Influence of copper vapor contamination on dielectric properties of hot air at 300-3500 K in atmospheric pressure

Influence of Copper Vapor Contamination on Dielectric Properties of Hot Air at 300-3500 K in Atmospheric Pressure

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ABSTRACT

The influence of copper vapor contamination on the dielectric properties of hot air at atmospheric pressure was numerically predicted in heavy particle temperature range 300-3500 K. Dielectric properties of hot gases are very important for effective design of switching devices and other applications. Copper vapor is known to be injected from the electrodes into the hot gas during arc interruption in a circuit breaker, which may substantially affect the dielectric strength of the hot gas. Analysis of equilibrium composition for a hot air contaminated with copper vapor and computations of Boltzmann equation made it possible to study the dielectric properties of interest. The result indicates that 1.0% copper vapor contamination remarkably increases the effective ionization coefficient $\bar{\alpha}$ and thereby decreases the critical electric field $(E/N)_{cr}$ drastically. This arises from a much lower ionization potential of the copper atom.

Index Terms — **Dielectric properties of hot air, copper contamination, critical electric field, Boltzmann equation.**

NOMENCLATURE

e	electronic charge (C)
E	electric field strength (V m^{-1})
$f_0(\epsilon)\epsilon^{1/2}$	electron energy distribution function (EEDF) (J^{-1})
G	Gibbs' free energy of system (J)
G_s^0	Gibbs' energy of formation for species s (J mol^{-1})
H_s^0	enthalpy of formation for species s (J mol^{-1})
h	Planck's constant ($= 6.626 \times 10^{-34}$ J s)
$I_{\rm att}$	energy loss rate in electron attachment processes per unit energy (m^{-3} s^{-1} J^{-1})
$J_{\rm el}$	energy loss rate in elastic collisions with heavy species (m^{-3} s^{-1} J^{-1})
$J_{\rm f}$	energy gain by electrons from the electric field (m^{-3} s^{-1})
$J_{\rm inel}$	energy loss in excitation collisions with heavy species (m^{-3} s^{-1})
$J_{\rm ion}$	energy loss in ionization collisions with heavy species (m^{-3} s^{-1})
k	Boltzmann's constant ($=1.38 \times 10^{-23}$ J K^{-1})
$L_{\rm g}$	the number of species in gas phase
$L_{\rm sol}$	the number of species in solid or liquid phase
$m_{\rm e}$	mass of the electron (kg)
M_s	mass of species s (kg)
n_e	total electron number density (m^{-3})
$n(\epsilon)d\epsilon$	electron number density with energies from ϵ to $\epsilon + d\epsilon$ (m^{-3})
N	total number density (m^{-3})
N_s^0	number density of species s in the ground state (m^{-3})
P	pressure (Pa)
P_0	standard pressure ($=$ 101 325 Pa)
$R_{\rm un}$	universal gas constant ($=$ 8.31 J K^{-1} mol^{-1})
T	equilibrium temperature (K)
$T_{\rm e}$	electron temperature (K)
$T_{\rm h}$	heavy particle temperature (K)
ν_d	electron drift velocity (m s^{-1})
x_s	mole fraction of species s ($= N_s^0/N$)
$X_{\rm Cu}$	fractional copper content (%)
$y_s^{\rm g}$	mole number of species s in gas phase (mol)
$y_{\rm s}^{\rm sol}$	mole number of species s in solid or liquid phase (mol)
$Z_s^{\rm int}$	internal partition function of species s
$\Delta H_{{\rm f}s}$	standard enthalpy of formation for species s (J mol^{-1})
Δt	time step (s)
$\Delta\epsilon$	increment of energy (J)
ϵ	kinetic energy of an electron (J)
$\epsilon_s^{\rm i}$	energy threshold for ionization state of species s (J)
$\epsilon_{s,j}^{\rm ex}$	energy threshold for the j-th state of species s (J)
$\mu_s^{\rm g0}$	standard chemical potential of species s in gas phase (J mol^{-1})
$\mu_s^{\rm so10}$	standard chemical potential of species s in solid or liquid phase (J mol^{-1})
$\bar{\nu}$	energy exchange rate resulting from elastic collisions (s^{-1})
$\sigma_s^{\rm m}$	electron impact momentum transfer cross section for species s (m^2)
$\sigma_{s,j}^{\rm ex}$	electron impact excitation cross section for the j-th state of species s (m^2)
$\sigma_s^{\rm i}$	electron impact ionization cross section for species s (m^2)
$\sigma_s^{\rm a}$	electron attachment cross section for species s (m^2)

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1 INTRODUCTION

UNDERSTANDING the dielectric properties of a hot gas is required for various practical applications. In circuit breakers, for example, a hot gas remains between the electrodes just after large current interruption, because an arc plasma is formed inevitably between the electrodes during a large current interruption process. This remaining hot gas usually retains temperatures of a few thousand degrees Kelvin after arc interruption. On the other hand, a transient recovery voltage (TRV) is applied to this hot gas between the electrodes after current interruption. The hot gas at first experiences the 'thermal failure region', where energy balance in the hot gas dominates success or failure of the arc interruption [1]. After successful interruption in the thermal failure region, the temperature of the hot gas continues to decrease while the TRV increases. If this hot gas has a lower dielectric strength than the applied electric field strength, then an electrical breakdown of the hot gas occurs, causing reignition of the arc. Such a failure resulting from an electrical breakdown of a hot gas is called 'dielectric failure' [1]. This also can occur between parts where high voltage is applied in a disconnector (DS), a molded case circuit breaker (MCCB), or other switching devices. Therefore it is very important to understand the dielectric strength of a hot gas for effective design of switching devices.

Only a few experimental works have been reported on the breakdown phenomena in hot gases with heavy particle temperatures up to 3500 K. For example, Eliasson and Schade have reported experimental results for breakdown voltage of hot SF_6 [2, 3]. Rothhardt *et al.* have experimentally measured the temperature dependence of the breakdown voltage of air, N_2 and SF_6 up to 3500 K [4–6]. Recently, Yan *et al.* and Cliteur *et al.* attempted a numerical investigation in a simple manner for prediction of the dielectric strength of hot SF_6 gases [7, 8]. However, detailed investigations have scarcely been performed concerning electron energy distribution functions (EEDFs), ionization and electron attachment coefficients in hot gases. The author has investigated the critical electric strength and effective ionization coefficient of hot air and hot N_2/O_2 mixtures in the temperature range of 300–3500 K [9, 10]. This investigation introduces a prediction method for the dielectric properties of hot gases, the results of which have been found to be in good agreement with experimental ones.

For consideration of dielectric strengths of hot gases remaining in a circuit breaker, the effects of copper vapor existence may be taken into account. The copper vapor is inevitably injected from the electrodes during an arc interruption process, which is expected to affect the properties of the arc plasma and the hot gas. Until now, the influence of copper vapor contamination has been investigated theoretically on transport and thermodynamic properties of the arc plasma. Chervy *et al.*, for example, calculated the thermodynamic and transport properties of SF_6 contaminated with copper vapor [11]. Those of air contaminated with copper have been calculated by Sakuta *et al.* [12]. Raynal *et al.* computed net emission coefficient of SF_6 with copper [13]. However, the influence of copper vapor on the dielectric strength has hardly been studied.

This paper reports the influence of copper contamination on the dielectric strength of hot air or a $78\%N_2 + 22\%O_2$ uniformly distributed gas mixture at atmospheric pressure with heavy particle temperature range of 300–3500 K for uniform electric field application to uniform hot air. The critical electric field strength $(E/N)_{cr}$, which gives zero effective ionization coefficient $\bar{\alpha} = 0$, is one of the most important and fundamental factors for the study of electrical breakdown phenomena. This study computed the critical electric field strengths $(E/N)_{cr}$ of hot air with copper vapor by solving the Boltzmann equation combined with equilibrium composition of air with copper at 300–3500 K. The result reveals that 1.0% copper vapor contamination drastically decreases $(E/N)_{cr}$ by 63% compared with $(E/N)_{cr}$ in pure hot air at temperatures around 2100 K .

2 PREDICTION PROCEDURE OF DIELECTRIC STRENGTH OF A HOT GAS

Prediction procedure for dielectric strength of a hot gas follows the author's previous work [9,10]. The electrical breakdown phenomenon in hot gases is considered to have some differences from that in a cold gas: (a) Increasing heavy particle temperature T_h from 300 to 3500 K decreases the total number density according to the state equation $N = P/(kT_h)$ if the pressure is fixed. (b) An increase in T_h changes the particle composition by thermal dissociation and formation of particles, and also phase transition among solid, liquid and gas phases. (c) It also changes the energy exchange rate through elastic collisions between electrons and heavy particles. Considering the above differences, the present calculation predicts dielectric properties of hot air with copper in the following procedure.

2.1 CALCULATION FOR EQUILIBRIUM COMPOSITIONS OF HOT AIR WITH COPPER

In this calculation, the air is assumed to be a uniform gas mixture of $78\%N_2 + 22\%O_2$. For air, an increase in heavy particle temperature T_h up to 3500 K involves N_2 and O_2 dissociations; then N, O and NO are produced. On the other hand, copper is in solid phase below its melting temperature, and then copper comes to be in liquid phase above its melting temperature. Moreover, copper is evaporated to be in the gas phase above its boiling temperature. A further temperature increase causes ther-

mal ionization of copper atoms. Such particle composition change is estimated by calculating the equilibrium composition of air with copper as a function of temperature using a thermodynamic method.

2.2 SOLVING BOLTZMANN EQUATION BY THE TWO-TERM EXPANSION APPROXIMATION

The electron energy distribution function (EEDF) in hot air with copper to which an electric field is applied was computed using the equilibrium composition derived in the previous procedure. In the calculation of EEDF, a change in the energy exchange rate between electrons and heavy particles by increasing T_h is also considered. Direct effects of copper in solid or liquid phase on the EEDF are not taken into account for simplicity. At the same time, the ionization coefficient α and electron attachment coefficient η are calculated considering copper vapor existence in hot air.

2.3 EVALUATION OF CRITICAL ELECTRIC FIELD STRENGTH

An electron avalanche can occur when the effective ionization coefficient $\bar{\alpha} = \alpha - \eta$ is positive. A zero effective ionization coefficient is therefore a critical value for the electrical breakdown phenomena of gases. Critical electric field strengths, which give $\bar{\alpha} = 0$, are computed in the heavy particle temperature range of 300 to 3500 K for copper vapor concentrations of 0–10 %.

3 EQUILIBRIUM COMPOSITION OF HOT AIR CONTAMINATED WITH COPPER

Equilibrium compositions of hot air with copper were calculated by minimization of the Gibbs free energy of the system on the assumption of equal electron and heavy particle temperatures [14]. The Gibbs free energy G can be expressed as

$$G = \sum_{s=1}^{L_g} y_s^g \mu_s^g + \sum_{j=1}^{L_{sol}} y_j^{sol} \mu_j^{so10} \tag{1}$$

$$\mu_s^g = \mu_s^{g0} + R_{un} T \ln\left(\frac{y_s^g}{\sum_{p=1}^{L_g} y_p^g}\right) + R_{un} T \ln\left(\frac{P}{P_0}\right) \tag{2}$$

Chemical potentials μ_s^{g0} and μ_s^{so10} for species s were calculated by

$$\mu_s^{g0} = -R_{un} T \ln\left[\left(\frac{2\pi m_s kT}{h^2}\right)^{3/2} Z_s^{int}(T)\frac{kT}{P_0}\right] + \Delta H_{fs} \tag{3}$$

$$\mu_s^{so10} = -G_s^0 + H_s^0(T_0) + \Delta H_{fs} \tag{4}$$

where T_0 is the reference temperature.

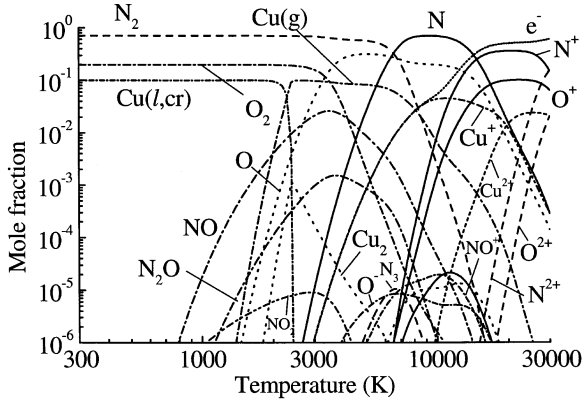

Figure 1. Equilibrium composition of a 90%Air + 10%Cu mixture at a pressure of 1.01×10^5 Pa.

In the calculation of the particle composition, the author considered the following 31 species in gas phase and a copper in solid or liquid phase: N, O, NO, N_2, O_2, NO_2, NO_3, N_2O, N_2O_3, N_2O_4, N_2O_5, N_3, O_3, N^+, N^{2+}, N^-, O^+, O^{2+}, O^-, NO^+, NO_2^-, N_2^+, N_2^-, N_2O^+, O_2^+, O_2^-, Cu(cr,l), Cu_2, Cu(g), Cu^+, Cu^{2+} and the electron, where Cu(cr,l) indicates copper in the solid or liquid phase and Cu(g) is copper atom in the gas phase [15]. The fractional copper content X_{Cu} is defined as

$$X_{Cu} = \frac{y_{Cu(cr,l)}^{sol} + 2y_{Cu_2}^g + y_{Cu(g)}^g + y_{Cu^+}^g + y_{Cu^{2+}}^g}{y_{Cu(cr,l)}^{sol} + \sum_{s \neq e}^{L_g} y_s^g} \times 100 \quad [\%]. \tag{5}$$

The temperature range in these investigations was between 300–30 000 K.

Figure 1 illustrates a calculated equilibrium composition of a 90%Air + 10%Cu mixture at a pressure of 101 325 Pa. This figure indicates that O_2 is dissociated to produce O atoms to a great extent around 3000 K. On the other hand, NO molecules are markedly produced from 1500 to 3000 K, as well as N_2O. Copper atom substantially turns to be in gas phase around 1700 K. In the temperature range of 300–3500 K, which is of interest in this paper, ten species N_2, O_2, NO, N_2O, O, N, Cu_2, Cu(g), Cu^+ and the electron are found to predominate in air with copper.

Copper atom is one of the most active species on the dielectric properties of hot gases. Then, mole fraction of copper atom in gas phase is shown in Figure 2 for different X_{Cu} as a function of temperature. Mole fraction of copper atom increases markedly until its complete evaporation. After that, a slight decrease in mole fraction can be found for a temperature increase to 5000 K. A further temperature increase reduces the mole fraction of copper atom. This reduction is attributed to the thermal ionization of copper. The copper atom in gas phase is found to

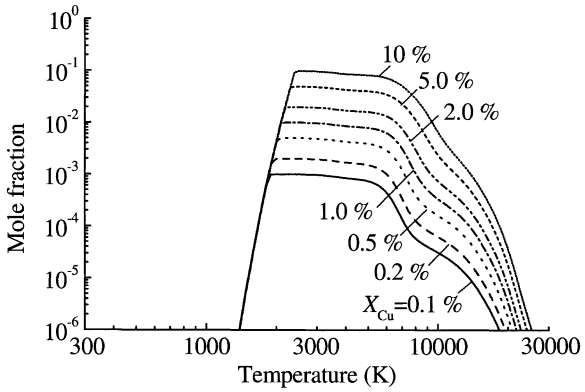

Figure 2. Mole fraction of Cu atom in gas phase in air with copper at a pressure of 101 325 Pa with different fractional Cu contents.

increase steeply in the same curve around 1700 K at any X_{Cu} until its complete evaporation. This means that degree of copper contamination hardly depends on X_{Cu} below around 1500 K.

4 ELECTRON ENERGY DISTRIBUTION FUNCTION IN HOT GASES UNDER HIGH ELECTRIC FIELD

4.1 TWO-TERM EXPANSION OF THE BOLTZMANN EQUATION

The electron energy distribution function (EEDF) can be obtained by solving the Boltzmann equation for time-dependent number density of electrons. Adoption of zero-dimensional two-term spherical harmonic approximation can simplify the Boltzmann equation as follows [16–18]

$$\frac{\partial n(\epsilon)}{\partial t} = -\frac{\partial J_{\mathrm{f}}}{\partial \epsilon} - \frac{\partial J_{\mathrm{el}}}{\partial \epsilon}\frac{\partial J_{\mathrm{inel}}}{\partial \epsilon} + \frac{\partial J_{\mathrm{ion}}}{\partial \epsilon} + I_{\mathrm{att}} + \left(\frac{\partial n}{\partial t}\right)_{\mathrm{e-e}} \tag{6}$$

$$J_{\mathrm{f}} = \frac{2Ne^2(E/N)^2\epsilon}{3m_{\mathrm{e}}(2\epsilon/m_{\mathrm{e}})^{1/2}\Sigma_s x_s \sigma_s^{\mathrm{m}}(\epsilon)}\beta \tag{7}$$

$$J_{\mathrm{el}} = -\bar{\nu}\left[n\left(\frac{kT_{\mathrm{h}}}{2} - \epsilon\right) - kT_{\mathrm{h}}\epsilon\frac{\partial n(\epsilon)}{\partial \epsilon}\right] \tag{8}$$

$$\bar{\nu} = N\left(\frac{2\epsilon}{m_{\mathrm{e}}}\right)^{1/2}\sum_s x_s \frac{2m_{\mathrm{e}}}{M_s}\sigma_s^{\mathrm{m}}(\epsilon) \tag{9}$$

$$\beta = \frac{n(\epsilon)}{2\epsilon} - \frac{\partial n(\epsilon)}{\partial \epsilon} \tag{10}$$

$$J_{\mathrm{inel}} = \left(\frac{2}{m_{\mathrm{e}}}\right)^{1/2}\sum_s\sum_j N_s^0\int_{\epsilon}^{\epsilon+\epsilon_{s,j}^{\mathrm{ex}}}\epsilon^{1/2}\sigma_{s,j}^{\mathrm{ex}}(\epsilon)n(\epsilon)d\epsilon \tag{11}$$

$$J_{\mathrm{ion}} = \left(\frac{2}{m_{\mathrm{e}}}\right)^{1/2}\sum_s N_s^0\int_{\epsilon}^{\epsilon+\epsilon_s^{\mathrm{i}}}\epsilon^{1/2}\sigma_s^{\mathrm{i}}(\epsilon)n(\epsilon)d\epsilon \tag{12}$$

$$I_{\mathrm{att}} = -\left(\frac{2}{m_{\mathrm{e}}}\right)^{1/2}\sum_s N_s^0\epsilon^{1/2}\sigma_s^{a}(\epsilon)n(\epsilon) \tag{13}$$

$$n(\epsilon) = n_{\mathrm{e}}f_0(\epsilon)\epsilon^{1/2} \tag{14}$$

and

$$\int_0^{\infty} f_0(\epsilon)\epsilon^{1/2}d\epsilon = 1 \tag{15}$$

The calculation of J_{el} in equation (8) accounts for the thermal energy of heavy species [16]. The last term on the right hand side in equation (6) indicates collision term between electron and electron, that was obtained as follows [16, 18]

$$\left(\frac{\partial n}{\partial t}\right)_{\mathrm{e-e}} = \xi\left[\frac{3}{\epsilon^{1/2}}n(\epsilon)^2 - 2\epsilon^{3/2}\frac{\partial \psi}{\partial \epsilon}\frac{\partial \beta}{\partial \epsilon} - \frac{\psi}{\epsilon^{1/2}}\beta\right] \tag{16}$$

$$\psi = 3\int_0^{\epsilon} n(\epsilon')d\epsilon' - \frac{1}{\epsilon}\int_0^{\epsilon}\epsilon' n(\epsilon')d\epsilon' + 2\epsilon^{1/2}\int_{\epsilon}^{\infty}\frac{n(\epsilon')}{\epsilon'^{1/2}}d\epsilon' \tag{17}$$

$$\xi = \frac{2}{3}\pi e^4\left(\frac{2}{m}\right)\frac{1}{2}\ln\Lambda \tag{18}$$

$$\Lambda = \frac{3kT_{\mathrm{e}}}{2e^2}\left(\frac{kT_{\mathrm{e}}}{4\pi n_{\mathrm{e}}e^2}\right)^{1/2} \tag{19}$$

$$T_{\mathrm{e}} = \frac{2}{3k}\int_0^{\infty} f_0(\epsilon)\epsilon^{3/2}d\epsilon \tag{20}$$

The reason why the present calculation considers the collision term between electron and electron is that copper contamination may markedly raise electron density, which may affect the EEDF.

In solving the Boltzmann equation, the energy range was set to 0–50 eV (1.0 eV = 1.602×10^{-19} J), and the energy increment was fixed at $\Delta\epsilon = 0.025$ eV for consideration of sharp electron impact vibrational excitations of molecules. Equation (6) was solved using a combination of implicit and explicit methods, details of which are described in [16–18]. Time dependent computation was performed with a time step of $\Delta t = 1.0$ ps until convergence to derive the steady state solution of EEDF.

4.2 ELECTRON IMPACT COLLISION CROSS SECTIONS

As shown in Figure 1, the dominant species are 10 particles N_2, O_2, NO, N_2O, N, O, Cu_2, Cu(g), Cu^+ and the electron in air with copper in the heavy particle temperature range of 300–3500 K. Thus, the electron impact cross sections for all these species are necessary to solve the Boltzmann equation. The electron impact cross sections for N_2, O_2, N_2O, N and O were obtained in [19]. The electron impact cross section of Cu(g) was given in [20]. The present calculation neglects the effect of Cu_2 on EEDF for simplicity because of lack of data on Cu_2 cross

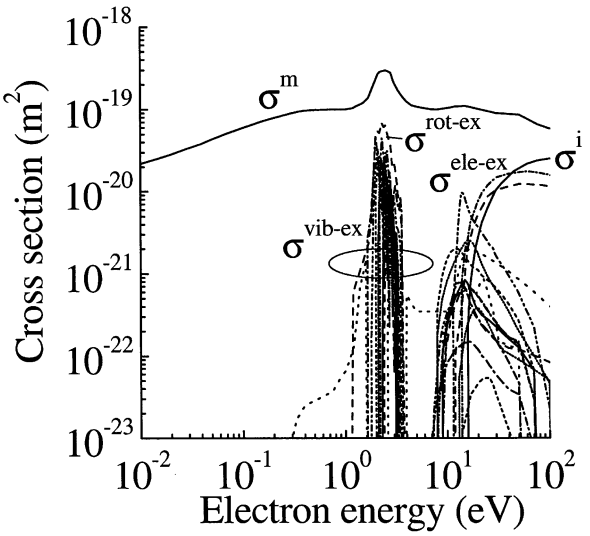

Figure 3. Electron impact cross section in N_2.

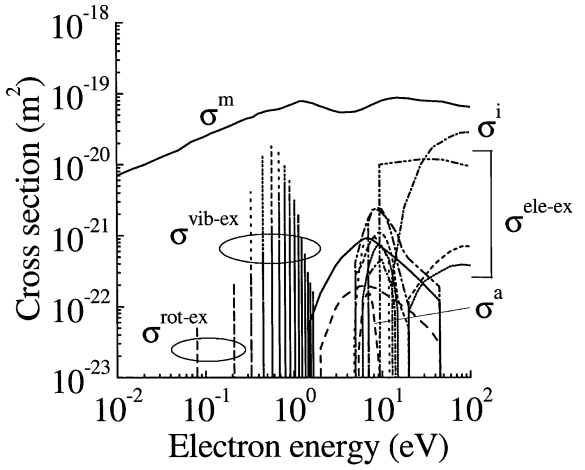

Figure 4. Electron impact cross section in O_2.

section and low density of Cu_2. The cross section between electrons and ions was calculated by the following Coulomb cross section

$$\sigma_{e-ion} = 4\pi\frac{e^4}{\epsilon^2}\ln\Lambda \qquad (21)$$

Figures 3, 4 and 5 show, as examples, the respective electron impact collision cross sections of N_2, O_2 and Cu. The data on N_2, for instance, include the following cross sections: one momentum transfer cross section σ^m, one rotational excitation cross section σ^{rot-ex}, nine vibrational excitation cross sections σ^{vib-ex}, thirteen electronic excitation cross sections σ^{ele-ex} and one ionization cross section σ^i. This electron impact cross section set of N_2 is characterized by large vibrational cross sections at electron energies around 2.0–3.0 eV. The O_2 also has large vibrational cross sections in the range of 0.3–1.0 eV. Another important fact is that O_2 has electron attachment cross sections,

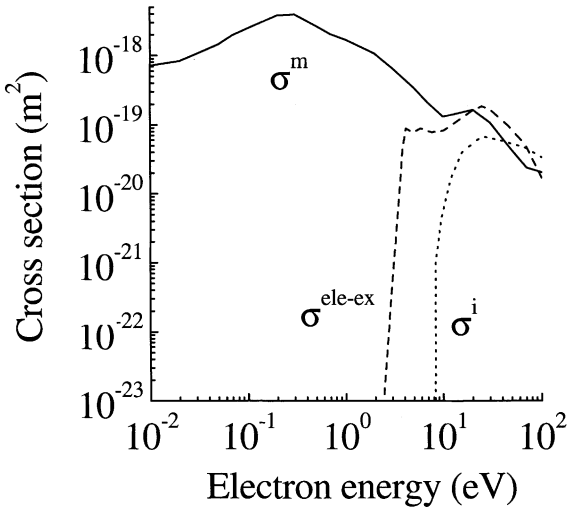

Figure 5. Electron impact cross section in Cu.

which affects the effective ionization coefficient $\bar{\alpha}$ of gases. It should be noted that Cu has a much lower ionization threshold of 7.73 eV than the other species.

The two-term expansion approximation of the Boltzmann equation is adopted to obtain EEDF without large errors, because the momentum transfer cross sections are much larger than the other inelastic cross sections for all species.

5 ELECTRON ENERGY DISTRIBUTION FUNCTION IN AIR WITH COPPER

Figure 6 depicts the calculated EEDF in a 90%Air + 10%Cu mixture at a pressure P of 101 325 Pa at a heavy particle temperature T_h of 3000 K. The reduced electric field strength E/N is adopted as a parameter. The unit of

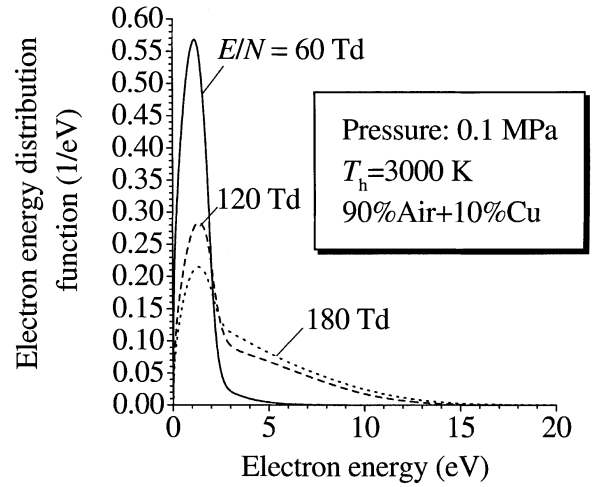

Figure 6. Electron energy distribution function in a 90%Air + 10%Cu mixture at a heavy particle temperature of 3000 K at a pressure of 101 325 Pa. Reduced electric field strength E/N is taken as a parameter.

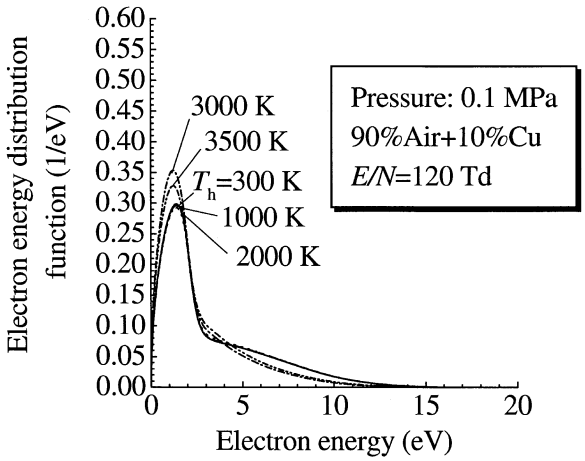

Figure 7. Electron energy distribution function in a 90%Air + 10%Cu mixture at a reduced electric field strength E/N of 120 T_d at a pressure of 101 325 Pa. Heavy particle temperature T_h is taken as a parameter.

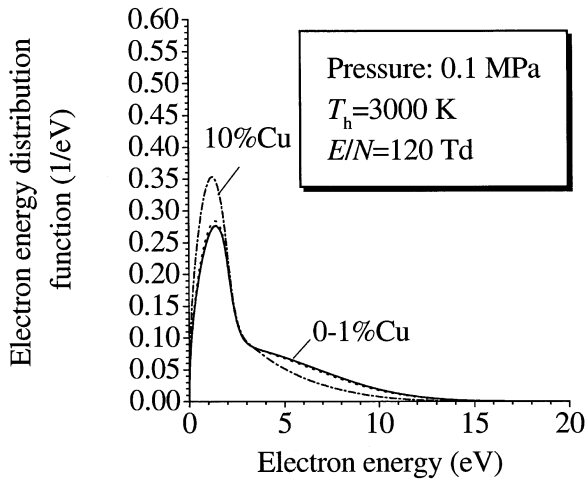

Figure 8. Electron energy distribution function in Air/Cu mixtures at a reduced electric field strength E/N of 120 Td at a pressure of 101 325 Pa. Heavy particle temperature is fixed at 3000 K. Fractional Cu content X_{Cu} is taken as a parameter.

the E/N is Td (1.0 Td $= 1.0\times10^{-21}$ V m^2). A magnitude E/N of 100 Td corresponds to an applied electric field strength E of 245 kV m^{-1} at $T_h = 3000$ K and $P = 101\,325$ Pa. The calculated EEDF is found to be reduced to low values markedly around electron energies 2.0–3.0 eV (1.0 eV $= 1.602 \times 10^{-19}$ J) for any E/N. This is attributable to large vibrational excitation cross sections of N_2, which decays the electron kinetic energy colliding with N_2. Another noticeable point in Figure 6 is the dependence of EEDF on E/N. An increase in E/N elevates the EEDF in the energy range above 3.0 eV and decreases it in the energy range below 3.0 eV at the same time. This is because high E/N accelerates electrons and raises electron kinetic energies.

Influence of T_h on the EEDF in a 90%Air + 10%Cu mixture at a constant E/N of 120 Td can be found in Figure 7. Increasing T_h up to 3500 K elevates the EEDF at electron energies below 3.0 eV while decreasing it at energies above 3.0 eV. This arises mainly from increasing concentration of the copper vapor which has a larger momentum transfer cross section. However, for $X_{Cu} < 1.0$ %, the above tendency is hardly seen because low density of the copper atom.

Figure 8 shows the EEDF at $P = 101\,325$ Pa for different X_{Cu}. The applied E/N is fixed at 120 Td. An increase in X_{Cu} up to 1.0 % hardly changes the EEDF. However, X_{Cu} to 10% changes the EEDF; the EEDF at energies below 3.0 eV rises, while the EEDF at energies above 3.0 eV decreases. This is also ascribed mainly to markedly increasing concentration of the copper vapor. On the other hand, for $T_h < 2000$ K, it was confirmed that increasing X_{Cu} to 10% hardly changes in the EEDF.

Although some influences of T_h and X_{Cu} on the EEDF are seen as mentioned above, they seem to be smaller on the dielectric properties as described later.

6 COLLISION IONIZATION AND ELECTRON ATTACHMENT COEFFICIENTS

The collision ionization coefficient α of Townsend and electron attachment coefficient η are very important to understand dielectric properties of gases because these coefficients remarkably influence an electrical breakdown phenomena of gases. The quantities α and η and the effective ionization coefficient $\bar{\alpha}$ were calculated as follows

$$\frac{\bar{\alpha}}{N} = \frac{\alpha - \eta}{N} \tag{22}$$

$$\frac{\alpha}{N} = \frac{1}{\nu_d}\sum_s \left(\frac{2}{m_e}\right)^{1/2} \int_0^\infty x_s \sigma_s^{i}(\epsilon) f_0(\epsilon)\epsilon d\epsilon \tag{23}$$

$$\frac{\eta}{N} = \frac{1}{\nu_d}\sum_s \left(\frac{2}{m_e}\right)^{1/2} \int_0^\infty x_s \sigma_s^{a}(\epsilon) f_0(\epsilon)\epsilon d\epsilon \tag{24}$$

and

$$\nu_d = -\left(\frac{2}{m_e}\right)^{1/2}\left(\frac{eE}{3N}\right)\int_0^\infty \frac{1}{\sum_s x_s \sigma_s^{m}(\epsilon)}\frac{df_0}{d\epsilon}\epsilon d\epsilon \tag{25}$$

6.1 INFLUENCE OF HEAVY PARTICLE TEMPERATURE

Figure 9 shows the reduced ionization coefficient α/N and the reduced electron attachment coefficient η/N in 90%Air + 10%Cu at different T_h as a function of the reduced electric field E/N. First, the author discusses the effect of T_h on α/N and η/N. The curve $\alpha/N - E/N$ is hardly affected with T_h below 1000 K. However, a further increase in T_h over 1500 K substantially enhances α/N. This enhancement of α/N with T_h results from the ele-

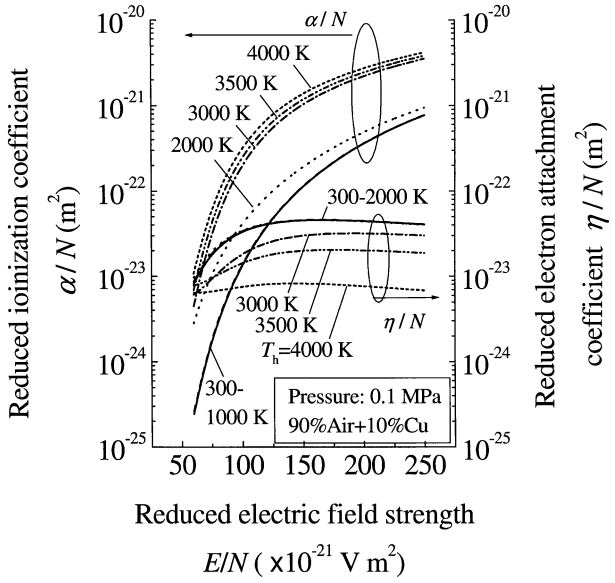

Figure 9. Reduced ionization coefficient α/N and electron attachment coefficient η/N in a 90%Air + 10%Cu mixture as a function of reduced electric field strength E/N. Heavy particle temperature T_h is taken as a parameter.

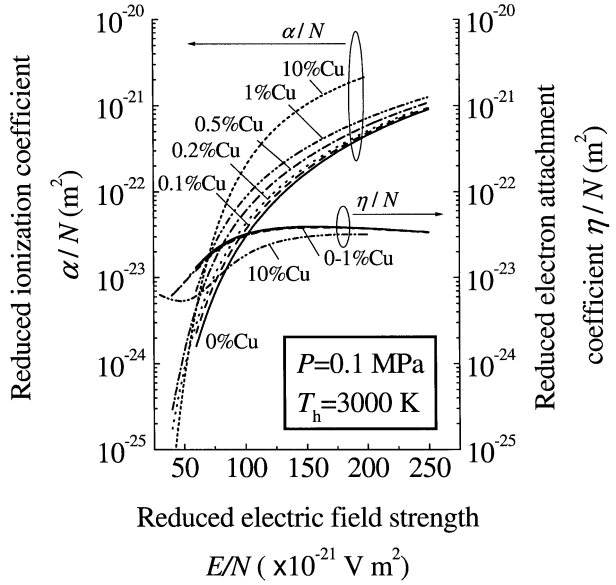

Figure 11. Reduced ionization coefficient α/N and electron attachment coefficient $\bar{\alpha}/N$ in Air/Cu mixtures as a function of reduced electric field strength E/N at a heavy particle temperature T_h of 3000 K. Fractional Cu content is taken as a parameter.

vated NO and Cu mole fractions with increasing T_h as indicated in Figure 1. The molecule NO has a lower ionization potential of 9.25 eV compared to N_2 15.58 eV and O_2 12.07 eV. The Cu atom also has a much lower ionization potential of 7.73 eV. These lower ionization potentials of NO and Cu promote further ionization of gases. The ionization potentials of six dominant particles in air with copper are summarized in Table 1. On the other hand, the electron attachment coefficient η/N is reduced by increasing T_h from 3000 K or more. This is mainly because of reduction in the mole fraction of O_2 due to thermal dissociation, as represented in Figure 1. The O_2 molecules are responsible for electron attachment process through the reaction $O_2 + e \rightarrow O + O^-$ in case of air. The O_2 dissociation decreases electron attachment efficiency of air.

Table 1. Ionization potential.

Species	N_2	O_2	NO	N_2O	N	O	Cu
I.P. (eV)	15.58	12.07	9.25	12.89	14.53	13.61	7.73

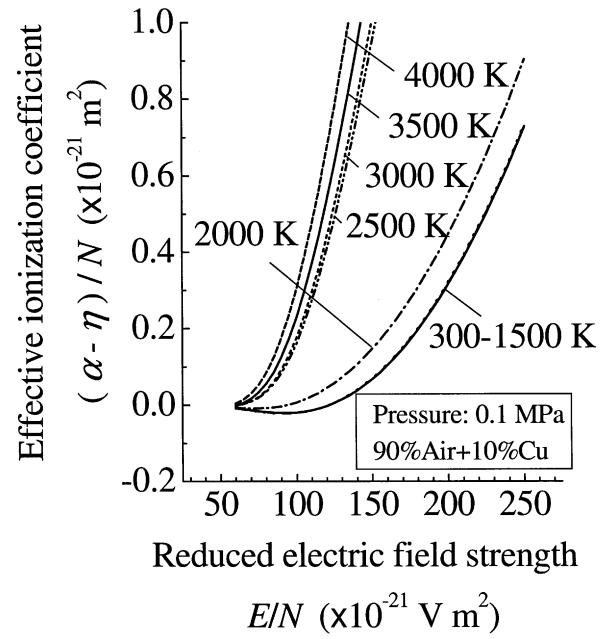

Figure 10. Reduced effective ionization coefficient $\bar{\alpha}/N$ in a 90%Air + 10%Cu mixture as a function of reduced electric field strength. Heavy particle temperature T_h is taken as a parameter.

Both the enhancement of α/N and the reduction of η/N with increasing T_h effectively promote ionization of gases. Figure 10 shows the reduced effective ionization coefficient $\bar{\alpha}/N = (\alpha - \eta)/N$ versus E/N. The quantity $\bar{\alpha}/N$ is enhanced with an increase in T_h over 2000 K. This means that an electron avalanche and then electrical breakdown in a hot air with copper can occur much more easily than in a cold gas.

6.2 INFLUENCE OF FRACTIONAL COPPER CONTENT

Figure 11 denotes α/N and η/N in air with copper at $T_h = 3000$ K and $P = 101\,325$ Pa for different X_{Cu}. The quantity α/N rises as X_{Cu} increases from 0% to 10%. Only 1.0%X_{Cu} contamination elevates α/N by three times at $E/N = 100$ Td. This is attributed to the increasing mole fraction of copper vapor which has a much lower ionization potential. On the other hand, η/N is hardly changed with increasing X_{Cu} up to 1.0%.

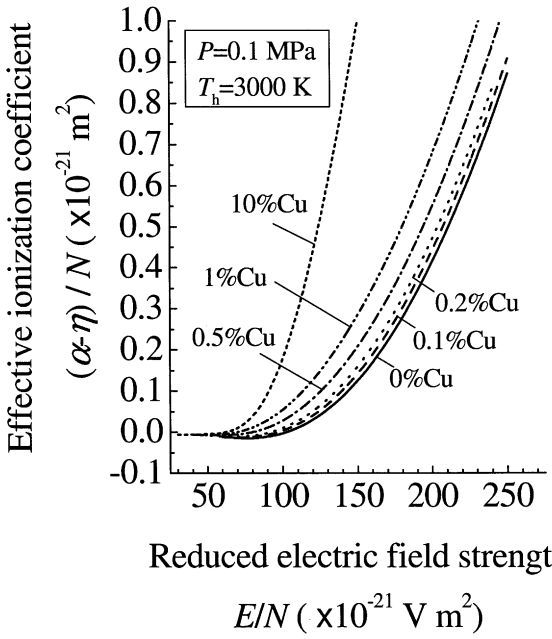

Figure 12. Reduced effective ionization coefficient $\bar{\alpha}/N$ in Air/Cu mixtures as a function of reduced electric field strength at a heavy particle temperature of 3000 K. Fractional Cu content is taken as a parameter.

Effective ionization coefficient $\bar{\alpha}/N$ at different X_{Cu} at $T_h = 3000$ K is depicted in Figure 12. Higher X_{Cu} drastically elevates $\bar{\alpha}/N$, because of rising α/N.

7 CRITICAL ELECTRIC FIELD STRENGTH

Critical electric field strength E_{cr} is defined as the electric field that gives zero effective ionization coefficient $\bar{\alpha} = 0$. This means that the ionization is completely balanced by the electron attachment. This E_{cr} can be evaluated from Figures 10 and 12. Figure 13 indicates the dependence of the reduced critical electric field strength $(E/N)_{cr}$ on T_h for different X_{Cu}. The case of $X_{Cu} = 0$ % corresponds to pure air. The phenomenon in air case is already published in [9, 10]. At a $X_{Cu} = 0\%$, $(E/N)_{cr}$ is 121.4 T_d, which scarcely depends on T_h from 300 K to 1500 K. This $(E/N)_{cr}$ of 121.4 Td is a little higher than an experimentally estimated value of 100 Td at 300 K [21]. Increasing T_h over 1500 K degrades $(E/N)_{cr}$. As a result, $(E/N)_{cr}$ has a magnitude of 85.4 Td at a $T_h = 3500$ K. This magnitude is 0.7 times as high as that at 300 K. That decrease in $(E/N)_{cr}$ by increasing T_h is attributed to the elevated NO mole fraction and the reduced O_2 mole fraction. This calculated $(E/N)_{cr}$ versus T_h in pure air has been compared with experimental results, which showed good agreement between them[9, 10].

The influence of copper vapor contamination is interpreted as follows: The quantity $(E/N)_{cr}$ at $X_{Cu} > 0\%$ also has a value of 121.4 Td at $T_h < 1500$ K, similar to the pure air case. In this temperature range, copper vapor is

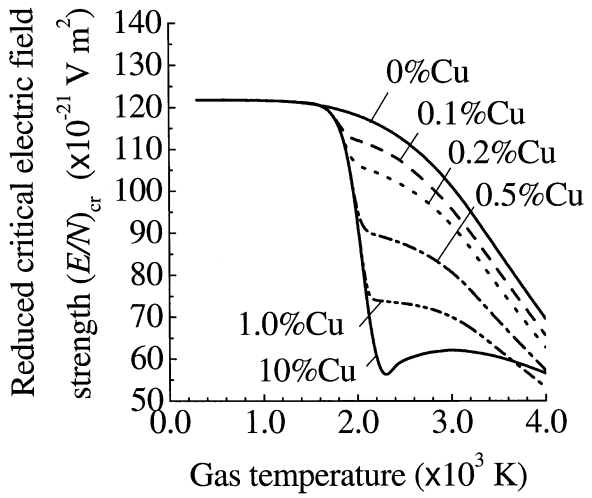

Figure 13. Dependence of critical reduced electric field strength $(E/N)_{cr}$ in Air/Cu mixtures on heavy particle temperature at a pressure of 101 325 Pa. Fractional Cu content X_{Cu} is taken as a parameter.

hardly added into air in the gas phase, which scarcely affects $(E/N)_{cr}$. On the other hand, it should be noted that, at $T_h > 1500$ K, $(E/N)_{cr}$ in copper contamination case decays markedly with an increase in T_h. The magnitude of $(E/N)_{cr}$ at a X_{Cu} of only 1.0% is 0.63 times that in the pure air case at a $T_h = 2100$ K. In this way, a slight contamination of copper vapor was found to remarkably decrease $(E/N)_{cr}$ in air. This drastic decrease in $(E/N)_{cr}$ results from a lower ionization potential of copper atom contaminated around 1700 K. A change in the EEDF by copper contamination, on the other hand, is not major factor for the above $(E/N)_{cr}$ change.

8 CONCLUSIONS

The influence of copper contamination on the dielectric field strength of a hot air in the temperature range 300−3500 K was predicted numerically by combining the equilibrium composition calculation and the Boltzmann equation solution. Copper vapor contamination causes a small change in the electron energy distribution function; however, it markedly elevates the ionization coefficient α because of the much lower ionization potential of the copper atom. The critical electric field strength $(E/N)_{cr}$, which gives zero effective ionization coefficient $\bar{\alpha} = 0$, was quantitatively derived for temperature range 300−3500 K and fractional copper content of 0−10 %. From the results, it was found that only 1.0% copper contamination drastically reduces $(E/N)_{cr}$ around 2000 K.

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