Journal of Education for Pure Science- University of Thi-Qar
Vol.9, No.2 (June, 2019)
Website: jceps.utq.edu.iq *Email: jceps@eps.utq.edu.iq*

DOI: http://doi.org/10.32792/utq.jceps.09.02.18

Numerical Simulations of Cloud Condensation Processes

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Received 08/04/2018, Accepted 29/05/2018, Published 02/06/2019

Abstract:

Clouds are collections of tiny particles of water and/or ice that are large enough to be visible. The two required ingredients for the formation of cloud are water vapor and aerosols. The spontaneous growth of Cloud Condensation Nuclei (CCN) into cloud droplets under supersaturated water vapor conditions is described by classic Köhler theory. The aim of this work is to model Köhler theory and investigate effects of mass, solubility, and composition of the CCN in the formation and growth of cloud droplets. Sodium Chloride (NaCl) and Ammonium Sulfate ($(NH_4)_2SO_4$) were used as a solute material. The results showed that both mass and solute material affect the nucleation of cloud droplet. Increasing mass of solute would increase the critical radius and decrease the supersaturation required for activating the droplet. It was found that the use of NaCl produce critical radius larger than that of $(NH_4)_2SO_4$ and the required supersaturation for NaCl solute is lower than that of $(NH_4)_2SO_4$ solute. This is due the fact that NaCl has lower molecular weight than $(NH_4)_2SO_4$. The results also indicate that cloud temperature has minor effect on the cloud droplet activation. The model can be used to investigate more suitable solute materials to determine which is best for cloud seeding projects.

Keywards: Numerical ,Simulations ,Cloud Condensation.

Introduction:

Cloud modeling is a very useful tool for investigating and understanding the thermodynamically and microphysical processes that take place inside the cloud. Cloud models are characterized according to their complexity and dimensionality. The simplest models include cloud parcel model, cloud bulk model, and cloud drop model. Complex models which involve parameterization are mainly used with General Circulation Models [1]. The dimensionality of cloud model includes one, two, and three dimension model. In one dimension model the vertical development of cloud is considered and can be time dependent or independent. Two and three dimensions model consider the horizontal dimensions [2]. Among early simple models are those developed by some researchers [3-7]. Al-Jumaily et al., [8] developed an operational one-dimensional cloud model to investigate the effects force lifting and entrainment on cloud development.

Abdul Rahman [9] developed a two dimensional model to study the convection processes within cloud. Abdul Wahab [10] studied the role of updraft and surface temperature in the warm cloud processes. The aim of this research is to model Köhler theory to study effects of mass, solubility, and composition on the Cloud Condensation Nuclei (CCN) on the formation and growth of cloud droplets.

Theoretical Aspects

a) S*aturation Vapor Pressure over a Curved Droplet (The Curvature Effect)*

The saturation vapor pressure over a curved water surface, $e_s(r)$ is greater than that over a flat surface, $e_\infty(r)$. This is expressed mathematically as [1]

$$e_s(r) = e_\infty(r)\exp\left(\frac{2\gamma}{R_v\rho_l T}\frac{1}{r}\right) = e_\infty(r)\exp\left(\frac{a}{r}\right) \tag{1}$$

where γ is surface tension of water-air interface (~0.075 N/m), ρ_l is the density of liquid water (~1000 kg/m^3), T is the temperature, and r is the radius of curvature (or radius of the droplet).

For a droplet to be in equilibrium with the environment (meaning the droplet will neither grow nor evaporate), then the environmental vapor pressure **e** must A: ; If this is not true, the droplet will either grow or evaporate. This is summarized as:

A O A :N;	the drop will evaporate
A L A :N;	the drop will remain the same size
A P A :N;	the drop will grow via condensation

For a droplet to be in equilibrium then

5 L A / A¶ = : N ; (2)

where 5 is the *equilibrium saturation ratio*.

The saturation ratio is just relative humidity expressed as a ratio rather than a percent. The equilibrium saturation ratio is the saturation ratio required for the droplet to be in equilibrium. If the environmental saturation ratio is less than the equilibrium saturation ratio the droplet will evaporate. If the environmental saturation ratio is greater than the equilibrium saturation ratio the droplet will grow.

For very small drops the equilibrium saturation ratio is extremely large. The increase of equilibrium saturation ratio with decreasing radius is known as the *curvature effect*. Homogeneous nucleation (condensation of pure water with no dust or aerosols present) requires a relative humidity of 400 – 500%! Though this can be achieved in a laboratory, such high relative humidity does not occur in the atmosphere. Therefore, homogeneous nucleation cannot explain the initial formation of cloud droplets [11].

b) Saturation Vapor Pressure over a Solution (The Solute Effect)

A dissolved substance (solute) lowers the saturation vapor pressure of water. A formula expressing this for dilute solutions is given by *Raoult's Law* [11]

$$e' = \chi_w e_s \tag{3}$$

where χ_we is the mole fraction of the water. It is given by

$$\chi_w = 1 - \frac{3im_s}{4\pi\rho_l}\frac{M_w}{M_s}\frac{1}{r^3} = 1 - \frac{b}{r^3} \tag{4}$$

where *i* is the ion factor (the number of ions that one molecular weight of water, M_s is the molecular weight of solute, ρ_l is the density of liquid water, and *r* is the radius of the droplet.

The ratio of the saturation vapor pressure of the mixture over that of pure water is then

$$e'/e_s = 1 - \frac{b}{r^3} \tag{5}$$

The reduction of saturation vapor pressure by introducing a solute is known as the *solute effect*. For droplets of small radius, the saturation vapor pressure over the drop is much less than that over pure water. As radius increases the saturation vapor pressure of the solution approaches that of pure water.

c) Combination of the Curvature and Solute Effects

The combined effects of the curvature and solute are expressed by applying the correction from equation (5) to the equilibrium saturation ratio given by equation (2) to get [11]

$$S_{eq} = \left(1 - \frac{b}{r^3}\right)\exp(\frac{a}{r}) \tag{6}$$

Equation (6) can be approximated well by

$$S_{eq} \cong \left(1 + \frac{a}{r} - \frac{b}{r^3}\right) \tag{7}$$

Figure (1) shows a plot for equation (7). The curve of the total effect is referred to as *Köhler Curve* [12]. The radius at which the Köhler curve is a maximum can be found by taking $\frac{\partial s}{\partial r}$ and setting it equal to zero. This radius is called the *critical radius*, r_c, and the saturation ratio at this point is called the *critical saturation ratio, S_c*. They have the values of

$$r_c = \sqrt{\frac{3b}{a}} \tag{8}$$

$$S_c = 1 + \sqrt{\frac{4a^3}{27b}} \tag{9}$$

The critical radius is of fundamental importance for the cloud droplet growth. At radii below the critical radius ($r < r_c$) the droplets are in stable equilibrium. If S increases the droplets will grow to a larger size and then stop. If S decreases the droplets will shrink to a smaller size and then stop. Droplets at radii below the critical radius are called haze particles. At radii above the critical radius ($r > r_c$) the equilibrium is unstable, and the droplets will spontaneously grow larger, even though S is not increasing. Droplets whose radius equals the critical radius ($r = r_c$) are said to be *activated* [13].

Results and Discussion

In this work equation (7) was used to calculate the equilibrium saturation ratio $_{co}$for different solute types and masses. Sodium Chloride (NaCl) and Ammonium Sulfate ($(NH_4)_2SO_4$) were used as a solute materials. Table (1) gives data related to these two materials.

Table (1): Data for solute materials

Material	Code	Ionic factor	Molecular Weight
Sodium chloride	NaCl	2	58.44
Ammonium Sulfate	$(NH_4)_2SO_4$	3	132.14

Figures (2) shows Köhler curves for NaCl and $(NH_4)_2SO_4$ for masses of 10-18, 10-17, 10-16, and 10-15 g at 273 oK. It is seen that in all cases increasing the solute mass by one tenth of its original value would decrease the critical value of supersaturation needed to activate the cloud droplet to be unstable, i.e. to grow faster without the need for an excess of water vapor.

The reduction in the critical supersaturation is linearly related to the increase of the solute mass. For example increasing NaCl mass from 10-18 g to 10-17 g would decrease the critical supersaturation from more than 0.04 to 0.015. Further increase in the mass to 10-16 and 10-15 would reduce the critical super saturation to about 0.05 and 0.0 respectively. Comparison of the two curves show that the critical supersaturation value depends on the martial of the solute. For solute mass of 10-18 g the critical value of supersaturation are 0.04 and 0.055 for NaCl and $(NH_4)_2SO_4$ respectively. Figure (3) shows the effect of solute mass on critical droplet radius and critical supersaturation for NaCl (solid line) and $(NH_4)_2SO_4$ (dashed lines) assuming cloud temperature of 273 K. It is seen that the critical radius for both materials increases exponentially with increasing the solute mass and the increase for NaCl is faster greater than that for $(NH_4)_2SO_4$. The results also indicate that the critical super saturation is inversely proportional with solute mass and the effect is larger at small masses of solutes. Figure (4) illustrates the effects of cloud temperature on the growth of cloud droplet. Four values of cloud temperature (273, 278, 283, and 288 K) were used to calculate Köhler curves for the two solutes of mass 10-16 g. It is evident that the increase in cloud temperature would slightly reduce the value of critical supersaturation and this relation is not a linear relation and larger effect of changing cloud temperature are on values close to the peak of the Köhler curves for the two solutes. Figure (5) shows the effect of cloud temperature on critical droplet radius and critical supersaturation for NaCl and $(NH_4)_2SO_4$. assuming solute mass of 10-16 g It is obvious that increasing temperature would increase the critical radius and this effect is mostly important at temperatures close 273 K and insignificant at temperatures greater than 278 K. It can also be seen that the supersaturation is linearly decreases with increasing temperature.

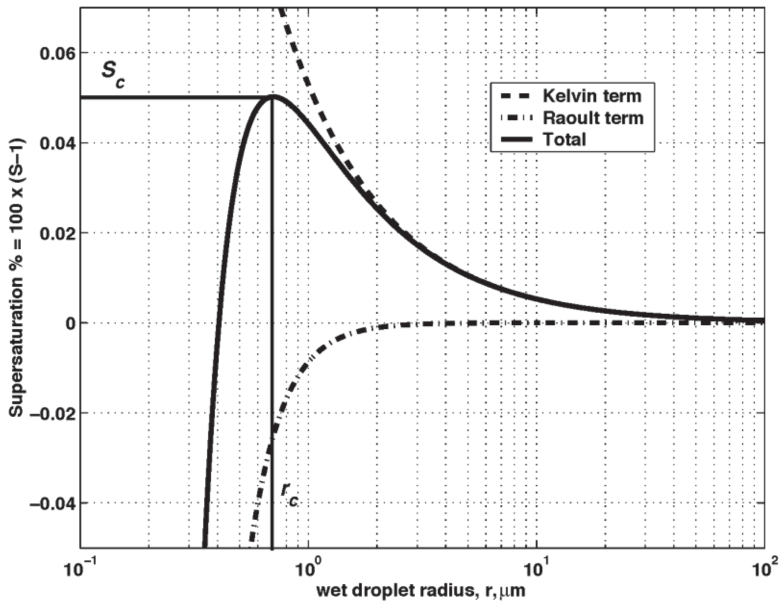

Figure (1): Köhler curve.

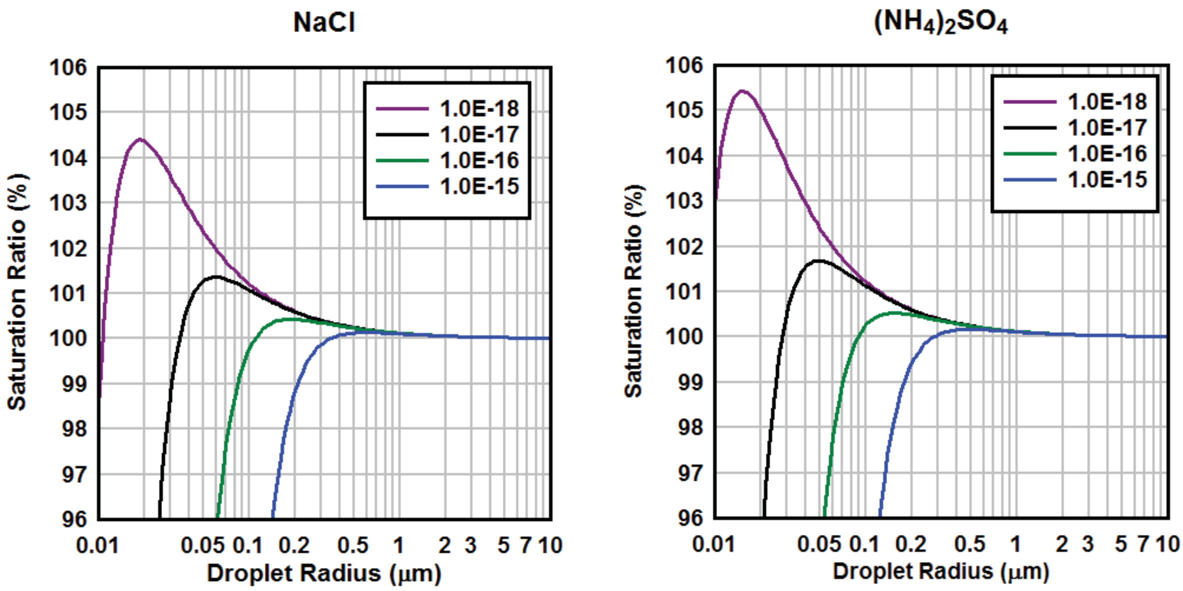

Figure (2): Köhler curves for NaCl, and $(NH_4)_2SO_4$ for different masses (in g) at 273 K.

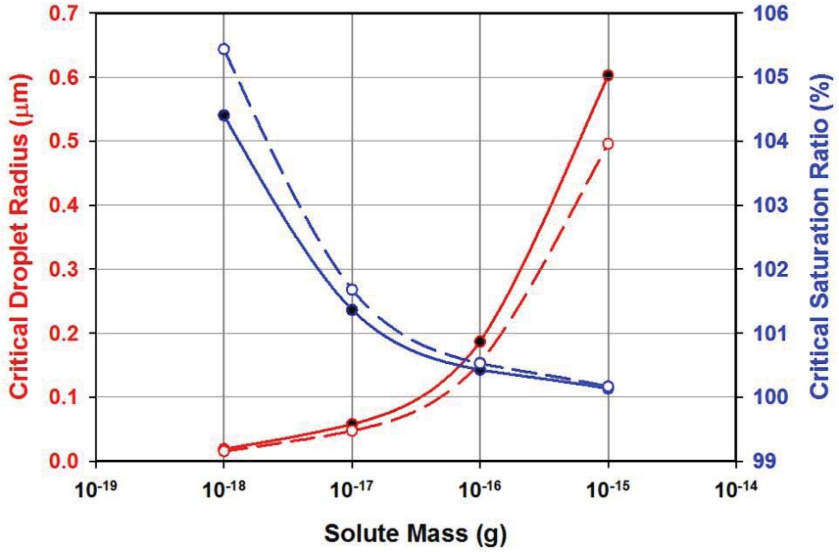

Figure (3): The effect of solute mass on critical droplet radius and critical super-saturation for NaCl (soild line) and $(NH_4)_2SO_4$ assuming cloud temperature of 273 K.

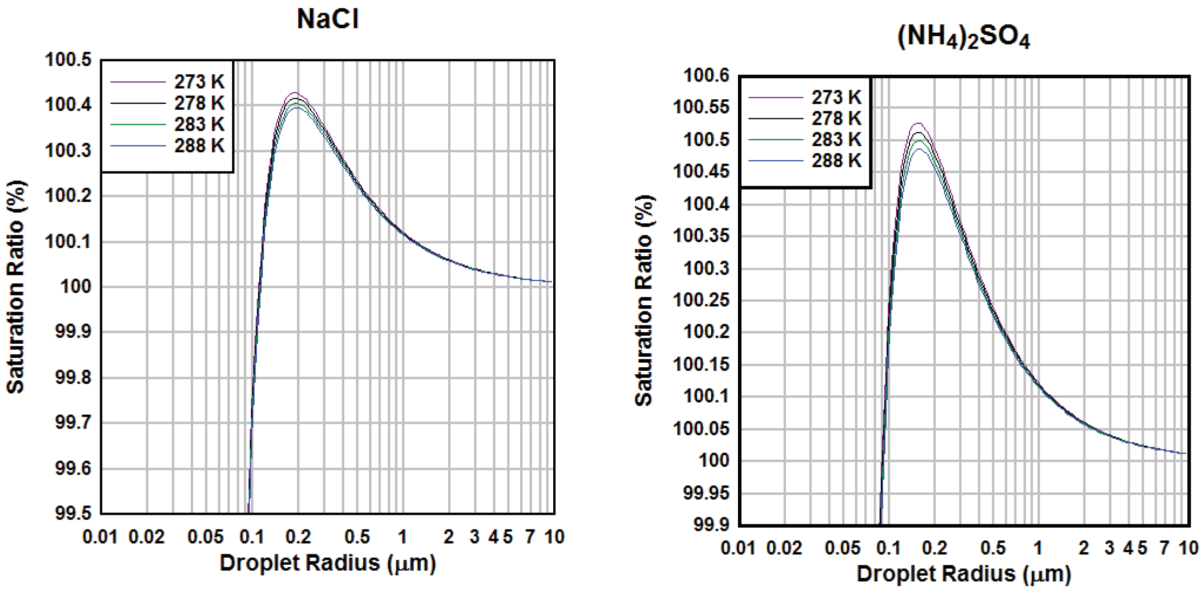

Figure (4): Köhler curves for NaCl, and $(NH_4)_2SO_4$ for different temperatures (in K) for solute mass of 10^{-16}g.

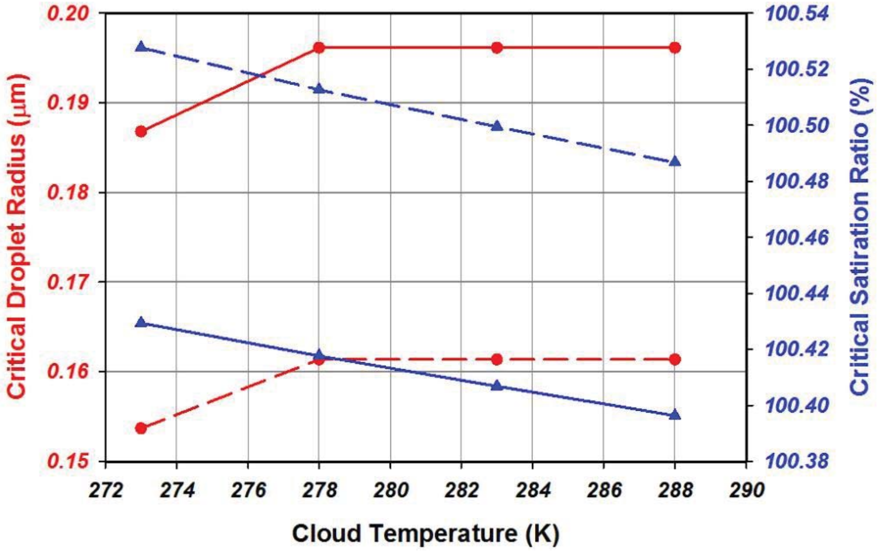

Figure (5): The effect of cloud temperature on critical droplet radius and critical supersaturation for NaCl (soild lines) and $(NH_4)_2SO_4$ (dashed lines) assuming solute mass of 10^{-16} g.

Conclusions

From the results of this work it can be concluded that the increase in solute mass cause decreasing the super saturation that needed to activate the droplet's growth, in other words it increases the critical radius. Cloud temperature, as a parameter, has a significant effect only at temperatures close to 273 K. The increase in temperature would increase the critical radius and decrease the critical super saturation. Among the two solute materials considered in this work NaCl found to be better than $(NH_4)_2SO_4$ in activating the cloud droplets. Further works should investigate the effect of other kinds of suitable solutes so a decision can be made on which martial should be used in cloud seeding projects.

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