Nov. 23, 1971 R. G. MOKADAM 3,621,667

COOLING APPARATUS AND PROCESS

Filed Nov. 28, 1969 2 Sheets-Sheet 1

FIG. 1

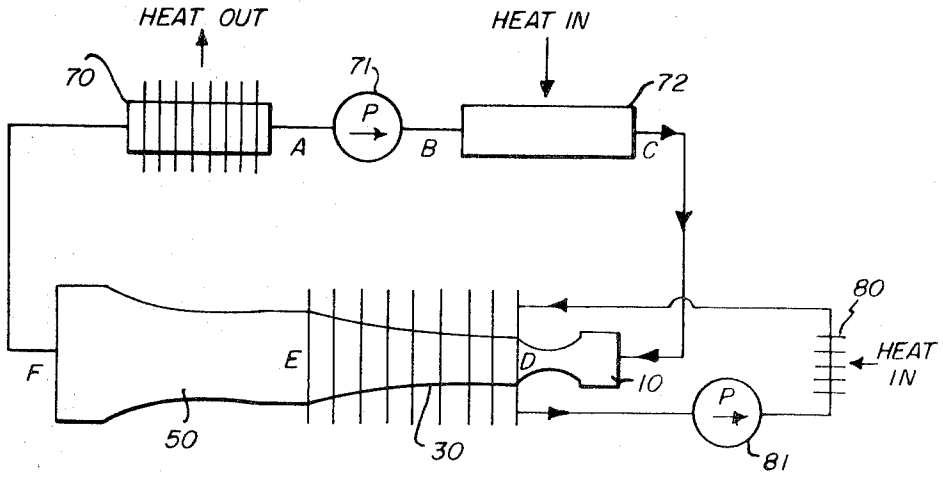
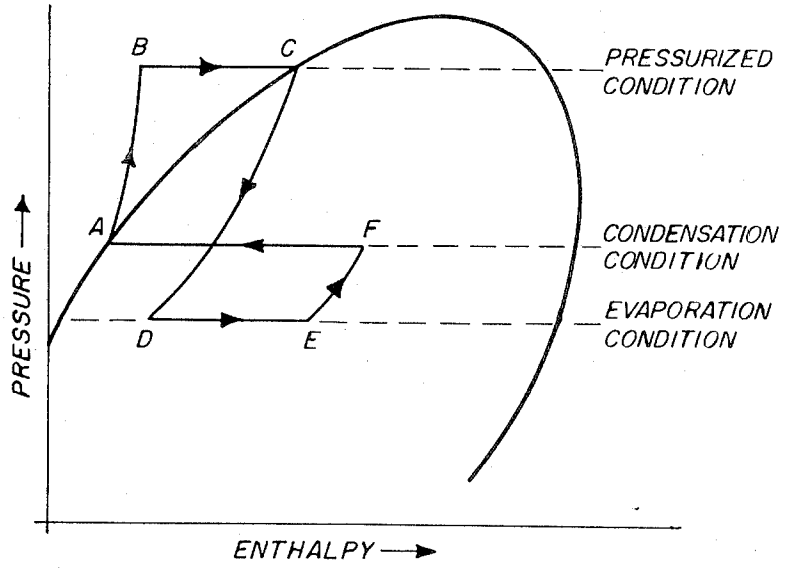



FIG. 2

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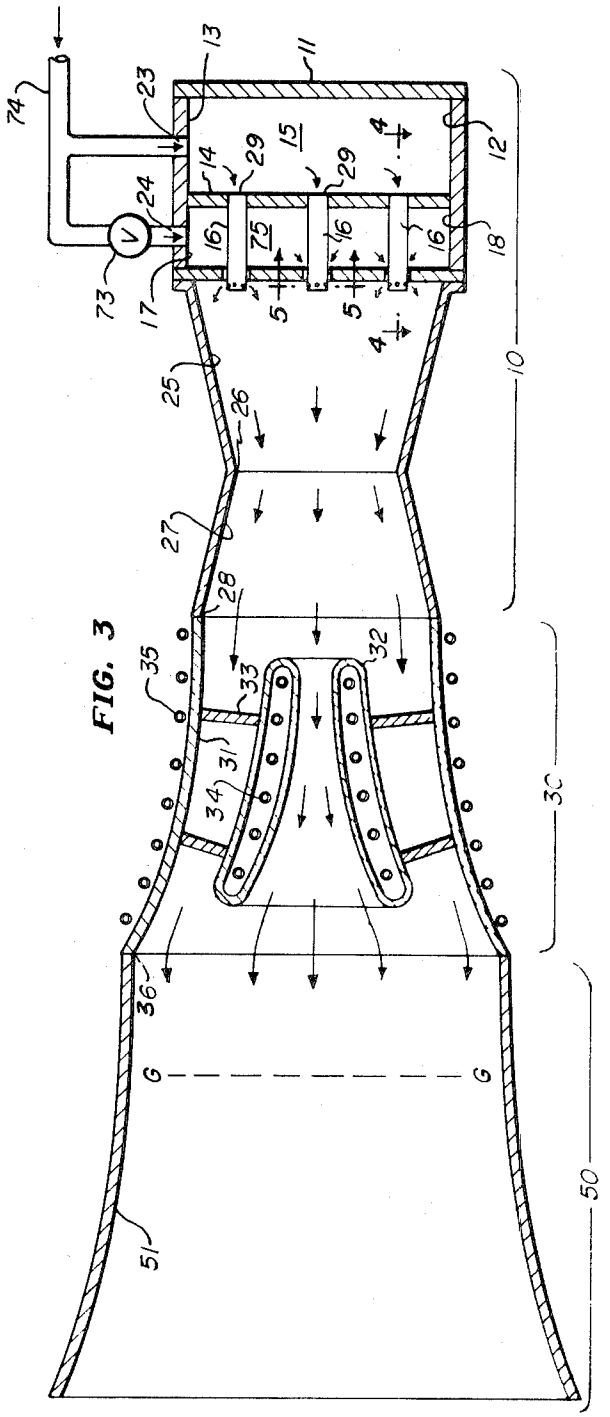


FIG. 3

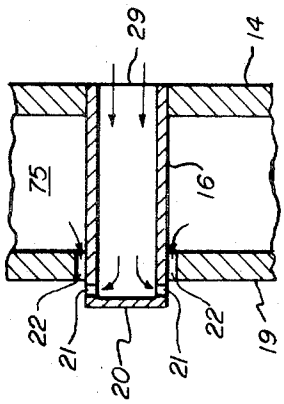


FIG. 4

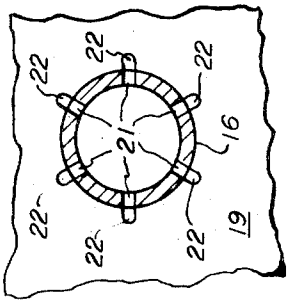


FIG. 5

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# COOLING APPARATUS AND PROCESS

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U.S. Cl. 62—116 10 Claims

## ABSTRACT OF THE DISCLOSURE

A high efficiency cooling process and apparatus utilizing a closed fluid refrigerant containing loop having a sequential communication; a liquid pump, a liquid heater, an adiabatic nozzle to obtain supersonic dual phase fluid flow and expansion of the fluid refrigerant to evaporation conditions, a dynamic evaporator for supersonic flow and in thermal exchange relationship with a confined volume to be cooled, a diffuser reducing the velocity of the fluid and increasing the pressure of the fluid to condensation conditions, and a thermal exchanger to condense the fluid to a liquid for recycling.

## BACKGROUND OF THE INVENTION

Cooling systems have generally required a vapor compressor to condense the vapor from the evaporator to higher pressure so that the heat taken up by the refrigerant may be rejected from the system at a higher temperature. Vapor compressors are usually mechanical compressors which are large in size, relatively inefficient, high in noise level and high in cost.

Ejectors or jet pumps have been proposed to overcome some of the above disadvantages in the operation of multiple phase cooling systems. However, ejectors have been found to be relatively inefficient due to momentum transfer through large velocity differences and heat transfer through large temperature differences existing between the driving and driven streams. Further, the separated two phases ejector systems have necessitated different treatments of the two phases resulting in complicated multiple loop systems.

Various nozzle type cooling systems have been proposed utilizing subsonic diabatic nozzles which have been relatively inefficient and requiring a vapor pump to compress the vapor flow to the cooler or condenser. This system again possesses the disadvantages referred to above of having a vapor pump in the system.

## DESCRIPTION OF THE INVENTION

My invention comprises a novel configuration of components providing a high efficiency cooling process and apparatus having minimum energy input requirements. I achieve high efficiency cooling by a closed loop refrigerant cycle comprising compressing a liquid refrigerant to a pressurized, sub-cooled state, heating the liquid at constant pressure until it is substantially completely saturated, passing the pressurized, saturated fluid through an adiabatic nozzle obtaining supersonic flow of liquid-rich two phase fluid at evaporator conditions of temperature and pressure, passing said fluid at supersonic velocities through a dynamic evaporator at substantially constant temperature and pressure and vaporizing a substantial portion of the liquid on surfaces of the evaporator in thermal exchange relation to a confined space to be cooled, passing the resulting vapor-rich refrigerant through an adiabatic trans-sonic diffuser to obtain suitable condenser pressure and velocity, condensing the vapor to liquid by thermal exchange with the exterior environment, and returning the liquid refrigerant for compression and recirculation.

Accordingly, it is an object of my invention to provide



an efficient closed refrigerant loop cooling process and apparatus to avoid many of the disadvantages of the prior methods discussed above.

Another object of my invention is to provide a cooling system utilizing expanded liquid to obtain desired cooling directly from evaporation through heat transfer with the heat load.

Still another object of my invention is to provide a cooling system wherein the refrigerant fluid is diffused to condensation conditions of pressure and temperature.

Another object of my invention is to provide an efficient cooling system through utilization in sequential combination of a refrigerant fluid adiabatic nozzle to obtain supersonic velocities, a supersonic dynamic evaporator in thermal exchange relation with the heat load, and a fluid trans-sonic diffuser to reduce the pressure and velocity of the refrigerant to condenser conditions.

Yet another object is to provide a cooling system using a liquid pump to obtain high pressure refrigerant and then adding heat energy to the liquid refrigerant at substantially constant pressure prior to introduction to the adiabatic nozzle.

A further object is to provide a cooling system with the minimal number of mechanical working parts.

These and other important objects of the invention will become apparent from the following description taken in conjunction with the drawings illustrating preferred embodiments wherein:

FIG. 1 is a schematic diagram of a cooling apparatus according to one embodiment of this invention;

FIG. 2 is a graph showing the specific enthalpy and pressure properties of the schematic system shown in FIG. 1;

FIG. 3 is a detail sectional view of the nozzle dynamic evaporator-diffuser suitable for use in the cooling apparatus of FIG. 1;

FIG. 4 is a cross section along the line 4—4 shown in FIG. 3; and

FIG. 5 is a sectional view shown along line 5—5 in FIG. 3.

Referring specifically to FIG. 1, the closed refrigerant loop comprises in sequential communication liquid pump 71, liquid heater 72, adiabatic nozzle 10, dynamic supersonic evaporator 30, trans-sonic adiabatic diffuser 50 and condenser 70. The cooling effect from the system is obtained in the dynamic evaporator where heat from the medium to be cooled is exchanged to the refrigerant causing vaporization of the refrigerant at substantially constant temperature and pressure. Room air to be cooled may be circulated directly through cooling passages surrounding the evaporator surfaces, or alternatively, a secondary non-evaporating refrigerant may be passed through the cooling passages surrounding the evaporator surfaces and utilized in a suitable thermal exchanger to cool room air.

Two important improvements in my cooling process are the improvements comprising utilizing expanded liquid directly for evaporation through thermal exchange with the heat load, and in diffusing supersonic refrigerant fluid to sub-sonic velocities and condenser pressures.

In FIG. 1 in a preferred embodiment pump 81 may be an air blower while thermal exchanger 80 represents the heat load added to the system by the pick up of heat from the closed space to be cooled, the warmed air being directly recirculated through the thermal exchange passages of the dynamic evaporator. In another embodiment a non-evaporating liquid refrigerant may be driven by pump 81 through thermal exchanger 80 wherein the liquid refrigerant acquires thermal energy from the closed space to be cooled and is recirculated through the thermal exchange passages of the dynamic evaporator.

The letters A through F in FIG. 1 represent the enthalpy pressure state of the refrigerant fluid as shown in FIG. 2.

At state A in the cycle as shown in FIGS. 1 and 2, the refrigerant fluid is entirely liquid having the lowest heat content in the cycle. The liquid is compressed nearly isentropically using a conventional liquid pump **71** to high pressure state B. The liquid at state B is sub-cooled. The pressurized sub-cooled liquid at state B is then passed through liquid heater **72** in which the liquid phase is maintained by control of both temperature and pressure. The liquid is heated at substantially constant pressure imparting thermal energy to the liquid to result in substantially saturated liquid at state C. The liquid heater **72** may be of any suitable type to impart thermal heat to the liquid. Gas fired heating is preferred, but thermal heat obtained from electrical energy or burning of mineral materials may be utilized. The liquid at state C being high pressure, high temperature, and substantially completely saturated enters an adiabatic nozzle wherein it is expanded substantially isentropically to obtain supersonic flow of excited two phase fluid at evaporator temperature and pressure. The liquid refrigerant is emitted from the nozzle in droplets in a vapor flow of from 2 to 4 times the velocity of sound, about 3 times the velocity of sound being preferred. The quality of the fluid at this point is liquid-rich and there is little slip between the different phases.

The fluid stream, at supersonic velocity, liquid-rich exits from the nozzle at state D at evaporation conditions of temperature and pressure and enters directly to a dynamic evaporator generally referred to as **30**. The liquid-rich fluid stream passes through the evaporator a substantial portion of the liquid being vaporized at substantially constant temperature and pressure without appreciable loss of kinetic energy. The velocity of the vapor-rich fluid at the evaporator exit may be somewhat lowered, but still supersonic. A large portion of the liquid in the fluid stream will vaporize on the thermal exchange surfaces of the evaporator, causing cooling of such surfaces. Thermal energy is added to the thermal exchange surfaces of the evaporator by direct circulation of air from the confined volume to be cooled or by circulation of a secondary non-evaporating refrigerant. This is the useful cooling effect obtained from the apparatus. The fluid emission from the evaporator is vapor-rich fluid at condition E.

The fluid at condition E passes into a trans-sonic diffuser which substantially adiabatically and isentropically reduces the fluid velocity to a very low velocity, thus increasing the pressure of the fluid to suitable pressure for condensation under ambient conditions, represented by state F. The fluid passes from the diffuser to a suitable thermal exchanger to substantially completely condense the vapor portion of the fluid flow resulting in condition A. The liquid at condition A is then returned to the pump for recyclization. The condenser exchanges to the exterior environment preferably by atmospheric air flow across the thermal exchanger surfaces. Other means of thermal exchange to the exterior environment such as water flow, as are well known in the cooling art, may be used.

Referring now specifically to the nozzle, supersonic dynamic-evaporator, trans-sonic diffuser portion of the apparatus shown schematically as **10**, **30** and **50** respectively in FIG. 1. FIG. 3 illustrates a detailed cross-sectional view of a preferred embodiment of this portion of the apparatus of the invention. The fluid flow through this portion of the apparatus is controlled by the geometry of the apparatus. As shown in FIG. 3 compressed, saturated refrigerant liquid from the liquid heater enters the nozzle in conduit **74**, a major portion of the liquid passing through entrance port **23** to liquid chamber **15** defined by walls **11**, **12**, **13** and **14**, and a minor portion of the liquid being flashed through suitable valve **73** to form vapor which passes through entrance port **24** into vapor chamber **75** defined by walls **14**, **17**, **18**, and **19**. These chambers may be of any suitable size and shape, preferably having a common wall as **14**. The liquid exits from liquid chamber **15** through tubes **16** defining conduits **29**, passing through vapor chamber **75** in closed fashion. There may be a series of ports **23** connected to conduit **74**, as well as a series of conduits **29** passing from chamber **15** for liquid exit. Likewise, there may be several ports **24** connected to conduit **74** through several valves **73**, as well as several sets of slots **22** for vapor exit.

FIG. 4 shows a more detailed cross-sectional view of this portion of the apparatus, denoted by line **4—4** in FIG. 3, showing tubes **16** extending through and beyond chamber **75**. Tubes **16** have a wall **20** across end of the tubes opposite the ends open to liquid chamber **15**, so that the liquid is emitted from the tubes through openings **21** in the tube walls, just exterior to chamber **75**. The openings **21** are of suitable size and shape to direct the liquid flow generally parallel to the wall **19**. The vapor from chamber **75** exits through slots **22** annular to tubes **16** and adjacent openings **21**. FIG. 5 is a detailed sectional end view, denoted by line **5—5** in FIG. 3, showing slots **22** arranged adjacent to openings **21**. The liquid and vapor impinge at this point so that complete mixing and dispersion of the liquid in vapor is obtained. The fluid nozzle is defined by wall **25** converging to throat **26** and wall **27** diverging to nozzle exit **28**. Nozzle dimensions for specific refrigerants and specific thermal exchange capacity systems may be readily computed such that the fluid expands to supersonic velocity in passing through the nozzle. The supersonic flow at the exit of the nozzle is approximately 2 to 4 times the velocity of sound, about 3 times the velocity of sound being preferred. The fluid emission at nozzle exit **28** is in the form of liquid drops suspended in vapor, the liquid quality of the fluid at this point being very high. Any nozzle shape resulting in such velocities and suitable mixing to obtain liquid-rich fluid flow with minimal slip is suitable for this process. The nozzle may be constructed of any suitable materials.

The fluid exiting from the nozzle passes at supersonic velocity directly into a dynamic evaporator generally designated as **30** wherein a substantial portion of the refrigerant liquid evaporates on thermal exchanger surfaces within the evaporator providing a cooling effect for thermal exchange for refrigeration or air conditioning purposes. It is desirable to provide a configuration within the evaporator providing large thermal exchange surfaces and effecting small changes in pressure and velocity of the fluid passing through the evaporator. The dynamic evaporator may be constructed of materials known in the art as being good thermal exchangers and operable at the pressure and temperature conditions obtained. It is desirable to minimize formation of a vapor film on the thermal exchange surfaces and to minimize the loss of kinetic energy of the fluid stream.

FIG. 3 shows a preferred configuration of a suitable dynamic evaporator generally designated **30**. Outer wall **31** defines the expanding volume of the evaporator flow chamber. To provide maximum surface for thermal exchange, inner cone **32** is rigidly maintained within the flow chamber by struts **33**. Liquid droplets from the supersonic liquid-rich fluid stream entering the evaporator deposit on both outer walls **31** and the walls of cone **32**. Both outer walls **31** and walls of cone **32** are in thermal exchange relation with the confined volume desired to be cooled. The vapor-rich fluid exits from the evaporator at supersonic velocities at exit **36**.

Tubes **35**, external to outer wall **31**, and tubes **34**, within the double wall of cone **32**, are suitable to provide flow of the exterior heat load carrying liquid or gas. One preferred embodiment of the invention is to circulate room air to be cooled in thermal exchanger relation to the walls of the dynamic evaporator for cooling and recirculation to the room. Another embodiment is to circulate secondary non-evaporating refrigerant, such as water at a fixed pressure, or chloronated aromatic compounds well

known as heat exchangers of sensible heat without heat of vaporization, such as Dowtherm produced by Dow Chemical Company, in thermal exchange relation with the dynamic evaporator surfaces and through a suitable thermal exchanger for desired cooling of a room or refrigeration spaces.

From the exit of the dynamic evaporator **36**, the vapor-rich fluid, still at supersonic velocity, enters the adiabatic diffuser generally shown as **50**. The adiabatic diffuser has expanding walls **51** reducing the velocity of the refrigerant fluid and a shock front denoted as line G—G will exist within the diffuser. The velocity of the refrigerant fluid will be decreased to a very low value and the static pressure increased to condensation condition, for the particular refrigerant used, as the cross-sectional area of the diffuser increases. At the diffuser exit, the fluid pressure has increased to the desired condenser pressure level and the velocity is only sufficient to cause it to pass at a suitable rate directly to condenser **70**.

Suitable refrigerants for the process and apparatus of my invention include any fluid having a high critical temperature in excess of 300° F., from 300 to 900° F. being preferred, and boiling at low temperatures, from about 30 to 60° F., and moderate pressures. Particularly preferred refrigerant fluids include water and halogenated hydrocarbons. The fluorinated hydrocarbon especially suitable for use in my invention is trichloro fluoro methane ($CCl_3F$), known in the air conditioning industry as f–11, and sold under the trademark Freon. Especially preferred refrigerants are selected from the group consisting of water and trichloro fluoro methane.

Referring to FIG. 2, using water as an exemplary fluid refrigerant suitable evaporation conditions are about 40° F. and 0.12 p.s.i.a.; condensation conditions are about 120° F. and 1.7 p.s.i.a.; and the pressurized condition for water is about 680 p.s.i.a., and in substantially saturated condition the temperature is about 500° F. Using water, the coefficient of performance of the system will be about 0.50, a reasonably high value. Also using water, the circulation rate of the refrigerant is approximately one pound per minute per ton of cooling.

Under similar exemplary conditions using f–11 the system will have the following properties: the evaporation pressure will be about 13 p.s.i.a., condensation pressure of about 42 p.s.i.a., and a highest temperature of about 300° F. under pressurized conditions at state C.

While in the foregoing specification this invention has been described in relation to certain preferred embodiments thereof, and many details have been set forth for purpose of illustration, it will be apparent to those skilled in the art that the invention is susceptible to additional embodiments and that certain of the details described herein can be varied considerably without departing from the basic principles of the invention.

I claim:

**1.** A process for cooling comprising compressing a liquid refrigerant to a pressurized condition, then heating said liquid at constant pressure to a substantially saturated state, passing the fluid through an adiabatic nozzle expanding to supersonic flow of liquid-rich two phase fluid at evaporation condition, passing said liquid-rich fluid at supersonic velocity through a dynamic evaporator at substantially constant temperature and pressure and vaporizing a substantial portion of the liquid on surfaces of the evaporator in thermal exchange relation with a confined space to be cooled, passing the resulting vapor-rich fluid through an adiabatic trans-sonic diffuser to condenser pressure and velocity, condensing the vapor to liquid by thermal exchange to the exterior environment, and returning the liquid refrigerant for compression and recirculation.



**2.** The process of claim **1** wherein said supersonic velocity is from 2 to 4 times the velocity of sound.

**3.** The process of claim **1** wherein said refrigerant has a critical temperature in excess of 300° F. and boils at from about 30° to 60° F.

**4.** The process of claim **3** wherein said critical temperature is from 300 to 900° F.

**5.** The process of claim **3** wherein said refrigerant is water.

**6.** The process of claim **1** wherein said refrigerant is water, said pressurized condition is about 680 p.s.i.a., said saturated state is at about 500° F., said evaporation condition is about 40° F. and 0.12 p.s.i.a., and said condenser pressure is about 1.7 p.s.i.a. at about 120° F.

**7.** The process of claim **1** wherein said refrigerant is selected from halogenated hydrocarbons wherein the halogenated substitution is selected from the group consisting of fluoro, chloro and mixtures thereof.

**8.** The process of claim **7** wherein said refrigerant is trichloro fluoro methane.

**9.** A cooling apparatus comprising in closed loop sequential communication, a liquid pump, a liquid heater, an adiabatic nozzle, providing two phase fluid flow at supersonic velocities, a dynamic supersonic evaporator in thermal exchange relation to the confined volume to be cooled, a trans-sonic adiabatic diffuser, and a condenser in thermal exchange relation to the external environment; said loop containing a fluid refrigerant having a critical temperature in excess of 300° F.

**10.** In a cooling apparatus, the improvement comprising in sequential communication; an adiabatic nozzle having separate entry means for liquid and vapor phases of a refrigerant fluid into a chamber defined by converging walls to a throat and diverging walls to the nozzle exit wherein said fluid is expanded to supersonic velocities and evaporator conditions; an evaporator adjacent said nozzle exit at one end and defined by diverging walls to an evaporator exit at the opposite end, said evaporator having internal thermal exchanger means and said walls providing thermal exchanger means to provide thermal exchange between said exchanger means and a heat load; and a trans-sonic diffuser adjacent said evaporator exit at one end and defined by diverging walls to a diffuser exit at the opposite end to reduce the fluid velocity to sub-sonic flow and increase the pressure to condensation condition.


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U.S. Cl. X.R.

62—498, 500