US007159407B2

(12) **United States Patent**
Chen

(10) **Patent No.: US 7,159,407 B2**
(45) **Date of Patent: Jan. 9, 2007**

(54) **ATOMIZED LIQUID JET REFRIGERATION SYSTEM**

(76) Inventor: **Kuo-mei Chen**, 10F-1, 493 Chian-Kuo 3rd Road, Kaohsiung (TW)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **10/865,659**

(22) Filed: **Jun. 9, 2004**

(65) **Prior Publication Data**

US 2005/0274130 A1 Dec. 15, 2005

(51) **Int. Cl.**
F25B 19/00 (2006.01)

(52) **U.S. Cl.** **62/100**

(58) **Field of Classification Search** 62/100, 62/115, 498, 500, 513, 434, 48.1, 57; 165/104.17
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

1,619,194	A	3/1927	Davenport	
1,619,196	A	3/1927	Davenport	
1,845,356	A	2/1932	Sorensen	
1,882,257	A	10/1932	Randel	
1,892,741	A	1/1933	Sorensen	
2,158,741	A *	5/1939	Christman	237/12.3 A
2,159,251	A	5/1939	Brizzolara	
2,386,554	A	10/1945	Holicer	
3,844,132	A *	10/1974	Miller et al.	62/268
3,909,957	A *	10/1975	Passey	34/92
4,221,240	A *	9/1980	Alexander, Sr.	139/1 R
4,237,695	A *	12/1980	Oberpriller et al.	62/63
4,608,119	A *	8/1986	Rowland	159/3
4,821,794	A *	4/1989	Tsai et al.	165/104.17
4,866,947	A	9/1989	Webster	
5,046,321	A	9/1991	Webster	
5,122,053	A *	6/1992	Basten	431/12
5,195,509	A *	3/1993	Rentschler et al.	601/4
5,444,986	A *	8/1995	Hino	62/66
5,500,238	A *	3/1996	Thienpont	426/511
5,788,667	A *	8/1998	Stoller	604/22
6,017,439	A *	1/2000	Gannon	205/703
6,180,843	B1 *	1/2001	Heinemann et al.	585/15
6,410,284	B1 *	6/2002	Aksenov et al.	435/173.1
6,518,349	B1 *	2/2003	Felix et al.	524/492
6,579,706	B1 *	6/2003	Grae	435/173.5
6,601,776	B1	8/2003	Oljaca et al.	
6,672,091	B1	1/2004	Lefor et al.	
6,793,007	B1 *	9/2004	Kramer et al.	165/80.4
2002/0146373	A1 *	10/2002	Edwards et al.	424/46

FOREIGN PATENT DOCUMENTS

JP	3-143502	A *	6/1991

(Continued)

OTHER PUBLICATIONS

"Additional jet vacuum cooling saves Pfizer $100,000", Petrochemical Processing, Croll-ReynoldsCo., Inc. paper, 2 pages.

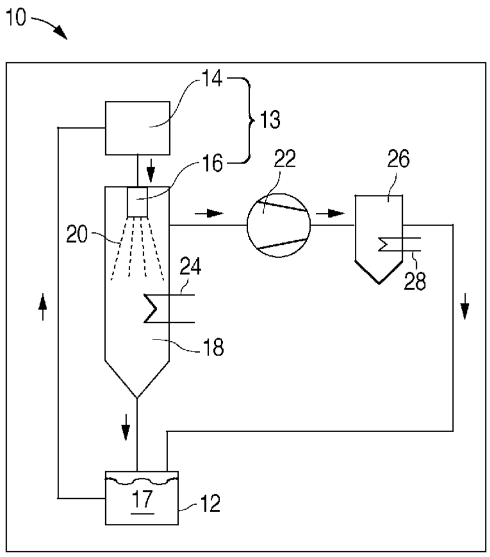
(Continued)

Primary Examiner—Mohammad M. Ali
(74) *Attorney, Agent, or Firm*—Patent Law Group LLP; David C. Hsia

(57) **ABSTRACT**

A system for controlling temperature includes an atomizer that forms micron-sized hydrogen-bonded refrigerant droplets within a chamber. A vacuum pump is coupled to the chamber to lower its interior pressure. Under these conditions, the refrigerant droplets evaporate while lowering the temperature of its immediate surrounding. In one embodiment, the atomizer includes a pump that forces a hydrogen-bonded liquid refrigerant through a nozzle.

30 Claims, 4 Drawing Sheets



FOREIGN PATENT DOCUMENTS

JP	5-214412 A	*	8/1993
JP	11-280650 A	*	10/1999

OTHER PUBLICATIONS

"When properly maintained, steam jet vacuum chillers can cut steam use in half for mill refrigeration applications, as it did at Weyerhaeuser's Flint River mill Less Environmental Impact/Steam Use Characterize Vacuum Chiller OPeration," downloaded from http://www.paperloop.com on May 24, 2004, pp. 1-7.

"Steam Jet Chiller Principle," Artisan Industries Inc., paper downloaded from http://www.artisanind.com/jetvac/chillerpoo.htm on May 24, 2004, 1 page.

A.D. Althouse et al., "Modern Refrigeration and Air Conditioning," The Goodheart-Wilcox Co., South Holland, IL., 1988, p. 295.

A.H. Lefebvre, "Fuel Atomization, Droplet Evaporatin, and Spray Combustion," in Fossill Fuel Combustion, edited by W. Bartok and A.F. Sarofim, John Wiley & Sons, New York, 1991, pp. 529-652.

S.P. Lin et al., "Drop and Spray Formation from a Liquid Jet," Annu. Rev. Fluid Mech. 30 (1998), pp. 85-105.

R.D. Reitz et al., "Mechanism of atomization of a liquid jet," Phys. Fluids 25, (1982), pp. 1730-1742.

P. W. Atkins, "The electric and magnetic properties of molecules," Physical Chemistry, fifth edition, Oxford University Press, 1994, pp. 770-771.

* cited by examiner

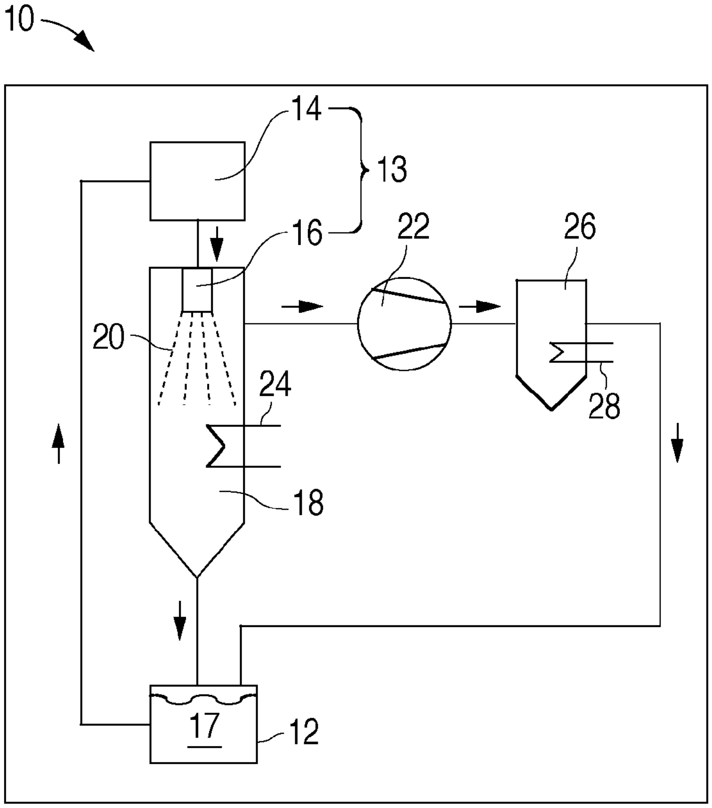


Fig. 1

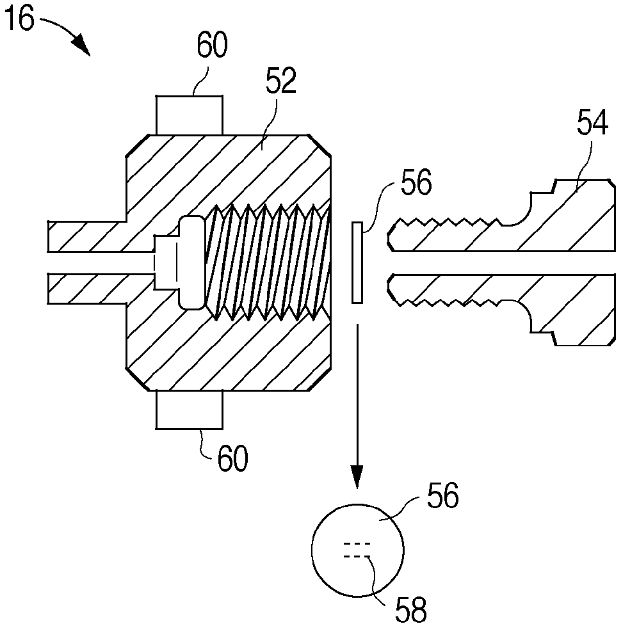


Fig. 2

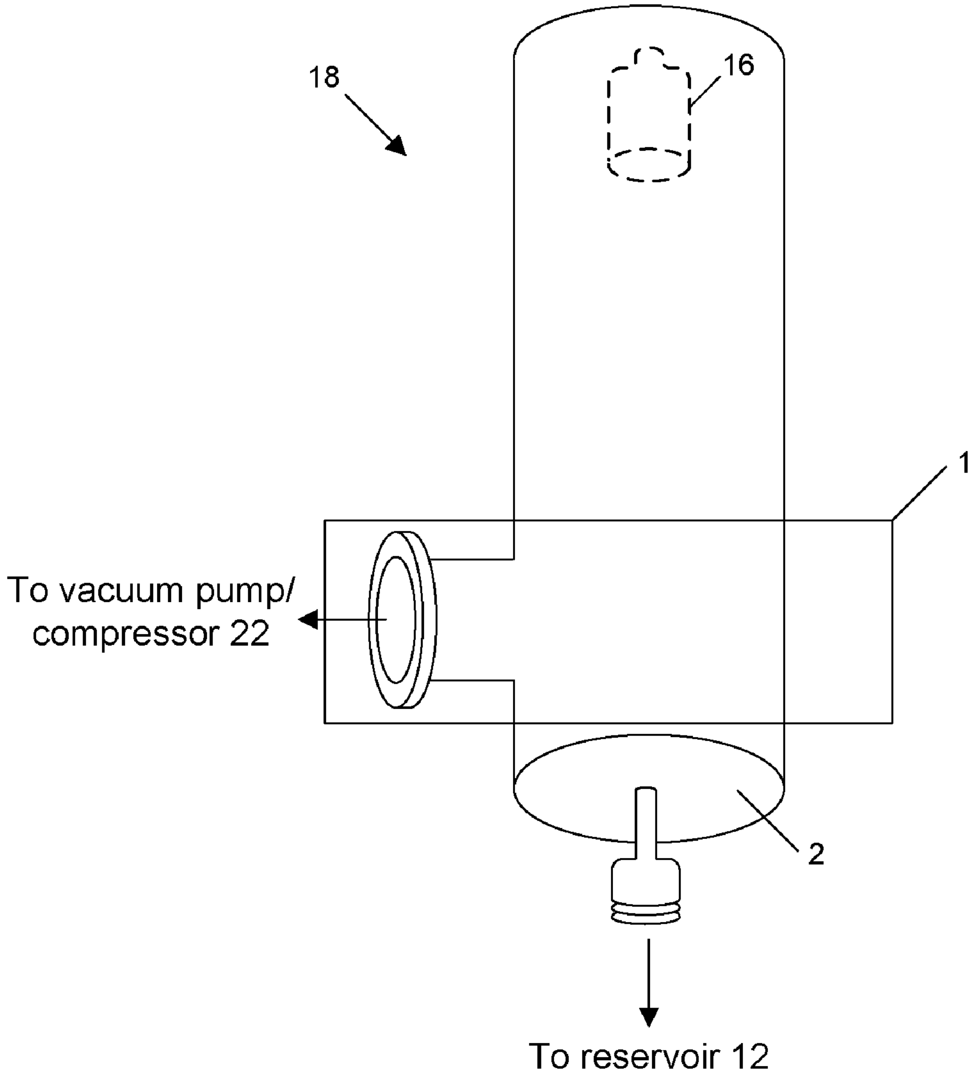


Fig. 3

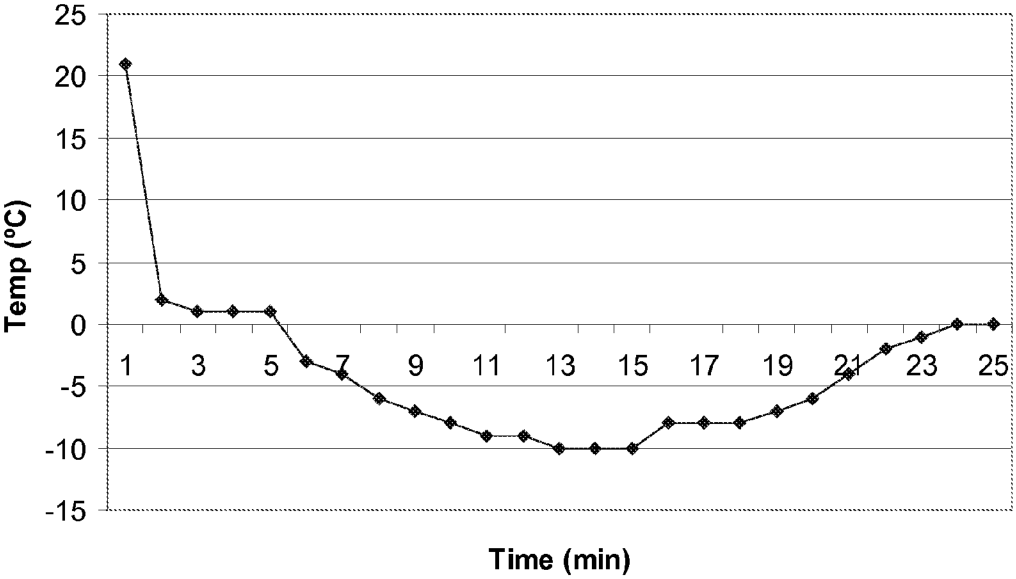

25
20
15
10
5
0
-5
-10
-15
Temp (ºC)
1
3
5
7
9
11
13
15
17
19
21
23
25
Time (min)

Fig. 4

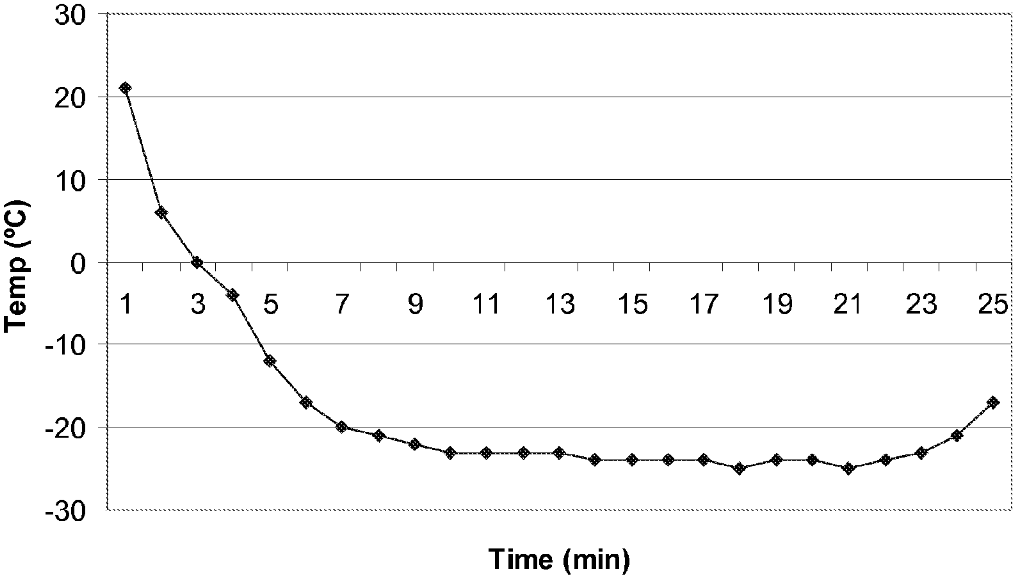

30
20
10
0
-10
-20
-30
Temp (ºC)
1
3
5
7
9
11
13
15
17
19
21
23
25
Time (min)

Fig. 5

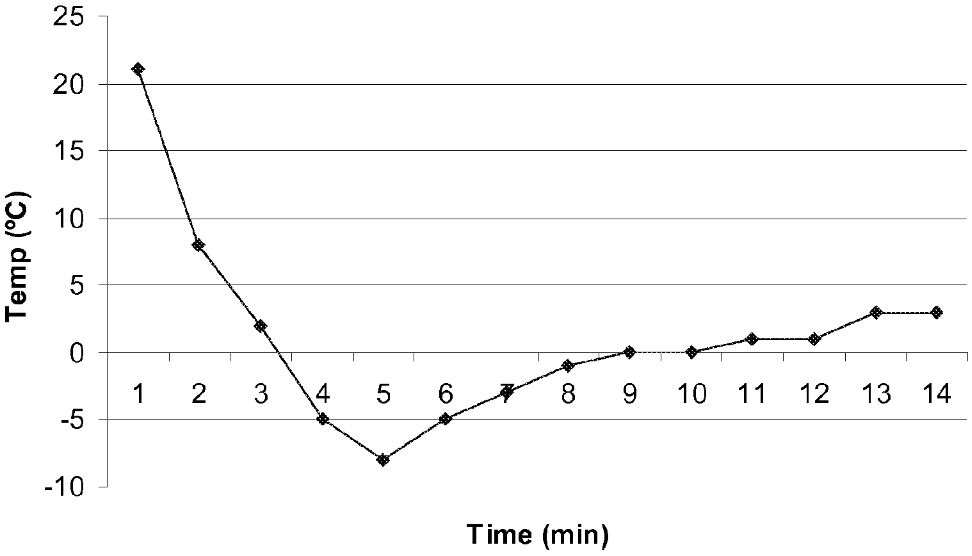

25
20
15
10
5
0
-5
-10
Temp (ºC)
1
2
3
4
5
6
7
8
9
10
11
12
13
14
Time (min)

Fig. 6

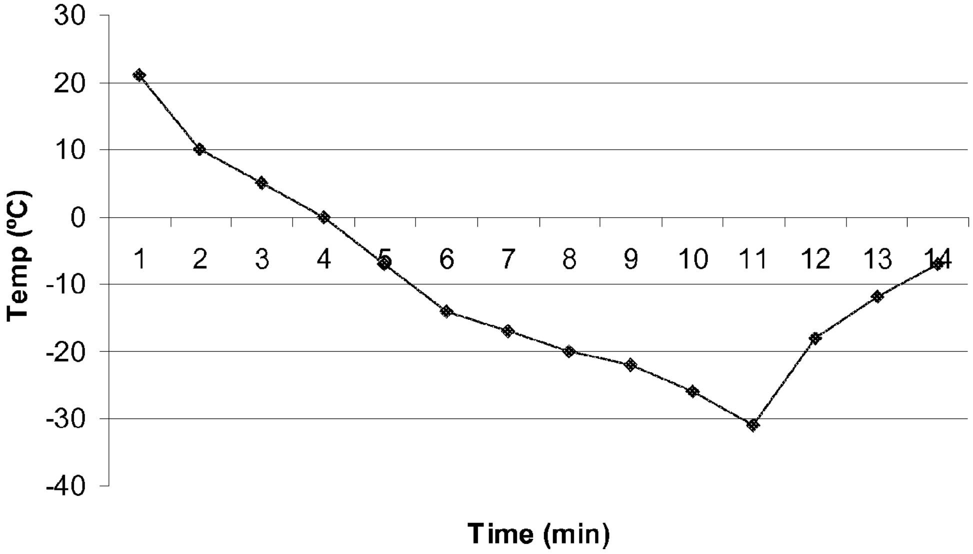

30
20
10
0
-10
-20
-30
-40
Temp (ºC)
1
2
3
4
5
6
7
8
9
10
11
12
13
14
Time (min)

Fig. 7

ATOMIZED LIQUID JET REFRIGERATION SYSTEM

FIELD OF INVENTION

This invention relates to refrigeration systems.

DESCRIPTION OF RELATED ART

Conventional refrigeration systems employ the compression technology of chlorofluorocarbon (CFC), hydrofluorocarbon (HFC), hydrochlorofluorocarbon (HCFC), and ammonia (NH_3) refrigerants. Gaseous refrigerants are compressed to the liquid state through heat exchanges with the environment. Evaporations of liquefied CFC or NH_3 refrigerants provide the cooling mechanism. Because the heat of vaporization of NH_3 is larger than those of CFCs, and that NH_3 is easily compressible to a condensed phase, NH_3 compression refrigeration systems are widely utilized in various manufacturing industries and in large storage facilities. On the other hand, the corrosive characteristics of NH_3 require that special operational precautions to be imposed. Thus, domestic refrigerators and air-conditioners (including motor vehicle ACs) invariably utilize the compression technology of CFC refrigerants. The formidable issues of ozone depletion and the greenhouse effect caused by CFC and HCFC refrigerants demand a new refrigeration technology.

In the prior art, water is not used as the refrigerant for a compression cycle refrigerating system. A. D. Althouse, C. H. Turnquist, A. F. Bracciano, "Modern Refrigeration and Air Conditioning," The Goodheart-Willcox Co., South Holland, Ill., 1988, p. 295. However, water is the refrigerant for steam jet refrigeration used in connection with air conditioning systems. Id. A steam jet refrigeration chiller employs the momentum of steam to pump away gaseous water molecules. Thus, evaporation of water in the chill tank under reduced pressure cools down the water reservoir in the chill tank. This is an inefficient method that relies on an inexpensive supply of high pressure steam and can only cool the water reservoir to about 4° C.

In the prior art, such as U.S. Pat. Nos. 2,159,251, 2,386,554, 4,866,947, 5,046,321, and 6,672,091, atomizers have been used instead of the expansion valve in conventional compression cycle refrigerating systems to improve the evaporation rate of the refrigerant.

Thus, what is needed is a refrigeration system that (1) employs a refrigerant that is environmental-friendly, chemically non-corrosive, non-flammable, and physiologically harmless, and (2) provides the same or better performance while consuming the same or less energy as conventional technologies.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a block diagram of a refrigeration system in one embodiment of the invention.

FIG. **2** is a schematic of a nozzle used to generate jets of micron-sized refrigerant droplets in one embodiment of the invention.

FIG. **3** is a schematic of a low-pressure heat exchanger for transferring heat away from ambient air to refrigerant droplets in one embodiment of the invention.

FIGS. **4** and **5** are charts illustrating the result of an open loop water refrigeration system in one embodiment of the invention.

FIGS. **6** and **7** are charts illustrating the result of an open loop alcohol refrigeration system in one embodiment of the invention.

Use of the same reference numbers in different figures indicates similar or identical elements.

SUMMARY

In one embodiment of the invention, a system for controlling temperature includes an atomizer that forms micron-sized hydrogen-bonded refrigerant droplets within a chamber. A vacuum pump is coupled to the chamber to lower its interior pressure. Under these conditions, the refrigerant droplets evaporate while lowering the temperature of its immediate surrounding. In one embodiment, the atomizer includes a pump that forces a hydrogen-bonded liquid refrigerant through a nozzle.

In one embodiment, a method for controlling temperature includes lowering the pressure within a chamber and generating micron-sized hydrogen-bonded refrigerant droplets within the chamber. Under these conditions, the refrigerant droplets evaporate while lowering the temperature of its immediate surrounding. In one embodiment, the refrigerant droplets are generated by pumping a hydrogen-bonded liquid refrigerant through a nozzle.

DETAILED DESCRIPTION

A liquid jet refrigeration system utilizes the atomization of hydrogen-bonded liquid refrigerants to meet environmental needs, occupational safety standards, and fast cooling rates. The evaporation efficiencies of environmental-friendly hydrogen-bonded liquid refrigerants are greatly enhanced by atomizing them into streams of micron-sized refrigerant droplets. In addition to the advantage of the large heats of vaporization of hydrogen-bonded liquid refrigerants, these gaseous refrigerants are easily condensed under compression. Energy consumptions of the liquid jet refrigeration system are more efficient in comparison with those of conventional technologies.

After 1950, refrigerants that are liquids at room temperatures (25° C.) and 1 atmosphere have never been considered for refrigeration systems using compression technologies. However, there are many hydrogen-bonded liquids that are environmental-friendly, chemically non-corrosive, non-flammable, and physiologically harmless (e.g., alcohol/water mixtures, such as ethyl alcohol (C_2H_5OH)). Above all, they exhibit heats of vaporization larger than those of NH_3 (ΔH_0^{vap}=40.6 kJ/mole, 43.5 kJ/mole, and 23.35 kJ/mole for water, ethyl alcohol, and ammonia, respectively).

According to their phase diagrams and thermodynamic properties, these liquid refrigerants evaporate spontaneously under reduced pressure. Meanwhile, the evaporated molecules that escape from the surface carry away the internal energy of the liquid (heats of vaporization). Thus, the evaporation of the liquefied refrigerant, e.g., at 25° C. initially, cools the remaining liquid into a state of lower temperature under reduced pressure. This refrigeration mechanism can be maintained in principle as long as a good vacuum environment (better than 10^{-2} mbar) is created above the liquid surface.

In practice, the rate of evaporation is not controlled thermodynamically but kinetically. According to the kinetic theory of gases, the rate of evaporation dN/dt is given by:

$$\frac{dN}{dt} = -\frac{\Delta P N_A A}{(2\pi MRT)^{1/2}}, \quad (1)$$

where ΔP is the pressure difference between the equilibrium vapor pressure of the liquid at temperature T and the gaseous pressure of the environment, N_A is the Avogadro number, M is the molecular weight, R is the gas constant, and A is the surface area of the liquid phase. When a 1 cm^3 liquid droplet is dispersed into 1 μm micro-spheres, the surface area is increased by four orders of magnitude (10^4). Consequently, the rate of cooling is substantially enhanced by atomizing the liquid into micron-sized droplets (i.e., dispersing a liquid into mist).

There are many techniques to atomize liquids into micron-sized droplets, including (1). liquid jet atomization by pumping a liquid through micron-sized pinholes, (2) ultrasonic atomization, (3) piezoelectric atomization, and (4) DC-discharge atomization. Presently, experiments demonstrate that liquid jet atomization serves the refrigeration purpose quite well. For example, a refrigeration chamber can be cooled from 21° C. to −20° C. around 6 minutes. The cooling mechanism is provided by the evaporation of micron-sized refrigerant droplets under reduced pressure. The micron-sized refrigerant droplets are created by pumping the liquid refrigerant through a nozzle having an array of micron-sized pinholes.

FIG. **1** illustrates a refrigeration system **10** in one embodiment of the invention. System **10** includes a liquid refrigerant reservoir **12** that stores a liquid refrigerant **17**. Liquid refrigerant **17** is preferably in a liquid state at 25° C. and 1 atmosphere. Liquid refrigerant **17** is preferably a hydrogen-bonded liquid such as water, alcohol (e.g., ethanol or methanol), an alcohol/water mixture (e.g., a 70:30 mixture of ethanol and water), or diethyl ether. In one embodiment, pure water refrigerant is used.

From liquid refrigerant **17** in reservoir **12**, an atomizer **13** generates micron-sized refrigerant droplets **20**. In one embodiment, atomizer **13** includes a liquid pump **14** and a nozzle **16**. Liquid pump **14** forces liquid refrigerant **17** through nozzle **16** to inject micron-sized refrigerant droplets **20** into a low-pressure chamber **18** (e.g., a heat exchanger). In one embodiment, liquid pump **14** (e.g., a NP-CX-100 from Nihon Seimitsu Kagaku of Tokyo, Japan) delivers a flow rate of 80 ml/min at a pressure of 30 bar.

FIG. **2** illustrates the details of nozzle **16**. Nozzle **16** includes a vacuum female fitting **52** and a vacuum male fitting **54** (e.g., VCR® fittings made by Cajon Company of Macedonia, Ohio). A nozzle plate **56** is inserted into vacuum female fitting **52** and secured by vacuum male fitting **54**. Nozzle plate **56** has micron-sized pinholes **58** (only one is labeled) that disperse liquid refrigerant **17** as jets of micron-sized refrigerant droplets **20** having a diameter of less than 50 μm.

In one embodiment, pinholes **58** have a diameter of 80 μm and generate refrigerant droplets **20** having a diameter of approximately 10 μm. In this embodiment, nozzle plate **56** is a stainless steel plate having a diameter of 13 mm and a thickness of 1 mm. In this embodiment, six or more pinholes **58** are laser-drilled into nozzle plate **56** (e.g., by a COMPEX 200 and SCANMATE 2E laser system made by Lambda Physik of Göttingen, Germany).

Nozzle **16** may include a heater **60** (e.g., an electric heater or a water heater that circulates room temperature water around the nozzle) to prevent liquid refrigerant **17** from clogging nozzle **16** when it freezes. Parameters such as the flow rate, the applied pressure, the number of pinholes in the nozzle array, and the pinhole size may be modified to generate the micron-sized refrigerant droplets of the appropriate size.

Referring back to FIG. **1**, a vacuum pump/compressor **22** reduces the pressure within heat exchanger **18** so that refrigerant droplets **20** evaporate when introduced into heat exchanger **18** and absorb heat from the remaining refrigerant droplets and its immediate surroundings. Vacuum pump/compressor **22** can be a mechanical pump or a Roots pump with a backup mechanical vacuum pump (e.g., a RSV 1508 Roots pump made by Alcatel of Annecy Cedex, France, and an SD-450 vacuum pump made by Varian of Lexington, Mass.). The large surface area of the atomized droplets greatly enhances their evaporate rate. In one embodiment, the pressure within heat exchanger **18** is reduced to 10^{-2} mbar. Heat exchanger **18** may include a conduit **24** that carries a medium (e.g., ambient air) that is cooled as the medium travels into and out of heat exchanger **18**. Alternatively, the medium can simply be blown over the outer surface of heat exchanger **18**.

FIG. **3** illustrates heat exchanger **18** in one embodiment of the invention. Heat exchanger **18** has an outlet to vacuum pump/compressor **22** located on an opposite end away from nozzle **16**. Heat exchanger **18** can be made of any conventional form, e.g., coil or fin types. The medium that is cooled can be any gaseous or liquefied heat transfer materials. In one embodiment, the medium is used to cool a space such as a room or a refrigeration compartment. Any refrigerant droplets **20** that do not evaporate are collected at the bottom of heat exchanger **18** and returned to reservoir **12**.

In one embodiment, system **10** is an open loop refrigeration system because liquid refrigerant **17**, like water, can be safely expelled into the environment. In this embodiment, vacuum pump/compressor **22** simply expels the gaseous refrigerant into the atmosphere. In this embodiment, reservoir **12** can be replaced by a water supply line (e.g., a city supplied water line to a home or a business).

In one embodiment, system **10** is a closed cycle refrigeration system because liquid refrigerant **17** cannot be safely expelled into the environment. In this embodiment, vacuum pump/compressor **22** compresses the gaseous refrigerant into an atmospheric pressure chamber **26** (e.g., another heat exchanger).

Referring back to FIG. **1**, heat changer **26** may include a conduit **28** that carries another medium (e.g., ambient air) that condenses the gaseous refrigerants as the medium travels into and out of heat exchanger **26**. Alternatively, the medium can simply be blown over the outer surface of heat exchanger **26**. As the gaseous refrigerant condenses, it heats the medium. The heated medium can be any gaseous or liquefied heat transfer materials. In one embodiment, the heated medium is expelled to the environment. In one embodiment, the heated medium is used to heat a space such as a room or a heating compartment. The cooled liquid refrigerant **17** then exits heat exchanger **26** and returns to reservoir **12**.

FIGS. **4** and **5** show the experimental results of one embodiment of an open loop refrigeration system **10** using a pure water refrigerant, a 6-pinhole nozzle **16**, and a flow rate of 80 ml/minute. Specifically, FIG. **4** shows the temperature recorded at location **1** (FIG. **3**) around heat exchanger **18**, and FIG. **5** shows the temperatures recorded at location **2** (FIG. **3**) at the bottom of heat exchanger **18**. As can be seen in FIGS. **4** and **5**, the temperature began to rise at the end of the experiment. This is because the water refrigerant started to clog nozzle **16** when it froze because nozzle **16** was not heated in the experiment. The results show that temperatures as low as −25° C. can be achieved, which is unexpected for a water refrigeration system and not disclosed by any known prior art.

FIGS. **6** and **7** show the experimental results of one embodiment of an open loop refrigeration system **10** using an ethanol refrigerant (99.5%), a 6-pinhole nozzle **16**, and a flow rate of 80 ml/minute. Specifically, FIG. **6** shows the temperature recorded at location **1** (FIG. **3**) around heat exchanger **18**, and FIG. **7** shows the temperatures recorded at location **2** (FIG. **3**) at the bottom of heat exchanger **18**. Again as can be seen in FIGS. **6** and **7**, the temperature began to rise at the end of the experiment. This is because the ethanol refrigerant started to clog nozzle **16** when it froze because nozzle **16** was not heated in the experiment.

For a fast cooling rate and an ultimate low temperature, methanol/water or ethanol/water refrigerant may be used in system **10**. For an environmentally friendly, chemically non-corrosive, non-flammable, and physiologically harmless refrigerant, pure water or ethanol/water refrigerant may be used in system **10**. Thus, water systems can find their roles in the market of domestic appliances, while pure ethanol, ethanol/water, and methanol/water refrigeration systems can be employed in manufacturing industries and in large storage facilities.

Various other adaptations and combinations of features of the embodiments disclosed are within the scope of the invention. For example, hydrogen-bonded liquid refrigerants are not limited to the specific chemical compounds mentioned above. The material, the fabrication method, and the characteristics of the nozzle are not limited to those mentioned above. Liquid atomization by other well-known techniques, such as ultrasonic, piezoelectric, and electric discharge methods, can be used in place of the pump and the nozzle. Numerous embodiments are encompassed by the following claims.

What is claimed is:

1. A compression cycle refrigeration system for controlling temperature, comprising:

a chamber;

a vacuum pump coupled to the chamber, the vacuum pump lowering pressure within the chamber;

a supply of a liquid hydrogen-bonded refrigerant;

an atomizer coupled between the supply and the chamber, the atomizer outputting micron-sized refrigerant droplets into the chamber, wherein the refrigerant droplets evaporate to form a gaseous refrigerant by absorbing heat from its surrounding; and

another chamber coupled between the vacuum pump and the supply, said another chamber being a heat exchanger including a conduit carrying a medium into and out from the heat exchanger to absorb heat from the gaseous refrigerant;

wherein the medium is an ambient air, the vacuum pump compresses the gaseous refrigerant into said another chamber, and the gaseous refrigerant condenses inside said another chamber to form the liquid hydrogen-bonded refrigerant by loosing heat to its surrounding and is returned to the supply.

2. The system of claim **1**, wherein the pressure within the chamber is reduced to 10^{-2} mbar or less.

3. The system of claim **1**, wherein the refrigerant droplets have diameters of about 10 microns.

4. The system of claim **1**, wherein the refrigerant droplets have diameters of 50 microns or less.

5. The system of claim **4**, wherein the atomizer is selected from the group consisting of an ultrasonic atomizer, a piezoelectric atomizer, and an electric discharge atomizer.

6. The system of claim **4**, wherein the atomizer includes:

a nozzle; and

a pump coupled between the supply and the nozzle, wherein the pump forces the liquid hydrogen-bonded refrigerant through the nozzle to form the micron-sized refrigerant droplets.

7. The system of claim **6**, wherein the nozzle comprises pinholes.

8. The system of claim **7**, wherein the pinholes have a diameter of 20 microns or less.

9. The system of claim **6**, wherein the nozzle further comprises a heater to heat the nozzle.

10. The system of claim **1**, wherein the liquid hydrogen-bonded refrigerant is in its liquid state at 25° C. and 1 atmosphere, and the chamber is cooled to −20°C. or less.

11. The system of claim **1**, wherein the liquid hydrogen-bonded refrigerant is water.

12. The system of claim **1**, wherein the hydrogen-bonded refrigerant is selected from the group consisting of alcohol and alcohol/water mixture.

13. The system of claim **12**, wherein the alcohol/water mixture comprises a 70:30 mixture of ethyl alcohol and water.

14. The system of claim **1**, wherein the chamber is another heat exchanger including another conduit carrying another medium into and out from said another heat exchanger to cool said another medium, and said another medium is transported away to cool a space.

15. The system of claim **1**, wherein another medium is moved over the outer surface of the chamber to cool said another medium, and said another medium is transported away to cool a space.

16. The system of claim **1**, wherein the supply is further coupled to the chamber to the chamber to collect any refrigerant droplets that do not evaporate.

17. A method for a compression cycle refrigeration system for controlling temperature, comprising:

reducing pressure within a chamber with a vacuum pump;

atomizing a liquid hydrogen-bonded refrigerant to form micron-sized hydrogen-bonded refrigerant droplets within the chamber, wherein the refrigerant droplets evaporate to form a gaseous refrigerant by absorbing heat from its surrounding;

compressing the gaseous refrigerant into another chamber;

condensing the gaseous refrigerant in said another chamber to form the liquid hydrogen-bonded refrigerant, wherein said condensing the gaseous refrigerant comprises passing a medium into and out of said another chamber through a conduit to heat the medium and the medium is an ambient air; and

returning the liquid hydrogen-bonded refrigerant for use in said atomizing.

18. The method of claim **17**, wherein the pressure within the chamber is reduced to 10^{-2} mbar or less.

19. The methods of claim **17**, wherein the refrigerant droplets have diameters of about 10 microns.

20. The method of claim **17**, wherein the refrigerant droplets have diameters of 50 microns or less.

21. The method of claim **20**, wherein said atomizing comprises a method selected from the group consisting of an ultrasonic atomizing method, a piezoelectric atomizing method, and an electric discharge atomizing method.

22. The method of claim **20**, wherein said atomizing comprises pumping the liquid hydrogen-bonded refrigerant through a nozzle.

23. The method of claim **22**, wherein the nozzle comprises pinholes, the pinholes comprising a diameter of 20 microns or less.

24. The method of claim **23**, further comprising heating the nozzle.

25. The method of claim **17**, wherein the liquid hydrogen-bonded refrigerant is in its liquid state at 25° C. and 1 atmosphere, and the chamber is cooled to −20° C. or less.

26. The method of claim **17**, wherein the liquid hydrogen-bonded refrigerant is water.

27. The method of claim **17**, wherein the liquid hydrogen-bonded refrigerant is selected from the group consisting of alcohol and alcohol/water mixture.

28. The method of claim **27**, wherein the alcohol/water mixture comprises a 70:30 mixture of ethyl alcohol and water.

29. The method of claim **17**, futher comprising passing another medium into and out of the chamber to cool said another medium and said another medium is transported away to cool a space.

30. The method of claim **17**, further comprising passed another medium over the chamber to cool said another medium is transported away to cool a space.

* * * * *

H_2O REFRIGERANT: EXPLOITATION OF DISPERSED WATER DROPLETS

KUO-MEI CHEN
Department of Chemistry, National Sun Yat-sen University, 70 Lien-hai Rd.
Kaohsiung, 804, Taiwan
Fax: 886-7-525-3912, e-mail: kmchen@mail.nsysu.edu.tw

ABSTRACT

To cope with the mandates imposed by the Montreal and the Kyoto Protocols, halogenated refrigerants will eventually be phased-out. H_2O, a natural working fluid which is environmental-friendly, chemically non-corrosive, non-flammable, and physiologically harmless, can be exploited as a high-performance refrigerant in the 4 ~ –25 °C temperature range. The successful operation of the water refrigeration system is based on the fact that the evaporation rate of the refrigerant is not controlled thermodynamically but kinetically. The refrigeration performance of micron-sized water droplets in a reduced pressure environment has been successfully demonstrated. A testing embodiment could be cooled down from room temperature to –20 °C within 6 minutes, where tap water at a flow rate of 80 mL/min was dispersed into micron-sized droplets by the liquid jet atomization technique. The exploitation of the water refrigerant in replacement of those with environmental and safety concerns is highly expected.

1. INTRODUCTION

Prior to the ratification of the Montreal and the Kyoto Protocols, compression technologies that utilize chlorofluorocarbon (CFC) refrigerants (Midgley and Henne, 1930) have dominated the domestic and the mobile air-conditioning markets for more than six decades. Under the control measures of the Montreal Protocol (UNEP, 2002), CFCs were phased-out on 1 January 1996 and hydrochlorofluorocarbons (HCFCs) will be phased-out on 1 January 2020 in developed countries. To comply with the first phase of the Kyoto Protocol, which has been effective since 1 January 2005, the amount of greenhouse gases emitted by developed countries should be reduced by 5.2% of the 1990 level during 2008–2012 (UNFCCC, 1997). As one of the six greenhouse gases specifically identified in the Kyoto Protocol, hydroflurocarbon (HFC) refrigerants can no longer be considered as long-term substitutes of CFCs.

To support the sustaining demands on refrigerated products and air-conditioned living spaces of modern societies, entrepreneurs have advocated compression technologies that employ propane, carbon dioxide, and ammonia refrigerants in recent years (Lorentzen, 1995), in spite of the fact that these chemicals exhibit inherent limitations and hazards in safety. This transition stage can be overridden if a high-performance refrigerant which meets all the safety and environmental protection codes, can be identified in time, especially in the fields of domestic refrigeration and mobile air-conditioning systems.

2. ALTERNATIVE TECHNOLOGY

Even though water is an active ingredient in steam jet and absorption (NH_3/H_2O and $LiBr/H_2O$) refrigeration systems (Althouse *et al.*, 1988), their state-of-the-art embodiments can only cool the water reservoir to 4 °C and their sole purpose is to air-condition large facilities. From past experiences, practitioners in the field are convinced that a refrigeration scheme based on a pure water refrigerant can never go beyond the standard freezing point of H_2O (0 °C) (Althouse *et al.*, 1988). On the contrary, a close examination on the temperature domain of metastability for liquid water at one atmospheric pressure reveals that supercooled water (still a liquid) can exist in the temperature range of 231–273 K (Angell, 1983 ; Debenedetti, 2003 ; Mishima and Stanley, 1998). Thermodynamically, the equilibrium vapor pressure differences between the supercooled water and ice are less than 20% in the temperature range of 0 ~ –25 °C (Kraus and Greer, 1984). Thus, the evaporative cooling is operative for both the liquid and solid micro-spheres so long as the external pressure is kept below 0.1 mbar (Kraus and Greer, 1984). In other words, the cooling effect is a kinetic process that relies on the surface area and the vapor pressure at a designated temperature of the refrigerant (Atkins, 1994). The refrigeration performance of the micron-sized water droplets in a vacuum environment (< 0.1 mbar) depends predominantly on the total surface areas of micro-spheres and partially on the relative abundances of these droplets in the supercooled and solid states. In the present work, an alternative technology which is based on dispersed water droplets in replacement of refrigerants with environmental and safety concerns is reported.

3. EXPERIMENT AND RESULTS

A schematic diagram of an experimental embodiment that measures the cooling rates of dispersed water droplets under a reduced pressure environment (< 0.1 mbar) is depicted in Fig. 1.

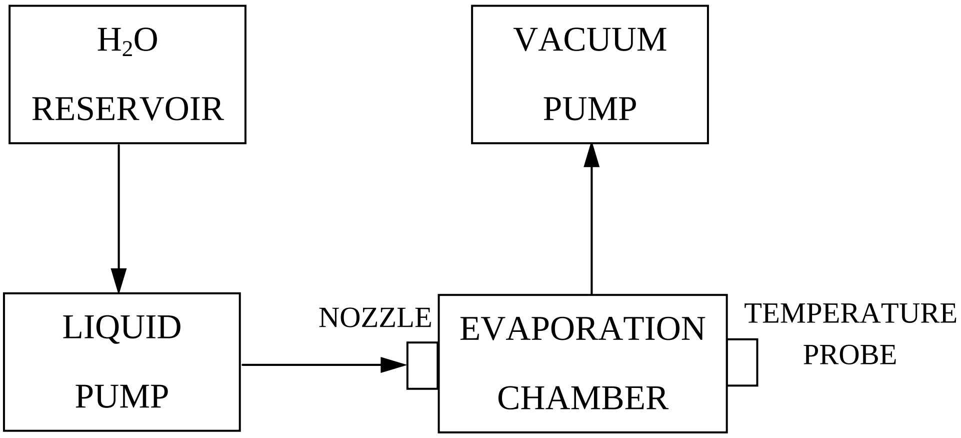


Figure 1: Schematic diagram of the experimental setup. A thermocouple termperature probe is attached to the outer surface of the evaporation chamber to measure its cooling rates.

The liquid pump (NP-CX-100, Nihon Seimitsu Kagaku, Japan) draws tap water from the refrigerant reservoir and forces liquid H_2O through a nozzle into the evaporation chamber. Six pinholes (diameters around 80 μm) are laser-drilled into the stainless steel nozzle plate. The instability of the liquid jets (Lin and Reitz, 1988) which is generated by forcing H_2O through these pinholes, disperses them into micron-sized water droplets. The liquid pump delivers a flow rate of 80 mL/min at a pressure of 30 bar. In the cooling rate measurements, the 1.5 L stainless steel evaporation chamber is pumped by a mechanical vacuum pump

(SD-450, Varian) to maintain an evaporative environment, with a pressure around 0.1 mbar or better. Typical results on the cooling rates of the water refrigerant are summarized in Fig. 2. The testing embodiment could be cooled down from room temperature to –20 °C within 6 minutes. The ultimate low temperature that utilizes the H_2O refrigerant is around –25 °C, which extends the exploitation scope of the water refrigeration system from the air-conditioning into the sector of refrigerated products.

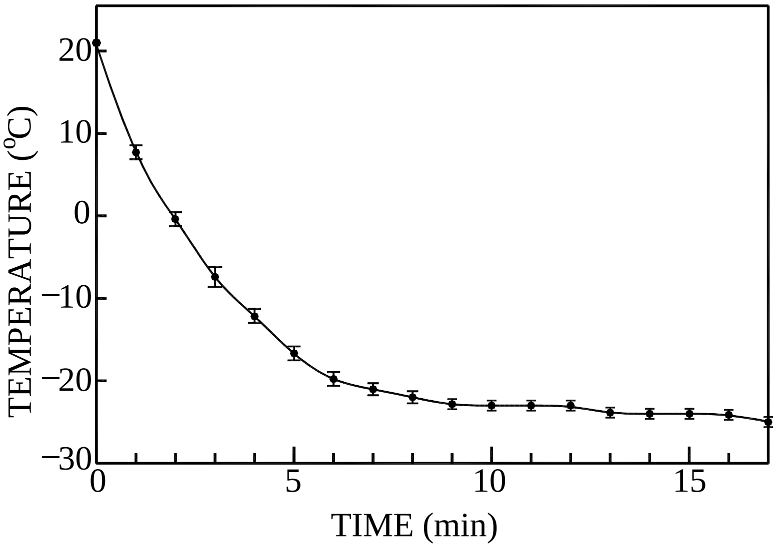


Figure 2: Cooling curve of the experimental embodiment. Error bars (1 standard deviation) are marked on the graph.

4. DISCUSSION AND CONCLUSIONS

The successful operation of the water refrigeration system is based on the fact that its evaporation rate is not controlled thermodynamically but kinetically. According to the kinetic theory of gases (Atkins, 1994), the rate of evaporation $\frac{dN}{dt}$ is given by

$$\frac{dN}{dt} = \frac{-\Delta P N_A A}{(2\pi MRT)^{1/2}}, \tag{1}$$

where ΔP is the pressure difference between the equilibrium vapor pressure of the liquid at temperature T and the external pressure of the environment, N_A is the Avogadro's number, M is the molecular weight, R is the gas constant, and A is the surface area of the liquid phase. When a 1 cm^3 liquid droplet is dispersed into 1 μm micro-spheres, the surface area is increased by four orders of magnitude. Consequently, the rate of cooling is substantially enhanced by atomizing the liquid into micron-sized droplets. At a water flow rate of 80 mL/min, the cooling capacity of the testing embodiment is estimated to be 34 kJ/min. The essence of the water refrigeration system relies on the physical principle of the kinetic evaporation process. In addition to the environmental and safety advantages in comparison with those of the halogenated refrigerants and other natural working fluids, the heat of vaporization of the hydrogen-bonded water (Atkins, 1994) ($\Delta H^{o}_{vap} = 40.6\ \text{kJ/mol}$) assures a satisfactory economy for every H_2O molecule pumped out of the embodiment, especially for an open-loop system in which H_2O can be expelled to the atmosphere. To improve the performance of the H_2O refrigeration technology, fundamental studies on the evaporation dynamics and reliable methods which can generate submicron-sized water droplets are indispensable (Krämer *et al*., 1999 ; Smith *et al* ., 2002 ; Stöcket *et al*., 2005 ; Wood *et al*., 2002). A patent which describes the technical aspects of the hydrogen-bonded liquid refrigerants and the practical embodiments has been granted (Chen, 2007).

A refrigeration method that enhances the evaporation rate of liquid water by dispersing H_2O into micron-sized droplets is reported. The enclosure probabilities of impurities (nucleation centers) inside the individual H_2O micro-sphere are greatly reduced such that the onset of freezing from the heterogeneous nucleation mechanism is delayed. Combining these two characteristic properties with a reduced pressure environment, we can transform tap water at room temperatures into the supercooled state (down to –25 °C) in a compact embodiment. In summary, the environmental-friendly, chemically non-corrosive, non-flammable, and physiologically harmless water, in the form of dispersed droplets, can be exploited as a high-performance refrigerant in the 4 ~ –25 °C temperature range.

REFERENCES

Althouse, A.D., Turnquist, C.H. and Bracciano, A.F., 1988, *Modern Refrigeration and Air Conditioning*, The Goodheart-Willcox Company, South Holland, Illinois.

Angell, C.A., 1983, Supercooled water, *Annu. Rev. Phys. Chem*., vol. 34: p. 593-630.

Atkins, P.W., 1994, *Physical Chemistry*, Oxford University Press, Oxford, 5th Edition.

Chen, K., 2007, Atomized liquid jet refrigeration system, US patent 7,159,407 B2.

Debenedetti, P.G., 2003, Supercooled and glassy water, *J. Phys*.: *Condens. Matter*, vol. 15: p. R-1669-726.

Krämer, B., Hübner, O., Vortisch, H., Wöste, L., Leisner, T., Schwell, M., Rühl, E. and Baumgärtel H., 1999, Homogeneous nucleation rates of supercooled water measured in single levitated microdroplets, *J. Chem. Phys*., vol. 111: p. 6521-7.

Kraus, G.F. and Greer, S.C., 1984, Vapor pressures of supercooled H_2O and D_2O, *J. Phys. Chem*., vol. 88: p. 4781-5.

Lin, S.P. and Reitz, R.D., 1988, Drop and spray formation from a liquid jet, *Annu. Rev. Fluid. Mech*., vol. 30: p. 85-105.

Lorentzen, G.,1995, The use of natural refrigerants: a complete solution to the CFC/HCFC predicament, *Int. J. Refrigeration*, vol. 18: p. 190-7.

Midgley, T. Jr. and Henne, A. L., 1930, Organic fluorides as refrigerants, *Ind. Eng. Chem*., vol. 22: p. 542-5.

Mishima, O. and Stanley, H.E., 1998, The relationship between liquid, supercooled and glassy water, *Nature*, vol. 396: p. 329-35.

Smith, J.N., Flagan, R.C. and Beauchamp, J.L., 2002, Droplet evaporation and discharge dynamics in electrospray ionization, *J. Phys. Chem. A*, vol. 106: p. 9957-67.

Stöckel, P., Weidinger, I.M., Baumgärtel, H. and Leisner, T., 2005, Rates of homogeneous ice nucleation in levitated H_2O and D_2O droplets. *J. Phys. Chem. A*, vol. 109: p. 2540-6.

Wood, S.E., Baker, M.B. and Swanson, B.D., 2002, Instruments for studies of homogeneous and heterogeneous ice nucleation in free-falling supercooled water droplets, *Rev. Sci. Instrum.* vol. 73: p. 3988-96.

UNEP (United Nations Environment Programme), 2002, *Production and Consumption of Ozone-Depleting Substances under the Montreal Protocol: 1986-2000*, UNEP, Nairobi, Kenya.

UNFCCC, 1997, *Kyoto Protocol to the United Nations Framework Convention on Climate Change.*