論文 Prediction Technology of Transient Defogging Pattern by CFD*

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Although many CFD application methods have been reported for estimating windshield defogging pattern, few examples of simulation show an accurate result of the transient clearing pattern. To predict the transient clearing pattern accurately, using a correct model of window glass clouding-clearing is important. As the result of our observation on fogged glass surfaces, fogging was discovered to be an aggregation of water droplets, so that a new dropwise condensation-evaporation model was developed and applied. Transient defogging patterns were simulated with the CFD code including this model, and accuracy was verified on a simplified compartment model and actual vehicles.

Key words : Computational fluid dynamics, Numerical analysis, Defroster, Windshield Simulation, Defogging

1. INTRODUCTION

The defogging is one of the most important functions required of an automotive air conditioning system, as it ensures clear vision to the driver. Since defogging depends not only on the air conditioning unit and ducting, but also on the fundamental design of the automobile, such as shape of register opening, front windshield, instrument panel design etc., it is strongly recommended that CAE be used at an early stage of development to enable faster development and improved quality.

In the last decade, a number of computational investigations were performed in this field.[1) 2)] However, most of the researches estimated defogging performance on the basis of windshield airflow velocity distribution. In recent years some report has been appeared that focused on predict transitional defrosting or defogging pattern.[3) 4)] Hassan, M.B[4)] attempted to predict how the windshield is cleared as time progresses, based on the assumption that fogging is a film of water covering the windshield. However, accuracy is not enough, especially in early time stage of defogging.

The authors have noticed that fogging is an aggregation of minute water-droplets by observing the phenomenon of fogging on an automobile windshield. The difference in shape between film and droplet inferences evaporating speed. Based on window-fogging model using water-droplets, an analyzing method of the defogging process have been derived and validated with experimental data. This paper describes the detail of the method and results.

2. FOGGING PHENOMENON

Next, the fogging phenomenon was observed through a microscope camera, in order to build a model for describing water evaporation and condensation processes. **Figure 1** shows a photo of a fogged windshield surface. From the photo, it is evident that water on the surface is distributed in the form of water-droplets and does not form a film. On the basis of these observations, this paper therefore employs a water-droplet model.

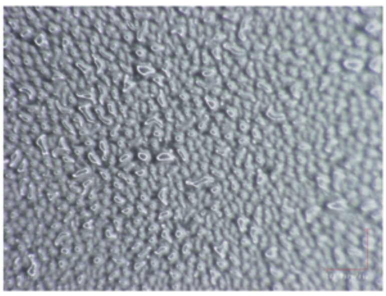

Fig. 1 Fogged windshield surface

Now, we would like to speculate on the differences between the water-droplet and water-film models. **Figure 2** compares both models. First, while the water surface area is constant regardless of water volume in the water-film model, it is to the 2/3 power of the

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volume in the water-droplet model. Second, while the air and glass surface contact area is also constant in the water-film model, it is different in the water-droplet model. Since direct heat transfer from the air to glass must be considered, less heat is transferred to the glass in the water-film model than in the water-droplet model. Third, differences in shape result in differences in heat transfer coefficient.

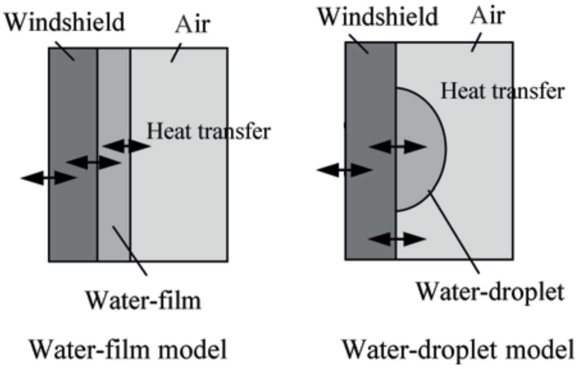


Fig. 2 Comparison of defogging models

Given these facts, it is reasonable to assume that the water-droplet model represents the actual phenomenon better than the water-film model. Since these differences between the models affect the speed with which water-droplets shrink, the water-droplet model is considered especially effective in predicting the windshield defogging time requirement.

3. METHODOLOGY

When the temperature of glass droplets below the dew point, moisture in the air condenses and forms water-droplets on the glass surface. Here, the shape of each water-droplet is assumed to have a hemisphere of radius r. This assumption is equivalent to assuming a 90-degree of contact angle between the glass surface and water surface.

The quantity of heat applied to a water-droplet during a unit time is expressed with the following formula, which takes into consideration heat transfer from the air, thermal conduction from the glass:

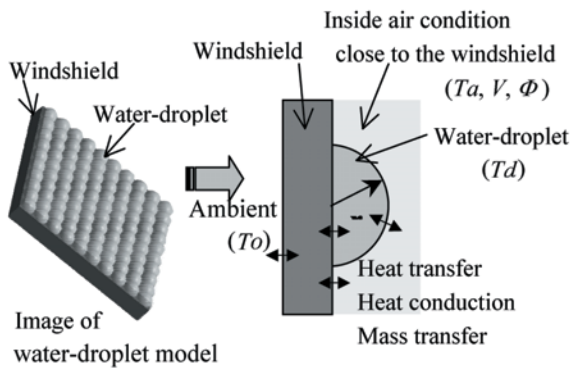
$$Qd = 2\pi r^2 h(Ta - Td) + \pi r^2 \frac{\lambda_g}{l/2}(Tg - Td) \quad (1)$$

where Td is the temperature of the water-droplet, Ta is the indoor air temperature close to the glass surface, Tg is the temperature of the glass, r is radius of water-droplet, h is heat transfer coefficient, λ is thermal conductivity and l is thickness of a glass mesh respectively. This process is depicted in **Fig. 3**.

The mass transfer of water vapor from the surface of water-droplets to indoor air m and the latent heat of the evaporation Ql is given as the following formula.

$$m = 2\pi r^2 h_D (Pd - \Phi Pa)\frac{M}{R_0 T} \quad (2)$$

where, h_D is mass transfer coefficient, Pd is saturated vapor pressure at the surface of a water-droplet, Pa is saturated vapor pressure at air temperature Ta, Φ is the relative humidity, M is molecular number of water and R_0 is general gas constant.



Assumption of water-droplet model

Fig. 3 Water-droplet mode

When evaporation from the surface of a water-droplet is assumed as analogous to heat transfer, equation (2) is translated as follows:

$$Ql = 2\pi r^2 \kappa h(Pd - \Phi Pa) \quad (3)$$

where h is heat transfer coefficient and the ratio between heat transfer coefficient and rate of evaporation is expressed by the coefficient κ.

When the formula (3) is a positive value, evaporation takes place and it forces the diameter of water-droplets to shrink. The speed of shrinkage is expressed with the formula below.

$$\frac{dr}{dt} = -\frac{\kappa h(Pd - \Phi Pa)}{\rho L} \tag{4}$$

where ρ is the density of water and *L* is latent heat of water. Heat transfer on the surface of a water-droplet is given by the Nusselt Number *Nu*; the formula is established for sphere.

$$Nu = 2 + 0.60 \mathrm{Pr}^{1/3} \mathrm{Re}^{1/2} \tag{5}$$

where *Pr* is Prantl number and *Re* is the Reynolds number.

In addition to evaporation, condensation may take place on the surface of a water-droplet at the top portion of the windshield before the evaporation takes place. To compensate for this, the following formula was used to obtain diametric changes over time after the paper.[5)]

$$\frac{dr}{dt} = \frac{0.0083}{4} \frac{\lambda_d}{\rho L} \frac{(Tsat - Td)}{r} \tag{6}$$

where λ_d is conductive heat transfer coefficient and *Tsat* is the saturated temperature of inside air.

STAR-CD was used to simulate airflow velocity, air temperature and humidity in vicinity to a windshield. The upwind difference scheme was used for convection terms, along with the standard k-ε model. The windshield glass is modeled with some layer meshes to simulate heat conduction through the glass. Water-droplet layer is placed between the windshield glass and inside air in order to obtain the radius of water-droplets by using original subroutine based on these formulas. All of the variables in the right hand part of equations (1) and (4) to (6) are given from airflow velocity, air temperature and humidity in the solution of STAR-CD.

4. VALIDATION

The basic model:

Initially, the reliability of the present model was examined by using a simplified basic model. **Figure 4** shows schematic of the model used in the validation. In the experiment, the device was placed in a climate control room in which ambient temperature and humidity were kept constant. A humidifier was used to fog the window from inside before hot air was introduced from outside.

The mesh system is shown in **Fig. 5**. The glass surface and nozzle is used with fine hexagonal meshes; other spaces are filled with coarse meshes. The total number of elements is 1,000,000.

Defogging patterns are compared between simulation and experiment in **Fig. 6**. Although the shape of the clear view in the simulation is a little different from that in the experiment, the change speed of a fine domain is very well in agreement.

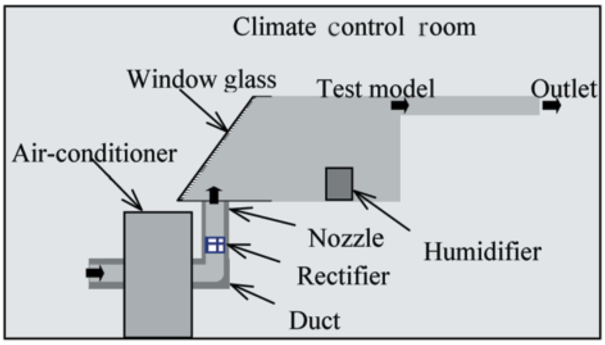
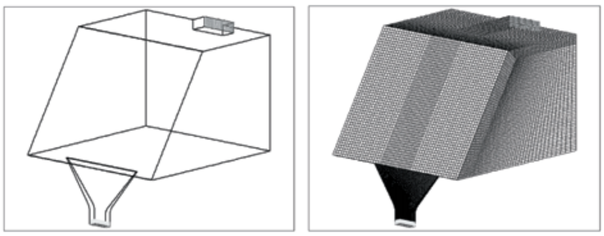
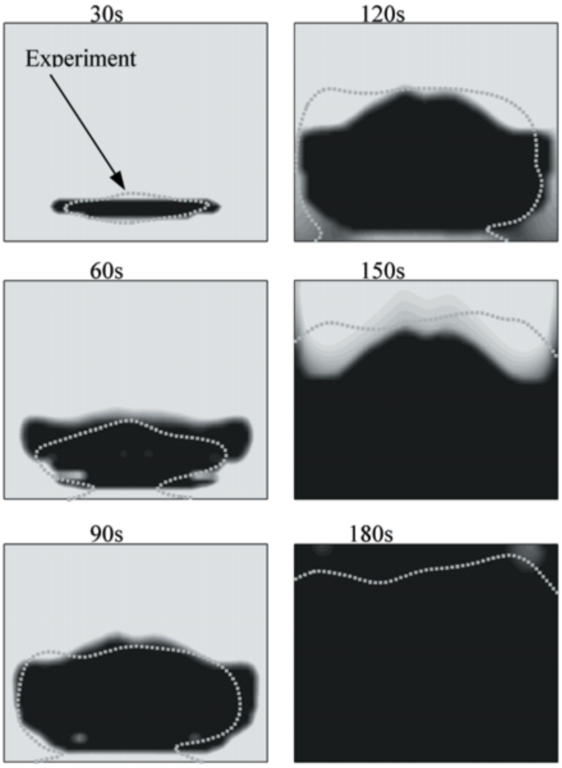


Fig. 4 Sketch of basic model



Calculation model:
Meshes:1,000,000
Transient calculation boundary conditions:
1.Ambient
Temperature:5(°C)
Humidity:50(%)
2.Inside of a basic model
Initial temperature:15 (°C)
Initial humidity:99%
3.Inlet air condition
Air volume:230(m^3/h)
Temperature: tested results
Humidity: dependent on temp.

Fig. 5 Calculation model of basic model



Comparison of defogging-pattern of simulation and experiment at every 30 seconds.

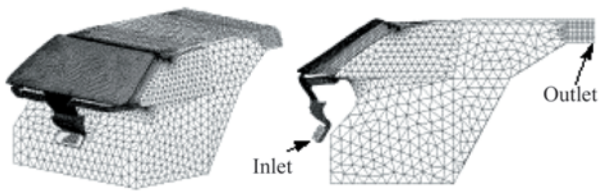
Fig. 6 Calculation results of defogging pattern

The automobile:

Next, the reliability of the new method was verified by comparing simulation results with an experiment using the automobile.

Figure 7 shows the numerical model of the automobile used in the experiment. The model includes the HVAC, the ducts, through to the front end of the compartment. It is an extensive model that even details the register grills. As with the basic model, the front windshield is covered with prism meshes. The total number of elements is 1,200,000.

Figure 8 shows the defogging pattern at every 30 seconds from 30 to 210. The defogging speed obtained with the simulation is about equal the same as that observed in the experiment. Although the shape of the clear view in the simulation is a little different from that in the experiment, it owes to the difference of the airflow velocity distribution.



Calculation model:
Meshes: 1200,000
Transient calculation boundary conditions:
1.Ambient
Temperature: -3(°C)
Humidity: 10(%)
2. Inside of an automobile model
Initial temperature: 10 (°C)
Initial humidity: 90%
3.Inlet air condition
Air volume: 304(m^3/h)
Temperature: tested results
Humidity: dependent on temp.

Fig. 7 Mesh model of automobile

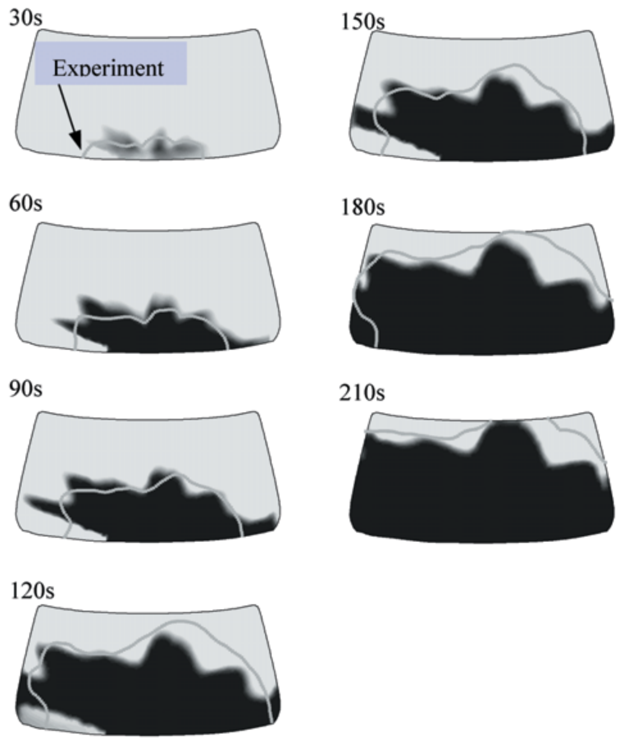


Fig. 8 Calculation results–defogging pattern

5. CONCLUSIONS

A new method was developed to predict defogging performance on an automobile, usingCFD. As the results of validation using experiment results, the following conclusions are obtained.

The new model, based on dropwise evaporation and condensation, is suitable to predict defogging. And it is possible to predict defogging by calculating changes in water-droplet diameter over time using temperature, airflow velocity and humidity distributions obtained via CFD analysis.

The present method well predicts transient defogging pattern improvements to CAE tools in cooperation with design and experiment groups.

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