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HUMIDITY CONTROL SYSTEM

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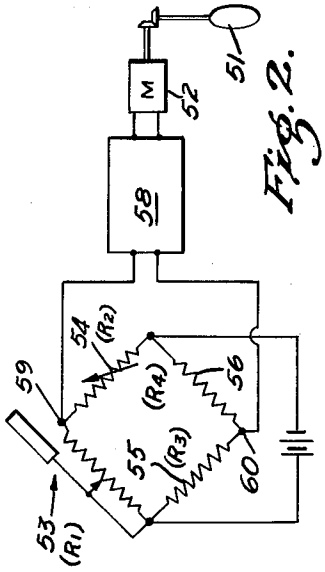


Fig. 2.

Fig. 1.

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HUMIDITY CONTROL SYSTEM

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Continuation of application Ser. No. 392,538, Nov. 17, 1953. This application Apr. 30, 1956, Ser. No. 581,807

29 Claims. (Cl. 62—172)

This invention relates to air conditioning systems of the air cycle type for supplying treated air to a confined place, and has particular utility in systems for cooling and dehumidifying air supplied to cabins or other compartments of aircraft.

Of the various types of air conditioning systems, the air cycle type has certain inherent advantages and generally may be made light in weight and small in bulk, whereby systems of the air cycle type are particularly well suited for use in aircraft. Though air cycle systems may be constructed in various arrangements of their component parts, all of them operate to reduce the temperature of the treated air by causing the air to expand. In those instances where such expansion is required as will reduce the temperature of the air below normal freezing temperatures, discrete ice particles and ice fog will be formed in the air. Such ice particles and ice fog deposit and accumulate on the inner walls of the conduits of the system, thereby restricting the flow of air through the system, altering the heat exchange characteristics of the parts of the system and preventing proper operation of the control mechanisms. Also, the treated air (i.e., conditioning air) should be supplied to the enclosure in a condition free of suspended ice particles. In practice, air cycle systems are arranged in such a way as to heat the expanded air slightly in order to melt the suspended ice particles prior to supplying it to the place to be air conditioned.

This application is a continuation of my previously filed application Serial No. 392,538, filed November 17, 1953, now abandoned.

It is an object of this invention to provide an air cycle system having control means for maintaining the conditioning air at a substantially constant humidity.

Another object is to provide an air cycle system having automatic control means responsive to both the temperature and pressure of the air prior to expansion thereof.

Another object of this invention is to provide an air cycle system wherein the mechanism for controlling flow of air in the system is maintained free from accumulation of ice particles, thus permitting it to operate freely in response to temperature and pressure fluctuations of the air.

It is a further object of this invention to provide, in an air cycle refrigeration and dehumidification system, a bypass means for the conditioning air, which means is so constructed and arranged as to allow the conditioning air to flow in part around the heat exchange parts of the system to prevent deposition and accumulation of ice upon such heat exchange parts.

A further object of this invention is to provide an air cycle system that maintains unrestricted flow of air therethrough and especially throughout that part of the system which is downstream of the place where expansion of the air occurs.

A still further object is to provide an air cycle system

that dehumidifies the air in an improved and efficient manner by separating moisture from the air prior to expansion and refrigeration thereof.

Another object is to provide an air cycle system wherein the water which has been removed from the air by dehumidification of the air is used in cooling the air at a place in the system which is upstream of the place at which moisture is separated from the air.

Further objects and advantages of the invention will before apparent from the following part of this specification in which the details of construction and mode of operation of a preferred embodiment of the invention are described with reference to the attached drawing, which is for illustrative purposes only, and wherein:

Fig. 1 is a schematic sketch of a dehumidifying and refrigerating system embodying the features of this invention; and

Fig. 2 is a schematic diagram of an embodiment of an electrical circuit for controlling the system illustrated in Fig. 1.

Referring now to the drawing, reference numeral 10 designates an enclosure, and for the purposes of this description may be considered as constituting a compartment in an airplane in which it is desired to maintain air conditions that are conducive to human comfort, or, should the airplane be a cargo-carrying craft, to maintain air conditions that are suited to the type of cargo being transported. The air treating system of this invention is connected to the compartment 10 by an outlet duct 11. Air to be treated and supplied to the compartment 10 is delivered from a source of compressed air which, in the embodiment illustrated, constitutes a jet engine represented by the rectangle 12.

From the jet engine 12 the conditioning air flows through a duct 13 to a compressor 14 where the pressure of the air is further increased. The compressor 14 has been included in the drawing merely for the purpose of illustrating a way in which energy released by the subsequent expansion of the conditioning air may be utilized in the system, as will be more fully explained later in this specification. From the compressor 14 the air flows through a duct 15 to one side of a first heat exchanger indicated generally at 16. The heat exchanger 16 includes a plurality of air passageways 19 about which the conditioning air from duct 15 passes in heat exchange relation with secondary or cooling air which flows through the heat exchanger from an inlet 17 to an outlet 18. In compressing the conditioning air the jet engine 12 and the compressor 14 greatly increase the temperature of the air, and the heat exchanger 16 has been provided for the purpose of at least partially reducing the temperature of the conditioning air. The cooling air for the heat exchanger 16 may be supplied from a ram air duct as illustrated at 17, or may, if desired, be supplied by means of a fan.

From the heat exchanger 16 the conditioning air flows through a duct 20 to the air cycle refrigeration and dehumidification system of this invention. This system includes an enlarged chamber 22 from which conditioning air passes into the outlet duct 11 to the enclosure 10. In the form shown in the drawing the chamber 22 is tapered at one end thereof toward its inlet opening 23. An expansion turbine 24 is mounted at the inlet opening 23 of the chamber 22 so that conditioning air passes directly from the turbine into the chamber 22.

Around the tapered inlet portion of the chamber 22 is an outer chamber 25 which is connected to the duct 20 to receive conditioning air from the heat exchanger 16. Such air flows through the chamber 25 around the outside surface of the tapered inlet portion of the chamber 22, and thus in heat exchange relation with air flowing

through the chamber 22. The outer chamber 25 covers the entire tapered portion of the chamber 22.

From the outer chamber 25 the conditioning air flows through a duct 26 and into a multi-pass regenerative heat exchanger indicated generally at 28. The heat exchanger 28 is arranged entirely within the chamber 22 with a first section 29 thereof being positioned upstream of its second section 30, so that air passing through the chamber 22 from the expansion turbine 24 to the outlet duct 11 will first contact the section 29 of the multi-pass heat exchanger and then contact the second section 30 of the heat exchanger. The chamber 22 is enlarged compared to the outlet of the turbine 24 to accommodate the regenerative heat exchanger 28 which would otherwise have to be made fairly long. Furthermore, the tapered inlet portion of the chamber 22 will convert the kinetic energy of the air into pressure energy. In other words, the velocity of flow of the air is reduced while its pressure is somewhat increased. The first section 29 constitutes a plurality of parallel tubes 31 having their ends fixed within baffle plates 32 and 33. The upstream end of the first section 29 of the multi-pass heat exchanger constitutes a manifold 34 which allows air flowing from the conduit 26 to be distributed for passage through each of the tubes 31. From the first section 29 the air flows through the manifold 35 at the outlet end of the first section 29 and thence through a plurality of parallel tubes 36 which constitute the second section 30 of the multi-pass heat exchanger 28. Thus the flow of air in the chamber 22 is in two separate paths arranged in heat exchange relation to each other. A first flow path includes the tubes 31 and tubes 36 of the sections 29 and 30, while a second flow path is formed by the walls of the chamber 22 which conducts air from the turbine 24 to the outlet duct 11.

As described so far, it will be observed that as the conditioning air flows into the turbine 24 it will expand and its temperature will drop. Under normal operating conditions such temperature drop will be sufficient to result in below normal freezing temperatures. Thus, discrete ice particles and ice fog will be formed in the expanded air, and such ice particles upon contact with the walls of the chamber 22 would normally tend to deposit and accumulate on the inside surfaces of the inlet portion of the chamber. By providing for the flow of hot air through the outer chamber 25, the walls of the inlet tapered portion of the chamber 22 are maintained at a temperature which is substantially higher than normal freezing temperatures, and ice particles or ice fog cannot be deposited on the inside walls of the inlet tapered portion of the chamber 22. Also, it will be seen that as the conditioning air flowing in the second flow path of the chamber 22 contacts the tubes of the regenerative heat exchanger 28, it will be heated by the hot air flowing in the first flow path, thus melting any ice particles and ice fog which may be carried by the expanded and cooled air.

As the conditioning air passes from the outer chamber 25 through the multi-pass heat exchanger 28 its temperature will be decreased and the temperature of the air passing through the second section 30 of the heat exchanger 28 will be less than that of the air passing through the first section 29. Thus it is seen that the expanded and cooled air from the inlet of the chamber 22 contacts the tubes 31, which are relatively warm, before it contacts the tubes 36 of the second section 30 and which are cooler than the tubes 31 of the first section 29. Described differently, heat exchange is established regeneratively in a way that provides for the transfer of heat between warm air and cold expanded air at the upstream side of the chamber 22, while downstream thereof heat exchange is established between air flows of less difference in temperature. Thus the air flow paths in the chamber 22 may be considered as being regenerative. The air flow through the two sections 29 and 30 of the heat exchanger 28 is in parallel as distinguished from a counter-current flow path. This arrangement prevents accumulation of ice particles on the tubes of the heat exchanger for those tubes of the heat exchanger which are contacted by the expanded air at its most reduced temperature are heated by air flowing from chamber 25 at its highest temperature.

From the second section 30 of the regenerative heat exchanger 28 the conditioning air flows through a duct 38 to the turbine 24 and thence through the chamber 22 as explained above. In flowing through the multi-pass heat exchanger, the temperature of the conditioning air is reduced, thus causing moisture to form in the air. A series of baffle plates 40 is provided in the duct 38 for removal of this moisture. As the conditioning air with its entrained moisture passes from the multi-pass heat exchanger 28, it impinges against the baffle plates 40 whereby the entrained moisture collects on the plates and runs down the walls of the plates. Openings 41 are arranged in the duct 38 at the base of the baffles whereby water from the baffles 40 passes through the openings 41 and collects in a container 42 mounted on the duct 38. Thus, excess moisture in the conditioning air is separated from the air before the air is expanded in the chamber 22, and the expanded air will have less actual moisture content and will form less ice particles within the expansion chamber than would have been formed had the moisture of the air not been separated out.

The water which is collected in the container 42 is passed through a pipe 44 to the inlet portion 17 of the first heat exchanger 16. The pipe 44 has a spray nozzle end 45 for spraying water into the cooling air prior to its passage through the heat exchanger 16. The cooling air which flows through the heat exchanger 16 is at a pressure which is less than that of the conditioning air which flows through the conduit 38, and thus the water which collects in the container 42 is forced by this difference in pressure through the pipe 44 and sprayed as a mist from the nozzle 45 into the secondary air entering the heat exchanger 16 from its inlet 17.

Such spraying of water into the secondary air stream causes quick evaporation of the water, thus substantially reducing the temperature of the secondary air due to the transfer of the necessary heat of evaporation from the secondary air to the water spray. Should the conditioning air be of high relative humidity, a larger amount of water will be separated from it by the baffles 40 than will be separated from conditioning air of low relative humidity. Since the amount of moisture sprayed into the cooling air from the nozzle 45 is thus dependent upon the original water content of the conditioning air, it is clear that the water separating means just described operates in a way that affects the water content of the conditioning air. Where the original water content of the conditioning air is high, a relatively large amount of water will be collected in the container 42 and will be discharged through the nozzle 45 into the secondary air of the heat exchanger 16, thus cooling the secondary air and in turn imparting a cooling effect upon the conditioning air. Where the original water content of the conditioning air is relatively low, a relatively small amount of water will collect in the container 42 whereby the secondary air in the heat exchanger 16 is cooled to a lesser extent than in the case previously described where the original water content of the conditioning air is high.

As explained above, the conditioning air flows from the conduit 38 into the turbine 24 where the air expands and passes into the chamber 22. The turbine 24 extracts work energy from the conditioning air as such air is expanded, and in the embodiment illustrated in the drawing this work is transmitted through the shaft 47 to the compressor 14 for motivating the compressor 14. It is to be understood, of course, that the shaft 47 of the turbine 24 may be connected for driving work absorbing means of a type other than the compressor 14, or for driving such other work absorbing means in addition to the compres-

sor 14. For example, the shaft 47 may, if desired, be connected in a well-known manner to a fan for passing secondary air through the heat exchanger 16.

The air cycle refrigeration and dehumidification system of this invention provides conditioning air to the enclosure 10 at a predetermined and substantially constand humidity. This constant humidity of the conditioning air is maintained by changing the amount of air flowing in contact with the tubes of the heat exchanger 28 in response to both temperature and pressure variations of the air of the first flow path issuing from the regenerative heat exchanger 28. Variation in the amount of air flowing in contact with the tubes of the heat exchanger 28 is made possible by humidity regulating apparatus which includes a by-pass duct 50 formed in the chamber 22 and arranged to allow the expanded air to pass through the duct 50 so as not to contact the tubes of the heat exchanger 28. In the embodiment illustrated, the by-pass duct 50 passes through the inlet manifold 34 of the first section 29 of the heat exchanger 28 and also through the outlet manifold of the second section of the multi-pass heat exchanger 28. The flow of air through the by-pass duct 50 is controlled by a butterfly valve 51 which is operatively connected to a motor 52. The motor 52 is a reversible motor and is actuated under the remote control of pressure and temperature sensitive control elements 53 and 54 respectively, within the duct 38. The pressure sensitive element 53 may constitute a bellows connected to the sliding arm of a variable resistance element, as illustrated on the drawing, or any suitable pressure transducer having a resistance which varies substantially linearly with variations in pressure. The temperature sensitive element 54 may, for example, constitute a thermistor having a resistance which varies substantially linearly with variations in temperature. The pressure sensitive element 53 and the temperature sensitive element 54 are positioned in the duct 38 between the outlet from the multi-pass heat exchanger 28 and the water separating baffles 40, and thus they actuate the valve 51 in response to temperature and pressure variations of the conditioning air just prior to the time that the entrained moisture being carried by the air is separated therefrom by the baffles 40.

As shown in Fig. 2, the elements 53 and 54 constitute arms of a Wheatstone bridge circuit having fixed resistance elements 55 and 56. The output of the Wheatstone bridge is connected to a control means 58 which in turn is electrically connected to the reversible motor 52 for actuating the valve 51. The control means 58 includes an amplifier and two relays controlled by the amplifier. Since the details of construction and mode of operation of such amplifier and relay system do not constitute a part of this invention, such system is represented herein only diagrammatically. For purposes of completeness of disclosure, however, the amplifier and relay system 58 may be made similar to that disclosed in the copending application of Brown et al., Serial No. 321,656, filed November 20, 1952, which application is owned by the same assignee as the instant invention and which discloses an electronic control system responsive to the unbalance of a Wheatstone bridge circuit and operatively connected through two relays to a reversible motor.

The temperature sensitive element 54 and the bridge are so adjusted that when the temperature of the air in the duct 38 is lower than a predetermined value while the air pressure remains constant it will cause the motor 52 to open the valve 51 to increase the flow of air through the by-pass duct 50. Since some of the expanded air is thus by-passed through the duct 50, there will be less of the expanded air passing in contact with the tubes of the heat exchanger 28. Thus, the temperature reduction of the air passing through the heat exchanger 28 on its first flow path will be less, and therefore less water vapor will be precipitated out from the air passing through the heat exchanger 28. Assuming conditions of constant pressure, should the temperature of the air contacting the temperature sensitive element 54 rise above a predetermined value, the element 54 will cause the motor 52 to close the valve 51, thus reducing the flow of air through the by-pass duct 50. With the reduction of flow of air through the by-pass duct 50 there will be an increase in the flow of expanded air around the tubes of the heat exchanger 28. Such increased flow of expanded air in contact with the tubes of the heat exchanger 28 will cause a further reduction in the temperature of the air flowing in the tubes. Thus, the air flowing in the tubes of the heat exchanger 28 being of a reduced temperature, will retain less water vapor. It is clear from the above, therefore, that the temperature sensitive element 54 functions to control the humidity of the gas passing through the system.

In a like way to that described above for the temperature sensitive element 54, the pressure sensitive element 53 functions to affect the humidity of the air passing through the system. The pressure of the conditioning air will vary essentially only with the altitude of the airplane which determines the pressure of the ambient air. Assuming a constant temperature, if the pressure of the air increases, saturation of the air with water vapor will occur at higher temperatures. Thus in order to maintain the humidity constant, the temperature of the air has to be increased when its pressure increases. There exists a substantial linear relationship between temperature and pressure for constant humidity of the air. Accordingly, assuming again a condition of constant temperature, if the pressure of the air in duct 38 rises, the valve 51 should be opened to increase the temperature of the air of the first flow path flowing into the duct 38 in order to maintain the humidity constant. On the other hand, if the pressure of the air should decrease while the temperature remains constant, the valve 51 must be closed to decrease the temperature of the air flowing into the duct 38 if the humidity is to be maintained constant. In this way the humidity of the air passing through the outlet duct 11 is controlled by both the temperature and pressure of the air passing through the duct 38 prior to the time when the entrained moisture in the air is separated therefrom by the baffles 40.

Though the movement of valve 51 due to change in temperature of the gas flowing in duct 38 has been explained above under assumed conditions of constant pressure, under actual conditions pressure variations occur simultaneously with fluctuations in temperature. The Wheatstone bridge circuit illustrated in Fig. 2 maintains the humidity of the conditioning air substantially constant by controlling the temperature of the air as a substantially linear function of the pressure of the air. The pressure responsive element (i.e., resistor R1 of the Wheatstone bridge) has a resistance which varies linearly with the pressure P of the air according to the formula: $R1=A-BP$, wherein A and B are constants peculiar to the particular resistance element employed. The temperature responsive element 54 constitutes resistor R2 of the Wheatstone bridge having a resistance which is a linear function of temperature T according to the formula: $R2=C-ET$, wherein C and E are constants peculiar to the particular resistance element used. Resistance elements 55 and 56 (i.e., resistors R3 and R4 respectively) are fixed resistors. The pressure and temperature of the air are both sensed at the same location in the system, i.e., immediately upstream of the water separation baffles 40. The output of the bridge at 59 and 60 thereof causes the motor 52 to operate the valve 51 in such a way that the Wheatstone bridge will seek a balance so that

$$\frac{R1}{R2}=\frac{R3}{R4}=\frac{A-BP}{C-ET}$$

Thus it will be seen that in order to balance the bridge circuit the air temperature must be changed in response to either pressure or temperature variations of the air. When the temperature of the air tends to increase, the valve 51 is controlled to decrease the temperature of the air as it passes the resistor 54. On the other hand, if the pressure should increase, the air temperature must be increased by control of the valve 51 to rebalance the bridge again. Over the range of temperatures and pressures likely to be encountered at the point where they are sensed, a linear temperature-pressure schedule will correspond very nearly to a schedule of constant humidity. This is a general property of air-water vapor mixtures and is independent of any mechanism described herein. Hence, it follows that the humidity of the air may be maintained essentially constant by maintaining a linear temperature-pressure relationship. Control at any desired humidity is obtained by proper preselection of resistance elements of the bridge.

It is to be noted further that the valve 51 in the bypass duct 50 is positioned within the inlet manifold 34 of the first section of the multi-pass heat exchanger 28. In that position the valve will be heated by air flowing through the heat exchanger prior to the time that such air is cooled. Accordingly, there is no likelihood for the valve to become iced from deposition and accumulation of ice particles from the expanded air. It is necessary to maintain the valve 51 free from icing so that it will not stick and may operate freely when driven by the motor 52.

I have described and illustrated one form of my invention which achieves all of the objects, features and advantages heretofore pointed out. It should be understood, however, that various alterations and modifications may be made without departing from the spirit and scope of my invention. I therefore, do not wish to be limited to the details disclosed herein but wish my invention to be broadly construed in accordance with the statement of invention and in accordance with the claims which are directed to my invention in its entirety and in its important subcombinations.

I claim:

1. In an air conditioning system, a conduit for conveying air from a compressed air source to a confined space, an upstream portion of said conduit being arranged in heat exchange relation with a downstream portion thereof, said downstream portion including air expansion means for expanding and cooling air passing therethrough, said upstream portion including a plurality of sections with the last section being arranged downstream of the first section with respect to the direction of flow of air through said downstream portion.

2. In an air conditioning system, a conduit for conveying air from a compressed air source to an enclosure, a first portion of said conduit being arranged within a second portion of said conduit to provide heat exchange between air passing through said portions, air expansion means in said conduit between said first and said second portions, and a by-pass duct bypassing said second portion for altering the amount of air flowing in heat exchange relation with that flowing through said first portion, said by-pass duct being in heat exchange relationship with a part of said first portion.

3. In an air conditioning system, a conduit for conveying air from a compressed air source to an enclosure, a first portion of said conduit being arranged within a second portion of said conduit to provide heat exchange between air passing through said portions, air expansion means in said conduit between said first and said second portions, a by-pass duct, the inlet of said duct opening into said second portion at a location upstream of said first portion, the outlet of said duct opening into said second portion at a location downstream of said first portion, and means in said duct for altering the amount of airflow in heat exchange relation with that flowing through said first portion.

4. In an air conditioning system, a conduit for conveying air from a compressed air source to an enclosure, a first portion of said conduit being arranged within a second portion of said cnduit to provide heat exchange between air passing through said portions, air expansion means in said conduit between said first and said second portions, a bypass duct for bypassing said second portion and having at least a part thereof arranged in heat exchange relation with a portion of said conduit upstream of said first portion, and valve means in said part for altering the amount of air flowing in heat exchange relation with that flowing in said first portion.

5. In an air conditioning system, a conduit for conveying air from a compressed air source to a confined space, an upstream portion of said conduit being arranged in heat exchange relation with a downstream portion thereof, said downstream portion including an air expansion turbine for expanding and cooling air passing therethrough, a bypass duct connected across said downstream portion and having a part thereof arranged in heat exchange relation with said upstream portion, regulating means in said part of said duct, and means responsive to the temperature of air flowing from said first portion and operatively connected to said regulating means for altering the flow of air through said duct.

6. In an air conditioning system, a conduit for conveying air from a compressed air source to a confined space, an upstream portion of said conduit being arranged in heat exchange relation with a downstream portion thereof, said downstream portion including air expansion means for expanding and cooling air passing therethrough, a bypass duct for bypassing a portion of said downstream portion and having a part thereof arranged in heat exchange relation with said upstream portion, regulating means in said part of said duct, and means responsive to the pressure of air flowing from said first portion and operatively connected to said regulating means for altering the flow of air through said duct.

7. In an air conditioning system, a conduit for conveying air from a compressed air source to a confined space, an upstream portion of said conduit being arranged in heat exchange relation with a downstream portion thereof, said downstream portion including an expansion engine for expanding and cooling air passing therethrough, a bypass duct for bypassing a portion of said downstream portion and having a part thereof arranged in heat exchange relation with said upstream portion, regulating means in said part of said duct, and means responsive to both the temperature and pressure of air flowing through said first portion and operatively connected to said regulating means for altering the flow of air through said duct.

8. In an air conditioning system, a conduit for conveying air from a compressed air source to a confined space, an upstream portion of said conduit being arranged in heat exchange relation with a downstream portion thereof, said downstream portion including an expansion turbine for expanding and cooling air passing therethrough, a bypass duct for bypassing a portion of said downstream portion, regulating means in said duct, means in said conduit between said upstream portion and said turbine for separating water from air passing in said conduit, and means responsive to both the temperature and pressure of air flowing through said first portion and operatively connected to said regulating means for altering the flow of air through said duct.

9. In an air conditioning system, a conduit for conveying air from a source of compressed air to an enclosure, a downstream portion of said conduit including an air expansion turbine and a chamber disposed downstream of said turbine, a first upstream portion of said conduit being arranged within said chamber to provide for the transfer of heat from air flowing in said upstream portion to air flowing through said chamber, a second upstream portion of said conduit being arranged to enclose the

inlet to said chamber to provide heat exchange between air passing through said second upstream portion and air passing through said chamber, and means in said conduit between said first upstream portion and said turbine for separating water from air passing through said conduit.

10. In an air conditioning system, a conduit for conveying air from a source of compressed air to an enclosure, a downstream portion of said conduit including an expansion turbine and a chamber disposed downstream of said turbine, a first upstream portion of said conduit being arranged within said chamber to provide for the transfer of heat from air flowing in said upstream portion to air flowing through said chamber, a second upstream portion of said conduit being arranged to enclose the inlet to said chamber to provide heat exchange between air passing through said second upstream portion and air passing through said chamber, means in said conduit between said first upstream portion and said turbine for separating water from air passing through said conduit, a third upstream portion of said conduit being arranged to provide for the transfer of heat between air flowing through said third upstream portion and a cooling fluid, and means for conveying water from said water separating means to cool air passing through said third upstream portion.

11. In an air conditioning system, a duct for connecting a source of compressed air to a space to be conditioned, a regenerative heat exchanger in said duct, said regenerative heat exchanger defining a first flow path and a second flow path downstream from said first flow path, said duct being so arranged that all of the said air passes through said flow paths, said flow paths being arranged in heat exchange relationship with each other, a water separator and an expansion turbine disposed in the order named between said first and said second flow path, whereby substantially all the moisture contained in the compressed air is removed prior to its expansion.

12. In an air conditioning system, a duct for connecting a source of compressed air to a space to be conditioned, a first heat exchanger in said duct having passage means for passing a cooling fluid therethrough, a regenerative heat exchanger in said duct downstream from said first heat exchanger, said regenerative heat exchanger defining a first flow path and a second flow path downstream from said first flow path, said flow paths being arranged in heat exchange relationship with each other, a water separator and an expansion turbine disposed in the order named between said first and second flow paths, and a connection between said water separator and said passage means of said first heat exchanger for injecting water from said water separator into said cooling fluid, thereby to evaporate the water in said cooling fluid to cool the cooling fluid.

13. In an air conditioning system, a main duct for connecting a source of compressed air to a space to be conditioned, a regenerative heat exchanger in said main duct, said regenerative heat exchanger defining a first flow path and a second flow path downstream from said first flow path, said flow paths being arranged in heat exchange relationship with each other, a water separator and an expansion turbine disposed in the order named between said first and said second flow path, a bypass duct directly interconnecting the discharge of said expansion turbine and said main duct downstream from said regenerative heat exchanger, a valve in said bypass duct, and means disposed between said first flow path and said water separator and responsive to the pressure and to the temperature of the air passing therethrough for controlling said valve in response to variations of both the temperature and pressure of said air, thereby to maintain substantially constant the humidity of the air flowing into said space.

14. In an air conditioning system, a conduit for conveying air from a compressed air source to a confined space, an upstream portion of said conduit being arranged in heat exchange relation with a downstream portion thereof, said downstream portion including air expansion means for expanding and cooling air passing therethrough, said upstream portion including a plurality of sections arranged for parallel flow therethrough with the last section being arranged downstream of the first section with respect to the direction of flow of air through said downstream portion whereby the heat exchange at the said last section is between airflows having reduced temperature differential.

15. In an air conditioning system, a conduit for conveying air from a compressed air source to an enclosure, a first portion of said conduit being arranged within a second portion of said conduit to provide heat exchange between air passing through said portions, air expansion means in said conduit between said first and said second portions, a by-pass duct for bypassing said second portion and having at least a part thereof arranged in heat exchange relation with a portion of said conduit upstream of said first portion, valve means in said part for altering the amount of air flowing in heat exchange relation with that flowing in said first portion, and condition responsive means responsive to air in said duct controlling said valve means to maintain a constant humidity in said duct.

16. In an air conditioning system, a conduit for conveying air from a compressed air source to a confined space, an upstream portion of said conduit being arranged in heat exchange relation with a downstream portion thereof, said downstream portion including an expansion turbine for expanding and cooling air passing therethrough; means in said conduit between said upstream portion and said turbine for separating water from air passing in said conduit, and said conduit being so arranged that all of the air passing through said turbine is air which has passed through said upstream portion and said water separating means.

17. In an air conditioning system, a conduit for conveying air from a source of compressed air to an enclosure, a downstream portion, said conduit including an air expansion turbine and a chamber disposed downstream of said turbine, a first upstream portion of said conduit being arranged within said chamber to provide for the transfer of heat from air flowing in said upstream portion to air flowing through said chamber, and a second upstream portion of said conduit being arranged to form an annular space enclosing the inlet to said chamber to provide heat exchange between air passing through said second upstream portion and air passing through said chamber.

18. In an air conditioning system a conduit for conveying air from a compressed air source to an enclosure, a first portion of said conduit being arranged in heat exchange relationship with a second portion of said conduit, air expansion means in said conduit between said first and second portions, a bypass duct bypassing said second portion for altering the amount of air flowing in heat exchange relation with that flowing through said first portion, and means responsive to air passing to said enclosure controlling said bypass duct in response to temperature and pressure whereby to maintain a constant humidity.

19. In an air conditioning system in combination: conditioning means for conditioning air including means for varying the temperature thereof, means for conveying air from the conditioning means to an enclosure, and means responsive to the pressure and temperature of air passing to the enclosure controlling the temperature varying means of said conditioning means prior to the cooling expansion of said air whereby to maintain a constant humidity.

20. In an air conditioning system in combination: means for conditioning air including means for varying the temperature thereof, means for conveying the conditioned air to an enclosure, and means responsive to pres-

sure and temperature of air passing to the enclosure controlling said means for varying the temperature of the air conditioned by said conditioning means, said responsive means being arranged to maintain a linear relationship between the pressure and temperature of the air whereby to maintain a constant humidity.

21. In an air conditioning system in combination: means for conditioning air, and means responsive to the conditioned air including devices responsive to the temperature and pressure thereof controlling the air flow in said conditioning means, the control means being arranged to maintain a linear relationship between the temperature and pressure of the conditioned air whereby to maintain a constant humidity.

22. In an air conditioning system a conduit for conveying air from a compressed air source to an enclosure, a first portion of said conduit being arranged in heat exchange relationship with a second portion of said conduit, air expansion means in said conduit between said first and second portions, a bypass duct bypassing said second portion for altering the amount of air flowing in heat exchange relation with that flowing through said first portion, and control means comprising devices responsive to pressure and temperature in said conduit for controlling said bypass duct, said control means being so arranged that a linear relationship is maintained between the temperature and pressure in said conduit whereby a constant humidity is maintained.

23. In an air conditioning system a conduit for conveying air from a compressed air source to a confined space, an upstream portion of said conduit being arranged in heat exchange relation with a downstream portion thereof, said downstream portion including an expansion engine for expanding and cooling air passing therethrough, a bypass duct for bypassing a portion of said downstream portion and having a part thereof arranged in heat exchange relation with said upstream portion, regulating means in said part of said duct, and means responsive to the temperature and pressure of air flowing through said downstream portion, said last means being operatively connected to said regulating means and being arranged to maintain a linear relationship between the pressure and temperature of the air whereby to maintain a constant humidity.

24. In an air conditioning system in combination: means for conditioning air including means for varying the temperature thereof, means for conveying conditioned air to an enclosure, means in said conveying means for removing entrained moisture from the air, and means responsive to temperature and pressure in said conveying means controlling the flow of air through the means for varying the temperature of air conditioned by said conditioning means, said means responsive to temperature and pressure being arranged to maintain a linear relationship between pressure and temperature of the air whereby a constant humidity is maintained.

25. In an air conditioning system a conduit for conveying air from a compressed air source to a confined space, an upstream portion of said conduit being arranged in heat exchange relation with a downstream portion thereof, said downstream portion including air expansion means for expanding and cooling air passing through water separating means arranged ahead of said air expansion means, and means comprising temperature and pressure responsive devices positioned substantially at the point of water separation for controlling the air conditioning system, said pressure and temperature responsive means being arranged to maintain a linear relationship between the pressure and temperature whereby a constant humidity is maintained.

26. In an air conditioning system in combination: means comprising an expansion turbine, means providing a heat exchange relationship between air passing to said turbine and expanded air flowing from said turbine, means for removing moisture from air flowing to said turbine, and means responsive to temperature and pressure of air flowing to said turbine controlling the performance of said heat exchanger, said temperature and pressure responsive means being arranged to maintain a linear relationship between the pressure and temperature whereby to maintain a constant humidity.

27. In a humidity control system having means for varying the condition of air flowing to an enclosure including means for varying the temperature of the air; control apparatus for controlling the amount of air subjected to the temperature varying means, said control apparatus comprising a bridge circuit; means responsive to pressure of the air controlling one leg of the said bridge circuit, and means responsive to temperature of the air controlling another leg of the bridge circuit whereby the control apparatus is effective to maintain a linear relationship between the pressure and temperature whereby a constant humidity is maintained.

28. In apparatus for controlling air conditioning means: control means including devices responsive to the temperature and pressure of conditioned air controlling the temperature of the air conditioned by said conditioning means, said control means being arranged to maintain a linear relationship between the temperature and pressure of the conditioned air whereby to maintain a constant humidity, the said control means comprising a bridge circuit having the said pressure responsive means arranged to adjust the resistance of one leg thereof and the temperature responsive means being arranged to control the resistance of another leg thereof.

29. In an air conditioning system having means for conditioning air, including means to which air is subjected for varying the temperature thereof and means for conveying air from the conditioning means to an enclosure: means responsive to the pressure and temperature of air passing to the enclosure controlling the amount of air subject to the means for varying the temperature of the air, said pressure and temperature responsive means being controlled relative to each other whereby to maintain a constant humidity in said air.

References Cited in the file of this patent

UNITED STATES PATENTS

2,250,946	Brown	July 29, 1941
2,412,071	Warner	Dec. 3, 1946
2,451,280	Del Mar	Oct. 12, 1948
2,474,441	Sparrow	June 28, 1949
2,484,850	Paget	Oct. 18, 1949
2,499,832	Palmatier	Mar. 7, 1950
2,562,918	Hynes	Aug. 7, 1951
2,622,406	Scofield	Dec. 23, 1952
2,632,307	Massey	Mar. 24, 1953
2,710,724	McMahon	June 14, 1955
2,757,868	Kreuttner	Aug. 7, 1956
2,844,322	Kautz	July 22, 1958