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Research Article

Condensation Zone Estimation and Determination and Comparison of Condensation by Numerical Analysis in Vehicle Lighting System

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Abstract

The condensation problem in automobile lighting system risks driving and driver safety. Condensation is the main cause of problems such insufficient lighting. In our study, the problem of condensation in vehicle headlights is discussed. The region where condensation will occur was estimated from the results obtained from the temperature analysis. The amount of condensed mass was calculated by the calculation method. Calculations were confirmed by numerical analysis. In the analyzes made in ANSYS 2022 R2 software, the transmission effects (conjugate effects) in the headlight components were taken into account. Boussinesq approach was used for natural convection and Monte Carlo approach was used for considering radiation effects. Mesh independence was was studied. Thermal analyzes were made at ambient temperature T_∞=5 °C and RH: 95% independent of time. As a result of the analysis, the indoor air temperature distribution, air flow profiles were examined and an estimate was made where the condensation would occur. Then, the thermal analysis results were read as the initial condition, and it was kept for 300 seconds. Water at 3 °C was sprayed onto the lens. Condensation formation analyzes were made in terms of time. After the formation of condensation, the power was turned on to the lighting elements and it was expected that the condensation would be removed within 1800 seconds as per the specification. The region where condensation is predicted and the region with condensation in the analyzes are compatible with the literature.

Keywords: Condensation, heat transfer, computational fluid mechanics, vehicle lighting, mass transfer

Araç Aydınlatma Sisteminde Yoğuşma Bölgesi Tahmini ve Yoğuşmanın Sayısal Analiz ile Belirlenmesi ve Karşılaştırılması

Öz

Otomobil aydınlatma sistemindeki yoğuşma sorunu, sürüş ve sürücü güvenliğini riske atmaktadır. Yetersiz aydınlatma gibi sorunların ana nedenleri arasında yoğuşma önemli bir problemdir. Çalışmamızda araç farlarında yoğuşma sorunu ele alınmıştır. Sıcaklık analizinden elde edilen sonuçlardan yoğuşmanın meydana geleceği bölge tahmin edilmiştir. Yoğunlaşan kütle miktarı hesaplama yöntemi ile hesaplanmıştır. Hesaplamalar sayısal analizle doğrulanöıştır. ANSYS 2022 R2 yazılımında yapılan analizlerde far bileşenlerinde ısı iletim etkileri dikkate alınmıştır. Doğal taşınım için Boussinesq yaklaşımı, radyasyon etkilerini dikkate almak için Monte Carlo yaklaşımı kullanılmıştır. Eleman sayısından bağımsızlık çalışması yapılmıştır. Termal analizler, T_∞=5 °C ortam sıcaklığında ve zamandan bağımsız olarak RH: %95 tanımlanarak yapılmıştır. Analiz sonucunda iç ortam hava sıcaklık dağılımı, hava akış profilleri incelenmiş ve yoğuşmanın nerede olacağı tahmini yapılmıştır. Daha sonra termal analiz sonuçları başlangıç koşulu olarak tanımlanmış ve 300 saniye lens üzerine 3 °C'de su püskürtülmüştür. Zamana bağşı yoğuşma oluşum analizleri yapılmıştır. Yoğuşma oluştuktan sonra aydınlatma elemanlarına güç tanımı yapılmıştır. Şartnameye göre 1800 saniye içinde yoğuşmanın giderilmesi beklenmiştir. Analizlerde yoğuşmanın tahmin edildiği bölgede oluştuğu, yoğuşmanın oluştuğu bölge literatür ile uyumlu çıkmıştır.

Anahtar Kelimeler: Yoğuşma, ısı transferi, Hesaplamalı akışkanlar mekaniği, taşıt aydınlatma, kütle transferi.

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1. Introduction

Nusselt (1914) is one of the pioneers in the field of condensation. Nusselt worked on calculating the heat transfer between the vertical plate and the stagnant condensed water vapor with simple theoretical analysis. Dehbi and Guentay (1997) derived a theoretical estimate of the rate of heat and mass transfer in a vertical condenser tube consisting of a mixture of steam and non-condensable gas. In the study, the algebraic equation for the film layer thickness is derived and the heat and mass transfer analogy is examined to understand the condensation rate. Liu et al. (2003) based on the estimation of when and where the condensation will occur, a time dependent condensation calculation was made. In this study, the condensation on the cube surface was investigated numerically and experimentally using the commercial Japanese CFD software STREAM 4.0 [3]. A theoretical and experimental study was first conducted by Preihs (2006) directly related to automobile headlights. In the study, the dew point temperature and the condensation area were estimated. It is concluded that the condensation area is sufficiently compatible with the estimated measurements for a two-dimensional geometry. In the study, the condensation model was first developed and validated experimentally, and then the effect of ventilation on condensation was investigated. They observed that condensation was significantly reduced by adding an air intake to the control volume and by properly positioning the vents. Deponti et al. (2009) dealt with the condensation problem in vehicle lighting systems in their study. The analysis made in the study was compared with the experimental data and the results were confirmed. Condensation is based on mass transfer with heat transfer. It has been determined that especially the condensation on the headlight affects the photometric values of the headlight negatively. It has been stated that the things to be considered in the study are the changing density values of the indoor air, the temperature values and the temperature of the outside air. It is stated that the ventilation holes that help prevent condensation and circulate the air in the headlight should be modeled in the condensation analysis. At the end of the study, it was determined that the analysis results and the test results were compatible It has been determined that there is condensation in the areas where the air is compressed. Erik (2006) tried to predict the condensation removal event in the transient regime using computational fluid dynamics. In the study, they developed a new droplet condensation-evaporation model. With the developed model, time dependent evaporation simulation was made using CFD code. As a result of the study, it was determined that the model based on droplet condensation and evaporation gave appropriate results. Another study on condensation using computational methods was done by Touichirou et al. (2005). However, most of these studies are based on the estimation of the characteristic of the fog formed from the speed profiles on the windshield. Hassan et al. (1999) estimated the demisting process of the windshield based on the time-dependent film layer acceptance. Shozawa et al. (2005) study is important in that it is directly related to condensation in vehicle lighting systems. They developed a numerical calculation method on this subject and then applied it to the condensation analysis in the headlight [9]. Oxyzoglou (2018), Herridge (2003) and Okada et al. (2001) conducted studies on condensation analysis in vehicle lighting systems.

The aim of this study is to estimate the region where condensation will occur, without the need for a long-term condensation analysis, and to find the approximate amount of condensation by calculation. The calculation method in the study was verified by numerical analysis. With the calculation method and approach, it is aimed to gain from long-term analysis time.

2. Material and Method

When the saturated steam comes into contact with a surface at a temperature lower than the saturation temperature at the same pressure, it begins to condense. If the condensation continues without condensing drops on the surface, it is called drop condensation. If the condensed drops combine on the surface and form a film, it is called film condensation. As the film formed on the surface becomes thicker, the heat transfer resistance increases. In the case of drop condensation, the thermal resistance is very small. In the case of drop condensation, the heat transfer is approximately 10 times higher than in film condensation. However, it is not possible to provide drop condensation on surfaces. Because a special substance or surface should be used to prevent the condensation drops from coming together. Therefore, unless otherwise stated, condensation will be used to mean film condensation. Under the subject of condensation mass transfer, it is heat and mass transfer that depends on relative humidity, flow pattern, fluid and surface temperatures.

2.1. Condensation on vertical plate

When condensation is examined in a vertical plate in terms of heat transfer, it is examined under the name of Nusselt theory, since it was first analyzed analytically by Nusselt. Known as film theory or Nusselt theory, this analytical analysis is based on some assumptions. These acceptances; The steam is low velocity or stagnant, the fluid properties are constant, and the liquid vapor surface is neglected by viscous friction. With these assumptions, the plate temperature is taken as T_y and the saturated steam temperature is taken as T_d. The condensed liquid film will get thicker and thicker from the top of the plate and will flow towards the bottom of the plate under the influence of weight. There are weight forces acting downwards and forces due to density change. In the upward direction, there are viscous frictional forces acting. If the balance of the forces acting on a volume element taken in the flow area is written and the necessary boundary condition assumptions are made, Equation.1 for the mass fluid flow rate depending on δ=δ(x) liquid film thickness, Equation.2 for the film thickness is used [13].

$$m(x) = \frac{g\rho_s(\rho_s-\rho_b)\delta^3}{3\mu_s} \tag{1}$$

$$\delta(x) = \left[\frac{4\mu_s k_s(T_d-T_y)x}{g(\rho_s-\rho_b)p_s h_{sb}}\right]^{\frac{1}{4}} \tag{2}$$

In order to describe the heat convection coefficient in the case of film condensation, if conduction along the length of the plate is neglected, the condensation heat generated during condensation will be transferred from the plate surface by conduction. For the average heat convection coefficient in the L-length plate, it is expressed as in Equation.3 from the previous description and integration [13-14].

$$h_m = 0.943\left[\frac{g\rho_s(\rho_s-\rho_b)h_{sb}k_s^3}{\mu_s(T_a-T_y)L}\right]^{1/4} \tag{3}$$

Thermo-physical properties in these equations should be taken at T_f=(T_d+T_y)/2. In case of condensation in a vertical pipe or plate, the amount of condensed liquid on a pipe or plate of unit width, m1L, is found from the expression in Equation:4:

$$m_{1L} = \frac{h_m(T_\infty - T_y)}{h_{sb}} \quad (4)$$

The number Re is described as in Equation.5. Depending on the Reynolds number, the heat transfer coefficient can be found from Equation 6 [13-14].

$$Re_\delta = 4\frac{m_L}{\mu_s} \quad (5)$$

$$\frac{h_m(V_s^2/g)}{k_s} = 1.47\, Re_\delta^{-1/3} \quad => \quad Re_L \leq 30 \quad (6)$$

In addition to these relations, based on the combination of heat and mass transfer, the flow is laminar or turbulent, after determining by the Re number, natural flow is assumed on the vertical plate and for laminar flow [13-14].

$$\text{Nu}= 0{,}59(Gr.Pr)^{1/4} \quad (7)$$

For turbulent flow;

$$\text{Nu}= 0{,}13(Gr.Pr)^{\frac{1}{3}} \quad (8)$$

The reason for accepting a vertical plate is that the lens element is considered a vertical plate [13-14].

$$\text{Nu}=\text{Sh}=\frac{hL}{k} \quad (9)$$

$$\text{Sc}=\text{Pr} \quad (10)$$

Gr.Sc>109 Turbulent, Gr.Sc<109 Laminar control and the system determined to be laminar or turbulent is solved according to equations 9 and 10. The expression of the condensed mass over Nusselt-Sherwood and Prandtl-Schmidt analogy is given in Equation.11. [13-14].

$$\text{m}_b = h_m(C_w - C_\infty) \quad (11)$$

2.1. Numerical Analysis and Boundary Conditions

In this study, numerical analysis was performed with the help of ANSYS 2022 R2 software. In-volume, laminar natural convection, three-dimensional and steady-state air flow is accepted. In thermal analyzes and condensation analyzes, the ambient temperature is 5 ºC and the relative humidity is defined as 95%. The conduction effects (conjugate effects) on the headlight components are taken into account. Boussinesq approach was used for natural convection and Monte Carlo approach was used for considering radiation effects. In the Monte Carlo method, a photon is irradiated with random access (Fluent Users Guide). It is repeated N times according to the maximum number of photons determined in the analysis. Detailed information on the equations solved and the approaches used can be found in the ANSYS 2022 R2 Solver Theory Guide (Flunet Theory Guide). The analyzes are given in Table 1, respectively. In order to determine whether condensation occurs or not, water was sprayed at 3 ºC and 0.5 m/s speed for 300 seconds as in Figure 1 and condensation formation was expected.

Table 1: Analysis Order and Boundary Conditions

Phase	Initial Conditions	Analysis	Bulbs	Analysis Type
1st	T_{amb}=5 ºC, RH=%95	Thermal	On	Steady-State
2nd	Results of 1st	Washing	Off	300 s
3rd	Results of 2nd	Defogging	On	3600 s

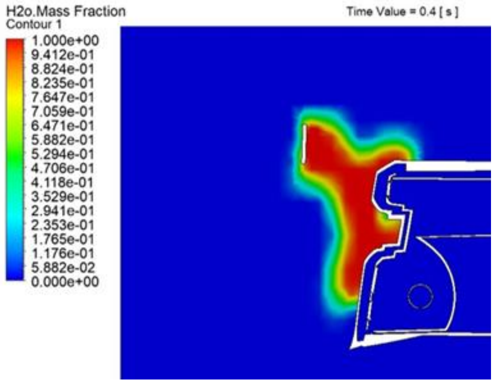


Figure 1 : Condensation analysis Water spray image at 3 ºC

2.3. Numerical Analysis and Boundary Conditions

The mesh image of the design, which is the subject of our study, is given in Figure 2. The study independent of the number of elements was made in thermal analysis. In thermal analysis, the number of elements was determined as 5325874, 7528961, 11548265 and 13286595. In the thermal analysis results, it was determined that the part temperatures did not change after 11548265 element number and the results were taken over 11548265 elements. In Figure 3, the variation of the temperature of the lens part depending on the number of elements is given.

Figure 2: Mesh Image Consisting of 11548265 Elements

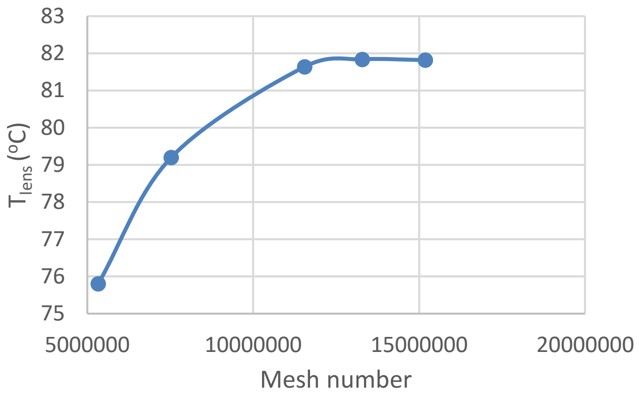
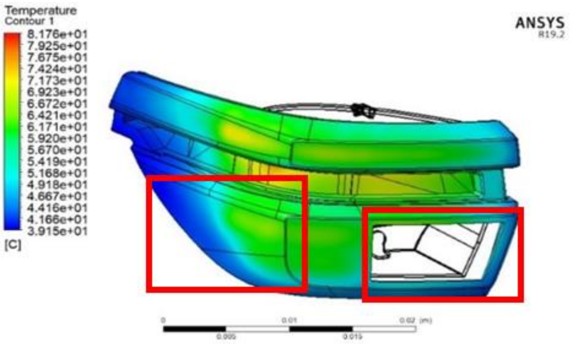


Figure 3: Temperature Results with Consisting of 11548265 Elements

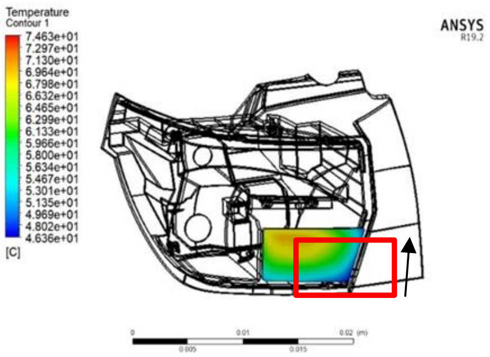
3. Results and Discussion

3.1. Results

Since condensation will occur on the lens part, the temperature of the lens part is given as a result in our study. Lens temperature distribution according to the thermal analysis result is given in Figure 4.



a)



b)

Figure 4. a) Main Lens Temperature Distribution b) Small Lens Temperature Distribution

According to the results obtained on the lens in the temperature analysis, it was predicted that condensation would occur in the regions related to the red frame in Figure 4. For the condensation sample calculation, the lens is considered as a flat plate and in Figures 4a and 4b, 25 mm upwards plate is accepted from the bottom right. The lens surface temperature in the condensation predicted region was again determined as 48 °C in Figure 4 a and b. The relative humidity of the air in the headlight interior volume was taken as 95% as in the analysis. H_2O mass flux was calculated as 9,3x10^{-6} kg/m^{2}s.

After the thermal analysis results, the water spray analysis, which is the 2nd phase analysis, was performed. In this analysis phase, condensation formation was observed with the bulbs closed for 300 seconds. It was determined that the condensation started in the 88th second. (Figure 5).

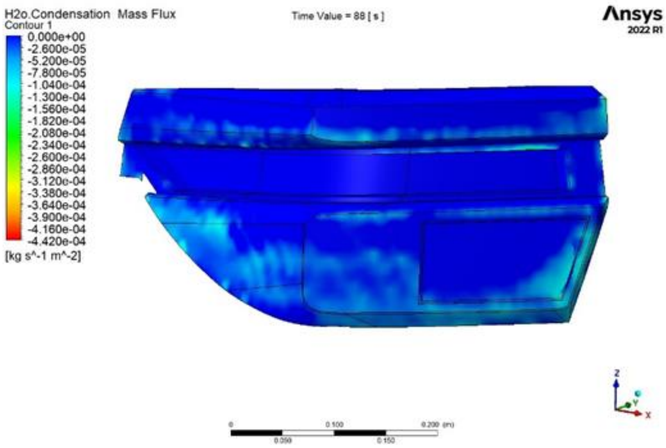
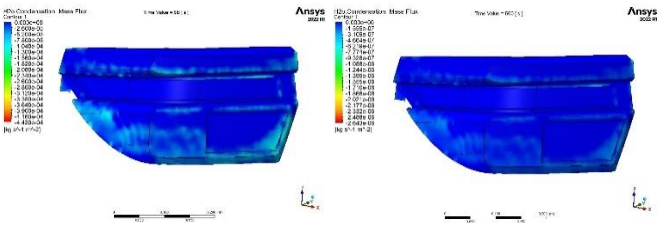
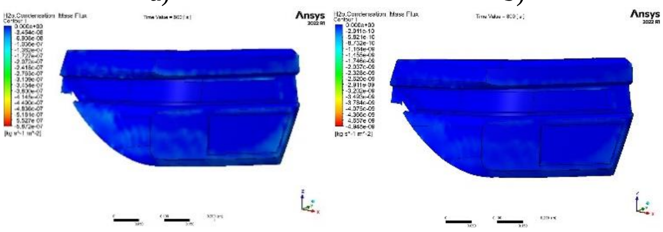


Figure 5: Lens on 88th second Condensation Formation

After 300 seconds, the analysis passed to Phase 3 and the bulbs in the system were powered. According to the OEM standard, the condensation formed was expected to disappear within 1800 seconds. It has been determined that the condensation starts to disappear from the 400th sec and completely disappears in the 800th sec. The 400th, 500th, 600th and 800th sec results are given in Figure 6 a, b, c, d, respectively.



a) b)



c) d)

Figure 6: Humidity Results a) 400th sec b) 500th sec c) 600th sn d)800th sec

The H_2O mass flux obtained as a result of the analyzes was determined as 9,8x10^{-6} kg/m^{2}s.

The amount of condensation at variable humidity rates was determined by the calculation method and is given in Figure 7.

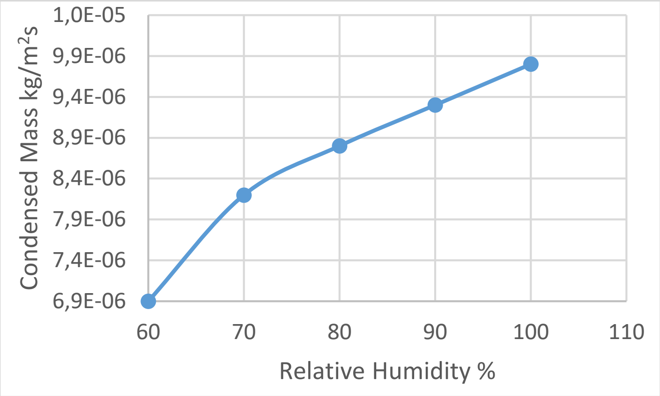


Figure 7. Condensation amount at variable RH (95%)

With the calculation method, condensation values that may occur at 95% relative humidity for different surface temperatures were also calculated and given in Figure 8.

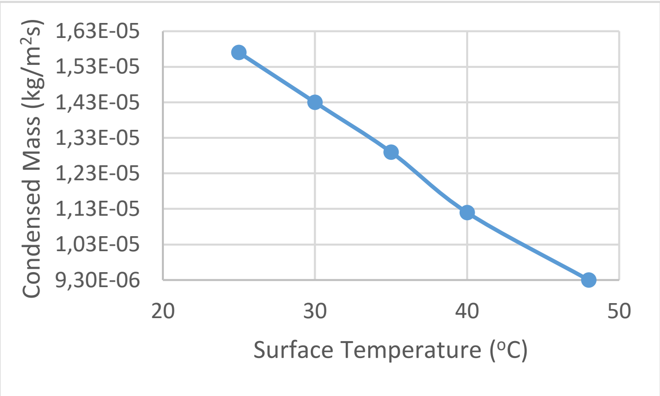


Figure 8. Condensation amount at constant RH (95%) based on variable lens surface temperature

3.2. Discussion

Considering the results obtained, it has been determined that the regions where condensation is likely to occur are regions with low air circulation and high humidity values. It has been determined from Figure 9 a and b that similar results were obtained by Okada et al. (2002) and Deponti et al. (2009).

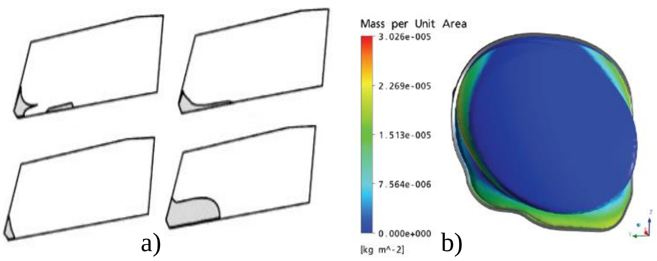


Figure 9.a) Okada et al. (2002) condensation region b) Deponti et al. (2009) analyze result

In Figure 8a, Okada et al. (2002) determined that there is condensation at the headlight corner points where the air movement and temperature are low. Yet in Figure 8b, Deponti et al. (2009) determined that the condensation formed on a sample fog lamp is in regions with low temperature and very slow air movement.

Yet in the study of Brunberg and Aspelin (2011) it was determined that condensation occurs in regions where the air movement is less and the temperature is lower than the general, as can be seen in Figure 9 a and b. In this study as well, condensation was detected in regions with low temperature values and regions with high humidity.

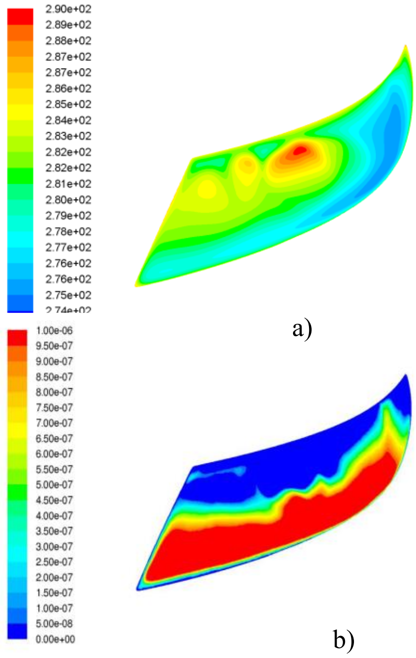


Figure 9. a) Temperature distribution on the outer lens (K) b) Water film thickness [m] on the lens

In particular, Okada et al. (2002) suggested in his study that the positions of the ventilation holes should be designed to ensure that the air coming out of the bulbs reaches the areas where there is a risk of condensation. In our study, it was observed that the condensation value, which started at the 88th second, was detected less at the 300th second with the help of ventilation holes, which supports the literature. In the study, graphs of the amount of condensation that may occur depending on the variable RH value and different surface temperature are given. While this study validates the literature, it has revealed to find the answer to the question of whether condensation will occur by calculation and perhaps to pass on design development without the need for condensation analysis.

4. Conclusions and Recommendations

As a result of this important data obtained, it is necessary to increase the temperature of the surface where condensation is predicted. Besides geometric design requirement has been put forward that will ease the air circulation in the region and help the hot air reach the surface. The condensation analysis in our study was analysed on a 24-core computer in 19 days. With the calculation method, the possible condensation location and amount can be determined within 1-2 days. The advantages that numerical analyzes bring to our science world and industry are indisputable. In our study, we show that certain predictions can be made in a much shorter time with the calculation method. In addition, we have shown that computation and numerical analysis are compatible with each other.

In our study, it has been demonstrated by both calculation and numerical analysis that the risk of condensation is high in regions with low temperature and high humidity. The importance of surface temperature, which has a risk of condensation, is also demonstrated by Figure 8 data.

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