 JQC, vol.1, no.1, pp.29-39, 2019

Analysis and Test on Influence Factors of Dew Drop Condensation in Dew Point Hygrometer

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Abstract: The condensation process of dew droplets is influenced by many factors. A dew point condensation image observation system was built to improve the response speed of dew point detector under different measuring conditions. The basic mechanism of dew drop condensation growth was studied and the influence of various factors on the dew drop growth rate were analyzed. And the accuracy of the influence results was verified based on the improved Hough transform circle detection. The results show that the growth rate of dew droplets is affected by ambient temperature, dew point temperature, mirror temperature and air velocity. The observed variation of the average radius of dew droplets is consistent with the theoretical calculations. The maximum radius error is less than 4 μm, the initial error is larger, and the error oscillates in the middle and late stages of condensation. The establishment of condensation mechanism is helpful to solve the problem in fast determination of dew point temperature under the cold start of dew point meter, and to improve the response speed.

Keywords: Atmospheric sounding, dew point hygrometer, dew droplet condensation growth mechanism.

1 Introduction

The dewpoint meter is a high-precision gas humidity measurement instrument that is commonly used in meteorological operations as a gauge of air humidity. The basic principle of the dew point meter is to make the water vapor in the measured gas close to saturation by pressure equalizing the temperature of the gas and condense on the condensing surface to obtain the dew point temperature of the gas to be measured [Sun and Wang (2009)]. Based on the measured dew point temperature and saturated vapor pressure calculation formula (WMO recommended Goff-Gratch formula) to calculate the relative humidity. Due to the cooling method and, the dew point detection method varies, a wide range of dew point instrument, the current international precision dew point meter thermoelectric cooling method and photoelectric method are used to detect condensation,

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but due to the influence of Raoult effect, Kelvin effect, pressure effect, and supercooled water effect on the measurement accuracy, the simple photoelectric method cannot identify the condensate species, which will lead to great errors in the measurement of relative humidity. Moreover, the measurement error in relative humidity is also one of the main factors affecting the measurement accuracy of chilled mirror dew point instrument [Su, Zhao and Gao (2011)].

The condensation process of dew drops is influenced by many factors. The growth rate of dew drops is different under different conditions of mirror temperature, ambient temperature and water vapor pressure. Meanwhile, the dew drop growth rate is influenced by the surface air flow rate, the wet and the heat transfer rate between the air and the condensing surface. The micro-physical process of dew drop condensation was first studied based on the growth of water vapor condensation and the Maxwell equations for water vapor diffusion, the relationship between temperature, vapor pressure, water vapor density, and water droplet radius were established. Daniel Beysens was later applied to the study of the condensation process of dew drops [Beysens (1995, 2006)]. Unlike condensation, dew drops condense on the surface of objects such as leaves of plants, window glass, etc. Surface temperature and material properties are closely linked. Due to the difficulty in the experimental measurement of dew drop coagulation rate, many theories have not been verified. Dong et al. measured the growth of dew drop by laser speckle [Dong (1999)], Julian E. et al. through the establishment of special devices, research the effect of relative humidity on the dynamic process of dew drop condensation [Castillo, Weibel and Garimella (2015)].

2 Dew point measuring principle introduction

The imaging dew point meter was designed based on a set of dew-point temperature measurement mechanism using image method [Dai, Gao and Zhao (2015, 2016); Dai, Zhao and Gao (2016)], which could clearly monitor the condensed mirror image in real time. The device is comprised by the mirror image acquisition device, data processing and controlling device collection, as shown in Fig. 1. When the dew-point meter is started, the temperature control unit cooling block starts to cool down the condensation mirror, then the CMOS sensor collects the mirror image and sends it to the detection and identification unit. The condensation detection algorithm detects generated condensation. If no condensate is detected, the cooling block continues cooling. Otherwise the cooling block is controlled to maintain the mirror temperature, while using the image recognition algorithm to identify the condensate phase [Xia, Ma, Shen et al. (2018); Hu, Yan, Xia et al. (2017)].

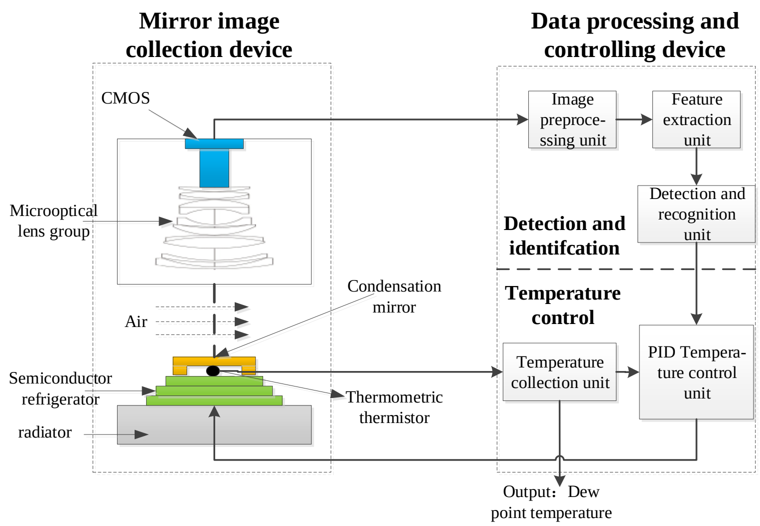


Figure 1: Imaging dew point structure

3 Single dew drop growth mechanism

When the humid air cooling saturation, dew drops began to condense in the mirror condensation, the formation of the condensed nuclei will be around the role of wet air condensation and growth. Can be set above the condensing mirror air flow rate is fixed, the outside world will continue to convey the moist air to the top of the mirror. In the small area above the mirror, a layer of barrier is formed between the airflow and the condensed mirror, and an interface is formed between the barrier and the airflow. In the barrier, the air will not flow with the upper air. Only in the molecular force within the proliferation movement [Castillo, Weibel and Garimella (2015)]. If the water vapor in the airflow aggregation is weak, the mass transfer rate per unit area through the interface can be expressed as:

$$w = D_{12}(p_r - p_s)/\delta_0 RT \tag{1}$$

Where D_{12} is the water vapor diffusion constant in the air. p_s and p_r is saturated vapor pressure and actual vapor pressure, respectively. R is the gas constant. T is the average temperature. δ_0 is the block the thickness of the area.

For calculation the size of δ_0, a temperature gradient at the interface between the barrier and the gas flow was assumed, the temperature was considered to be discontinuous at the interface. In this case, the relationship between the horizontal velocity U and the free airflow could be established by the thickness of the barrier layer, The relationship between aerodynamic viscosity μ and the number of Schmidt Sc, $Sc = \mu / D_{12}$ available:

$$\delta_0 = \frac{(x\mu/U)^{1/2}}{CSc^{1/3}} \tag{2}$$

Where $U \geq 1m/s$, x is the moving distance beyond the boundary of discontinuous temperature C is constant. Combining Eqs. (1) and (2), we could get the relationship between the time required for water vapor per unit mass to reach the mirror through the interface t_f and the air velocity [Weremczuk, Iwaszko and Jachowicz (2011)]:

$$1/t_f \sim w \sim \sqrt{U^*}(p_r - p_s)D_{12} \tag{3}$$

Where $U^* = U/\mu D_{12}^{1/3}$. Air flow rate is usually expressed as volume flow $F = UA_S$ or $F^* = U^* A_S$, A_S is the cross-sectional area of air flow. When the air flow rate is low, the barrier model will be no longer applied, because at this time δ becomes very small, all the water vapor will condense, not in line with the actual situation.

In order to remove dependence on flow rate and saturation, we can use relative time to express:

$$t^* = t/t_f \sim t\sqrt{F^*}(p_r - p_s)D_{12} \tag{4}$$

During a steady state of condensation, the volume of dew drops V with a radius of R is proportional to the time, $V \sim t$ or $R \sim t^{\mu_s}$, $\mu_s = 1/3$. Combining formulas (3) and (4), we get:

$$R \sim (U\Delta p D_{12}^{1/3} v^{-1/3})^{1/3} t^{1/3} \tag{5}$$

Where v is the kinematic viscosity of the air. $v = \dfrac{\mu}{\rho}$. ρ is the current air density, and the kinematic viscosity of the air is related to the ambient temperature:

$$\frac{\mu}{\mu_0} = \left(\frac{T}{288.15}\right)^{1/2} \frac{288.15 + C}{T + C} \tag{6}$$

Where $T_0 = 288.15K$, $C = 110.4K$. Calculate the derivative of (5), and add to the constant B to be determined. The dew drop radius growth rate can be expressed as:

$$\frac{\partial R}{\partial t} = B(U\Delta p D_{12}^{1/3} v^{-1/3})^{1/3} t^{-2/3} \tag{7}$$

$$R = R_0 + B(U\Delta p D_{12}^{1/3} v^{-1/3})^{1/3} t^{1/3} \tag{8}$$

R_0 is the radius of the initial dew drop. R_0 equals to 0 when there is no dew drop on the initial mirror surface. The above formula describes in the growth of dew drop within a certain range. However, when the latent heat which was released by water vapor condensation cannot be absorbed by the mirror, the temperature of the dew drop will increase and the dew drop will slow down or even stop. When the rate of the air flow is very high, dew drops will grow rapidly, in this case the dew drop growth theory experimentally measured.

4 Different factors on the growth rate of dew drop

In order to study the impact of different factors on the dew drop growth [Ucar and Erbil (2012)], the use of the basic idea of the control variable method, respectively, control the ambient temperature, dew point temperature, mirror temperature and air flow rate of 4 parameters were analyzed. In the test B is a constant value 1.265 based on historical data. D_{12} approximately constant 1.1×10^{-3} m^2/s. R_0 takes 0, dew drop radius unit is μm. In order to reflect changes in the rate of dew drop radius growth, it takes the base 10 logarithmic coordinates.

4.1 The impact of ambient temperature on the dew drop growth rate

The kinematic viscosity of wet air is the manifestation of the transport of water vapor molecules and dew drops, which is influenced by the ambient temperature and the current density of air. By the ideal gas equation of state, the density of air can be expressed by the current temperature. Therefore, the kinematic viscosity of air has a direct effect on the rate of the dew drop growth. In the experiment, take dew point temperature as 15°C, mirror temperature as 12°C, air velocity as 1 m/s, ambient temperature as 20°C, 18°C, and 16°C respectively, as shown in Fig. 2.

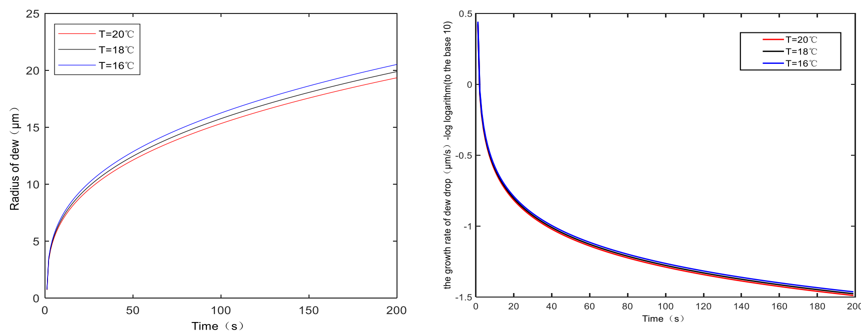


Figure 2: Effect of ambient temperature on dew drop growth rate

As is seen from Fig. 2, the ambient temperature changes have limited impact on the dew drop growth. On the whole, the higher the ambient temperature is, the slower the dew drop growth. The lower the ambient temperature is, the faster drop dew growth. It can be seen from the graph of radius growth that the growth rate of dew drops begins to coagulate faster and then grows slower and slower. The change of growth rate is not obvious when the ambient temperature changes from 16°C to 20°C.

4.2 The effect of dew point temperature on dew drop growth rate

Dew point temperature shows the amount of water vapor in the air. The higher the dew point temperature indicates the more water vapor content in the air, the dew drop growth rate would be faster. In the test, the ambient temperature is 20°C, the mirror temperature is 12°C, the air velocity 1 m/s and dew point temperatures of 17°C, 15°C, and 13°C respectively. The corresponding relative humidity were 82.2%, 72.9% and 64.1% respectively. The simulation results are shown in Fig. 3.

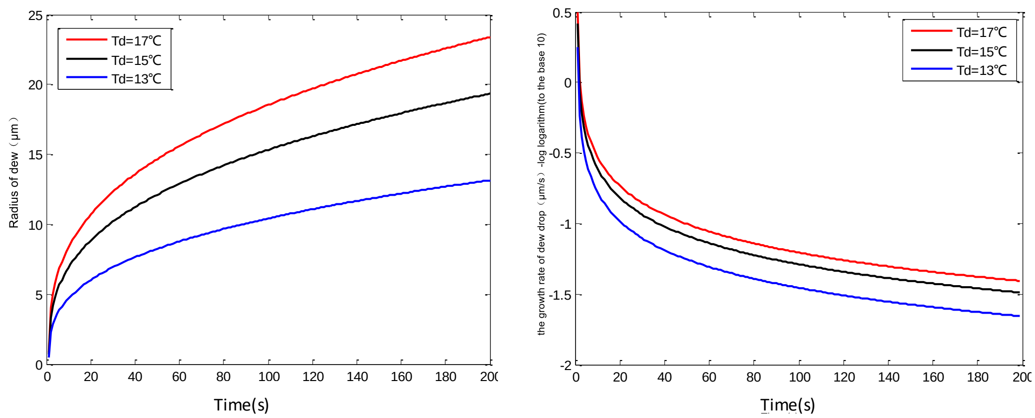


Figure 3: Dew point temperature drop rate of growth

The dew drop radius corresponding to the three dew point temperatures is greatly different which is illustrated in Fig. 3. The higher the dew point temperature, the faster the dew drop growth rate is. But at the same time it is found that the dew point temperature changes from 15°C to 17°C, which is smaller than from 13°C to 15°C. The results show that the change of dew-drip growth rate is more sensitive than that of high-humidity under the low humidity condition.

4.3 The effect of mirror temperature on the dew drop growth rate

The temperature of the mirror surface has a great influence on the condensation of the dew drop undoubtedly. In the humidity measuring instrument, the humid air close to the condensation mirror surface is first cooled by the mirror surface to reach saturation. Then the mirror surface is condensed. The lower the mirror surface temperature, the greater the volume saturated air in the unit time the larger the volume of wet air, the more condensation occurs. To simulate the influence of the mirror temperature on the dew drop growth rate, consider the mirror temperature is fixed during the condensation process. The influence of different mirror temperature on coagulation rate is analyzed in the experiment, the ambient temperature is 20°C, the dew point temperature is 15°C, the air flow rate is 1 m/s, and the mirror temperature is 12°C, 10°C, 8°C, respectively. The simulation results are shown in Fig. 4.

As can be seen from Fig. 4, the influence of the mirror temperature on the dew drop condensation rate is very obvious. The lower the mirror temperature, the faster the dew drop grows which is in good agreement with the actual situation.

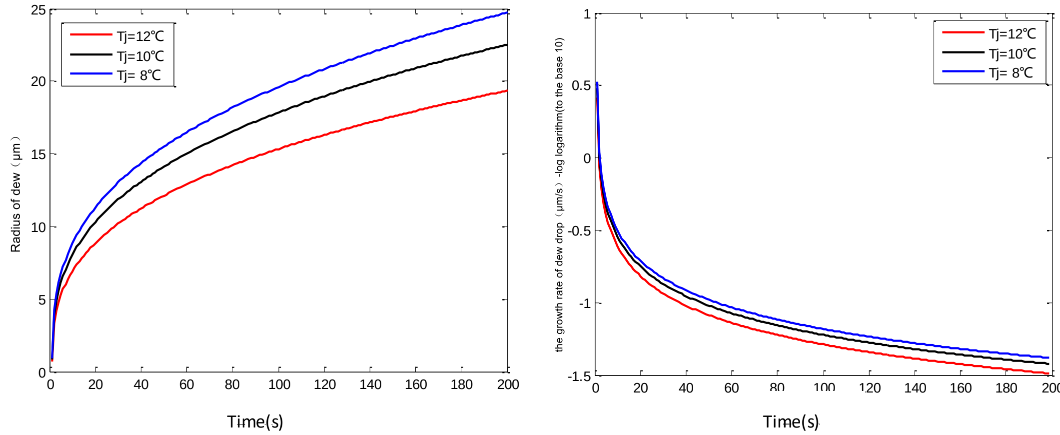


Figure 4: Mirror temperature on the dew drop growth rate

4.4 Air Velocity on dew drop growth rate

Air flow makes the barrier and the outside air quality exacerbated. The greater the air velocity, the more water vapor per unit area per unit time, the faster the growth of dew drops. In the test, the ambient temperature is 20°C and dew point temperature is 15°C, mirror temperature is 12°C. The air velocity is 1 m/s, 2 m/s and 3 m/s, respectively. The simulation results are shown in Fig. 5.

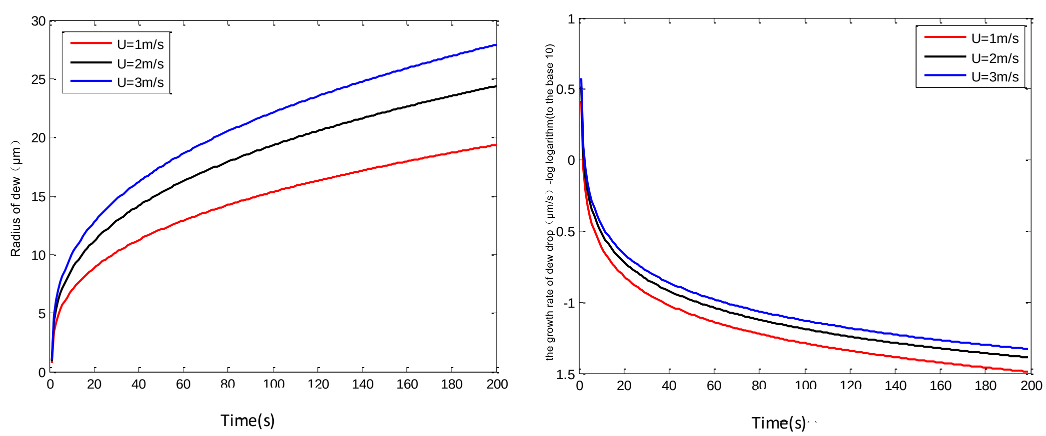


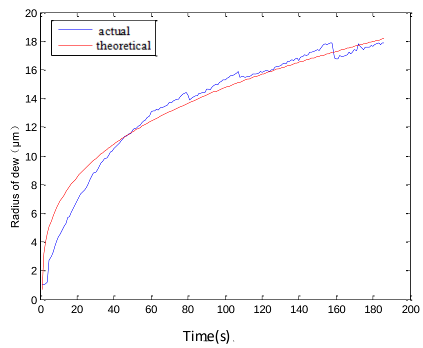
Figure 5: Air velocity on dew drop growth rate

It can be seen from the diagram that the dew drop growth rate is slower when the air velocity is low. When the air velocity increases, the radius of dew drop changes rapidly, and the air velocity has a significant effect on the condensation rate of dew drop.

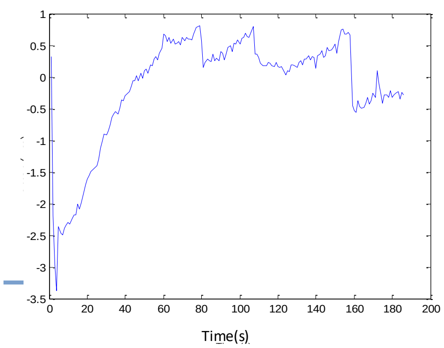
5 Test analysis

In order to test the correctness of the dew drop coagulation theory, the relevant experiment was carried out by using the clotted mirror image acquisition system. The testing equipment mainly includes a small confined temperature controllable test chamber, nitrogen, dew point generator and a flow meter. Our experiment, first fill the test chamber with nitrogen, remove the original wet air in the box, and then control the air temperature inside the box set to 20°C, cooling the condensed mirror. In the three experiments, the mirror temperature is set at 12°C, 11°C and 10°C respectively. When the mirror cooling is stabilized to a set temperature, the wet air with dew point temperature of 13°C is passed through the current meter to the test chamber. The air flow rate is controlled to 1 m/s. Through the real-time acquisition of the mirror image observed by CMOS, we get the images of different growth stages.

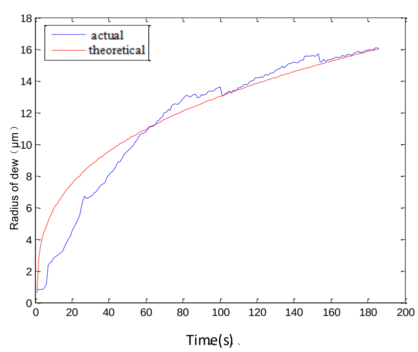
The time-series images are processed by improved Hough transform circular detection [Yang (2002); Gu (2007)]. The average radius of dew drops is extracted and compared with the theoretical calculation to calculate the error. Figs. 6(a), 6(b), 6(c) are the changes of the dew drop radius at the mirror temperature of 10°C, 11°C and 12°C, respectively.



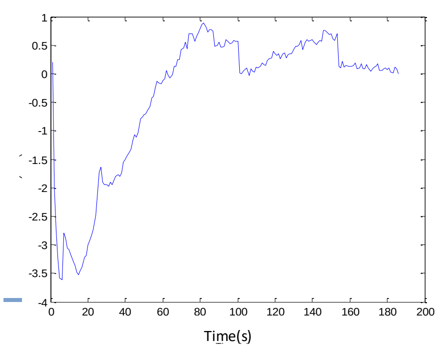
(*a1*)



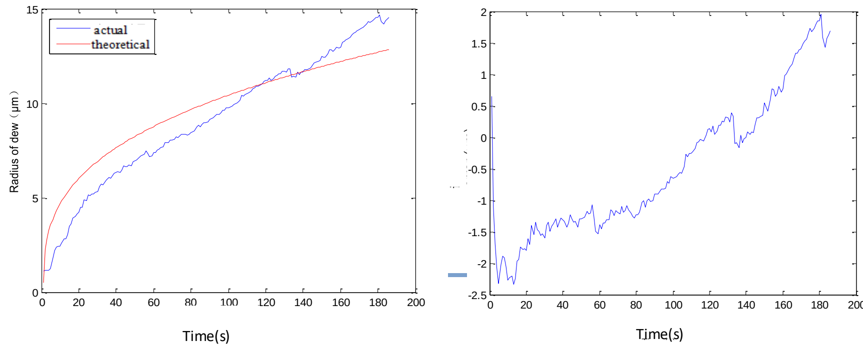
(*a2*)



(*b1*)



(*b2*)



(*c1*) (*c2*)

Figure 6: Dew drop growth curve at different mirror temperatures

As can be seen from Fig. 6, the actual variation of the average droplet densities at different mirror temperatures is in good agreement with the theoretical calculation, and the maximum radius error is less than 4μm. Dew drops in the initial stage of growth and the theoretical error is larger, the error gradually reduced in the mid and late growth. The main reason is that the minimum radius of the circle detection is 5 pixels, that is, the actual size of 1μm, for the radius less than 1μm dew drops cannot be detected, making the initial error larger. In the middle and later condensation, the error oscillates, which may be caused by the collision of adjacent dew droplets and the jump of detection radius.

6 Conclusion

To measure the response speed of dew point temperature using dew point analyzer, the microphysical process of dew drop growth is analyzed, and relevant experiments are carried out to verify the results. The main conclusions are listed as follows:

(1) The growth rate of droplets is affected by ambient temperature, dew point temperature, mirror temperature, and air velocity. The higher the ambient temperature, the growth of dew droplets becomes slower; and the lower ambient temperature, the higher the dew point temperature, and the lower the mirror temperature would make the growth of dew droplets become faster. Air velocity promotes the growth of dew droplets. The larger the velocity lead to the faster the growth of dew droplets.

(2) According to the experimental verification, the actual variation of the average radius of dew droplets is in good agreement with the theoretical calculation, and the maximum radius error is less than 4μm. In the initial growth stage, the error between dew droplets and theoretical results is large, which is mainly attributed that the circle detection algorithm has a minimum detection range, and cannot detect dew droplets whose radius is less than 1μm, which makes the initial error larger. In the middle and late stages of condensation, the errors oscillate, which may be due to the collision of adjacent dew droplets, resulting in the jump of detection radius.

In the future, image recognition technology [He, Ouyang, Wang et al. (2018); Qi, McIntosh and Sun (2018); Qi, McIntosh and Sun (2018)] will be further studied to identify dew and frost.

Acknowledgement: Project supported by the National Public Welfare Research Fund of China (Grant No. GYHY201206035), the National Natural Science Foundation of China (Grant Nos. 41475022, 41775165, 41706109).

References

Beysens, D. (2006): Dew nucleation and growth. *Science Direct*, vol. 7, pp. 1082-1100.

Beysens, D. (1995): The formation of dew. *Atmospheric Research*, vol. 39, no. 1-3, pp. 215-237.

Castillo, J. E.; Weibel, J. A.; Garimella, S. V. (2015): The effect of relative humidity on over desorption dynamics. *International Journal of Heat and Mass Transfer*, vol. 80, pp. 759-766.

Dai, Z. H.; Gao. T. C.; Zhao, S. J.; Chen, D. J. (2015): Based on the morphology of dew-point instrument to identify the research of supercooled water. *China Society for Instrumentation Society of Meteorological and Hydrological Instruments Branch*, pp. 124-128.

Dai, Z. H.; Gao. T. C.; Zhao, S. J.; Zhai, D. L. (2016): Condensation type humidity sensor system design and test. *Foreign Electronic Measurement Technology*, vol. 9, no. 35, pp. 86-91.

Dai, Z. H.; Zhao, S. J.; Gao. T. C.; Zhang, Z. Y. (2016): System design and experimental testing of humidity sensor based on condensation method. *International Workshop on Materials, Manufacturing Technology, Electronics and Information Science*, pp. 225-236.

Dong, Z. Q. (1999): Using laser speckle measurement of condensation process of growth. *Laboratory Research and Exploration*, vol. 2, no. 18, pp. 55-57.

Gu, Y. (2007): Image recognition based on hough transform and geometric properties. *Auto Exposition*, no. 4, pp. 86-88.

He, L. L.; Ouyang D. T.; Wang, M.; Bai, H. T.; Yang, Q. L. et al. (2018): A method of identifying thunderstorm clouds in satellite cloud image based on clustering. *Computers, Materials & Continua*, vol. 57, no. 3, pp. 549-570.

Hu, K.; Yan, H.; Xia, M.; Xu, T.; Hu, W. et al. (2017): Satelite Imagery cloud classification based on transfer learning. *Terrestrial Atmospheric and Oceanic*, vol. 40, no. 6, pp. 856-863.

Qi, C.; McIntosh, S.; Sun, H. Y. (2018): Identifying materials of photographic images and photorealistic computer generated graphics based on deep CNNs'. *Computers, Materials & Continua*, vol. 55, no. 2, pp. 229-241.

Sun, X. J.; Wang, X. L.; Li, H.; Zhang, W. X.; Yan, W. (2009): *Atmospheric Exploration*. Meteorological Press.

Su, X. Y.; Zhao, S. J.; Gao, T. C.; Yang, S. C. (2011): Study on the chilled mirror dew point meter and its key technologies. *Acta Metopeauolica Sinica*, no. 5, pp. 323-328.

UcarandH, I. O.; Erbil, Y. (2012): Dropwise condensation rate of water breath figures on polymer surfaces having similar surface free energies. *Applied Surface Science*, vol.

259, pp. 515-523.

Weremczuk, J.; Iwaszko, R.; Jachowicz, R. (2012): The method of water molecules counting during condensation process in the dew point detector. *Sensors and Actuators B: Chemical*, pp. 137-141.

Xia, Z. H.; Ma, X. H.; Shen, Z. X.; Sun, X. M.; Xiong, N. N. et al. (2018): Secure image LBP feature extraction in cloud-based smart campus. *IEEE ACCESS*, vol. 6, no. 1, pp. 30392-30401.

Yang, Z. M.; Zhou, Q. G. (2002): Graph recognition based on Huff transform theory. *Journal of Chongqing Polytechnic College*, no. 4, pp. 16-17.