Influence of Ice Surface on The Particle Composition in an Arc

Zijia Wang[1], Jianlin Hu[1], Wei Meng[1], Hongfei Deng[1], Zixin Xiang[1], Ting Zhu[1], Zhan Song[1], Xingliang Jiang[1]r

Dept. of High Voltage and Insulation Technology, College of Electrical Engineering, Chongqing University Chongqing, China.

Zija Wang:202111021016@cqu.edu.cn

Abstract—**The characteristics of an arc that propagates over the ice surface are different from the arc in the air. Fully understanding the influence of the ice on the particle composition of the arc is the first step to reveal the discharge mechanism on the ice surface and support the electrical design for power equipment. Based on Dalton's partial pressure law, Saha's law, mass action law, stoichiometric conservation, and the measured emission spectrum, this paper proposed a physical model to analyze the particle composition of an arc on the ice surface. The particle composition within the arc at different arc temperatures was studied. Results show that compared with the arc in the air, the ice has a great influence on the arc channel's particle composition under the same temperature. The results in this paper provide a reference for studying the arc's particle composition and support the theoretical study on revealing the mechanism of an arc propagating over an ice surface.**

Keywords—***arc discharge, icing, plasma particle composition, local thermodynamic equilibrium, thermal plasma***

I. INTRODUCTION

Icing will reduce the electrical performance of insulators in service, and discharge is easy to occur on the ice surface. In serious cases, it may lead to insulator flashover, which greatly impacts the reliable operation of transmission lines. A full understanding of the particle components in the ice arc is the basis for studying the arc's transport parameters and thermodynamic parameters and provides a basis for further revealing the physical mechanism of ice arc discharge and preventing icing flashover.

The arc under atmospheric pressure has the characteristics of high temperature and large currents. The existing measurement methods are difficult to directly measure the particle composition in the arc. Therefore, researchers usually use a theoretical model combined with numerical calculation to study the composition of arc particles under different working conditions and then calculate other physical parameters of arc. In recent years, physical models for calculating the particle composition of arc plasma have been widely used in electrical, aerospace, and other industrial fields. Scholars calculated the particle composition in the arc when a small amount of water vapor was mixed into high-purity nitrogen [1] and found that a small amount of water vapor would weaken the ionization process nitrogen atoms. By calculating the particle composition in the arc of Ar-N_2 mixture at different pressures, scholars found that the pressure increase will inhibit the dissociation and ionization of nitrogen[2]. By calculating the particle composition in the dry air arc under different pressure, scholars found that the pressure increase will inhibit the dissociation and ionization of oxygen in the air arc[3]. It can be seen that the research on the component characteristics of arc particles mainly focuses on-air or simple gas mixture, and the component characteristics of ice arc are still lacking. Limited by the complexity of ice surface discharge, the research of ice surface arc is still based on experimental measurement of its macro characteristics. The theoretical calculation and analysis of the micro-component characteristics of arc play an important role in revealing the mechanism of ice arc discharger.

However, the research methods on the physical characteristics of ice arc are mainly experiments. There is a lack of literature on estimating the internal particle composition of ice arc through theoretical calculation, and the research on analyzing ice arc from the perspective of arc particle composition is still insufficient.

Therefore, this paper is based on the assumption of local thermodynamic equilibrium. Combined with the research results of ice surface discharge in recent years [4], the specific reaction types in the arc are determined. The particle components of dry air arc and ice arc at different temperatures (300 ~ 35000K) are calculated. Through comparative analysis, the effects of ice on the electron number density and dissociation degree in the arc are summarized, which lays a foundation for calculating the physical parameters of the ice arc.

II. PHYSICAL MODEL

In this paper, inert gas and other impurity gases are not considered, and it is considered that the water produced by the ice surface exists in the arc in gaseous form. The following table shows the possible chemical reactions :

TABLE I. **THE POSSIBLE CHEMICAL REACTIONS**

Reaction equation	Participating particle	Reaction energy (eV)	Serial number
$N_2 \leftarrow\rightarrow N+N$(dissociation)	N_2;N	9.792	①
$N \leftarrow\rightarrow N^+ +e$(ionization)	N^+;e	14.534	②
$N_2 \leftarrow\rightarrow N_2^+ +e$(ionization)	N_2^+;e	15.580	③
$O_2 \leftarrow\rightarrow O+O$(dissociation)	O_2;O	5.166	④
$O \leftarrow\rightarrow O^+ +e$(ionization)	O^+;e	13.618	⑤
$O_2 \leftarrow\rightarrow O_2^+ +e$(ionization)	O_2^+;e	12.069	⑥
$H_2O \leftarrow\rightarrow H+OH$(dissociation)	H_2O;H;OH	5.154	⑦
$H \leftarrow\rightarrow H^+ +e$(ionization)	H^+;e	13.598	⑧

H+H←→H_2 (dissociation)	H;H_2	4.516	⑨
OH←→O+H (dissociation)	OH;O;H	4.453	⑩
N+H←→NH (dissociation)	N;H;NH	3.718	⑪

Arc is a kind of plasma and belongs to thermal plasma. It can be considered that it is in a local thermodynamic equilibrium (LTE) state, and the electron temperature is equal to the arc temperature. The ionization process of gas particles in arc satisfies the Saha equation; The molecular dissociation process satisfies the Guldberg-Waage equation. Therefore, the ionization and dissociation processes in the arc can be described by equations:

$$\begin{cases} \dfrac{n_A \cdot n_B}{n_{AB}} = \left(\dfrac{2\pi m_A \cdot m_B k T_e}{m_{AB} \cdot h^2}\right)^{1.5} \cdot \dfrac{Z_A \cdot Z_B}{Z_{AB}} \cdot e^{\left(-E_{JAB}/kT_e\right)} \\ \dfrac{n_i^+ \cdot n_e}{n_i} = 2\left(\dfrac{2\pi m_e k T_e}{h^2}\right)^{1.5} \cdot \dfrac{Z_i^+}{Z_i} \cdot e^{\left(-E_{di}/kT_e\right)} \end{cases} \quad (1)$$

Where nab is a molecule; n_A and n_B are molecular dissociation products; m is the particle mass; E_j is dissociation energy; E_d is ionization energy; h stands for Planck constant. Z represents the partition function, which is related to temperature. According to reference [5], in the temperature range studied in this paper, the ratio of partition function can be approximately equal to 1.

The total particle number density, the pressure, and the temperature in the arc meet the law of gas partial pressure, which can be expressed as:

$$P = (N/V)/(R/N_A) \cdot T = n_{sum} \cdot k \cdot T \quad (2)$$

Where N is the total number of particles in the arc; V is the arc volume; R is the molar gas constant; N_A is the Avogadro constant; k is Boltzmann constant; n_{sum} is the total particle number density in the arc.

The arc is electrically neutral macroscopically, which can be expressed as:

$$n_e = \sum j \cdot n_i^{+j} \quad (3)$$

Where n_e represents the total electron number density in the plasma; n_i^{+j} represents the number density of a positive ion in the plasma; j is the charge coefficient of this positive ion. When the charge is 1, j = 1.

The initial proportion of water molecules in the air can be set in advance. The stoichiometric ratio of nitrogen, hydrogen, and oxygen in the arc remains unchanged, which can be expressed as follows:

$$\begin{aligned} \sum i \cdot n_N / \sum i \cdot n_H &= \frac{2 \times (1-a) \times \gamma_N}{2 \times a} \\ \sum i \cdot n_O / \sum i \cdot n_H &= \frac{2 \times (1-a) \times \gamma_O + a}{2 \times a} \end{aligned} \quad (4)$$

n_N, n_O, and n_H are particles containing nitrogen, hydrogen, and oxygen in the arc, respectively. i is the atomic number of corresponding elements contained in the particles. a is the preset percentage of water molecules in the total number of particles. γ_N and γ_O represents the proportion of nitrogen and oxygen in the air, where γ_N is 78.084% γ_O is 20.946%.

III. RESULT

A. Particle composition in the arc without ice surface

When calculating the particle composition in the arc without the influence of ice surface, the reaction of the arc is governed by components ①-⑥ in Table I. By using the physical model in Chapter 2, the number density of all particles in the arc in dry air is calculated as shown in Figure 1.

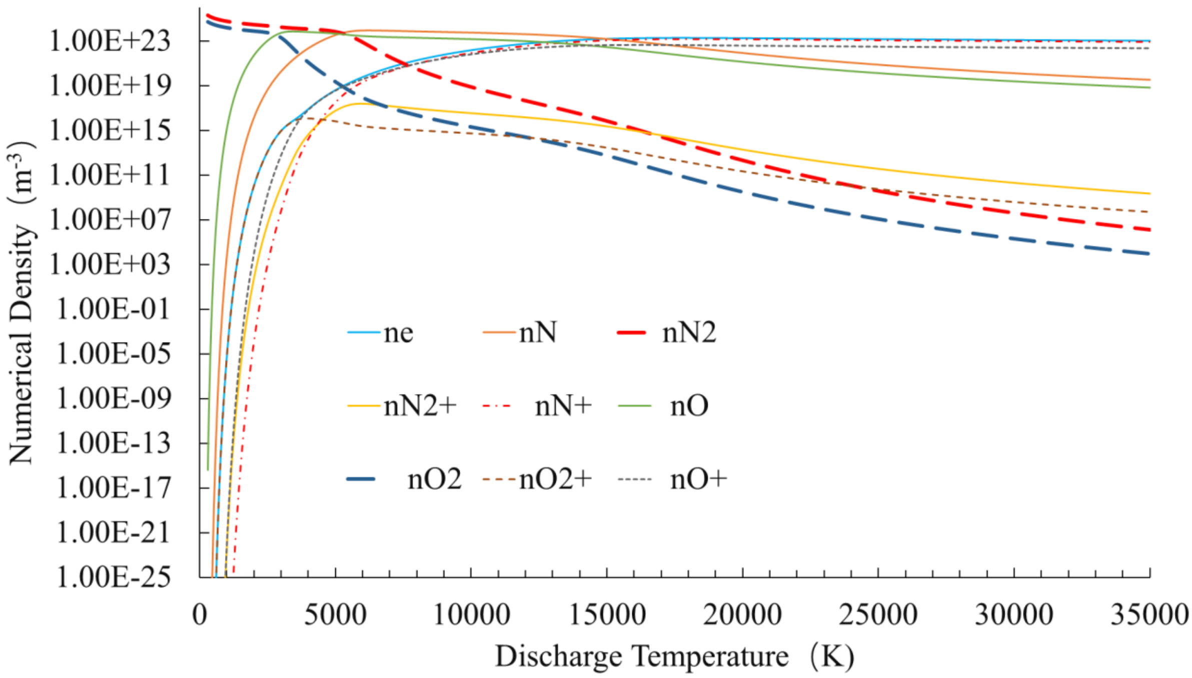

Fig. 1 the number density of all particles in the arc in dry air

By comparing the research of the other scholars [6], Figure 2 shows the calculation results of electron number density in the arc of dry air:

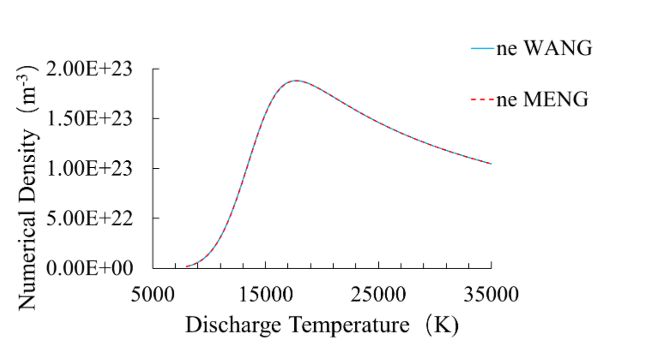

Fig. 2 electron number density in the arc of dry air:

Through comparison, it can be found that the data error is minimal. The order of magnitude of the maximum relative error is 10^{-10} which proves the effectiveness of the physical model and calculation method.

Figure 1 shows that the N_2 and O_2 curves are similar. Both begin to decline from the low-temperature section, and with the increase of temperature, the O_2 curve decreases faster, and the slope suddenly increases at 3000K, which indicates that O_2 begins to decompose before N_2 in the initial stage of the reaction, mainly because the dissociation energy of O_2 is smaller than N_2. N. The curves of O, N_2^+, and O_2^+ rise sharply from the beginning and then decrease gradually after reaching the maximum, indicating that these particles begin to ionize gradually at higher temperatures; The curves of N^+, O^+, and e all increase sharply at first, then decrease slightly, and finally tend to saturation, and differ significantly from the order of magnitude of other particles (about 10^4). In addition, there is little difference between the curves of N^+ and e, indicating that the ionization of nitrogen atoms is dominant in the reaction inside the arc.

B. Particle composition in the arc with the ice surface

The difficulty of solving equations (1) ~ (4) is that it is a nonlinear equation system with 15 unknowns, and the nonlinearity of this equation system is very high.

This paper used the Newton-Raphson method to obtain the particle number density in the arc under the influence of ice surface, as shown in Figure 3.

By analyzing the number density curves of all particles, it can be found that N_2, O_2, and H_2O are similar, and the curve decreases from the beginning, while water molecules decline the fastest, reaching the order of magnitude of 10^1 at 700K, which shows that most water molecules have been decomposed in the initial stage of the reaction. The main reason is that the dissociation energy of these three particles is small. The dissociation energy of the water molecule is the smallest among the three particles; The curves of H_2, H, and OH rise sharply from the beginning and drop sharply after reaching the maximum at about 500K, indicating that these three ionizing particles basically do not exist in the arc; The curves of N, N_2^+, NH, O, and O_2^+ are similar. The curves rise suddenly and then slowly decrease to the initial state. The curves of e, N^+, O^+, and H^+ increase slowly at first, then decrease slightly, and finally tend to saturation. From the variation law of the curve, it can be found that when the arc temperature is lower than 5000K, the primary reaction in the arc is the dissociation of initial particles. When the temperature is between 5000K and 10000K, the ionization reaction in the arc gradually replaces the dissociation reaction as the primary reaction type. When the temperature exceeds 10000K, the ionization reaction continues, and all particles are gradually converted into the primary ions of their constituent elements. Finally, when the temperature exceeds 20000K, the number density of the primary ions tends to be saturated.

C. Effect of ice surface on the electron number density in an arc

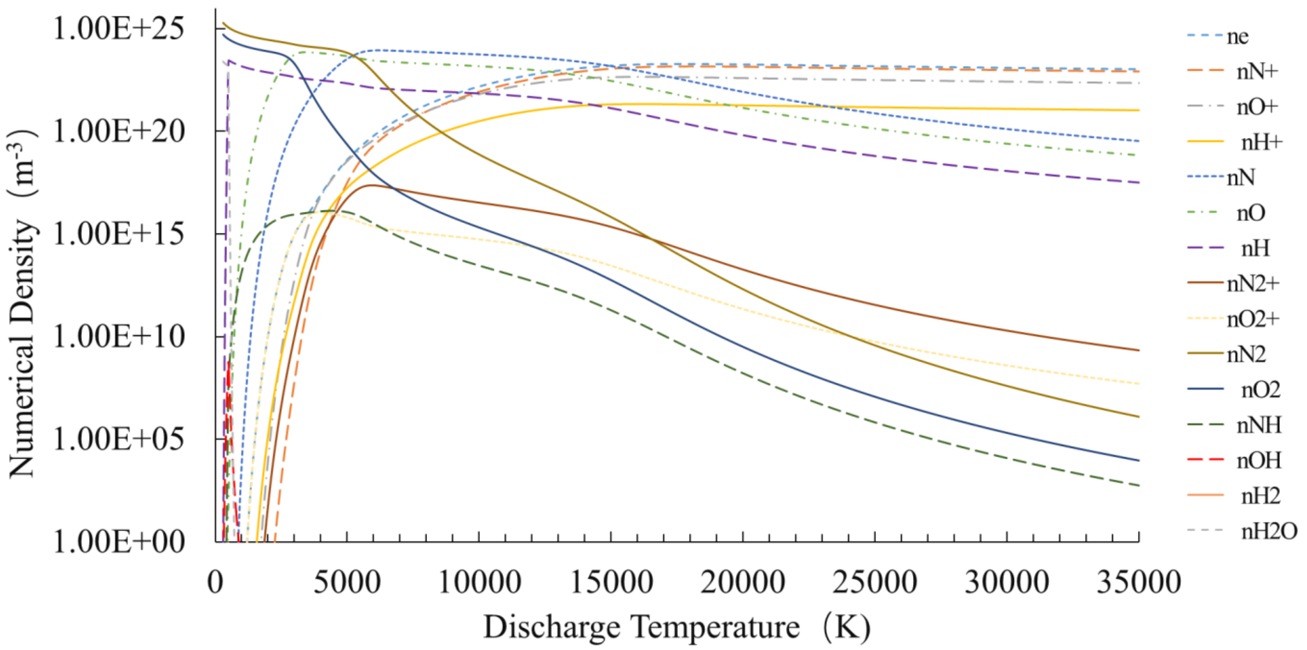

Fig. 3 the number density of all particles in the arc under the influence of ice surface

The current in the arc consists of electron current and particle current. Due to the light electron mass, its speed is much faster than that of heavy ions under the action of an external driving force, so the electron current is dominant in the arc current. Therefore, the electron number density is an important parameter to reflect the electrical characteristics of the arc.

The Figure 4 shows the electron number density in the dry air arc and the ice surface arc (water molecules account for 1%) with arc temperature:

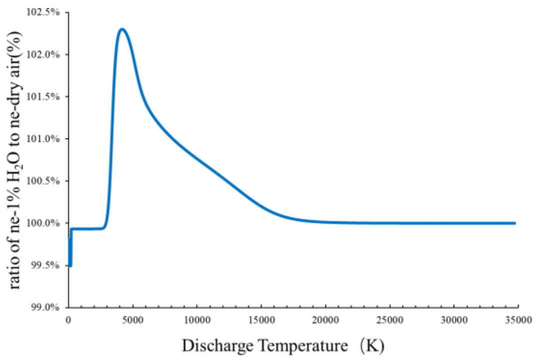

Fig. 4 ratio of ne-1% H_2O to ne-dry air

Figure 5 shows the excess electron density:

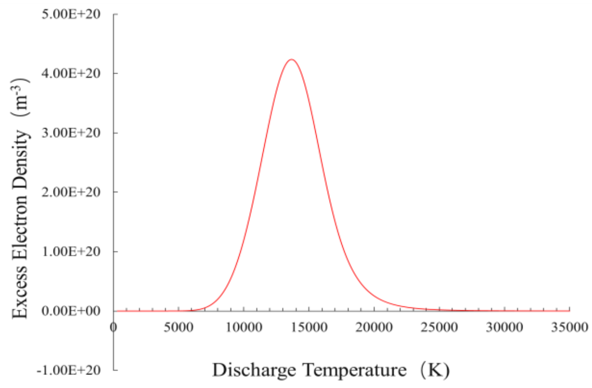

Fig. 5 Excess Electron Density

It can be seen from the figure that when the temperature is less than 3000K, compared with the dry air arc, when there are water molecules, the electron number density of the ice arc is slightly lower than that of the dry air arc. When the temperature exceeds 3000K, the electron number density is positively correlated with the temperature and increases to the maximum at about 14000K (4.24×10^{20}). The increase is mainly due to the ionization of water molecules and particles produced by their dissociation. The temperature range of the ice arc is usually less than 10000K. The calculation results show that the addition of water molecules can significantly increase the electron number density of the arc in this temperature range. It can be seen from the figure that the existence of ice has an inhibitory effect on the generation of arc, and the inhibitory effect is negligible. However, after the arc is generated, it will promote the development of the arc.

D. Effect of ice surface on the degree of dissociation in an arc

The degree of dissociation can reflect the degree of dissociation of molecules in the arc, according to the formula [7]:

$$J = \sum n_C / (\sum n_C + \sum n_F)$$

Where J is the degree of dissociation, n_C is the particle number density of dissociation products in the arc, and n_F is the particle number density of molecules in the arc.

The dissociation degree of arc under different conditions can be obtained, as shown in the figure below.

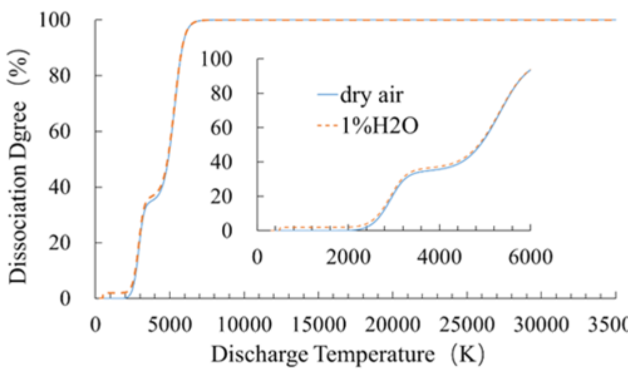

Fig. 6 The dissociation degree of arc

The following figure can be obtained by comparing the dissociation degree of dry air arc with that of the arc with water molecules accounting for 1%.

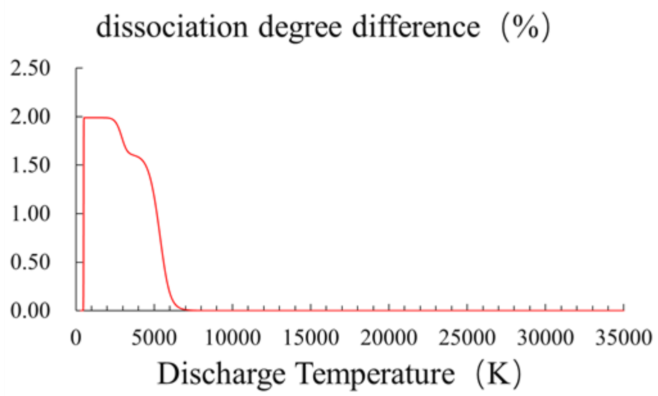

Fig. 7 the difference of the dissociation degree of arc

It can be seen from the figure: compared with dry air arc, when there are water molecules, when the temperature reaches about 700K, the difference of dissociation increases rapidly, remains stable between 800K and 3000K, and decreases rapidly when the temperature exceeds 3000K. When the temperature is 3000K ~ 6000K, the dissociation degree of the ice arc is slightly greater than that of the dry air arc, but when the temperature continues to rise, there is little difference between the two cases. When the temperature exceeds 10000K, the effect of ice on the degree of dissociation is less than 5-10%.

This is mainly because the dissociation energy of water molecules is less than that of nitrogen and oxygen molecules. When the temperature is lower than 6000K, water molecules begin to dissociate in large quantities.

IV. CONCLUSIONS

Based on the assumption of local thermodynamic equilibrium, this paper calculates the particle components of dry air arc and ice arc at different temperatures (300K ~ 35000K), compares and analyzes the influence of ice on the internal particle components of arc, and focuses on the influence of ice on the conductive particle components of arc:

(1) Through the supplementary water molecule dissociation equation and the ionization equation of its constituent atoms, the physical model of ice arc calculation is improved, and the number density of all particles in ice arc in the temperature range of 300K ~ 35000K is obtained. Compared with the calculation results in the existing literature, it is proved that the calculated data are effective and reliable.

(2) It is found that the existence of ice has a noticeable effect on the electron number density. When the temperature is lower than 3000K, the excess electron density of 1% H_2O air. is negative.When the temperature exceeds 3000K, the excess electron density of moist air, compared to dry air, is positively correlated with the temperature and increases to the maximum value at about 14000K (4.24×10^{20}).

(3) It is found that the existence of ice will affect the dissociation of particles in the arc. When the temperature is below 6000K, the existence of ice will promote the dissociation of molecules in the arc. When the temperature exceeds 6000K, the existence of ice has little effect on the dissociation in the arc.

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