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# Measurement of Temperature and Velocity Fields in a Heater Unit by Liquid Crystal Thermometry and Particle Image Velocimetry

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***Abstract*:** Temperature and velocity fields in a heating unit for automobiles are measured through a model experiment in water tunnel using flow visualizations and image analysis to investigate the mixing mechanism of the flow that has passed through the heater and not passed through it inside the unit. The temperature fields are measured by the liquid crystal visualization technique combined with the field calibration using full color spline fitting technique, and the velocity fields are evaluated by a particle imaging technique with a cross-correlation algorithm. These results indicate an enhanced flow mixing at larger mix-door angles, which results in a shorter mixing distance of temperature and velocity downstream of the mix door. The enhanced flow mixing is caused by the high velocity fluctuations created by the flow separation over the mix door.

***Keywords*:** flow visualization, temperature measurement, flow measurement, liquid crystal, particle image velocimetry, heater unit.

## 1. Introduction

The heater unit has been used for the air-conditioning system in the automobile to supply warm air to the room inside the automobile. It consists of the heater core, the mix door and the mixing chamber. For designing the unit geometry, the air-mixing performance in the mixing chamber and the pressure loss inside the unit are important factors for consideration. Therefore, the temperature and velocity distributions inside the unit have to be measured for evaluating these basic performances of the unit. Although the whole velocity field in the heater unit is measured by particle image velocimetry by Fujisawa et al. (1995,1997,1999) and Yamamoto et al. (1996), the measurement of temperature distribution in the whole flow field has not been studied yet with enough spatial resolution.

Recently, the intrusive technique for measuring the temperature in a thermal flow has been studied by using the liquid crystals in a form of encapsulated particles. When it is illuminated by white light, the color of the liquid crystal particles changes from red at low temperature, passes through green and blue to violet at high temperature. These optical characteristics of the liquid crystals are reviewed by Kasagi et al. (1989). The visualization of temperature field by liquid crystal can be made quantitative by calibrating the hue of the liquid crystals versus the temperature, which is described by Dabiri and Gharib (1991) and Ozawa et al. (1992). Later, the full color calibration was considered by Kimura et al. (1993) with the neural networks. The color to temperature calibration techniques of the liquid crystals have been studied comparatively by Fujisawa and Adrian (1999), using hue,

hue/intensity and full color parameters (hue, saturation and intensity) as calibration variables. More recently, the high accuracy calibration technique considering the viewing angle effect is found to be very effective for measuring the temperature distributions by Fujisawa et al. (2000). This technique uses the full field calibration with full color spline fitting technique, which provides a very efficient transformation of color to temperature compared with that of the neural networks.

The purpose of the present paper is to investigate the mixing mechanisms of the thermal flow in the heater unit model by measuring the temperature and velocity in the whole flow field with the liquid crystal thermometry and particle image velocimetry, respectively.

## 2. Experimental Apparatus and Procedures

### *2.1 Experimental Setup*

Figure 1 shows an illumination of the experimental model of heater unit, which has a reduced scale of 15% of the prototype unit. It consists of a heater core, a mix door and a mixing chamber. By changing the mix-door angle to the main flow, the flow rate of the main flow over the mix door and that through the heater core can be controlled, which results in a change of temperature at the exit of the heater unit. The heater core is consisted of 10 heaters of 3mm in diameter, which are heated by electric power of 40W (4W   0.15W for each heater). The experimental unit is made of an acrylic resin for visualization purposes having a thickness of 10mm, so that the heat loss to the surrounding air is considered to be small. This experimental unit is located in the vertical test section of a water tunnel, which provides a uniform velocity and temperature at the inlet of the heater unit. In the present experiment, the inlet velocity is set to $U$=50mm/s and the inlet side length of the square cross-section is $B$=30mm, so that the Reynolds number is $Re$ (=$UB/\nu$)=1500, which is one order smaller than the operating condition of the prototype unit. The present experimental condition agrees with the previous experiments by Fujisawa et al. (1999). The influence of the Reynolds number on the qualitative nature of the thermal flows and the mixing mechanism of the thermal flows in the heater unit was found to be small by Fujisawa et al. (1997, 1999).

Illumination is provided by two stroboscopes located around the heater unit model, which produces light sheets having a thickness of 5mm at the mid plane of the unit. They are positioned not to be shaded by the heater core as described in Fig.1. The liquid crystal particles are used for visualizing the temperature fields, so that the color images are taken by a color CCD camera having $768 \times 494$ pixels in resolution and the images are digitized by color frame grabber having a resolution $512 \times 480$ pixels and 8bit for RGB, respectively. The velocity field is measured independently using spherical tracer particles of 300$\mu$m in diameter and the specific gravity of 1.02,

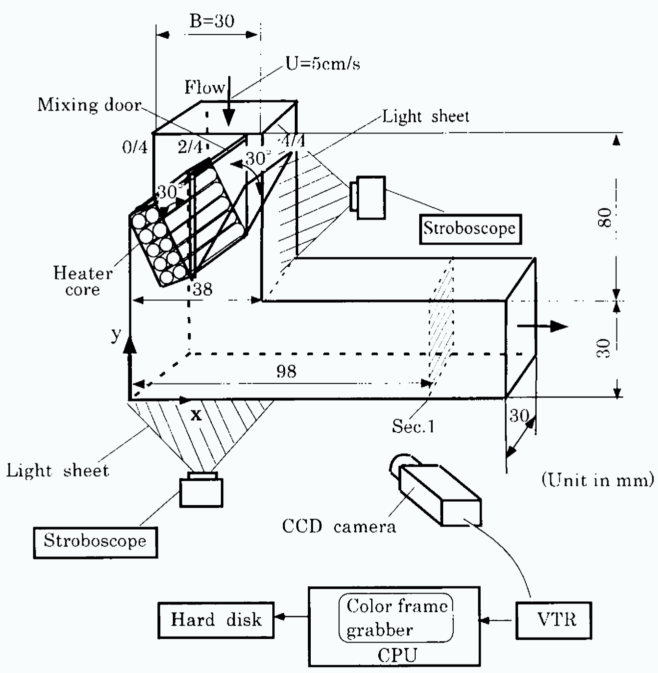


Fig. 1. Experimental model of heater unit.

which are made of nylon. In this experiment, the images are taken by a monochrome CCD camera having a resolution of 725 × 492 pixels with an illumination of light sheet from two stroboscopes.

### *2.2 Temperature Measurement*

The liquid crystals used in the present experiment are encapsulated chiral nematic particles of diameter 10$\mu$m (prepared by Japan Capsule Products Co.), which have specific gravity of 1.02. For the temperature visualization, these liquid crystals are added to water as working fluid to form a very dilute suspension with a volume concentration of 0.004%. The color of the liquid crystals changes with an increase in temperature from brown at 27.7℃ through green and blue to violet at 30℃, so that the color sensitive temperature range is about 2.3K. The liquid crystal does not show any color at the other temperature. The color-temperature calibration is carried out with uniform temperature images taken at the test section of the same experimental facility without operating the heater core. The uniform temperature is varied by the heating unit located upstream of the heater-unit model. The uniformity of the temperature is confirmed by the observation of the color of the liquid crystals at highly sensitive temperature ranges between 28.0℃ and 28.5℃ and is found to be much smaller than the accuracy of the Cu-Co thermocouple used in the present experiment. The uniform temperature images are captured by the color CCD camera, while the corresponding temperature is measured by a thermocouple located at the upstream of the heater unit. It is noted that the temperature difference between the center of the heater unit and the thermocouple was estimated to be less than 0.01K. Details of the calibration technique and the optical characteristics of the liquid crystals are described by Fujisawa et al. (1998)

The color to temperature transformation of the liquid crystals is carried out with full color calibration in HSI color space using spline fitting technique. This technique is extended to the field calibration by applying the calibration to each small segment of the image to consider the viewing angle effect of liquid crystals. It should be mentioned that this field calibration technique makes it possible to consider the effect of non-uniform illumination of the light sheet, which was found to be important in the present experiment especially nearby the heater core, where the light intensity varies due to the reflection of the light sheet (see Fig.2). (Uniform color images were observed when the light sheet was focused on the inlet channel only.) In order to consider the viewing angle effect of the liquid crystals and the non-uniformity of the illumination, the visualized image was divided into 82 × 75 segments and the spline fitting technique was applied to each segment. This technique allows the spatial calibration error due to the spline curve fitting as small as 0.06K. The details of this field calibration technique are described by Fujisawa et al. (2000). Hence, the uncertainty interval at 95 percent coverage in the present temperature measurement is estimated to be 0.14K, which includes the jittering of the image signals. Mean and fluctuating temperatures are obtained from 200 frames of instantaneous temperature images taken at frame interval of 30 frames/s.

### *2.3 Velocity Measurement*

The velocity distributions are evaluated from a set of monochrome images taken at frame interval of 30 frames/s. However, the time interval between the successive exposures of stroboscopes is set to 5ms by controlling the trigger pulses to the stroboscopes with computer (Huang and Fiedler, 1994). The cross-correlation algorithm is used for estimating the velocity distributions from the successive images of 512 × 480 pixels. The window size is set to 28 × 28 pixels and the search area is 42 × 42 pixels, of which combination is found to minimize the error vectors with enough spatial resolution. The sub-pixel interpolation process is incorporated to the analysis to improve the accuracy of velocity measurement. The uncertainty interval at 95 percent coverage is estimated to 3.5mm/s, which is 7% of the main flow velocity.

## 3. Results and Discussions

### *3.1 Temperature Visualization by Liquid Crystal Particles*

Figure 2 shows the color images visualized by the liquid crystal particles suspended in the water of the test heater unit operating at three different mix-door angles $\alpha$=1/4 (15 ), 2/4 (30 ) and 3/4(45 ), which are defined as the angle relative to the full operating angle (60 ). The brown color at the upstream of the heater unit indicates the lowest temperature in the color sensitive temperature range of the present liquid crystals. The color changes to blue at the downstream of the heater core and it varies to green in the downstream of the mixing chamber. Therefore, the temperature of the fluid increases at the heater core and it decreases slightly in the downstream

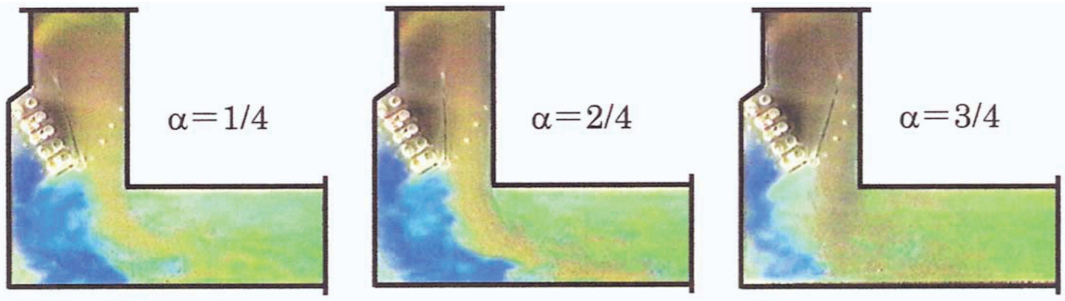


Fig. 2. Temperature visualization of thermal flow in heater unit by liquid crystals ($U$=50mm/s).

mixing with the low temperature fluid flowing over the mix door. Although the qualitative nature of temperature change in the heater unit is independent of the mix-door angles, the color distributions in the mixing chamber and the uniformity of the color in the downstream channel are influenced by the change in the mix-door angles. Therefore, the whole temperature field in the heater unit is studied quantitatively by transforming the color of the visualized images to temperature.

### *3.2 Time-averaged Properties of Temperature and Velocity*

Figures 3 and 4 show the time-averaged distributions of temperature $\theta$ (℃) and velocity $u$(mm/s) in the heater unit at various mix-door angles, which are measured by the liquid crystal themometry and the particle image

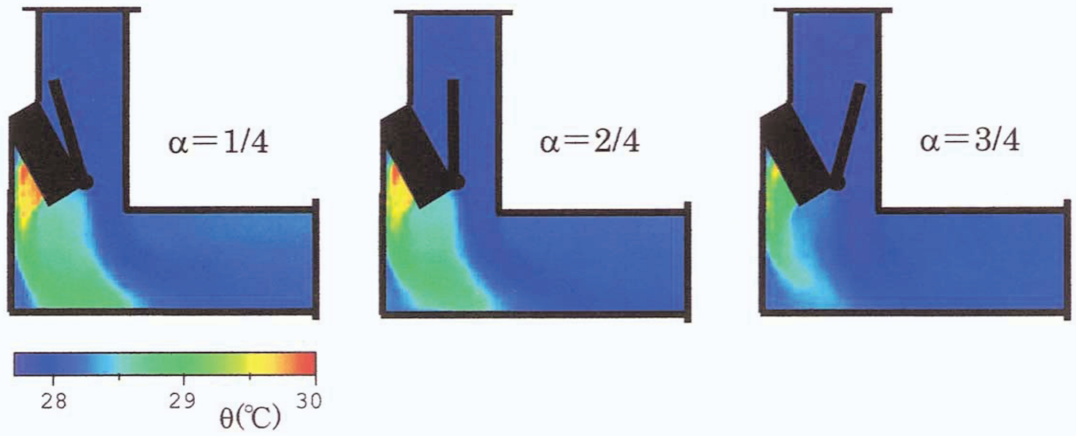


Fig. 3. Mean temperature distributions in heater unit.

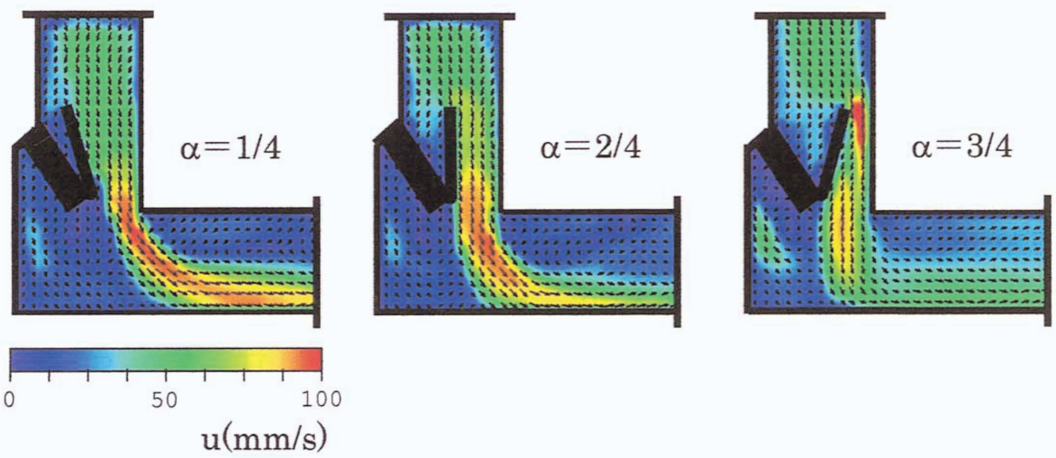


Fig. 4. Mean velocity distributions in heater unit.

velocimetry, respectively. The magnitude of the temperature and the velocity are indicated by the color bars given at the bottom of the figures. The highest temperature appears at the downstream of the heater core and this area extends to the mixing chamber, where the magnitude of the flow velocity is small and the flow is recirculating in counter-clockwise direction (bottom left corner in Fig.4). On the other hand, the inlet flow having a low temperature comes into the mixing chamber over the mix door and merges with the high temperature flow through the heater core. This flow over the mix door impinges on the bottom wall of the heater unit and turns the flow direction to the exit of the heater unit. Although these qualitative natures of the flow are independent of the mix-door angles, the flow mixing characteristics in the heater unit are influenced by the change in mix-door angles. When the mix-door angle is small ($\alpha$=1/4), the inlet flow over the mix door is largely accelerated at the corner of the heater unit, so that the velocity magnitude along this flow is very large. With an increase in mix-door angles, the accelerated flow area invades into the recirculating flow region downstream of the heater core ($\alpha$=2/4) and this area is further extended by the appearance of flow separation over the mix door ($\alpha$=3/4). Therefore, the highest velocity along the bottom wall is fairly reduced with an increase in mix-door angles. It is also observable that the impinging position of the main flow shifts to the heater core side with an increase in mix-door angles, which results in a reduction in the size of recirculating region downstream of the heater core. The velocity magnitude of the recirculating flow in this region increases with an increase in mix-door angles, which is mainly due to the increased flow rate through the heater core. These features of the velocity distribution in the recirculating region are reflected in the temperature distribution shown in Fig.3. The high temperature area downstream of the heater core is narrowed with an increase in mix-door angles, which corresponds to the invasion of the main flow to the recirculating region and an enhanced flow mixing in this area with an increase in mix-door angles. On the other hand, the main flow separates at the corner of the heater unit and the separated flow area is formed over top wall of the exit channel. The velocity distributions in this area indicate a recovery of the separated flow area with an increase in mix-door angles, which results in a uniform velocity profile at the exit channel as seen in the case of $\alpha$=3/4. The temperature in the separated flow area downstream of the unit corner is slightly higher than the main flow temperature as seen in the case of $\alpha$=1/4, which is expected to be due to the convective heat transfer of the heater flow by the three-dimensional vortical motion induced by the flow separation at the top wall. However, the temperature difference between the main and separated flow area is reduced with a recovery of separation region at larger mix-door angles. Therefore, the uniformity of the temperature profile at the exit channel is improved at larger mix-door angles $\alpha$=3/4.

Figures 5(a), (b) show the cross-sectional distributions of temperature (a) and velocity (b) at the exit channel ($x$=98mm) of the heater unit, respectively. The temperature difference $\Delta\theta$ (=$\theta$–$\Theta_u$) is normalized by $\Delta\Theta$ (=$\Theta_u$–$\Theta_d$) and the velocity $u$ is normalized by the mean velocity $U$ averaged over the inlet cross-sectional area of the unit, where $\theta$ is a local temperature, $\Theta_u$ and $\Theta_d$ are the average temperature measured upstream and downstream of the unit, respectively. It is clearly seen that the cross-sectional distributions of temperature and velocity become more uniform with an increase in the mix-door angles $\alpha$ and highest uniformity is obtained at $\alpha$=3/4. Detailed observation shows that the velocity is larger near the bottom wall and the temperature is higher at the top wall at smaller mix-door angles, which indicates the impinging effect of the main flow on the bottom wall and the convective heat transfer at the separation region over the top wall, respectively. However, further study is

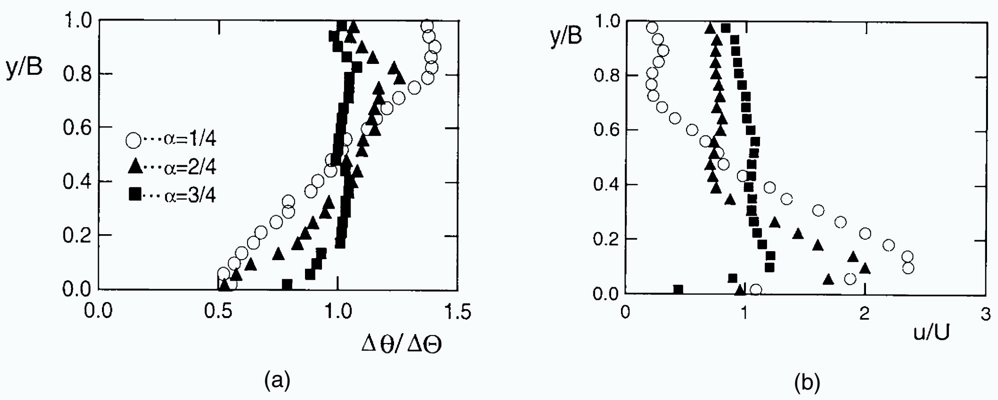


Fig. 5. Cross-sectional profiles of mean temperature and velocity at the exit channel: (a) Mean temperature; (b) Mean velocity.

necessary to clarify the mechanism of convective heat transfer by measuring the three-dimensional flow field in the cross section of the heater unit.

### *3.3 Fluctuating Properties of Temperature and Velocity*

Figures 6 and 7 show the distributions of temperature fluctuations and velocity fluctuations in the heater unit, respectively. The temperature fluctuations are larger where the temperature gradient is higher as observed in Fig.3. While, the velocity fluctuations are larger where the velocity gradient is higher as seen in Fig.4. These results indicate that the temperature and velocity fluctuations are mostly governed by the gradient type diffusion law. At smaller mix-door angles $\alpha$=1/4 and 2/4, high velocity fluctuations are observed along the shear layer of the main flow. However, the area of large velocity fluctuations are widely spread over the mixing chamber at $\alpha$=3/4, which is due to the creation of high velocity fluctuations by the flow separation over the mix door. On the other hand, temperature fluctuations are widely spread over the mixing chamber at smaller mix-door angles $\alpha$=1/4 and 2/4, but restricted to just downstream of the heater core at larger mix-door angle $\alpha$=3/4. These results indicate that the thermal mixing is enhanced at the downstream of the mix door and results in a spreading of low temperature fluctuations at larger mix-door angles. In other words, the spreading of high velocity fluctuations by the flow separation over the mix door produces an enhanced flow mixing at $\alpha$=3/4, which results in the uniformity of temperature distributions at the exit channel of heater unit.

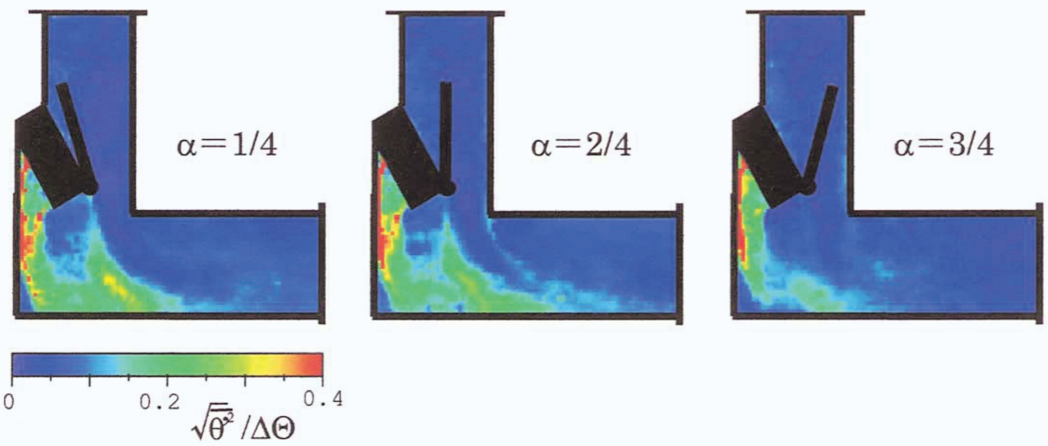


Fig. 6. Distributions of temperature fluctuations in heater unit.

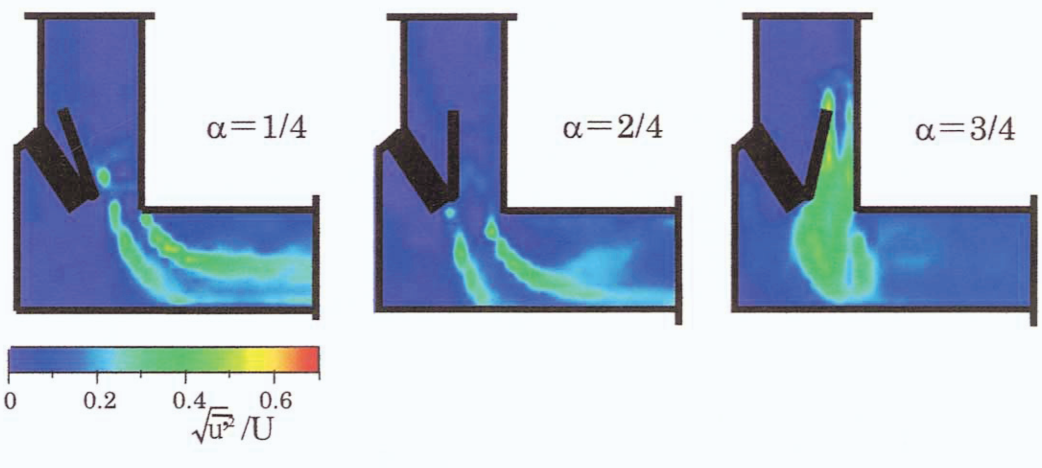


Fig. 7. Distributions of velocity fluctuations in heater unit.

## 4. Conclusions

The temperature and velocity distributions of thermal flow inside a heater unit have been measured by liquid crystal thermometry and particle image velocimetry, respectively. The results can be summarized as follows.

(1) The whole temperature field inside the heater unit is measured by liquid crystal thermometry considering the viewing angle effect of liquid crystal and the non-uniformity of the illumination.

(2) The measurement of mean temperature and velocity indicates the mixing mechanism in the heater unit at various mix-door angles. Uniformity of temperature distributions is extended to the downstream of the heater core with an increase in mix-door angles, which is due to the appearance of the separating flow area over the mix door.

(3) The measurement of temperature and velocity fluctuations indicates the presence of high velocity fluctuation and the corresponding low temperature fluctuations in the mixing chamber at larger mix-door angles. These results support the improved mixing of the thermal flow by the contribution of flow separation over the mix door.

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