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We developed a highly efficient aerosol catalyst for weather modifications. Such aerosols could be employed at high altitudes, which provides a possible solution for the long-term poor combustion performance problem. Hopefully, this nucleating agent work will draw attention from the broad environment research community.
Agl-KI aerosol catalysts with excellent combustion and nucleation performance for weather modification

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The glaze icing of overhead transmission lines seriously influences the security operation of the power grid, resulting in huge economic loss. Here, by employing AgI-KI aerosol catalysts with good combustion performance, we found that the formation of glaze icing could be controlled and eliminated before it causes damage to transmission lines, as revealed by a 0.5 m$^3$ low temperature cabinet, a 1 m$^3$ isothermal clouding chamber and a 60 m$^3$ environment climate chamber, respectively. The higher nucleation rate ($\sim 10^{10}$) of AgI-KI aerosols than blank ($\sim 10^9$) was found to be beneficial for deicing performance. Our results suggest that such aerosol could be a better choice for deicing technology.

1 Introduction

With the rapid development of technologies, the world’s electric energy demand keeps growing. On one hand, transferring renewable energy resources including solar and wind energy into electric energy has attracted lots of interests from the research community. On the other hand, the safety and efficient supply of electric power have gradually become an important topic.

Natural disasters such as freezing rain may cause severe damages to the electric power supply system by forming glaze icing on high-voltage transmission lines. In general, the formation of glaze icing occurs when freezing rain contacts with transmission lines with temperature below 0 °C. The accumulation of glaze icing may then induce problems such as ice flash trip, phase flashover, or even line break when the loading overweights its ultimate strength. Moreover, under certain circumstances, it may further cause collapse of power towers and grids.

For instance, in 1998, the ice disasters in Quebec and Ontario of Canada almost destroyed the power transmission system, especially the overhead transmission lines. Most recently, China (2008) and the United States (2019) also encountered serious snowfall and freezing rain issues. The formed glaze icing leads to break and crush of transmission lines and power towers, resulting in enormous economic loss as well as negative impacts on daily life. Thus, it would be important and imperative eliminate glaze icing efficiently.

To achieve that, various strategies have been developed, such as thermal and mechanical deicing. Yet they all suffer high energy consumptions and costs problems. More importantly, these conventional methods may not inhibit the formation of glaze icing, i.e., they may only remove the glaze icing covered on transmission lines. A more straightforward strategy should be weather modification aerosol catalysts. The working principle is to first launch the aerosol catalyst into cloud by employing solid propellants. When reaching certain altitude, the catalyst will explode and release numerous aerosol particles that could act as bases to facilitate the heterogeneous nucleation of supercooled water. As a result, the freezing rain will form snow/ice before hitting transmission lines, thereby reducing the amounts of glaze icing. To achieve that, various types of reagents have been investigated, such as organic molecules, copper sulfide, lead iodide, loess, etc. Among them, silver iodide (AgI) has been considered as one of the most suitable candidates for weather modifications, due presumable to its hexagonal crystal structure, which is similar to that of the ice crystal. However, further development of AgI aerosol was limited by its poor combustion performance at high altitude, viz., the aerosol catalyst may not be fully burned in clouds, thereby limiting their practical applications. It should be mentioned that previous literature mainly focused on promoting ice nucleation efficiency of aerosols, while fail to investigate their combustion performance as well as practical deicing performance. To resolve this instability problem, a new AgI based aerosol doping with potassium iodide (KI) was developed and first reported by our group. Such aerosol was proved to be combustion stable under extreme environments, providing a possible solution to this long-term instability problem. However, the effects of doping KI to aerosol nucleation and deicing properties remains unknown, which is imperative and crucial to be investigated.

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It is, therefore, the purpose of the current report, to investigate the deicing properties of the combustion stable AgI-KI aerosols. The aerosol/propellant composites were fabricated via a simple vacuum pouring method. By employing a 0.5 m³ low temperature cabinet and a 1 m³ CAMS isothermal cloud chamber, the ice formation/nucleation properties of different aerosol catalysts were measured. The effects of temperature and reaction time were also discussed. Moreover, a 60 m³ environment climate chamber was adopted to evaluate the deicing performance of these aerosols under practical conditions. In addition, the morphologies, chemical and structural properties of aerosols before and after deicing experiments were also evaluated via SEM, FTIR and XRD techniques. Our results indicated that the AgI-KI aerosols exhibited excellent ice nucleation performance, which shows great potential to be employed into practical applications.

2 Experimental

2.1 Materials

Hydroxyl-terminated polybutadiene (HTPB), nitrogen pyridine compounds (MAPO), ammonium perchlorate (AP) and toluene diisocyanate (TDI) are all provided by Liming Research Institute of Chemical Technology. Diocyl sebacate (DOS) was purchased from Beijing Chemical Reagent Factory. Silver iodide (AgI) and potassium iodide (KI) are purchased from J&K Scientific.

2.2 Fabrication of aerosol

The total mass of raw materials is 50 g. All solid components needed to be screened and dried while all liquid components were dried in vacuum. To fabricate aerosols, first, liquid components (HTPB, DOS and MAPO) were mixed and stirred for 5 minutes. Then, mixing solid components (AP, AgI and KI) and stirred for 10 minutes. After that, the solid components mixture was added into liquid mixture, stirring for 15 minutes to achieve a homogeneous phase. Next, the curing agent (TDI) was added and stirred for 15 minutes. Finally, the drug was vacuumed and solidified in an oven at 50 °C for 7 days. The as-fabricated aerosols were sealed and preserved.

2.3 Characterizations

The ice formation properties of aerosols were measured via a 0.5 m³ Low temperature chamber. The chamber is composed of temperature and humidity control system, trays, ignition device and sensor system. The nucleation rate of the aerosol was measured via a 1 m³ CAMS (Chinese Academy of Meteorological Sciences) isothermal cloud chamber. The deicing performance of aerosol catalysts in practical applications was evaluated by the environment climate chamber from China Electric Power Research Institute was adopted to simulate freezing rain conditions. The chamber has a volume of 60 m³, with cooling power of 5 kW. A cycle refrigeration system was employed to maintain the temperature inside the chamber. In addition, several sets of sensors were equipped to measure both temperature and humidity at various positions inside the chamber. The supercooled water is composed of 100% ultrapure water, with temperature varies from -5 to -2 °C. The height of the nozzle is 5 m, and water was sprayed horizontally from the nozzle.

The FTIR spectra was measured via a Nicolet iS50 FT-IR spectrometer in the wavenumber range of 500 cm⁻¹~4000 cm⁻¹. The scanning electron microscopy (SEM) measurements were carried out on a Regulus 8230 instrument. X-ray diffraction (XRD) patterns were obtained using a Rigaku Smartlab Diffractometer with Cu Kα as the X-ray source.

3 Results and discussion

3.1 Fabrication of aerosol catalysts

The aerosols with and without AgI-KI catalyst were fabricated via simple pouring method (Details shown in Experimental parts and Figure 1). In this work, the commonly employed HTPB, MAPO, DOS, AP, AgI and KI are mixed. Figure 1. Schematic illustration of aerosol fabrication process.

3.2 Ice/snow formation measurements (0.5 m³)

To investigate the deicing performance of AgI-KI aerosols, we first resolve to the 0.5 m³ low temperature cabinet. The

| Formula No. | HTPB | DOS | AP | TDI | MAPO | AgI | KI |
|-------------|------|-----|----|-----|------|-----|----|
| 1           | 17.1 | 3.2 | 78.5 | 1.0 | 0.2  | 0.0 | 0.0|
| 2           | 17.1 | 3.2 | 78.5 | 1.0 | 0.2  | 5.0 | 5.0|
| 3           | 17.1 | 3.2 | 78.5 | 1.0 | 0.2  | 6.0 | 30.0|
| 4           | 17.1 | 3.2 | 78.5 | 1.0 | 0.2  | 5.0 | 0.0|

AP/HTPB solid composite propellants were adopted, where AP acts as the oxidizer to produce high energy when being ignited, HTPB as the binder to form polymer matrix, and TDI as the curing agent to solidify the matrix. To make comparison, aerosols with and without AgI-KI catalyst were both fabricated. The formulas of the aerosols were summarized in Table 1. Note that the sum of weight percent from HTPB to MAPO is one hundred, with additional components such as AgI and KI are extra weight percent. Due to the relative high price of AgI, it would be impractical to conduct comprehensive evaluations to every formula. Thus, only two of the best formulas (2 and 3) were selected to perform deicing measurements.

| Figure 1. Schematic illustration of aerosol fabrication process. |
| Table 1. Formulas of aerosols (% by weight) employed in this work. |
picture of the cabinet was shown in Figure S1. The essential working principle of the apparatus is to evaluate the ice/snow formation performance by measuring the mass of ice/snow dropped on the tray (Figure 2a). It should be mentioned here that a higher ice/snow mass here is beneficial for glaze icing elimination37, as it indicated more supercooled water was consumed before it contacts the tray. The ice formation results were summarized in Figure 2b and Table S1. All measurements were conducted for 40 minutes, with a temperature of -10 °C to minimize the measurement error, as suggested by previous literature38. It should be noted that a low temperature generally enhances the nucleation rate, which is beneficial for future deicing performance. Comparing to the unmodified aerosols (1st), AgI-KI aerosols exhibited an average of 50% enhancement in terms of ice mass, with formula 2# (5% AgI-5% KI) showed the best deicing performance (25.2 g) during the measurement.

The effects of reaction time on formula 2# ice formation properties were also investigated. As shown in Table S2 and Figure 3, no significant growth of ice mass was observed before reaching 20 minutes. Then, it exhibited a dramatic increase for almost 40 minutes, with the icing mass raised from 6.2 g (20 min, -10 °C) to 25.2 g (40 min, -10 °C), and then to 38.2 g (50 min, -10 °C). After that, the rate of icing formation became smooth. The whole curve fitted well in a non-linear Boltzmann function, which indicated a different ice formation mechanism from the case where no aerosol was applied. The above results indicated that aerosol catalyst begin to influence the icing formation after 20 minutes, and the whole process can last up to more than 1 hour. It is worth mentioned here that such non-linear curve might be related to the diffusion process of aerosol particles after ignition inside the cabinet, as well as the growth process of the formed ice nucleating particles, which all require additional time to complete. We expect further investigation on the kinetics of this process to understand its mechanism.

We then conducted the measurements under different temperatures to investigate its impacts on aerosols ice formation performance. Each measurement was conducted for 35 minutes. As can be observed in Figure 4, as the temperature decreased, the icing mass tend to be increased (linear relationship) (e.g., ~22 g at -10 °C versus ~24 g at -12 °C), indicating that a lower temperature is beneficial for their deicing performance.

3.3 Nucleation rate measurements (1 m³)
To further investigate the ice formation performance of aerosol catalysts in a larger volume, a 1 m³ CAMS isothermal cloud chamber (Figure S2) was employed to measure their ice nucleation rates. The nucleation rate is defined as the total number of ice nucleating particles generated per unit mass of AgI, which is time-irrelevant. The nucleation rates were measured following methods in supporting information39. Figure S3 showed the picture of ice crystals during the measurement. It is worth mentioned here that in weather modification, one of the most important parameters is the ice nucleation rate, as it would determine the amount of glaze icing formed on the transmission line.

All measurements were conducted under a temperature of -10 °C, and the nucleation rate results were summarized in Table 2. It can be observed that all modified aerosols (2# and 3#) exhibited much higher nucleation rates than the unmodified 1st sample, which indicates the excellent catalysis effects of AgI-KI additives. The formula 2# (5% AgI+5% KI) exhibited the highest nucleation rate of 1.8×1015, in sharp contrast to formula 1# (<107). Moreover, nucleation rates of both formula 2# and 3# were higher than that of AgI-only formula (4#, ~4×1013), indicating an improved nucleation effect of AgI-KI. The aerosols developed in this work also show much better nucleation rates comparing to previous other reports, such as AgI-NH4I (~1013, -10 °C), AgI-NaI (~1012, -10 °C), loess (~106, -15 °C), etc. Moreover, previous report27 on the nucleation rate of AgI-KI solution (<1013, -10 °C) is much lower than AgI-KI aerosol catalyst developed in this study (~1015, -10 °C). The higher nucleation rate indicates a faster consumption of freezing rain, which is in principle beneficial for deicing performance, in consistent with our previous 0.5 m³ ice formation results.
3.4 Deicing measurements (60 m³)
To better understand the deicing performance of aerosol samples in practical conditions, a 60 m³ environment climate chamber was employed to simulate freezing rain. During the measurements, two types of nozzles, small sized and extra-fine sized, were both prepared to produce freezing rain with different sizes and falling speeds. The picture showed the chamber inside was illustrated in Figure S4. Figure S5 illustrated the spatial arrangement inside the chamber regarding the distribution of nozzle, transmission lines and rotating rod. The diameters of the rain produced from small sized and extra-fine sized nozzles were estimated to be around 2 mm and less than 0.5 mm, respectively. In addition, the falling speed of rains may be evaluated according to the near free-fall equation, which is similar to the falling process of raindrops in atmosphere environment.

To conduct the measurements, the temperature inside the tank was maintained below -10 °C via a cycle refrigeration system. The water was sprayed at 45° direction to form freezing rain. After 5 minutes, the aerosol samples were ignited. Then, conducting intermittent spraying at 30 s/30 s and maintain the temperature of the nozzle at around ±3 °C to prevent the nozzle from freezing. After 30 minutes, stop spraying water, and keep the tank closed for 10 minutes. Last, measuring the mass of glaze icing formed on transmission lines to determine the deicing performance of aerosols. We evaluated the deicing potential of formula 2®, as it exhibited the best performance during 0.5 m³ and 1 m³ measurements.

3.4.1 Small sized nozzle
The deicing performance of aerosols was investigated by employing small sized nozzles first. The measured data were shown in Table 3. The mass of glaze icing on transmission lines and rotating rods exhibited a dramatic decrease (from 287.0 to 143.6 g) after adding AgI-KI aerosol catalysts, which indicated their excellent deicing properties. The released aerosol particles may help facilitating the nucleation process of supercooled water before it contacts any substance (Figure S6). As a result, the amount of glaze icing on the transmission line could be reduced. In addition, the rotating rod exhibited a smoother surface than transmission lines, therefore the amount of glaze icing is also smaller.

3.4.2 Extra-fine sized nozzle
The deicing results using extra-fine sized nozzles were summarized in Table 4, which exhibited the same trend as the small sized nozzle results. After adding aerosols, the amount of glaze icing on transmission lines and rotating rod were both reduced, and there is also less glaze icing on rotating rod than transmission lines, in consistent with previous results. Our results showed that the employment of aerosols may effectively reduce the amount of glaze icing under different spray speeds.

### Table 3. Comparison of glaze icing mass of small nozzle (1 g aerosol)

| Formula | Transmission lines | Rotating rods | Total mass |
|---------|--------------------|---------------|------------|
| Blank   | 222.7              | 64.3          | 287.0      |
| 2®      | 117.2              | 26.4          | 143.6      |

### Table 4. Comparison of glaze icing mass of extra-fine nozzle (1 g aerosol)

| Formula | Glaze icing mass (g) |
|---------|----------------------|
|         | Transmission lines   | Rotating rods | Total mass |
| Blank   | Blank                | Blank         | Blank      |
| 2®      | 417.6                | 105.0         | 522.6      |

3.5 Characterization of aerosol samples
To reveal the change of aerosol catalyst with formula 2®, their morphologies and chemical properties before and after burning were measured via SEM and FTIR techniques, respectively. The planar SEM images were shown in Figure 5. As can be observed, the initial aerosol sample consists of many tens of micro powders. After ignition, numerous tiny particles with nanometer-sized were generated, and each may act as a nucleation site to facilitate the ice nucleation process. In practical applications, the freezing rain will first contact with these aerosol particles before reaching transmission lines, leading to reduced amounts of glaze icing. The FTIR results were presented in Figure 6. The peaks could be attributed to AP, HTPB, TDI, etc. However, these peaks no longer existed after burning, which indicated that the components of the products were different from their initial forms. In addition, XRD measurements were conducted to obtain the structure information of the sample. As shown in Figure 7, several new diffraction peaks were detected after burning, which indicates the change of the sample structure.
4 Conclusions

In summary, AgI-KI modified aerosols with good combustion performance were fabricated via vacuum pouring method. By employing 0.5 m³ low temperature cabinet and 1 m³ CAMS isothermal cloud chamber, the ice formation/nucleation properties of aerosols were evaluated. We revealed that the aerosols may begin affect the nucleation process after 20 mins, and low temperature is beneficial for ice formation. Future study on the non-linear behavior of the time-icing mass curve is expected to better reveal its reacting mechanism. In addition, after adding AgI-KI catalysts, the nucleation rate increased dramatically from the initial ~10^2 to ~10^2. To investigate its deicing performance in practical environment, a 60 m³ environment climate chamber was adopted. The results indicated that AgI-KI aerosols exhibited excellent deicing performances, in consistent with previous nucleation results. Last, the morphologies, chemical and structural properties of aerosol catalysts before and after experiments were also investigated via SEM, FTIR and XRD techniques. The results suggested that their compositions changed after burning. We expect there will be more related work on mechanism investigation and practical deicing measurements such as field experiments coming in the near future.

Author Contributions

All the deicing experiments were carried out by TS, with the assistance from XL, XG, MZ and RY. The characterization of aerosols before and after burning were carried out by TS and FX. The analysis of the data was carried out by TS and FX, with the help of MZ and RY. FX wrote the manuscript with contributions of all the co-authors.

Conflicts of interest

There are no conflicts to declare.

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Notes and references

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