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Effect of Electric Field Induced Nucleation on Relaxation Time and Polarizability

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ABSTRACT

The electric field exists in the clouds. The maximum electric field produced near the lightning channel affects the rate of condensation of water. The formation of the same size of critical nucleus in absence and presence of electric field is considered. An equivalence between supersaturation ratio and external electric field shows that the supersaturation ratio decreases exponentially with increase in external electric field. The increase in polarizability of water vapour molecules in the nucleation of water vapour condensation and ice glaciations, result in increase of Gibbs free energy and henceforth the increase in nucleation rate, but at the same time decrease in relaxation time, the effective polarizability varies nearly inversely as the absolute temperature.

KEYWORDS: Polari ability, nucleation rate, relaxation time, Gibbs free energy.

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INTRODUCTION

There exists electric field in the clouds and the rate of condensation of water is affected due to the maximum electric field produced near the lightning channel.

The effective role of the electric field on the production of ice crystals in cloud chambers was experimentally demonstrated due to the accumulation of accelerated charged water molecules to the crystals tips, thereby increasing the rate of nucleation.[1]

The effect of electric field on the condensation of water vapour is demonstrated theoretically. It shows that under similar temperature conditions a bigger size of drop can be produced in a given time than the one obtained in absence of an electric field. The polarization of water vapour molecules in the electric field of the central dipole – the embryo of water alone is discussed.[2]

Singh et al.[3]considered the resultant effect due to an extrinsic electric field and the electric field due to the central dipole. The theoretical aspects applied to the nucleation process in water vapour condensation and ice glaciations shows that the critical size of the nucleus is attained in a time less than that in electric field free nucleation. In the presence of an extrinsic electric field the nucleation rate is enhanced considerably.

The polarizability of the water vapour molecules in the presence of extrinsic electric field plays an effective role in the nucleation rate of water vapour condensation and ice glaciation. The increase in polarizability results in the increase in Gibbs's free energy and henceforth the increase in nucleation rate, simultaneously decreases the relaxation time[4, 5].

The formulation of the relaxation time required for the attainment of the steady state concentration of embryos of critical size has been discussed [6-9]. Collins[9] deduced that the relaxation time is independent of the free energy of formation of the nucleus, but it varies as the square of the critical radius.

Aerosols present in the atmosphere affect the climate of the Earth by changing cloud properties[10]. Various researches show that the presence of the ions may increase the aerosol formations. The role of the ions in the formation of aerosols is an important process in the atmosphere. The rate of nucleation is generally proportional to the ion densities and the negative ions are essential in nucleation[11]. Evidence for microphysical mechanisms have been reported experimentally in various papers[11-15].

Atmospheric aerosols affect the climate of Earth by scattering sunlight and serve as cloud condensation nuclei (CCN). Various enhanced aerosol formation events are explained on the basis of the presence of Sulphate ions. These sulphate aerosols are formed partly during the oxidation of the oceanic emissions and partly from volcanoes and various combustion processes. Various laboratory researches on warm cloud formation show reduction in the cloud lifetime on increasing the density of Sulphate ions.[16]

Clouds are essential in the Earth's radiation budget and hydrology. Any change in cloud properties have effective impacts on climate[17]. Aerosol effects on clouds can transform cloud properties on climate[18].

The dust particles have an effective role of in cold cloud processes and can also affect warm clouds by acting as Cloud Condensation Nuclei (CCN) changes of which affect their radiative as well as precipitation properties[19-22] .

The effect of an extrinsic electric field on the relaxation time through the calculations for the critical size of the nucleus in homogeneous nucleation is discussed. The comparison with homogeneous nucleation for relaxation times and the rate of nucleation exposes that the electric field even in electrically active clouds is insufficient to make the homogeneous processes as effective as the heterogeneous process. Further extrinsic electric field is theoretically applied to suppress the hail formation.[10]

THEORETICAL CONSIDERATION

(i) In absence of electric field

The fundamental quantity of significance in the nucleation process of water vapour condensation and ice glaciation is the Gibbs free energy of germ formation. The relaxation time is found to be independent of Gibbs free energy. Therefore, we consider only relaxation time of germ formation and hereby study the effect of an electric field on the process of self nucleation and we also investigate the heterogeneous case for comparison.

The relaxation time is the characteristic time to achieve the quasi steady state (germ concentration equilibrium). In the absence of an electric field Collins[9] evaluated the relaxation time

$$\tau_0 = \frac{9\pi kT(n_w^*)^{2/3}}{\mu'^2_w \beta_w \sigma_{w/o}} \qquad \text{....(1)}$$

Where k, the Boltzmann constant; T, the temperature of the system; n_w*, the number of water molecules in a critical nucleus; βw, the frequency of collision of single molecule per unit area; $\sigma_{w/v}$, the surface tension of water vapour interface and μ'_w is a constant given by

$$\mu'_w = 4\pi\left(\frac{3m_w}{4\pi\rho_w}\right)^{2/3} \qquad \text{....(2)}$$

Where, m_w, is the molecular mass and ρ_w, the density of water. The number of water molecules in a critical nucleus is given by

$$n_w^* = \left(\frac{r_w^*}{1.958\times10^{-8}}\right)^3 \qquad \text{....(3)}$$

where, r_w is the radius of critical nucleus with

$$r_w^* = \frac{2\sigma_{w/v} M_w}{\rho_w RT \ln S} \quad \text{....(4)}$$

In this expression $S_{v.w}$ is the supersaturation ratio of the water vapour over the plane water surface; M_w is the molecules weight of water and R is the universal gas constant.

(ii) In presence of electric field

The increase in radius with respect to time

$$\frac{dr_w}{dt} = \left(\frac{\rho}{\rho_w}\right)\left(\frac{9\alpha\lambda E^2}{m_w r_w}\right)^{1/2} \quad \text{....(5)}$$

where, ρ being density of water vapour molecules, α is the polarizability (5×10^{-23} cm^3) ; λ is the mean free path (~10^{-5} cm) and E is the extrinsic inducing electric field.

Integrating eqn (5) within the limits $r_w = 0$ to r_w^* (critical radius of the nucleus) and t = 0 to $t = \tau_N$ (relaxation time) , we get

$$r_w^* = \left[\frac{3\rho\left(\frac{9\alpha\lambda E^2}{m_w}\right)^{1/2}\tau_N}{2\rho_w}\right]^{2/3} \quad \text{....(6)}$$

Putting $\lambda = 10^{-5}$ cm, $\alpha = 5 \times 10^{-23}$ cm^3, $m_w = 5 \times 10^{-23}$gm, $\rho_w = 1$ and $\rho = 10^{-5}$ (at ~10^oC), we get

$$r_w^* = \left(3.18 \times 10^{-7} E \tau_N\right)^{2/3} \quad \text{....(7)}$$

From Eqn. (7), the relaxation time in presence of electric field is

$$\tau_N = \frac{r_w^{*\,3/2}}{3.18 \times 10^{-7} E} \quad \text{....(8)}$$

Thus, the relaxation time for the growth of a nucleus in the presence of an electric field varies inversely with the applied electric field. Under the combined effect of an electric field and diffusion, the reduced relaxation time $\boldsymbol{\tau_{0N}}$ is given by

$$\frac{1}{\tau_{0N}} = \frac{1}{\tau_0} + \frac{1}{\tau_N}$$

$$\tau_{0N} = \frac{\tau_0 \tau_N}{\tau_0 + \tau_N} \quad \text{....(9)}$$

Murino[2] obtained an expression for the drop growth in presence of electric field without considering the dipole contribution. By taking the growth time as relaxation time, his expression can be written as

$$\tau_M = \frac{r^*_w{}^{3/2}}{1.8\times10^{-7}E} \quad \text{....(10)}$$

(iii) Equivalence between electric field and supersaturation ratio

If the same size of nucleus is obtained in two cases: in absence and presence of electric field[11], we get

(r_w*) in absence of electric field = (r_w´*) in presence of electric field

which reduces to

$$E_{eq} \ln S_{v,w} = \frac{k'}{T\tau} \quad \text{....(11)}$$

Where E_{eq} is the equivalent electric field and k´ is a constant given by

$$k' = \frac{4M_w\sigma_{w/v}}{3R\rho_v\left(\frac{m_w}{9\alpha\lambda}\right)^{1/2}}$$

For a given value of temperature and relaxation time, Eqn (10) becomes

$$E_{eq} \ln S_{v,w} = k'' \quad \text{....(12)}$$

Where, $k'' = \frac{k'}{T\tau}$

From Eqn. (11) we have

$$S_{v,w} = \exp\left[\frac{k''}{E_{eq}}\right] \quad \text{....(13)}$$

which shows that the supersaturation ratio $S_{v.w}$ varies exponentially with equivalent electric field $E_{eq.}$ .Awasthi and Pathak[25] have also shown that in presence of pollutants and electric field nucleation is sensitive to supersaturation ratio.

(iv) Polarizability of water vapour molecules

The polarizability of water vapour molecules in presence of external electric field plays an important role in the nucleation rate of water vapour condensation and ice glaciations. The polarizability decreases with increase in the temperature and hence there is decrease in Gibbs' free energy and hence nucleation rate is decreased.

The moment induced on water embryo is

$M = Er_w^3$

Where, r_w is the radius of water embryo and E is the inducing electric field.

The moment induced on a water vapour molecule (following Kittel[26]) is given by

$\mathbf{M_1=\alpha E}$

where, $\boldsymbol{\alpha}$ **(=5x10^{-23}cm^3**) is the polarizability neglecting the vibrational motion.

Recently, the value of polarizability $\boldsymbol{\alpha}$ has been modified[4] by as introducing vibration motion,

$$\alpha_{eff} = \alpha + \frac{\rho_0^{\,2}}{3kT} \qquad \text{....(14)}$$

where, ρ_0 is the dipole moment of water molecule; k, the Boltzmann constant and T, the temperature.

RESULTS AND DISCUSSIONS

Typical values of relaxation times τ_0, τ_M, τ_N and τ_{0N} in water vapour condensation at 273k and electric field 5 esu as a function of supersaturation ratio, are calculated using Eqn. (1), (8), (9) and shown in Table 1.

Table1: **Variation of τ_0, τ_M, τ_N, and τ_{0N} as the function of $S_{v,w}$**

$S_{v,w}$	r_w^* (A^o)	τ_0 (μs)	τ_M (μs)	τ_N (μs)	τ_{0N} (μs)
1.005	2225.00	258300	11664.50	66008.200	52580.00
1.050	227.50	26400	3812.67	2158.120	1995.00
1.500	27.37	3177	159.10	90.056	87.59
2.000	16.01	1859	84.92	40.289	39.44

Thus, for the homogeneous nucleation in the presence of an electric field of 5 esu, our present modification provides a decrease of 43.98% in the relaxation time compared to the values estimated following Murino[2], and 98.8% compared to the values in the absence of an electric field. The nucleation is achieved more quickly and hence there is a marked enhancement in nucleation rate in presence of an electric field.

The effective polarizability α_{eff} of water varies nearly inversely as the absolute temperature. Using Eqn. (14), the values of α_{eff} of water molecules varying with temperature are shown in Table2

Table2: **Calculated values of α_{eff} varying for different temperatures using α_{eff}=5x10^{-23}cm^3, k=1.38x10^{-16}erg k^{-1} and ρ_0=1.81x10^{-18} esu.**

T (K)	α_{eff} (×10^{-23} cm^3)
243	8.254
253	8.125
263	8.006
273	7.896

Thus, we observe that with increase in temperature, the values of effective polarizability decreases.

CONCLUSIONS

From above study it is concluded that the polarizability decreases with increase in temperature and hence there is decrease in Gibbs' free energy and nucleation rate. Also, relaxation time for the growth of nucleus in the presence of an external electric field varies inversely with the applied electric field. An equivalence between supersaturation ratio and external electric field shows that the supersaturation ratio decreases exponentially with increase in extrinsic electric field.

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