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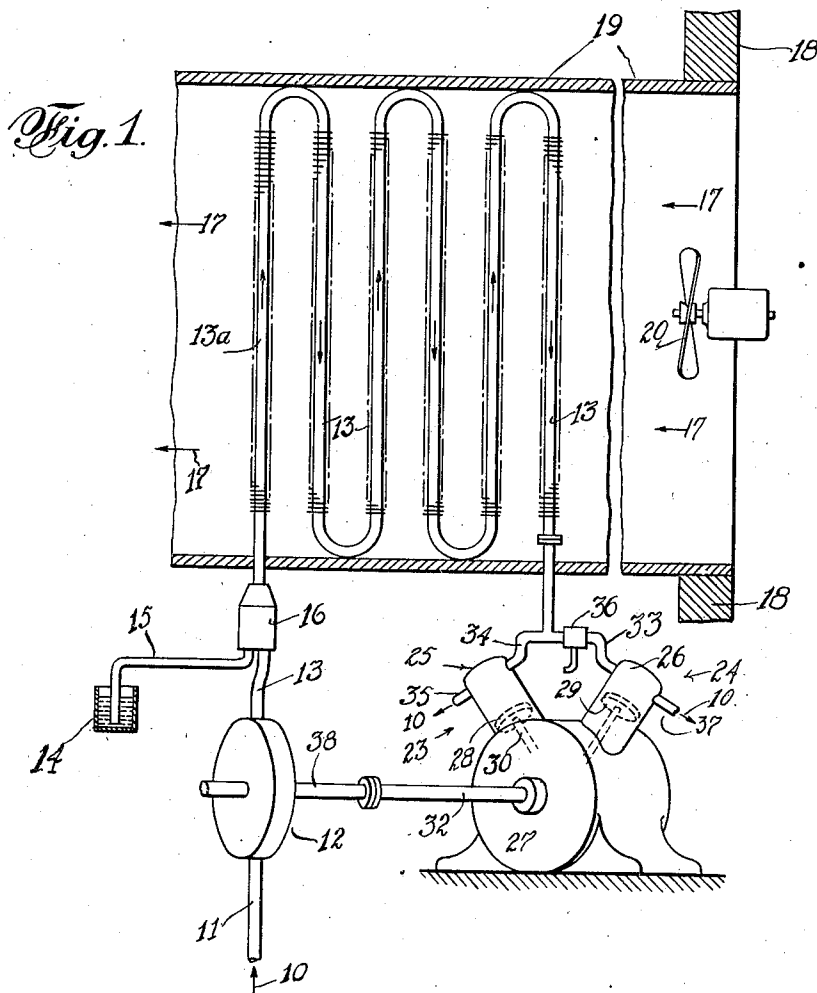
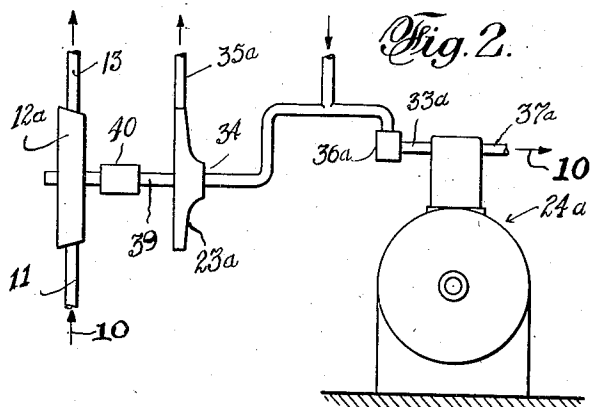
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2,175,163

METHOD AND APPARATUS FOR PRODUCING REFRIGERATION

Filed Sept. 2, 1937

2 Sheets-Sheet 1



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2 Sheets-Sheet 2

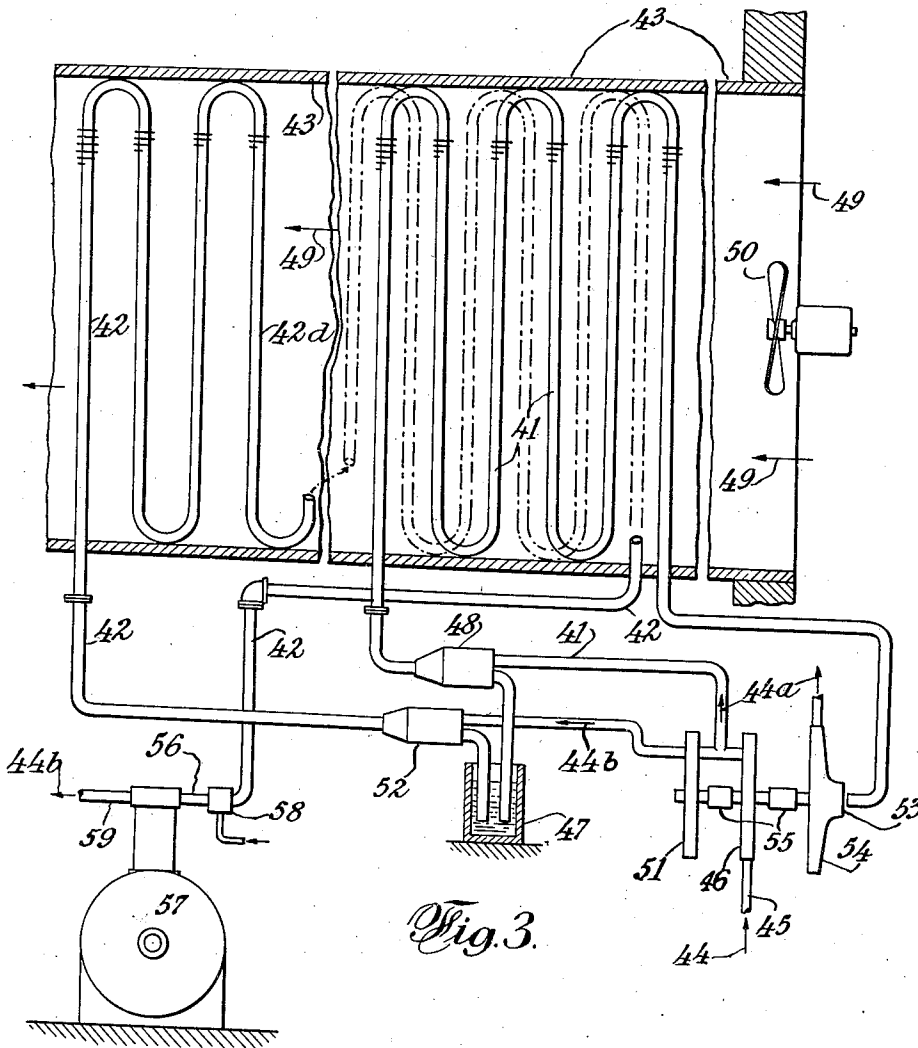


Fig. 3.

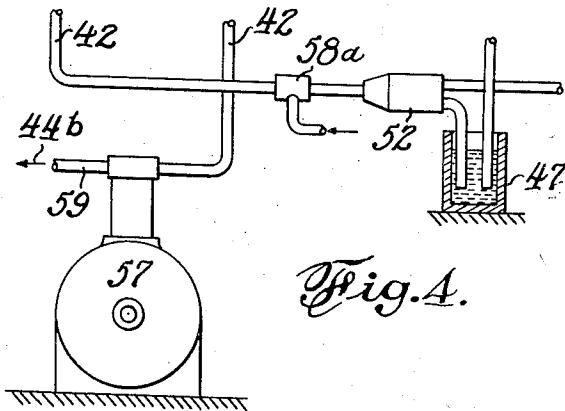


Fig. 4.

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METHOD AND APPARATUS FOR PRODUCING REFRIGERATION

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Application September 2, 1937, Serial No. 162,073

16 Claims. (Cl. 62—90)

This invention relates to improvements in evaporative cooling processes carried out at controlled sub-atmospheric pressures, as generally and broadly described and claimed in my copending application, Serial No. 125,823, filed February 15, 1937; and in its more particular aspects to improvements in apparatus for practicing such process.

The cooling, or refrigeration, method with which the invention is primarily concerned may be briefly described as comprising the steps of expanding any gaseous working fluid to sub-atmospheric pressure of such degree as materially to decrease the vapor pressure thereof, then saturating it with the vapors of an unchilled liquid, and finally passing the expanded-saturated fluid through a closed path in indirect counterflow, heat-exchanging relation with the medium to be cooled. For a more complete description of the process and a better understanding of its nature and advantages, reference may be had to the above-identified co-pending application.

The principal object of the invention is to provide an improved method, and combination of apparatus, for compressing and discharging the working fluid from its closed path after an interchange of heat between the fluid and the medium to be cooled has been effected; and more specifically, to utilize the inherent pumping capacity of an internal combustion engine, in combination with that of a separate compressor element, for achieving this desired end in a most economical manner.

It is a further object of the invention to provide a modified and improved process comprising a series of cooling stages each operating at a different sub-atmospheric pressure, and an apparatus for practicing the process including a plurality of working fluid conduits which are arranged in series with respect to the flow of medium to be cooled and in series-parallel relation with a plurality of expander elements so that working fluid may be supplied to each at a different sub-atmospheric pressure.

The full nature of the invention, along with various other objects and advantages, will be more fully understood from a consideration of the following description when read in connection with the accompanying drawings, in which:

Figure 1 is a diagrammatic view, in elevation, illustrating the application of the improved compressing and discharging method and apparatus to a single stage, sub-atmospheric evaporating cooling process of the general type above defined.

Fig. 2 is a like view, illustrating a modified compressor-expander-engine combination adapted to be substituted for the same parts of the apparatus of Fig. 1.

Fig. 3 is a like view illustrating the two-stage cooling process of the invention, and the application of the compressing and discharging method and apparatus thereto.

Fig. 4 is a fragmentary diagrammatic view illustrating a modified arrangement of the structure of Fig. 3, only those parts being shown which are necessary to a complete understanding thereof.

A general understanding of the sub-atmospheric evaporative cooling process will best be gained by a consideration of the practical adaptation thereof illustrated in Fig. 1. In that embodiment a volume of working fluid 10, which may be assumed to be air at 95° dry bulb and atmospheric pressure, is intaken through conduit 11, and expanded, through expander 12, to some desired sub-atmospheric pressure. The expanded air is then passed through the closed path defined by conduit 13, in contact with an unchilled and unheated water surface, for the purpose of saturating it with water vapor, and thus cooling it, by evaporation in accordance with well known psychrometric laws. Preferably the water surface extends throughout the entire length of the path, and the evaporative cooling of the air is a progressive and continuous process, all as will hereinafter more fully appear.

The extent of expansion will depend upon the degree of reduction of vapor pressure, wet bulb temperature, and total heat content necessary to secure the desired degree of cooling. Usually, a pressure reduction of substantially five inches of mercury will suffice, but if the wet bulb temperature and vapor pressure of the incoming air are relatively high, then greater reductions will be utilized.

The water necessary to produce the above-mentioned surface may be introduced into the conduit in any desired way. The method here illustrated utilizes the difference in air pressure, existing on the opposite sides of the conduit 13, to force water from reservoir 14, through tube 15, and to spray it into the mixing chamber 16. There the spray meets the high velocity stream of expanded air, some of it is immediately evaporated, and the excess is carried along by the air throughout the length of the conduit. In this manner the walls of the conduit are kept wetted, and, conversely, the air is kept in constant contact with a water surface.

The medium to be cooled may, for example, be a second volume of air, 17, which has been returned from an air conditioned enclosure defined by the walls 18, through conduit 19, under the influence of any appropriate fan or the like, 20.

The arrangement of the conduit 13 in the conduit 19 is such that the working fluid 10 passing therethrough, in the direction indicated by the arrows, meets the incoming medium to be cooled, 17, in indirect counterflow, heat-exchanging relation. More specifically, the part of the working fluid in the section 13a of the conduit will be saturated with water vapor at the wet bulb temperature of the fluid as it leaves the expander—the lowest temperature attainable in the process—and as this fluid passes through the conduit from left to right, as viewed in Fig. 1, its temperature, due to the absorption of heat from the medium to be cooled, will tend constantly to rise. Conversely, the temperature of the medium 17, moving through its conduit in the opposite direction, will lose heat and its temperature will tend constantly to decrease. In other words, the warmest fluid meets the warmest medium, while the coldest fluid is in heat exchange relation with the coldest medium. In this way a maximum amount of cooling is obtained for any given working fluid temperature spread.

The water vapor content of any gaseous fluid is, of course, a function of the temperature of that fluid. If, as above assumed, the fluid is saturated, or substantially so, in the portion 13a of the conduit, then as its temperature increases during the heat interchange, its saturation vapor pressure will increase and its ability to evaporate water will increase correspondingly. Since the fluid is at all times in contact with an unchilled water surface—the wetted walls of the conduit—it is evident that the evaporation of moisture by the fluid will continue throughout the entire heat interchange. From the foregoing it will be evident to those skilled in the art, that the process is carried out substantially along a saturation line. This means, of course, that the heat picked up by the fluid will be converted principally into latent, rather than sensible, heat; and translated into other terms, it means that for any given temperature spread, the fluid will pick up a quantity of heat far in excess of that represented by its sensible heat gain.

The expansion of the working fluid into the left hand portion of the conduit 13, can be continued only so long as a like amount of fluid is withdrawn from the right hand terminal of the conduit. Since air, the fluid chosen, is available in unlimited quantities, and costs nothing, it may be thrown away when it has served its function. In each modification relating to the phase of the invention, the inherent pumping capacity of an internal combustion engine is made use of to assist in the evacuation of the conduit—to supplement a pump in withdrawing air from the system, and in compressing and discharging the heated and moisture laden fluid therefrom—in a manner which will be considered hereinafter.

In the modification of Fig. 1 the compressor or pump 23 is of the reciprocating piston type, and its cylinder 25 may conveniently be mounted with the cylinder 26 of the internal combustion engine 24 upon a common crank case so that its piston 28 may be connected, through rod 30, directly to the crankshaft 32 of the engine. This arrangement provides for the direct driving of the

pump in a very simple way, and also avoids the duplication of many parts.

The fuel for the engine 24 may be illuminating gas, gasoline, fuel oil, or the like. Whatever its character, it is mixed with a relatively large volume of air and "sucked" into the cylinder by the movement of the piston 29. Since the fluid which must be exhausted from the conduit 13 is air, it is apparent that the engine may be used as a pump supplementing the capacity of pump 23. Accordingly the engine intake 33 is connected to one arm of the manifold at the terminal of conduit 13, and the pump intake 34 is connected to the other arm thereof. In operation, of course, the pump 23 will exhaust a part of working fluid (air) from conduit 13, and discharge it to the atmosphere at 35. The remaining part will be intaken through the carburetor or mixing valve 36, the resulting mixture will be compressed in the cylinder, and burned, and at the completion of the power stroke the spent gases will be discharged through the exhaust opening 37, all in the well understood manner. From the foregoing it will be evident that the working fluid which is intaken into the engine will be compressed and discharged exactly as required for an operation of the cooling process. The power for the operation of the above described system is, in the last analysis, derived entirely from engine 24. In the preferred arrangements this requirement is minimized, is very considerably reduced, by recovering energy made available by the expansion of the working fluid, and by utilizing this recovered energy to assist in the subsequent compression step. One way of accomplishing this is shown in Fig. 1. There a turbine, or other comparable device, is used as an expander 12, and its shaft 38 is coupled directly to the crank shaft 32 of the engine. With such an arrangement the only power taken from the engine will be that represented by the inefficiency of the expander and of the pumping element, the ordinary friction losses resulting from the passage of the working fluid through its conduit at high velocity, and the work due to increased heat content of medium 10.

The directly connected expander-compressor-engine combination above described is advantageous from the standpoint of simplicity. With this arrangement, however, all of the elements must run at the same speed, or, if gear trains are used, then in some definite speed ratio. Such an arrangement is relatively inflexible, and does not lend itself to a control of the expansion of the working medium. An equally simple, and much more flexible system, is illustrated in Fig. 2. In that modification, the compressor 23a (illustrated diagrammatically as a centrifugal blower) is driven entirely by the energy derived from the expansion of the working fluid through expander 12a. Hence both of these elements are mounted upon a common shaft 39 journaled in bearings 40. Obviously the expander will not provide sufficient power to compress the entire volume of working fluid to atmospheric pressure, for some losses will be encountered both in expansion and compression, and otherwise. Accordingly, this element is designed to handle only a portion of the total volume, and the remainder is exhausted, compressed and discharged by the engine 24a in exactly the same way as was described in connection with Fig. 1. This expander-compressor combination, 12a—23a, is termed a "free floating" element, the name of course being derived from the fact that the constituent parts float along

together without any mechanical connection with the engine. As such, it has certain very definite advantages with regard to design, construction and operation. Thus, the element may be designed to operate at high speeds; and the bulk thereof may be limited in that way. Further, both constituent parts of the element may be mounted in a common casing so as to avoid the use of stuffing boxes, and other complications.

The engine, too, may be designed for operation at optimum speeds. Moreover, the arrangement lends itself most readily to control of the degree of expansion of the working fluid. To accomplish this it is only necessary to increase or reduce the engine speed; and the free floating will follow the variation in definite relation.

A modified cooling process, utilizing the general principles set forth in the identified co-pending application, and briefly described above, is shown in Fig. 3. Here the closed path for the working fluid is divided into a plurality of stages arranged, physically, one behind the other so that the medium to be cooled may be passed successively thereover; and the working fluid is expanded separately, and at different pressures, into each of these individual paths. In the preferred embodiment, a given volume of working fluid is first expanded to some desired low pressure corresponding to the pressure which is to be carried in the first stage, that is, the first working fluid path, and a portion of this expanded fluid is then conducted through that path, saturated with water vapor, and, when spent, is compressed and discharged from the system. The remaining part of the expanded fluid is further expanded to some lower pressure, and passed through the second working fluid path. After saturation, and heat exchange with the medium to be cooled, it is compressed and discharged. Only two stages have been illustrated, but others may be added where desired.

The apparatus for carrying out the process comprises a plurality of working fluid conduits 41, 42, and others if desired, arranged one behind the other within the path of the medium to be cooled (defined by the conduit 43) so that the latter medium may be passed counterflow to the working fluid in each stage, and counterflow to the stages. Considering the operation of the process, a single volume of air (working fluid) 44 is intaken through inlet 45 and expanded at 46, to some desired low pressure, say 7 inches of mercury vacuum, for example. A portion of this expanded air 44a is then passed through the first stage, comprising the conduit 41. Unchilled water from reservoir 47 is sprayed into this high velocity stream of air 44a through injector 48, the latter being arranged to operate in any desired way for the purposes, and in the manner, hereinbefore described. As the working fluid 44a, cooled by evaporation, passes through its conduit, from left to right as viewed in Fig. 3, it will be in indirect counterflow, heat-exchange relationship with the volume of relatively warm air 49 taken from any desired source, and passing, from right to left as indicated by the arrows, through the conduit 43 under the influence of fan 50. Accordingly, the working fluid will absorb heat from the medium to be cooled along a saturation line exactly as was hereinbefore described, and the air 49 will be cooled substantially to the wet bulb temperature of the fluid 44a as the latter leaves the expander 46. In this stage of the process, the interchange may be continued until the temperature of the medium 44a substantially equals that

of the incoming air 49; and in practice, it is so continued within economical limits.

The remaining portion of the original volume of air, 44 is passed through a second expander, 51, wherein its pressure is further reduced, say to 10 inches of mercury vacuum, for example, and the expanded volume 44b, is then led through the conduit 42 comprising the second stage of the process. Water, again from the reservoir 47 or any other source, is sprayed into this high velocity stream of air by means of the injector 52, so as to saturate the air and maintain the sides of the conduit in a wetted condition.

This latter portion of the working fluid too, passes in counterflow, heat-exchange relation with the air 49 so as to absorb heat along a saturation line, and thus cool the air to some desired final low temperature. When, during the course of this interchange, the temperature of the fluid 44b rises to a point approximating that of the working fluid 44a in some part of its conduit 41, then it is led away for disposal in a suitable manner. So far, for purposes of clarity in description, it has been assumed that this occurs at a point subsequent to the first stage; that the two stages are located, physically, one behind the other as shown in full lines in Fig. 3. Actually, however, the temperature of the working fluid in the section 42d of its conduit, is somewhat lower than that of the medium in the section 41a of the first stage, and likewise, of course, lower than that of the air surrounding section 41a. Further interchange between the fluid 44b and air 49 is thus economically feasible. Accordingly, the conduit 42 may be extended, as shown in dotted lines in the drawings, so that it parallels a portion of the conduit 41. Theoretically, it may be continued for the full length of the latter conduit, as shown, but economic considerations may dictate a stoppage short of that limit. The practical limit cannot be defined with precision, but it will usually be found desirable and economical to arrange the conduits 41 and 42 so that the second stage overlaps the first one.

The volume of fluid 44a, after heat exchange, as above described, is discharged into the inlet 53 of the compressor 54 (corresponding to compressor 23 of Figs. 1 and 2), and in that compressor, of course, its pressure is raised to some point above atmospheric sufficient so that it may be discharged to the ambient atmosphere. The power to drive this compressor may be derived from any desired source. In the preferred embodiment, the compressor, and the two expander elements 46 and 51, are mounted upon a common shaft journaled in appropriate bearings 55 to form a free floating element of the type described in connection with Fig. 2. Thus, the power derived from the expansion of the entire volume of air 44 is utilized to re-compress only that portion of the total represented by 44a.

The portion of fluid 44b must also be compressed and discharged from its conduit, 42, when the heat-exchange has been completed. While any type of compressor will serve the purpose, it will be apparent from the foregoing that the situation lends itself very readily to the use of an internal combustion engine, as shown. Accordingly, the conduit discharges into the intake manifold 56 of an internal combustion engine 57 (corresponding to engine 24 of Figs. 1 and 2) so that the fluid, after mixing with an appropriate volume of fuel gas or vapor in the carburetor or mixing valve 58, may pass into the cylinder of the engine, and be compressed, burned and dis-

charged, through exhaust 59, all in the manner described in connection with Fig. 1. The engine, of course, furnishes all of power required for the operation of the system, but that power is only that needed to offset the various losses which are inherent in the process and mechanical adjustment. It will again be noted, however, that the utilization of the pumping capacity of an engine instead of a separate pump driven by the engine reduces the needed equipment and the losses incurred in its operation.

In the apparatus of Fig. 3, as above described, it will be noted that the fuel is mixed with the working fluid subsequent to the heat exchange. Certain benefits may be derived, however, by introducing this material through the carburetor, or mixing valve 58a prior to the exchange as shown in Fig. 4. Thus, if a liquid fuel such as gasoline is used, then the evaporation thereof by the air stream will absorb a certain amount of heat over and above that absorbed by the evaporation of the water vapor. On the other hand, if the fuel is manufactured, or natural, gas, this gas will have a certain water vapor absorbing capacity, over and above that of the air. In either case, the introduction of the fuel, as at 58a, will tend to increase the heat-absorbing capacity of the system, and this, at no extra expenditure of energy.

The staged cooling process, above described, produces certain economies both in construction and operating costs. In practicing it, as will be noted, only a part of the total volume of working fluid is expanded to the final low pressure; the major portion being expanded to some lesser extent. Consequently, the losses occasioned in expanding and re-compressing are minimized. Further, the second stage volume, 44b, is of such proportions that it may be handled very effectively by the pumping effect of the engine. Control of expansion may be easily and effectively obtained, too, and this by merely throttling the engine. All of the advantages derived from the use of the free floating element, heretofore set forth in connection with the description of Fig. 2, likewise apply.

An advantage, common to both of the processes disclosed, flows from the well known fact that the performance of any internal combustion engine may be improved by saturating the air, utilized as a part of the fuel mixture, with water vapor. In this connection it is to be noted that the working medium, as it leaves its path, is in substantially saturated condition. Hence the use of this air in the engine will tend to improve the performance, rather than decrease it.

Since certain changes may be made in the foregoing process and in the apparatus for practicing it, it is intended that the foregoing shall be construed in a descriptive rather than in a limiting sense.

What I claim is:

1. The method of cooling a medium, which comprises expanding a volume of air to sub-atmospheric pressure of such degree as will materially reduce its water vapor pressure, passing such expanded air through a closed path in contact with an unchilled water surface which extends substantially the full length of the path, passing a medium to be cooled through a second closed path in counterflow, heat-exchanging relation with the saturated-expanded air in the first path, withdrawing such air and discharging it from the first-mentioned closed path, and utilizing the pumping capacity of an internal combustion

engine to assist in such withdrawal and discharge.

2. Apparatus for cooling a medium, comprising a conduit, means for expanding air to sub-atmospheric pressure of such degree as will materially reduce its water vapor pressure and for discharging the expanded air into said conduit adjacent one end thereof, means for injecting water into said conduit in such quantities as will maintain its surfaces wetted substantially throughout its length, means for passing a medium to be cooled over said conduit in counterflow, heat-exchanging relation with the expanded air therein, and means including an internal combustion engine having its intake manifold connected to said conduit for withdrawing, compressing and discharging said air from said conduit.

3. Apparatus for cooling a medium, comprising a conduit, an expander element for expanding air into one end of said conduit at sub-atmospheric pressure and for recovering the energy of such expansion, means for injecting water into said conduit, a compressor for withdrawing, compressing and discharging a part of the air from the other end of said conduit, means for utilizing the recovered energy of expansion in driving said compressor, an internal combustion engine having its intake also connected to the said other end of said conduit for withdrawing, compressing and discharging the remainder of said air; and means for passing the medium to be cooled over said conduit in indirect, counterflow, heat-exchanging relation with the expanded air.

4. Apparatus for cooling a medium comprising a conduit, an expander element for expanding air into one end of said conduit at sub-atmospheric pressure and for recovering the energy of such expansion, means for injecting water into said conduit adjacent the first-mentioned end thereof, a compressor for withdrawing, compressing and discharging a part of the air from the other end of said conduit, said expander and said compressor being mechanically connected so that the former drives the latter, an internal combustion engine having its intake also connected to the said other end of said conduit for withdrawing, compressing and discharging the remaining part of said air; and means for passing the medium to be cooled over said conduit in indirect counterflow, heat-exchanging relation with the expanded air.

5. Apparatus for cooling a medium according to claim 4, further characterized in that the compressor, expander and engine are all mechanically connected together so that the former is driven by the combined effort of the latter two.

6. Apparatus for cooling a medium according to claim 4, further characterized in that the engine shaft has no physical connection either with the expander or with the compressor.

7. Apparatus for cooling a medium, comprising a first conduit defining a path for such medium; second and third conduits arranged one behind the other in said first conduit; a first expander element adapted to expand a volume of air to a predetermined sub-atmospheric pressure, to discharge a portion of said expanded air into one end of said second conduit, and to recover the energy of such expansion; means for injecting water into said second conduit; and a compressor for withdrawing, compressing, and discharging said air from the other end of said second conduit; a second expander element adapted to expand the remaining portion of said volume of air to some lower sub-atmospheric pressure, to dis-

charge it into one end of the third conduit, and to recover the energy of such expansion; means for injecting water into the third conduit; an internal combustion engine having its intake connected to the other end of said third conduit for withdrawing, compressing and discharging air therefrom; means for connecting said first and second expanders with said compressor whereby to drive the latter; and means for passing the medium to be cooled through said first conduit over said second and third ones in indirect, counterflow, heat-exchanging relation with the expanded air in the latter two.

8. The method of cooling a medium, which comprises expanding a volume of working fluid to sub-atmospheric pressure of such degree as will materially reduce the vapor pressure of such fluid, passing a part of such expanded fluid through a first closed path in constant contact with water, whereby to saturate such fluid with the water vapor, further expanding the remaining part of said volume of fluid to some lower sub-atmospheric pressure, passing such further expanded fluid through a second closed path in constant contact with water whereby to saturate it with water vapor, and passing the medium to be cooled in counterflow, heat-exchanging relation successively with the expanded fluid in the first and second paths.

9. The method of cooling a medium, which comprises expanding a volume of air to a predetermined sub-atmospheric pressure such as will materially reduce the vapor pressure of such air, passing a part of the expanded air through a first closed path in contact with a water surface extending substantially the full length of the path, further expanding the remaining part of the air to some desired lower sub-atmospheric pressure, passing such further expanded air through a second closed path in contact with a water surface extending substantially the full length of the path, and passing the medium to be cooled in indirect, counterflow, heat-exchanging relation with the expanded air in the first and second mentioned paths.

10. The method of cooling a medium, which comprises expanding a volume of air to a predetermined sub-atmospheric pressure such as will materially reduce the vapor pressure of such air, passing a part of the expanded air through a first closed path in contact with a water surface extending substantially the full length of the path, further expanding the remaining part of the air to some desired lower sub-atmospheric pressure, passing such further expanded air through a second closed path in contact with a water surface extending substantially the full length of the path, passing the medium to be cooled in indirect, counterflow, heat-exchanging relation simultaneously with the expanded air in parts of the first and second mentioned paths and then with the expanded air in the remaining part of the second mentioned path, and finally compressing the different portions of expanded air and discharging them from their respective paths.

11. The method of cooling a medium according to claim 10, further characterized by the steps of recovering the energy of each expansion of the air, and utilizing such energy to assist in the subsequent compression step.

12. The method of cooling a medium according to claim 10, further characterized by the steps of recovering the energy resulting from both expansion steps and utilizing such energy in compressing and discharging the air only from the first mentioned path.

13. The method of cooling a medium which comprises expanding air to sub-atmospheric pressure of such degree as will materially reduce the vapor pressure of such air, passing such expanded air through a first closed path in substantially constant contact with water whereby to saturate such air with water vapor, expanding air other than that passed through the first closed path to some lower sub-atmospheric pressure, passing such other expanded air through a second closed path in substantially constant contact with water whereby to saturate it with water vapor, and passing the medium to be cooled in counterflow heat exchanging relation with the expanded air in the first and second mentioned closed paths.

14. The method of cooling a medium according to claim 13 characterized by the further step of withdrawing the expanded air and compressing and discharging it from the closed paths.

15. Apparatus for cooling a medium comprising a first conduit defining a path for such medium; a first expander element adapted to expand air to a predetermined sub-atmospheric pressure, a second conduit disposed in the first one and having an end connected with said first expander to receive air thereupon, means for injecting water into said second conduit, and means for withdrawing, compressing and discharging air from the other end of said second conduit; a second expander element adapted to expand air to some sub-atmospheric pressure which is lower than that attained by the first mentioned expander, a third conduit disposed in the first mentioned one behind the second mentioned conduit, said third conduit having connection at one of its ends with said second mentioned expander to receive expanded air therefrom, means for injecting water into said third conduit, means for withdrawing, compressing and discharging air from the other end of said third conduit; and means for passing a medium to be cooled through said first mentioned conduit over said second and third mentioned ones in indirect counterflow heat-exchanging relation with expanded air in the latter two conduits.

16. Apparatus for cooling a medium according to claim 15 further characterized in that said expanders are adapted to recover energy from the expansion of air therethrough, in that the means for withdrawing air from one of said conduits is a compressor, and in that said compressor is connected to said expanders to be driven thereby.

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