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A Study on Ice Slurry Production by Water Spray

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Key Words : Ice slurry, Ethylene glycol, Spray droplets, Cold heat transport material

Abstract

A theoretical and experimental study is performed to investigate the characteristics of ice slurry product. By diffusion-controlled evaporation model the possibility of ice slurry is theoretically anticipated. The water vapor evaporated from the surface of droplets is extracted continuously from the chamber by a vacuum pump. The droplet diameter is measured by silicon immersion method. The ice slurry is obtained by spraying droplets of ethylene glycol aqueous solution in the chamber where pressure is maintained under the triple point of water. The droplet with the diameter of $300\mu m$ and the initial temperature of 20℃ was changed into ice particle within the chamber of 1.33m in height.

Nomenclature

a : Radius of a droplet, m
C_p : Specific heat, $J/(kg \cdot K)$
c : Vapor concentration, kg/m^3
D_p : Diameter of droplet, m
D_{p1} : Initial diameter of droplet, m
D_{p2} : Diameter of droplet after δt, m
D_v : Diffusion coefficient of vapor, m^2/sec
h_{fg} : Latent heat of vaporization, J/kg
k : Thermal conductivity, $W/(m \cdot K)$
M : Molecular weight, $kg/mole$
m : Mass of a droplet, kg
P_{inj} : Spraying pressure at nozzle, $kg_f/cm^2 \cdot G$
$\overline{R}$: Universal gas constant, $N \cdot m/(mole \cdot K)$

Greek letters

λ : Mean free path, m
ρ_p : Density of droplets, kg/m^3

Subscripts

a : Value at the droplet surface($r=a$)
g : Gas phase
l : Liquid phase
∞ : Value at the surroundings($r=\infty$)

1. Introduction

The development of non-CFC refrigerants has been actively carried out since confirming

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that CFCs contribute to the destruction of the ozone layer. However, the developed alternatives of CFCs also conflict with the new criteria of environmental disruption such as the GWP(Global Warming Potential). Thus, in the field of refrigeration, there is interest in using natural refrigerants, such as water, air and helium.

In particular, research using water as a refrigerant has recently been carried out because water is a common and harmless substance in nature and is safer than the other refrigerants. This research is of interest despite of the large specific volume of water vapor. Consequently, an attempt to make ice using water has begun in earnest, particularly since the development of vapor compressor with good performance at low pressure has been solved.(1) It is a very attractive idea to use water as a refrigerant and to use water for making fluid ice slurry with a high density of cold energy.(2)

The technology of ice production by water spray has been long used for making artificial snow at ski slopes. It is made by spraying water into the atmosphere through a compressor. Ice particles are formed by transferring latent heat of water droplets to the atmosphere. However, the technology of making ice slurry is different from that of making snow. The process of this technology is that water is sprayed in a vacuum chamber with adiabatic walls and the water vapor formed from the droplet surface is continuously removed from the chamber, and the vapor absorbs the latent heat of vaporization from the droplets. As a result, the droplet temperature declines steadily until all the droplets are changed to ice.

In the present study, both theoretical analysis and experiments were carried out to verify the following questions: When water is sprayed in a chamber with a height of 1.33m at an ambient temperature, can it be possible for a part of the droplets or all of the droplets to be changed to ice before the droplets reach the chamber bottom? What kind of conditions are needed for producing ice? Can they be realized to get a transportable ice slurry at the chamber bottom?

Through the investigation of the evaporating phenomena of a single liquid droplet by the diffusion-controlled evaporation model, the evaporating process of the atomized water droplet, related to the pressure condition of the chamber, was estimated for several droplet sizes. The change of droplet diameter with the spraying pressure was observed in vacuum chamber using the oil bath for collecting droplets, and the droplet size of an aqueous solution was compared with the tap water under the same spraying pressure. The production process of the transportable two-phase ice slurry, obtained by spraying an aqueous solution mixed with ethylene glycol in a vacuum chamber, was also observed.

2. Theoretical analysis

2.1 Rate of mass reduction of a droplet

Research on the analysis of the evaporation of a droplet has been found in several references.(3,4) Assuming that the evaporation at the droplet surface can be explained by diffusion-controlled evaporation, the rate of mass reduction of the droplet with time, as shown in Fig.1, is given by

$$\dot{m}=4\pi a^2 D_v\left(\frac{dc}{dr}\right)_a \tag{1}$$

where $\dot{m}$ represents the mass reduction rate of droplet, a is the radius of droplet and D_v, the diffusion coefficient. The radial gradient

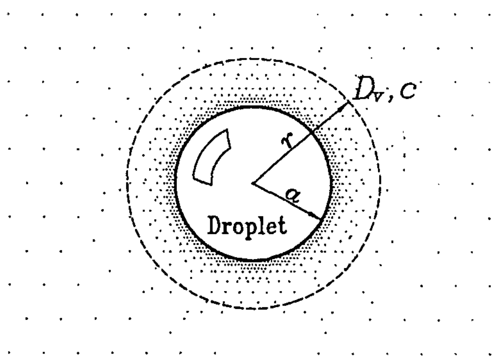

Fig.1 Diffusion controlled evaporation model

of vapor concentration is determined by the following equation.

$$\frac{dc}{dr} = \frac{\dot{m}}{4\pi D_v r^2} \tag{2}$$

Integrating equation(2) gives

$$c_a - c_\infty = \frac{\dot{m}}{4\pi D_v}\int_a^\infty \frac{dr}{r^2} = -\frac{\dot{m}}{4\pi D_v a} \tag{3}$$

$$\dot{m} = -4\pi a D_v (c_a - c_\infty) \tag{4}$$

where c_a and c_∞ are the vapor concentrations at $r=a$ and ∞, respectively. Assuming the water vapor as the ideal gas, equation(4) can be expressed as follows by the relation $c = MP/\overline{R}T$.

$$\dot{m} = -4\pi a D_v \frac{m}{\overline{R}}\left(\frac{P_a}{T_a} - \frac{P_\infty}{T_\infty}\right) \tag{5}$$

where M represents the molecular weight of water vapor, $\overline{R}$ is the universal gas constant, P_a, T_a and P_∞, T_∞ are the pressures and the temperatures of water vapor at $r=a$ and ∞, respectively.

2.2 Rate of variation of droplet size[5,6]

The mass variation of a droplet can be described as follows from the relation of dD_p^3/dt

$$= 3D_p^2\, dD_p/dt,$$

$$\dot{m} = \frac{\pi}{2}\rho_p D_p^2 \frac{dD_p}{dt} \tag{6}$$

where ρ_p and D_p represent the density and the diameter of droplet, respectively. From equation(5) and (6), the variation of droplet size is derived by

$$\frac{dD_p}{dt} = \frac{4D_v M}{\overline{R}\rho_p D_p}\left(\frac{P_\infty}{T_\infty} - \frac{P_a}{T_a}\right) \quad \text{for } D_p > \lambda \tag{7}$$

where λ represents the mean free path of water vapor. By integrating both sides, the rate of the droplet size variation with time from D_{p_1} to D_{p_2} can be obtained by

$$\int_{D_{p_1}}^{D_{p_2}} D_p\, dD_p = \int_0^t \frac{4D_v M}{\overline{R}\rho_p}\left(\frac{P_\infty}{T_\infty} - \frac{P_a}{T_a}\right)dt \tag{8a}$$

$$D_{p_2}{}^2 - D_{p_1}{}^2 = \frac{8D_v Mt}{\overline{R}\rho_p}\left(\frac{P_\infty}{T_\infty} - \frac{P_a}{T_a}\right)$$

$$\text{for } D_p > \lambda \tag{8b}$$

2.3 Temperature variation of droplet surface[7,8]

The temperature of a droplet in an infinite space would be determined by balancing the latent heat loss due to its evaporation and the heat conduction due to the temperature difference between the droplet surface and the surroundings. If the droplet is as small as 100 micrometers, we assume that natural convection in a droplet can be ignored.

The thermal conduction equation can be expressed by

$$\frac{\partial T}{\partial t} = \frac{k_g}{\rho_g C_{p_g}}\left(\frac{2}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial r^2}\right) \tag{9}$$

When the droplet temperature is lower than the surroundings ($T_a < T_\infty$),

the heat obtained from surroundings

$$= 4\pi a^2 k_g \left(\frac{dT}{dr} \right)_a \tag{10a}$$

and *the heat released by evaporation*

$$= h_{fg}\dot{m} = 4\pi a^2 D_v h_{fg} \left(\frac{dc}{dr} \right)_a \tag{10b}$$

where k_g and h_{fg} represent the thermal conductivity of water vapor and the latent heat of vaporization of water, respectively. Assuming the thermal equilibrium at the droplet surface, the following relations can be obtained from equation(10).

$$k_g \left(\frac{dT}{dr} \right)_a + D_v h_{fg} \left(\frac{dc}{dr} \right)_a = 0 \tag{11}$$

Meanwhile, the radial density gradient at the droplet surface, derived by equation(1) and (4), is expressed by

$$\left(\frac{dc}{dr} \right)_a = \frac{\dot{m}}{4\pi D_v a^2} = -\frac{(c_a - c_\infty)}{a}$$
$$= -\frac{1}{a} \frac{M}{\bar{R}} \left(\frac{P_a}{T_a} - \frac{P_\infty}{T_\infty} \right) \tag{12}$$

If the droplet is small enough, the radial temperature gradient at its surface can be given by

$$\left(\frac{dT}{dr} \right)_a = -\frac{(T_a - T_\infty)}{a} \tag{13}$$

By substituting equation(12) and (13) into equation(11), the temperature difference between the surroundings and the droplet surface can be rewritten as

$$T_\infty - T_a = \frac{D_v h_{fg} M}{\bar{R} k_g} \left(\frac{P_a}{T_a} - \frac{P_\infty}{T_\infty} \right) \tag{14}$$

This equation shows that the droplet temperature at steady state does not depend upon the droplet size.

From the relation that "variation of internal energy in a droplet = heat obtained from surroundings by heat conduction - heat loss by evaporation", the temperature variation of the droplet after reaching the quasi-steady state can be obtained as follows.

$$\delta T_p = \frac{\text{heat loss by evaporation} - \text{heat obtained by heat conduction}}{4/3\pi a^3 \rho_p C_{pl}} \tag{15}$$

$$\frac{\pi}{6} \rho_p D_p^3 C_{pl} \delta T_p =$$
$$\left\{ \pi D_p^2 h_{fg} D_v \left[-\frac{2M}{D_p \bar{R}} \left(\frac{P_a}{T_a} - \frac{P_\infty}{T_\infty} \right) \right] \right.$$
$$\left. + \pi D_p^2 k_g \left[-\frac{2}{D_p} (T_a - T_\infty) \right] \right\} \cdot \delta t \tag{16}$$

$$\delta T_p = -\frac{12}{\rho_p C_{pl} D_p^2} \left\{ \frac{h_{fg} D_v M}{\bar{R}} \left(\frac{P_a}{T_a} - \frac{P_\infty}{T_\infty} \right) \right.$$
$$\left. - k_g (T_\infty - T_a) \right\} \delta t \tag{17}$$

where C_{pl} represents the specific heat of droplet.

2.4 Result of theoretical analysis

When the vacuum chamber is at the saturation state with a pressure value of 0.6113kPa, equivalent to the triple point of water, the temperature variation at the droplet surface with the different initial droplet sizes calculated by equation(17) is shown in Fig.2. It can be seen from the Fig.2 that the droplet temperature at the steady state does not depend on the droplet size.

However, the smaller the initial droplet size is, the faster the droplet temperature decreases towards the steady state. Although the initial droplet temperature is 20℃, the temperature of the droplets decreases to 0℃ within 0.07sec for sizes smaller than 300 micrometers. There-

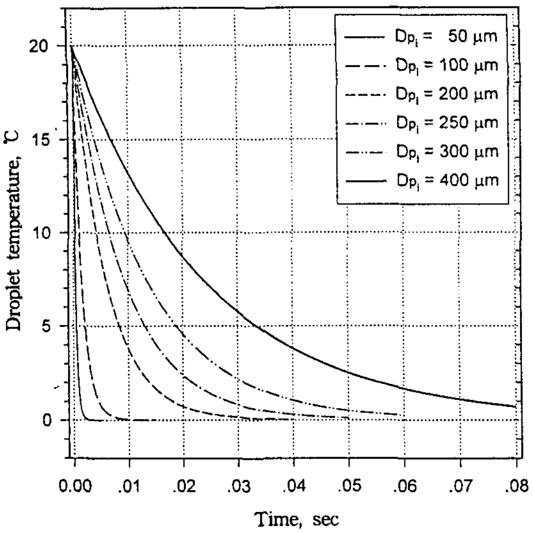

Fig.2 Effect of initial droplet diameter on variation of droplet temperature

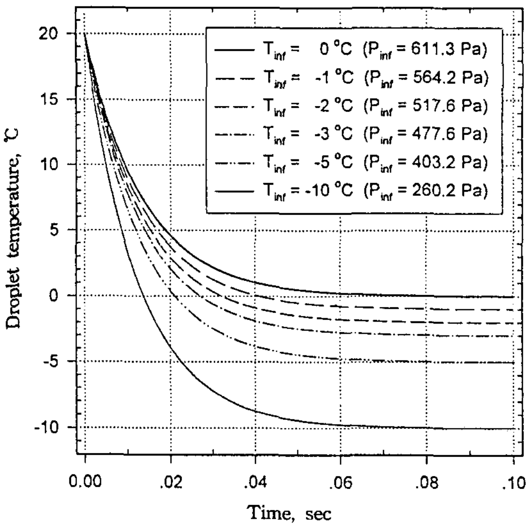

Fig.3 Effect of surrounding pressure on variation of droplet temperature

fore, it is estimated that if the droplet size of water spray at the ambient temperature becomes smaller than 300 micrometers in an insulated chamber maintained at the pressure of 0.6113kPa, the droplets can be changed to ice within the falling time of 0.07sec.

In the case that a droplet with a temperature of 20℃ and a size of 300 micrometers is sprayed in an insulated chamber, the temperature variation of the droplet with time is shown in Fig.3. Here, the result is obtained by assuming that the droplet does not change to ice. From Fig.3, the chamber pressure should be maintained at about 0.477kPa(=0.0047atm, 3.5torr) in order to change the droplet to ice within 0.07sec, if there exists some supercooling to begin the formation of ice.

Based on the above theoretical results, it is found that ice slurry is able to be produced due to the vaporization of water with a temperature of 20℃. For this production, the conditions described below should be satisfied:

- Initial droplet should be smaller than 300 micrometers.
- Staying time of droplet should be over 0.07sec.
- Pressure in chamber should be maintained below 0.477kPa(0.0047atm, 3.5torr)

3. Experimental methods and results

3.1 Experimental apparatus

Based on the above analysis, we used a spray nozzle with a mean droplet size of 300 micrometers. A vacuum chamber(1) with a height of 1.33m was used so that the droplet would stay in the chamber for more than 0.07sec.

A schematic of the experimental apparatus for producing ice slurry and observing the characteristics of spray droplets from a nozzle is shown in Fig.4. The apparatus consists of a compressed air tank(18) with a pressure regulator, a mixing unit(17) for mixing water with ethylene glycol, a spraying water control unit(16) and a water filter.(15) In order to measure the pressure and the temperature of spraying water to nozzle with accuracy, the pressure

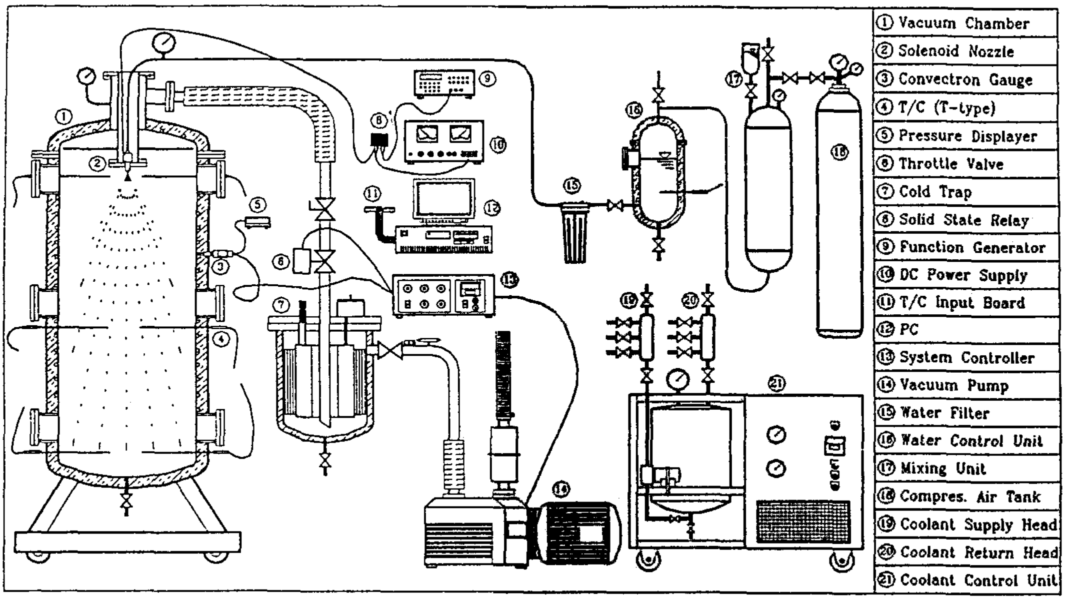

Fig.4 Schematic diagram of ice slurry making system

transducer and thermocouple was set up at the position of 10mm below the nozzle. The pipes of the system were insulated.

The vacuum exhaust line consists of a vacuum pump(14) with exhaust volume of 1.5m^3/min, a cold trap(7) positioned before the vacuum pump to protect the pump and a throttle valve(6), of which opening/closing was operated by the system controller(13) corresponding to the electrical signal from the pressure sensor.(3)

As a part of the chamber's internal structure for exhausting vapor, a disc-shaped plate is located in the flange of the upper chamber space to prevent the entrainment of the spray droplets to the vapor outflow from the chamber, while the gas or vapor can be extracted through the gap between the flange and the plate. For the cold trap, copper tubes of outer diameter of 1/2 inches were set up around the cylindrical chamber filled with liquid nitrogen so that vapor is condensed while passing through the tubes. The coolant control unit(21) is to compensate for the heat transferred to the sight glasses and the flange of the vacuum chamber, and is to control the initial temperature of water spray to be below the ambient temperature.

Thermocouples are located at the chamber inner space and surface. The temperature data are acquired by an A/D converter in a PC(12) with a thermocouple input board(11) receiving the electrical signal from thermocouples. The pressure data are obtained by the pressure gauge controller(5) converting the signal from the vacuum gauge(3) established at the chamber.

The nozzle used in the present study is the fuel injection valve used in MPI(Multi Point Injection) of gasolin engine. It consists of a main body and a needle with an electromagnet. According to the movement of magnet, needle moves to about 0.1mm upward from the seat. Water is attomized by the pindle attached to the end of needle.

3.2 Measurement of diameter of spray droplet

The droplet collecting method using an oil bath was chosen to measure the size of spray droplets in the vacuum chamber because of its simplicity. Silicon oil, which is commonly used for the collection of water droplets, was selected as the oil.

The oil bath was located on the chamber bottom, and then water was sprayed for 10 seconds after the chamber pressure becomes 0.133kPa(1torr) by a vacuum pump. The oil bath on which spray droplets were collected was drawn from the chamber through the sight glass, and the droplet size was measured by the polaroid camera attached to an electron microscope of 50~10,000 magnification.

The size of picture obtained by the electron microscope at the lowest magnification is 95 $\times 73\text{mm}^2$ on which 10~15 collected droplets were observed. Sampling was performed 2~4 times at every different position.

Figure 5 shows the droplets photographed by the electron microscope. From the figure, it is found that the spraying droplets have almost spherical shape. The SMD(Sauter Mean Diameter) as an average diameter for a spray is given by the following equation(18).

$$D_{ab}=\left[\frac{\Sigma N_iD_i^a}{\Sigma N_iD_i^b}\right]^{1/(a-b)} \tag{18}$$

where a, b are constants related to the spray condition.

Figure 6 shows the relation between the spraying pressure and the average diameter of droplets for the aqueous solution mixed with 7% ethylene glycol. As known from this figure, the average diameter of spray droplets rages 200~350 micrometers, and it tends to decrease as the spraying pressure increases.

As the viscosity of ethylene glycol($6.51\times10^{-2}N\cdot s/m^2$) at 0℃ is about 37 times higher than that of water($1.75\times10^{-3}N\cdot s/m^2$), it is found, from Fig.6, that the average diameter increases as the viscosity of liquid increases.

3.3 Ice slurry production by water spray

The shape of ice slurry obtained by water spray and the temperature variation at diffe-

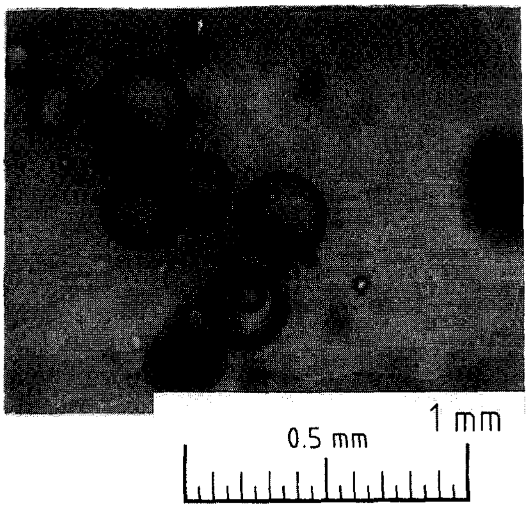

Fig.5 Microphotograph of droplets

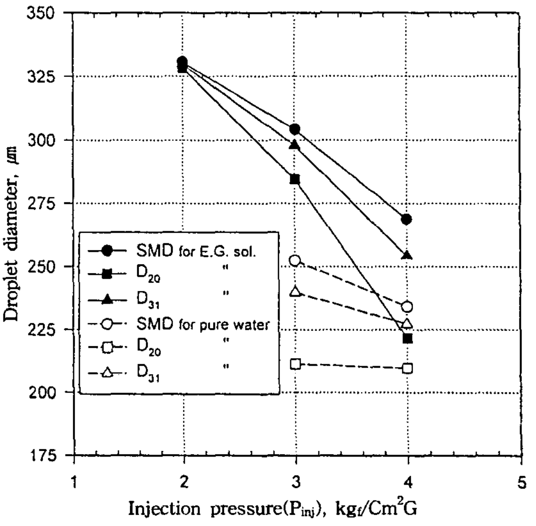

Fig.6 Mean diameters of droplets captured in oil bath

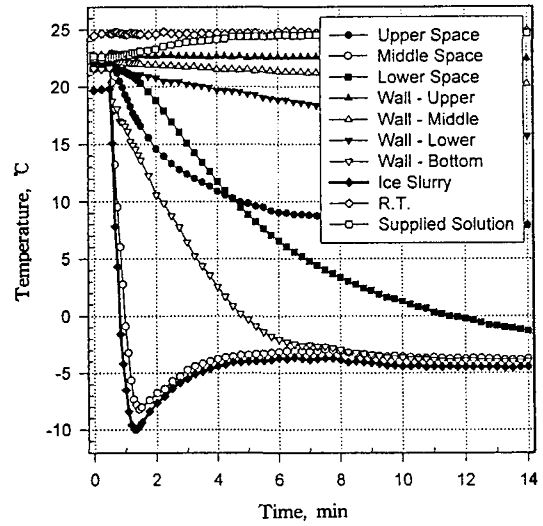

Fig.7 Temperature variations in chamber by spraying water solution : Ethylene glycol 7%, $P_{inj}=2kg_f/cm^2G$, Duty = 5%

rent locations in the chamber, when the ice slurry making system operated under the vacuum exhaust condition, were also observed.

Figure 7 shows the temperatures at each location in the chamber, when the pressure of vacuum chamber reached below 1 torr and the aqueous solution mixed with 7% ethylene glycol was sprayed with the spraying pressure of $2kg_f/cm^2G$.

From the Fig.7, the temperature at the middle space in the chamber also decreases up to about -10℃, similar to that of ice slurry, because the inner space of chamber is under the quasi-equilibrium state due to the vaporization of droplets. The temperature at the lower space in the chamber, however, slowly decreased in comparison to the middle space. It is because the temperature at lower space in the chamber before starting spray is equal to that of the environment.

Figure 8(a) shows the manufactured ice slurry by spraying the aqueous solution mixed with 7% etylene glycol in the vacuum chamber. the ice slurry is similar to a gruel coexisting with solid and liquid phases. The ice produced by spraying city water without ethylene glycol is shown in Fig. 8(b). It was found that the produced ice particles coalesce together and formed the stiff lump of ice. the lump of ice must be difficult to be extracted.

(a) Aqueous solution(ethylene glycol 7%)

(b) Water(no ethylene glycol)

Fig.8 Photographs of ice obtained by spraying water or its aqueous solution

Therefore, we use the aqueous solution containing some amount of ethylene glycol, a kind of antifreeze. The reason for using just 7% ethylene glycol is to control the supercooling as about -3℃ which is found from the preliminary experiment.

3.4 Example for calculating ice storage heat

For the droplet spray condition described below, the ice storage heat is calculated by using the results of the theoretical analysis and experiment.

- Injection pressure(P_{inj}) : $3kg_f/cm^2G$
- Temperature of spraying water(T_{pi}) : 20℃, water
- Chamber pressure : $P_\infty=(P_{sat})_{-5℃}=0.403kPa$
- Distance from nozzle to chamber bottom : 1.33m

Assumptions used here are :

- A droplet reaching the chamber bottom does not continue to vaporize any more.
- The state of the chamber inner space is self-controlled as an adiabatic, saturation condition.
- The phase change of a droplet is performed at 0℃ without supercooling.

Under the above conditions, the flow rate of water spray per unit time ($\dot{G}$), the size of spray droplets(D_{pi}), the number of spray droplets per unit time ($\acute{N}$), etc., are determined from the spray characteristics of nozzle as follows.

$$\dot{G}=89.75g/(10\min)=1.50\times10^{-4}kg/\sec$$

$$D_{pi}\fallingdotseq250\mu m=2.50\times10^{4}m\ ;\ SMD$$

$$m=\frac{\pi}{6}\rho_p D_p^3=8.18\times10^{-9}kg$$

$$\acute{N}=\dot{G}/m=1.83\times10^{4}\#/\sec$$

The mass reduction of a droplet(δm) by vaporization can be calculated as follows.

$$\delta m=\frac{\pi}{6}\rho_l\left\{\frac{D_{p2}^3}{1+(\rho_l/\rho_i-1)\times(I.P.F.)}-D_{p1}^3\right\}$$

$$=\frac{\pi}{6}\times1,000\times\left\{\frac{(2.4634\times10^{-4})^3}{1+(1,000/917-1)\times(34.85/100)}\right.$$

$$\left.-(2.5\times10^{-4})^3\right\}=-5.93\times10^{10}kg$$

The total ice storage heat produced by water spray droplets is obtained from the latent heat of ice and the number of spray droplets.

$$Q_c=-\delta m\cdot\acute{N}h_{fg}$$

$$=(5.93\times10^{-10})(1.83\times10^{4})(2.477\times10^{6})$$

$$=26.9W$$

where the latent heat of ice used above is calculated as follows.

$$※\ h_{fg}=\sqrt{(h_{fg})_{0℃}\times(h_{fg})_{20℃}}$$

$$=\sqrt{(2.501\times10^{-6})(2.454\times10^{6})}$$

$$=2.477\times10^{6}J/kg$$

3.5 Inducement of conditions for adequate ice slurry production

It is already known that in order to transport ice slurry in a tube, for a small system with tube size of below 100mm, an adequate I. P. F. ranges between 25% and 30%. To design a transportable ice slurry system with an adequate I. P. F. using the water spray method, information should be provided on the relations among the injection pressure, the atomized droplet size and the established chamber pressure(P_{inf}).

Figure 9 is the result of the present report by combining Fig.2, Fig.3, Fig.6 and the time for a droplet to reach the chamber bottom from the nozzle.

Conditions considered for the Fig.9

- Initial droplet temperature(T_{di}) : 20℃
- Adequate I. P. F. : 27.5%(at which 27.5% of the droplets are changed into ice when the droplets reach the chamber bottom)
- The freezing point of a droplet(T_f) : -2.42℃ (for an aqueous solution of 7% ethylene glycol)

Usage of the Figure 9

① *An example of application for the pre-*

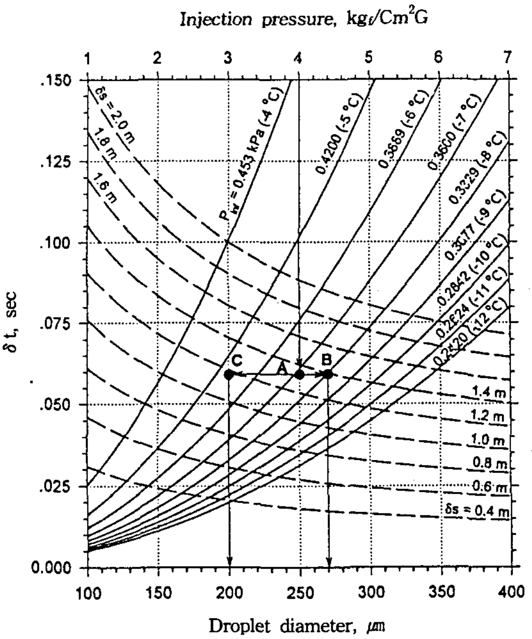

Fig.9 Optimizing chart for making transportable ice slurry(at I.P.F.=27.5%)

sent experimental apparatus :

A droplet size of about 270 micrometers is obtained with an injection pressure of $4kg_f/cm^2G$, and the distance between the nozzle and the chamber bottom is 1.33m. Then, the point A is obtained by drawing a line parallel to the y-axis from point '4' of the upper x-axis(injection pressure) to the dotted curve of $\delta s = 1.33m$.

The $P_{inf}(\fallingdotseq 0.3329kPa)$ can be read from the intersection B between the line parallel to the x-axis at A and to the y-axis at '270' of the lower x-axis(droplet diameter). It is found, therefore, that a chamber pressure of 0.3329kPa has to be maintained in order to obtain a transportable ice slurry.

② *For smaller spray droplets under the same spray pressure* :

If droplets of size 200 micrometers are sprayed under the same conditions of injection pressure and chamber size as in the case ① described above, a P_{inf} of about 0.41kPa can be read from the intersection C between the line parallel to the x-axis at A and to the y-axis at '200' of the lower x-axis. Thus, if droplets of this small size are sprayed under the same injection pressure, the chamber pressure can be maintained at a higher value.

4. Concluding remarks

This study was performed to produce the transportable ice slurry in an ice storage system by spraying an aqueous solution mixed with a certain amount of ethylene glycol in a decompressed chamber. The conclusions obtained in the present study are as follows:

1) The conclusions obtained from the theoretical analysis of the evaporation of a droplet are first described. The ice slurry is able to be produced due to the vaporization phenomena of water droplets even if the initial temperature of droplets is 20℃. For this production, the conditions described below should be satisfied :

- Initial droplet should be smaller than 300 micrometers.
- Staying time of droplet in chamber should be over 0.07sec.
- Pressure in chamber should be maintained below 0.477kPa.

2) The conclusions obtained using the experimental apparatus made by the results of theoretical analysis are :

- The average diameter of spraying droplets has the range of 200~350 micrometers. It tends to decrease as the spraying pressure increases.
- Although the wall of chamber and the spraying water is at ambient temperature, the temperature of the manufactured ice slurry decreases up to about -10℃.

- The ice slurry with fine ice particles was produced by spraying the aqueous solution mixed with 7% ethylene glycol in a decompressed chamber.
- In case of spraying city water without ethylene glycol, the stiff lump of ice was produced due to the coalescence of ice particles on the chamber bottom.

3) The ratio of the mass reduction of a droplet to the initial mass is 7.25% of the spraying water. The ice storage heat estimated from the ratio is 26.9W, so that the ice of 0.53kg can be produced from the spray of 1kg.

4) The optimizing chart(Fig.9) for examining the operating conditions to make a transportable ice slurry is proposed, using the relation of the residence time of a droplet in the chamber, the injection pressure, the spray droplet size and the chamber pressure.

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