On Mechanisms of Nucleation of Ice Crystals by Aerodynamic Cooling[①]

Huang Shihong (黄世鸿), *Qian Changguo* (钱昌国) ②, *Wang Weimin* (王伟民)③, *Li Ruxiang* (李如祥)

Department of Atmospheric Science, Nanjing University, Nanjing 210008

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ABSTRACT

The investigation of mechanisms of nucleation of ice crystals by aerodynamic cooling produced by supersonic airflow is carried out. Three processes are considered to be the principal causes for aerodynamic cooling and nucleation of ice crystals. They are: adiabatic cooling in supersonic airflow, cooling at the cores of vortices around the edge of airflow and entrainment of ambient stationary air into supersonic airflow. It is thermodynamically confirmed that the temperature lowering in supersonic flow depends on the Mach number M there and stagnant pressure P_o at a certain stagnant temperature T_o. The temperature will decrease by more than 6°C as M increases by 0.1. The influence of P_o on cooling is shown through the variation of mass flow rates, which increase with P_o.

Experiments in laboratory have shown that ice–forming rate ρ_i produced by supersonic airflow increases from 10^{11} to 10^{12} / g as M increases from 1.10 to 1.84 at P_o = 5 and 6 atm, and ρ_i increases from 4.3×10^{11} to 10.3×10^{12} / g as the mass flow rate increases from 3.5 to 5.7 g / s and P_o increases from 1.5 to 5.0 atm at M = 1.80 and T_o = 25°C. In field experiments the ice concentrations of 50 to 200 per liter in about 2000 m^3 were measured when air of about 0.5 g were spurted at a Mach number of M = 1.80 into supercooled fog with temperatures between −0.5°C and −4.6°C. These results are compatible with the prediction of aerodynamics.

The snapshot taken in experiments represents the detailed structures of vortex motion around a supersonic airflow.

Key words:. Aerodynamic cooling, Ice–forming rate, Supersonic airflow

I. INTRODUCTION

Modern ice phase modification is to initiate colloidal instability in a supercooled fog through the induction of artificial ice crystals. Two kinds of ice nucleants have been widely used. One is a kind of heterogeneous nucleants, made of crystalline solids dispersed in aerosol form, such as AgI. The other is a kind of evaporative coolants, such as dry ice and liquid propane. The mechanism of ice nucleation of coolants is homogeneous freezing of droplets induced by evaporation. Hicks and Vali (1973) have given a concise review on earlier works about dry ice and propane spray. Dry ice is currently widely employed in weather modification in China.

In addition of those ice nucleants, Vonnegut (1948) proposed another kind of operation

①This project was supported by the National Natural Science Foundation of China.

②Institute of Acoustics, Nanjing University, Nanjing 210008.

③Meteorological Institute of Air Force, Nanjing 211101.

of ice nucleation. A parcel of compressed air, expanded rapidly and adiabatically, could be chilled and initiate the generation of ice crystals. The method of supersonic expansion generating ice nucleus has been investigated by Fukuta and Paik (1976). Aerosols of organic ice nucleating agents were created with superheated steam, then experienced a rapid adiabatic expansion through a supersonic nozzle. It was shown that the number of ice nucleus generated will be multiplied by a factor of 10^3 as Mach numbers increase from 1 to 2. Weistein and Hicks (1976) have also performed a series of experiments under controlled and free environment conditions. when compressed air expands adiabatically, its cooling initiates the generation of ice crystals in supercooled water fog. Experimental results have shown that approximate 1 cm^3 air at standard pressure, compressed nearly to 4 atm and releasing through a supersonic nozzle, could produce 10^8 ice crystals in total. Huang, et al. (1991) have conducted some experiments using facilities as air compressor and supersonic nozzles. The results showed that the critical pressure initiating the nucleation of ice is 2.1 atm in supercooled fog ($t = -2°C$), and a great number of ice crystals could be observed when the stagnant pressure P_o is 0.2 atm higher than that critical pressure.

In recent years, Rangno and Hobbs (1983; 1984), Kelly and Vali (1991) carried out some interesting and important observations. They pointed out that when an airplane passes through supercooled clouds ice crystals could be found on its passage. Such phenomenon has been termed as "Aircraft Produced Ice Particles" (APIPs). As for the mechanism of APIPs, Vonnegut (1986) suggested that it was due to homogeneous nucleation of water vapor since the temperature in vortices at propeller tips or wing tips may drop below −40°C after adiabatic expansion there. Kelly and Vali (1991) also considered that vortex cooling is one of the most plausible mechanisms of APIPs.

Both supersonic expansion and vortex cooling are termed "aerodynamic cooling". The vortex cooling takes place, however, not only in propeller tips or wing tips, but also in high speed airflow where there is a sharp velocity gradient between moving air and its surrounding stationary air. This paper reports our preliminary results on aerodynamic cooling and its effect on the generation of ice crystals.

II. THE EFFECTS OF M AND P_o ON COOLING DURING SUPERSONIC EXPANSION

The supersonic airflow is generated by a Laval nozzle, which consists of a converging "entry section" and a diverging "exhaust section" with a "throat" in between. According to the first law of thermodynamics the states in an adiabatic flow of an ideal gas hold the relation

$$dh + d(v^2 / 2) = 0 \qquad (1)$$

where dh is the change of enthalpy per unit mass, which can be expressed as

$$dh = c_p dT \qquad (2)$$

and $d(v^2 / 2)$ is the change of kinetic energy per unit mass with a directional velocity v. As for the states before and after the expansion,

$$c_p T_1 + (v_1^2 / 2) = c_p T_2 + (v_2^2 / 2) = \text{constant} \qquad (3)$$

can be obtained. Then using

$$c_p = \gamma R / (\gamma - 1) \qquad (4)$$

and

$$a^2 = \gamma RT, \tag{5}$$

where R, γ and a are the specific gas constant, the ratio of specific heats at constant pressure and at constant volume, and the sound speed, respectively, inserting (4) and (5) into (3) to eliminate c_p and setting $M = v/a$, we have

$$T_1(1+\frac{\gamma-1}{2}M_1^2) = T_2(1+\frac{\gamma-1}{2}M_2^2) = \text{constant}. \tag{6}$$

Assuming $T_1 = T_0$, $v_1 = 0$ and $M_1 = 0$ in the stagnant state, and $T_2 = T$ and $M_2 = M$ at the exit of the nozzle, we have

$$\frac{T_o}{T} = 1 + \frac{\gamma-1}{2}M^2. \tag{7}$$

So the temperature reduction is

$$\Delta T = |T - T_o| = \frac{\alpha T_o}{1+\alpha}, \tag{8}$$

where

$$\alpha = \frac{\gamma-1}{2}M^2. \tag{9}$$

As shown in (8), the temperature reduction ΔT increases as M and T_o increase. Examining cooling potentials of M and T_o shows that the increase of M is more effective than the increase of T_o. Temperature will be lowered more than 6°C if M increases only 0.1 (Fig. 1). Temperature in supersonic airflow could drop to −40°C below at $M = 1.0$ and 1.1, and $T_o = 278$ K and 273 K, respectively. So the homogeneous nucleation of ice crystals (condensation–freezing process) will occur in an airflow containing water vapor. Mach number is considered to be the ratio of kinetic energy of an airflow to the energy of random motion of air molecules, and could be used to rate the degree of transforming heat energy to kinetic energy of directional motion.

In addition to Mach number, the contribution of stagnant pressure P_o to cooling is also considered. Airflows through a supersonic nozzle reach sound speed at its "throat" and have a velocity v at its exit if P_o exceeds a certain critical value. This characteristic is not altered with different P_o. The same temperature reduction, therefore, is obtained at the exit at different P_o if T_o keeps constant. The influence of P_o on cooling is expressed through the variation of mass flow rates, which increase with increasing P_o. The continuity equation of a flow of incondensable gas, is

$$dm/dt = \rho v A \tag{10}$$

where dm/dt, ρ, v and A are the mass flow rate, gas density, flow velocity and cross-section area of a nozzle, respectively. Substituting the state equation into (10), we get

$$dm/dt = PvA/RT. \tag{11}$$

Inserting (5) and $v = Ma$ into (11) to eliminate v, we have

$$dm/dt = PMA(\gamma/RT)^{1/2} \tag{12}$$

and the adiabatic relation is

$$P_o / P = (T_o / T)^{\gamma/(\gamma-1)}. \tag{13}$$

Substituting (13) into (7) to eliminate T_o / T, we have

$$P = P_o(1 + \frac{\gamma-1}{2}M^2)^{-\gamma/(\gamma-1)}. \tag{14}$$

Then, inserting (7) and (14) into (12) to eliminate P and T, we obtain

$$dm / dt = P_o A M(\frac{\gamma}{RT_o})^{1/2}(1 + \frac{\gamma-1}{2}M^2)^{-(\gamma+1)/2(\gamma-1)}. \tag{15}$$

As shown in (15), the mass flow rate of a nozzle increases with increasing P_o at fixed T_o (Fig. 2). Therefore, the increase of P_o results in producing more ice crystals due to more air mass to be expanded adiabatically. Ice forming rate ρ_i, defined as the number of ice crystals produced by a unit mass of supersonic airflow, was measured in our experiments. The facilities used in the experiments consist of a thermostatically controlled cold chamber of volume 370 liters, a Laval nozzle with an exit diameter of 2 mm, a compressed air source connected to the nozzle by a pipe, an electrically controlled solenoid valve installed in the pipe, and an ultrasonic nebulizer which blows water drops of 3 to 12 μm in diameter into the chamber. The experimental procedures are as follows. Regulating the temperature in the cold chamber and the stagnant pressure of the air source to desired values, fixing a Laval nozzle with a given Mach number, and disseminating fog drops into the chamber until the water content w reaches 0.15 gm^{-3}, switching the solenoid valve with triggering time of about 0.15 s. After a supersonic flow spurts out from the nozzle, a large quantity of ice crystals. The air mass spurting out from the nozzle is measured by a gasometer. The ice–forming rates of six Laval nozzles of different Mach numbers 1.10, 1.36, 1.58, 1.67, 1.80 and 1.84 are alternatively measured at T_o = 298 K, t = −8°C (chamber temperature), and P_o = 5 and 6 atm, respectively. The ice–forming rates are also measured for a Laval nozzle of M = 1.8 and at T_o = 298 K, t = −8°C and different stagnant pressures P_o.

It is shown in Fig. 1 that as M increases from 1.10 to 1.84, the ice–forming rate ρ_i increases from 4.2×10^{11} to 11.5×10^{11} g^{-1} at P_o = 5 atm and ρ_i increases from 5.2×10^{11} to

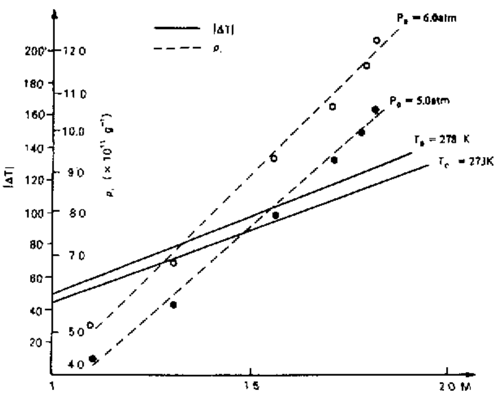

Fig. 1. Temperature drop ΔT calculated by (8) and the ice–forming rate ρ_i obtained from the experiments (T_o = 298 K, t = −8°C and w = 0.15 gm^{-3} as a function of M (each point in the graph represents the median value of six experimental data).

12.4×10^{11} g^{-1} at $P_o = 6$ atm. The more the temperature drops, the higher the ice-forming rate is. It is consistent with the theoretical prediction of Eq. (8).

Fig. 2 shows that the ice-forming rate ρ_i increases from 4.3×10^{11} to 10.3×10^{11} g^{-1} and the mass flow rate increases from 3.0 to 5.7 gs^{-1} as the stagnant pressure P_o increases from 1.45 to 4.0 atm. So the more air emitted, the more ice crystals produced.

III. VORTEX COOLING CAUSED BY SUPERSONIC FLOW

Vonnegut (1950) made an interesting and important experiment with a thermometer mounted in the axis of a cylindrical, vortex-creating housing. The observation showed that the cooling in the core of a vortex generated by aircraft motion might originate from adiabatic expansion. As mentioned by him, the vortices at propeller tips and wing tips are likely to produce the greatest pressure reductions. The temperature change ΔT in the vortex is given by

$$\Delta T = -3.5 \times 10^{-4} v^2, \tag{16}$$

where ΔT is in degrees centigrade, and v is the true air speed in meters per second. The stronger the vortex, the lower the pressure and the temperature are.

The vortex cooling takes place, however, not only in propeller tips or wing tips, but also in high speed airflow, where there is a sharp velocity gradient between moving air and its surround stationary air. After a parcel of stationary air containing water vapor undergoes an adiabatic expansion, its velocity reaches v, at which the air spurts out. According to the thermodynamic prediction of Eq. (8), its temperature drops

$$\Delta T = -v^2 / 2c_p, \tag{17}$$

where c_p varies between 1004 to 1863 J $kg^{-1}K^{-1}$ with the water vapor content in airflow. So the theoretical value ΔT agrees well with the experimental one mentioned above by Vonnegut.

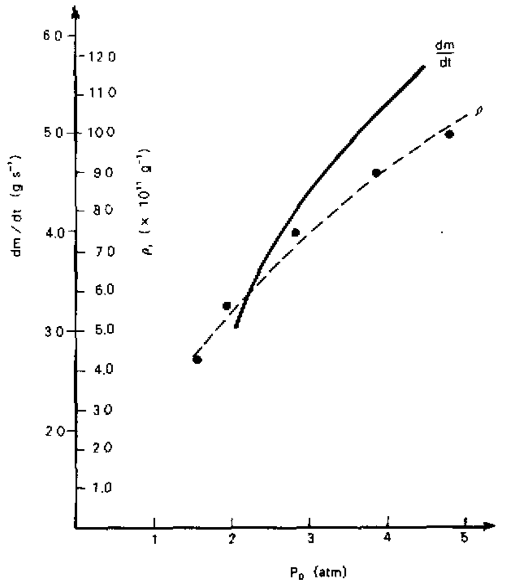

Fig. 2. The mass flow rate of air dm / dt calculated by (15) and the ice-forming rate ρ_i obtained from the experiments as a function of P_o ($M = 1.80$, $T_o = 298$ K and an exit diameter of 2 mm) (each point in the graph represents the median value of six experimental data).

When the velocity reaches the speed of sound (332 ms^{-1}), the temperature in a vortex might conceivably drop by as much as 35°C. At ambient temperature of about −8°C, it surely makes the temperatures well cooled below the homogeneous nucleation threshold (i.e. about −39°C). So Hobbs (1985) had come to the view "that the most likely mechanism for APIPs is the adiabatic expansion and cooling of air in the vortices produced at the tips of propeller blades and aircraft wings".

In order to confirm the existence of vortices around an airflow, the images of air moving at supersonic speeds are picked up by the difference between the densities of moving and stationary air. Fig. 3 exhibits the vortices around a parcel of air, which is spurting out from a nozzle of $M = 1.80$ at $P_o = 3.0$ atm in less than 0.15 s. This picture shows that the moving air seems to revolve and form vortex rings. It is possible to make a roughly quantitative estimation about the temperature drop in the vortex. Calculation based on above formula exhibits that in the air where the velocities reach about 600 ms^{-1} ($M = 1.80$), the temperature in vortices might drop by as much as 125°C.

For the airflows of $M = 1.10$ and 1.50 in our experiments, the temperature drops by as much as 45°C and 85°C, respectively. That might be sufficient to initiate homogeneous nucleation of ice. It is obvious, however, that the temperature changes in vortices produced by supersonic flow are over−estimated as the ambient stationary air entrains into the flow and makes the flow reduce its speed. But according to the hypothesis of Wang and Vonnegut (1984), it would be expected that the rate of nucleation should increase by as much as a factor of 5 for each degree that the temperature drops. Thus, the vortex cooling caused by supersonic airflow is partly responsible for the ice crystals generation.

IV. FIELD EXPERIMENTS

For further investigating the ice−forming performance of supersonic airflow in natural supercooled fog, some field experiments have been conducted on Lushan Mountain (29°35′N, 115°59′E), Jiangxi Province, at 1150 m above the sea level from December, 1991 to January, 1992. Some facilities, such as a Laval nozzle with an exit diameter of 2 mm and $M = 1.84$, an air compressor of model 2−DD3 / TA which can generate stagnant pressures more than 3 atm and be electrically controlled by a solenoid valve, were more than 3 atm and be electrically controlled by a solenoid valve, were used. Supersonic airflow could be inter-

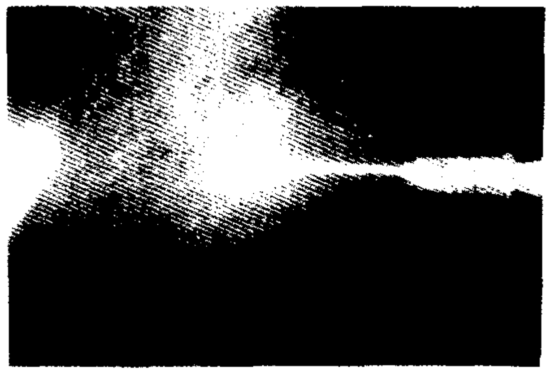

Fig. 3. Vortex motion of a parcel of air spurted out from the nozzle of $M = 1.80$ at 3.0 atm during 0.15 s.

mittently or continuously spurted out into natural supercooled fog of temperatures between −0.5°C and −4.6°C. Ice crystal samples were collected at the distances of 4, 10 and 20 m from the exit down wind by formvar method. At night the processes of generating and growing of ice crystals were examined through a light beam. During five days twenty test runs were conducted in supercooled fog. The results showed that ice crystals could be generated by supersonic flow in natural supercooled fog. Just after airflows were spurted out ice crystals were too small to be discerned. but as they grew up in about fifteen seconds, a great number of ice crystals could be distinguished in fog down wind. Ice crystals landed on the ground would accumulate 40 to 360 μm in three minutes. In four minutes all ice crystals were settled down and a clear space appeared. Shapes of ice crystals collected were column and hexagon. These experiments demonstrated that ice crystals can be explicitly observed in a space with dimensions of 90 m in horizontal distance, 20 m in width and 10 m in height after 0.5 g air is spurted out into supercooled fog in gentle breeze. However, some wind always blows in natural condition, different from that in laboratory, so it may be more difficult to estimate quantitatively the precise number of ice crystals. According to ice crystals settled on the ground collected in these test runs, concentrations of about 50 to 200 ice crystals per liter are quantitatively estimated in a volume of about 2000 m^3 down wind after 0.5 g air is emitted. The concentration of ice crystals decreases as the sampling spot is getting away from the emitting exit. As there is turbulent diffusion in atmosphere, the actual diffusion range of ice crystals is larger than the visible range mentioned above. Therefore, the number of ice crystals deduced from measured data is surely less than the actual number.

Consequently, the ice nucleability of supersonic airflow in a natural fog is as excellent as that in laboratory, and aerodynamic cooling would find many uses in supercooled fog dispersal and artificial precipitation.

V. CONCLUSIONS

Experiments in laboratory and in fields have shown that aerodynamic cooling produced by supersonic airflow is quite effective to ice nucleation. The results obtained in laboratory experiments showed that the ice-forming rate ρ_i increases from 5.2×10^{11} to $12.4\times10^{11}g^{-1}$ as Mach number increases from 1.10 to 1.84 at $P_o=5$ and 6 atm, and ρ_i increases from 4.3×10^{11} to $10.3\times10^{11}g^{-1}$ as P_o increases from 1.5 to 5.0 atm at $M=1.80$. And the experiments in natural fog showed that the concentrations of 50 to 200 ice crystals per liter could be attained after emitting 0.5 g air in a volume of about 2000 m^3 where the temperature of supercooled fog is between −0.5°C to −4.6°C.

The real pictures of supersonic airflow spurting out into still ambient air have been taken in our experiments, and they revealed the detail structures of airflow. In addition to the directional movements, it apparently shows vortices around the edge of the flow. They make ambient stationary air be entrained into the flow. so three processes are related to the mechanisms of nucleation of ice crystals. They are: cooling of adiabatic expansion in supersonic airflow, cooling at the cores of vortices and entrainment of ambient stationary air into airflow.

In the light of theoretical calculations on cooling induced by the adiabatic expansion and vortices, the temperature lowering depends upon the Mach number of airflow. The greater the Mach number, the more the temperature drops. It is shown that the temperature decreases down more than 6°C as M increases by 0.1. The increasing of stagnant pressure promotes the mass flow rate, but does not change the Mach number of the flow at the exit. These analyses agree well with our measurements of ice-forming rates.

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