air-cycle systems. The overall performance has been plotted on a chart 149 in terms of refrigeration capacity in tons per ten pounds per minute of bleed air flow (one ton equals 2,000 pounds of ice melted in 24 hours or 200 B.t.u./min.). Chart 149 was prepared on the basis of a turbine pressure ratio of 15. The refrigeration capacity has been plotted as a function of ambient absolute humidity expresed in grains per pound. A single horizontal line 150 represents the performance of the indirect system of the present invention. Direct system performance, on the other hand, is shown in four conceivable variations. The solid line 152 is plotted for a practical direct air-cycle system having a water separator of 75% efficiency and a thermostatic, non-icing control set for a 35° F. minimum temperature at the water separator. A first alternate direct system configuration is represented by the line 154 which is based on no separation of water and no non-icing control. A second alternate direct system configuration is represented by the line 156 which shows no separation of water but includes a 35° F. non-icing control. A third alternate direct system configuration is represented by the line 158 based on a hypothetical one hundred percent separation of water and the 35° F. non-icing control. The configurations represented by the lines 154 and 156 are not acceptable from a fog hazard standpoint and the configuration represented by the line 158 is at present unattainable and would in any event involve the most severe performance penalty of the five.

The performance comparison which is evident in the chart 149 is rather startling in that the indirect air-cycle system of the present invention, where one would usually expect to suffer a penalty in performance due to the additional heat transfer process, is actually 2.7 times better than the conventional 75% water separator direct system at a turbine pressure ratio of 15.

It should be noted, however, that this comparison is based on refrigeration capacity only and that the direct system has one advantage in its favor. It supplies an adequate flow of air for ventilating and pressurizing the cabin 64 as a by-product to its cooling function. However, for combat aircraft with a crew of one to three men, the minimum air quantity required to offset structural leakage is usually more than enough to provide adequate ventilation and probably would not exceed 10% to 15% of the flow required for refrigeration. Therefore, the penalty chargeable to the indirect system for the separate supply of pressurizing airflow required in addition to the flow for cooling would be relatively small when compared to the cooling performance advantage evident in the comparison chart. For this reason, the indirect system is very appropriate for application to high performance military aircraft where a small number of occupants is involved, but not advantageous in transport type vehicles where the ratio of ventilating (and pressurizing) flow to the refrigeration flow is of the order of one or more.

An example of the method of the present invention will be described in connection with FIGURE 1. During conditions of high ambient humidity air was bled from the engine 22 through line 24 into the primary heat exchanger 26 which cooled the air to about 230° F. before it passed through line 30 into regenerative heat exchanger **32**. The air was cooled by the heat exchanger **32** to about 82° F. before passing through line **34** into turbine **12** at approximately 210 p.s.i.g. The air left the turbine **12** at slightly above-atmospheric pressure and at a temperature of about −30° F. (or −120° F. dry-air-rated temperature) and cooled the coolant flowing in system **40** from 80° F. to 50° F. The 50° F. coolant entered the heat exchanger **62** in cabin **64** and cooled the interior thereof to 80° F. The heat exchanger **62** provided 1.68 tons of coolant per ten pounds per minute of bleed air. Air from the turbine **12** passed through the regenerative heat exchanger **32** and out outlet **39** to atmosphere at 167° F.

While the particular indirect air-cycle refrigeration systems and method herein shown and described in detail are fully capable of attaining the objects and providing the advantages hereinbefore stated, it is to be understood that they are merely illustrative of the presently preferred embodiments of the invention and that no limitations are intended to the details of construction or design or of the method steps herein shown and described other than as defined in the appended claims.

What is claimed is:

1. An air conditioning system for a vehicle comprising:

a source of air,

means for cooling the air from the source,

cold air passage means connected with the cooling means through which cooled air from the air cooling means is discharged,

conduit means for circulating a fluid in heat exchange relation with the cold air passage means and with the vehicle,

pump means connected to the conduit means for circulating the fluid through the conduit means,

the air cooling means includes an air expansion turbine having an air inlet connected to the source of air and an air outlet connected to and discharging cooled air into a duct forming the cold air passage means,

the air cooling means includes an air compressor connected to the turbine for absorbing work energy extracted from the air by the turbine to cool the air,

the conduit means including a liquid-to-air heat exchanger mounted adjacent a downstream side of the duct,

the liquid-to-air heat exchanger includes a bank of bare tubes mounted adjacent the downstream side of the duct to form an anti-icing screen to prevent the impingement formation of ice resulting from condensed moisture entrained in the cold air, and

the heat exchanger also includes a bank of finned tubes mounted adjacent and downstream of the bare tubes.

2. The air conditioning system of claim **1** wherein said liquid-to-air heat exchanger includes a coil of tubes encompassing said duct to heat the walls thereof and prevent ice from forming on said walls, said coil receiving said fluid upstream of said bare tubes and discharging said fluid into said bare tubes, said bare tubes discharging fluid into said finned tubes at the downstream side of said liquid-to-air heat exchanger and said finned tubes discharging said fluid at the upstream side of said finned tubes and adjacent the downstream side of said bare tubes.

3. An air conditioning system for a vehicle having a compartment and an engine comprising:

(a) a first conduit connected to said engine for bleeding air therefrom at a pressure substantially higher than atmospheric;

(b) heat exchange means connected to said first conduit for precooling said bleed air;

(c) air expansion means connected to said heat exchange means for receiving said bleed air and discharging it in a finally cooled condition at a reduced pressure;

(d) a first heat exchanger mounted adjacent said air expansion means for receiving the cooled air discharging therefrom;

(e) a second heat exchanger mounted in said compartment; and

(f) a second conduit connected in a closed circuit through said heat exchangers for circulating a fluid in heat transfer relationship therewith, said fluid being cooled by said cooled air flowing through said first heat exchanger and then flowing through said second heat exchanger to cool said compartment.

4. The air conditioning system of claim **3** including a third heat exchanger connected to said first conduit upstream of said air expansion means for cooling said bleed air and discharging it into said air expansion means.

5. The air conditioning system of claim **3** wherein said second conduit includes a first coil encompassing the discharge end of said air expansion means for heating said discharge end to prevent ice in said discharge air from forming thereon.

6. The air conditioning system of claim **3** including a third conduit for bleeding air from said engine to said compartment for pressurizing it.

7. The air conditioning system of claim **6** including a heat exchanger connected to said third conduit for receiving bleed air from said engine, said conduit including a second coil passing through said last mentioned heat exchanger, whereby the bleed air passing through said last mentioned heat exchanger heats said fluid flowing in said second coil.

8. The air conditioning system of claim **3** wherein said air expansion means includes:

(a) an air expansion turbine having an air inlet connected to said first conduit and an air outlet;

(b) a duct connecting said outlet to said first heat exchanger; and

(c) an air compressor connected to said turbine for absorbing the work energy extracted from said high pressure air by said turbine.

9. The air conditioning system of claim **3** wherein said first heat exchanger comprises:

(a) a bank of bare tubes mounted adjacent the discharge of said air expansion means to form an anti-icing screen to prevent the passage of any ice which may be entrained in said cooled air; and

(b) a bank of finned tubes mounted adjacent said bare tubes downstream thereof, said bare tubes and said finned tubes being connected in said closed circuit with said second conduit.

10. The air conditioning system of claim **4** including a duct for connecting said third heat exchanger to a source of ambient air for cooling the bleed-air flowing through said third heat exchanger.

11. The air conditioning system of claim **4** wherein said third heat exchanger includes a duct connecting said third heat exchanger to said turbine discharge for cooling the bleed-air flowing through said third heat exchanger.

12. The air conditioning system of claim **7** including a thermostatically controlled by-pass valve and by-pass line connected to said engine upstream of said last mentioned heat exchanger for by-passing said bleed-air around said last mentioned heat exchanger when a predetermined temperature is reached.

13. The air conditioning system of claim **12** including an altitude switch for activating said by-pass valve to by-pass said last mentioned heat exchanger at a predetermined altitude.

14. The air conditioning system of claim **8** wherein said second conduit includes a third coil encompassing said outlet duct for preventing ice from accumulating on the walls thereof.

15. The air conditioning system of claim **9** wherein said bare tubes are connected in said closed circuit for cross-parallel flow and said finned tubes are connected in said closed circuit to said bare tubes for cross-counter flow.

16. A liquid-to-air-heat exchanger comprising:

an enclosure having a cold air inlet;

a bank of bare tubes positioned downstream of the enclosure cold air inlet to form an anti-icing screen to prevent the impingement formation of ice resulting from condensed moisture entrained in said air, said bare tubes including a fluid inlet connectable to a source of fluid to be cooled by said air and a fluid outlet; and

a bank of finned tubes positioned adjacent the downstream side of said bare tubes, said finned tubes having a fluid inlet connected to the fluid outlet of said bare tubes and a fluid outlet for discharging said cooled fluid from said finned tubes.

17. A liquid-to-air heat-exchanger comprising:

(a) a bank of bare tubes positionable downstream of a source of cold air to form an anti-icing screen to prevent the impingement formation of ice resulting from condensed moisture entrained in said air, said bare tubes including a fluid inlet connectable to a source of fluid to be cooled by said air and a fluid outlet; and

(b) two connected banks of finned tubes positioned in tandem adjacent the downstream side of said bare tubes, a first bank of said finned tubes located nearest said bare tubes being arranged for cross-counter flow with a second bank of said finned tube which is located at more remote downstream position from said bare tubes, said finned tubes having a fluid inlet connected to the fluid outlet of said bare tubes and a fluid outlet for discharging said cooled fluid from said heat exchanger.

18. The heat exchanger of claim **17** wherein said bare tubes are arranged for cross-parallel flow.

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