Visualization and Color Image Processing of Flow Mixing in an Air Conditioning Unit for Automobiles*

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Flow mixing in an air conditioning unit for automobiles is studied experimentally in a water tunnel to investigate the mixing mechanisms of flow inside the unit at various mix-door angles. Flow visualization is carried out using tracer particles and the fluorescent dyes illuminated by Ar laser sheet, which allows the simultaneous measurement of velocity and diffusion distributions of the flow mixing in the unit by analyzing the captured color images. The measurement of velocity and diffusion distributions indicates enhanced flow mixing at certain mix-door angles, which is caused by the intense mixing of the main flow and the recirculating heater flow downstream of the mix-door. The temperature distribution measured in a prototype unit supports the mixing characteristics observed in the model unit, suggesting the usefulness of the present image analysis.

Key Words: Flow Measurements, Digital Image Processing, Flow Visualization, Turbulent Mixing, Laser Induced Fluorescence, Air Conditioning Unit, Automobile

1. Introduction

The air conditioning unit for automobiles supplies an air flow of an expected temperature into the available vehicle working space. When the air temperature in the working space is lower than the expected temperature, the air flow is heated by the heater core and the temperature is controlled by changing the opening angle of mix-door inside the unit. It is well known that the uniformity of the air temperature at the exit of the unit is an important nature for the unit design. The performance of the unit is influenced by the flow mixing characteristics in the mixing chamber, where the main and heater flows come together to be mixed downstream of the mix-door. In the past, flow visualization studies[(1),(2)] have been carried out for an air conditioning unit geometry and some features of the flow field are examined qualitatively. Although Kawahashi et al.[(1)] have reported the measurement of velocity distribution in the unit using the speckle method, the measured data are very few in the mixing chamber where the flow is recirculating and highly turbulent.

The purpose of this paper is to investigate the flow mixing mechanisms in a scaled model of the air conditioning unit at various mix-door angles. Velocity distributions were measured by the particle imaging technique, and the diffusion distributions of main and heater flows were visualized simultaneously by laser induced fluorescence combined with color image processing. The usefulness of this technique is discussed in comparison with measured temperature distributions in a prototype unit.

2. Experimental Apparatus and Procedures

Figure 1 shows an illustration of the experimental unit, which is a reduced scale model with a size of 15% of the prototype unit. It consists of a heater core, a mix-door and a mixing chamber. The mix-door can rotate at its axis to control the relative flow rate of main and heater flows. In a vehicle application, the

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heater core temperature reaches to 80°C, but the experimental condition required an isothermal flow condition because of the difficulty of simulating the heater core structure. In the present study, the heater core is replaced by a slit structure. The experimental unit is made of an acrylic resin for visualization purposes.

Figure 2 shows an experimental apparatus for visualizing the flow inside the unit and an image processing system. The experimental unit is located in the vertical test section of a water tunnel and the experiment is carried out with water as a fluid medium. The flow field is visualized by two fluorescent dyes, which allows the measurement of diffusion distributions of the main and heater flows. Dyes are injected from nozzle structures, consisting of 4 outlet nozzles on the main flow side and 5 nozzles on the heater flow side, with the diameter of the nozzles set to 0.7 mm. The main flow is visualized by fluorescein sodium whereas the heater flow is visualized by rhodamine B. For the purpose of velocity measurement, nylon tracer particles of 0.3 - 0.4 mm in diameter are also added to the flow field. By illuminating the flow with a sheet of Ar laser of 1.0 W, the fluorescein sodium appears green, the rhodamine B gives appears orange, and the tracer particle reflect blue light. The observation is made by a color CCD camera. The RGB images from the camera are digitized by a color frame grabber with a resolution of 512×512 pixels with 256 gray levels. The spatial resolution of a pixel is about 0.15 mm in the present experiment. The frame grabber is able to hold sequential color images up to 64 frames with a frame rate of 30 frame/s. The experiment is carried out at a main flow velocity U=0.05 m/s and the height of unit entrance B=30 mm, so that the Reynolds number $Re(=UB/\nu)$ $=1.5\times10^3$, where ν is a kinematic viscosity of fluid. Although the Reynolds number is about 1/10 of that of the prototype unit, the change of the flow field with the Reynolds number is considered to be small[(2)].

Figure 3 shows a flow chart of color image analysis. It is found that the orange image from the rhodamine B is obtained from the original RGB color images by R-B operation and the green image is obtained from the fluorescein sodium by G-B. Processed binary images are subsequently combined to show the diffusion distribution of rhodamine B, fluorescein sodium, and both of them, which corresponds to a heater flow, a main flow and a flow mixing region of both flows, respectively. Based on these results, the variations of mixing region with a change of mix-door angle are evaluated quantitatively. On the other hand, the velocity distributions are measured from a B image using a correlation algorithm. Erroneous velocity data are erased based on the comparative study of velocity magnitude and direction at the nearest 8 positions for the data which have a correlation level

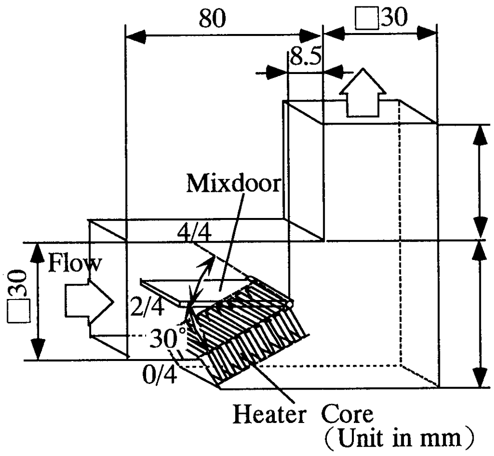

Fig. 1 Model unit for flow visualization

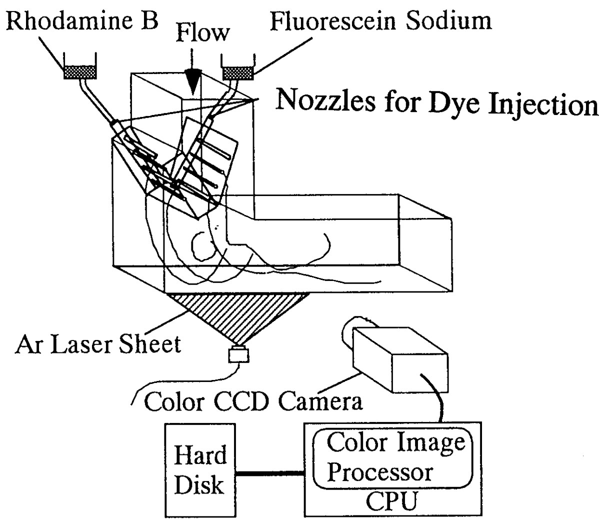

Fig. 2 Experimental apparatus for flow visualization and image processing system

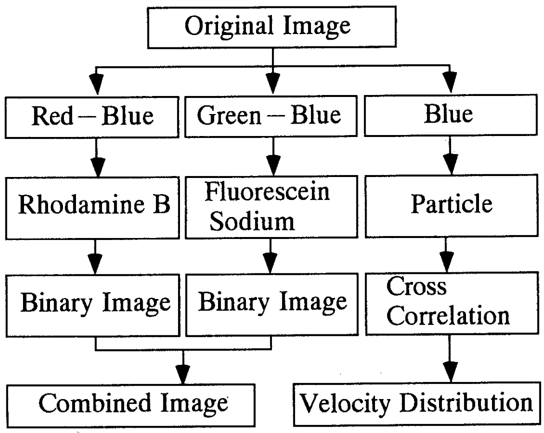

Fig. 3 Flow chart of image analysis

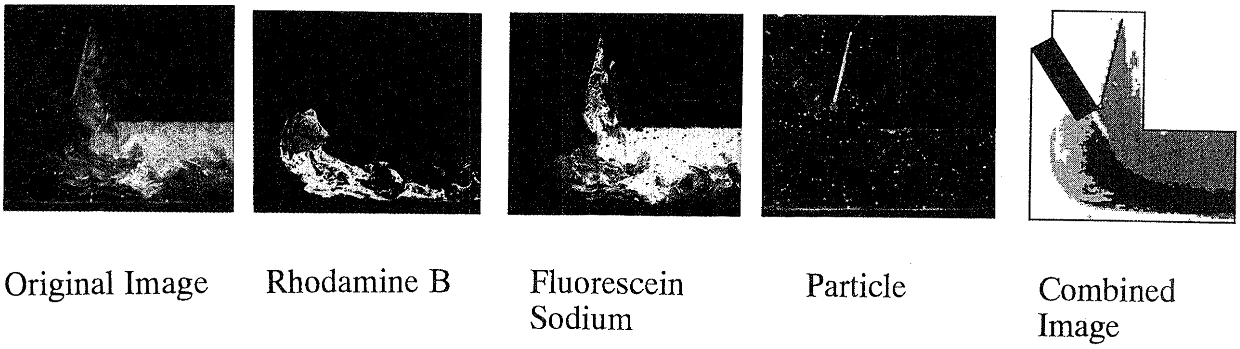

Fig. 4 Typical examples of original image and analyzed images

larger than 0.5. It is found that the number of erroneous vector increases rapidly as the correlation matrix size becomes smaller than 15×15 pixels, while the spatial resolution deteriorates with an increase in matrix size. Therefore, the matrix size is set to 15×15 pixels for present analysis. Figure 4 gives an example of an original image, analyzed images from rhodamine B and fluorescein sodium, a tracer particle image and also a combined diffusion distribution after averaging. In the present study, the results are shown either as time-averaged distribution or an instantaneous distribution of velocity and diffusion. The time-averaged results are obtained by averaging over 30 frames of sequential images with every 1/30 s interval, while the instantaneous results are from two images with 1/30 s interval. For estimating the velocity, each image is divided into two field images of 1/60 s interval, and then the correlation analysis are applied to the sequential two images of 256×256 pixels.

3. Results and Discussions

3.1 Mean velocity distributions

Figure 5 shows the mean velocity distributions inside the unit at various mix-door angles of $\theta=1/4$, 2/4, and 3/4, which are measured by the particle imaging technique based on the correlation algorithm. At the small mix-door angle $\theta=1/4$, the main flow is accelerated by contraction effect of the mix-door and it runs along the wall of the mixing chamber to the exit. Hence the accelerated flow is detected in the measured velocity distributions at the exit plane of the unit. As the flow separates at the sharp corner of the unit, a separating region is created downstream of the corner. On the other hand, a recirculating flow is formed downstream of the heater core as the heater flow runs along the unit wall to the exit. It is clear that the velocity of the heater flow is much smaller than the main flow because of the reduced flow rate of heater flow at this mix-door angle. Although similar flow features are observed in the flow with a mix-door

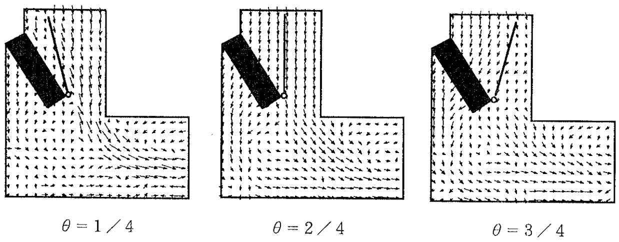

Fig. 5 Velocity distributions inside model unit at various mix-door angles

angle $\theta=2/4$, some quantitative changes are seen in the flow field, such as a decrease in the contraction effect of the main flow, and an increase in the flow rate through the heater core. This change in the flow field may result in a reduction of the recirculating flow region downstream of the heater core, as can be seen in the velocity distributions. When the mix-door angle increases to $\theta=3/4$, the main flow velocity is decelerated by the diverging effect of the mix-door geometry and the flow separation appears downstream of the mix-door. The recirculating flow region downstream of the heater core is reduced in size compared with that at small mix-door angles, which is due to an increased flow rate at the heater flow side. At this mix-door angle, the main flow advances to the recirculating region downstream of the heater core, which indicates the interaction of the decelerated main flow and the recirculating flow. These changes in flow field with an increase in mix-door angle are reflected in a more uniform velocity distributions at the unit exit, and the separation region near the unit exit is reduced.

3.2 Diffusion distribution in the flow mixing region

Figure 6 shows diffusion distributions in the flow mixing region of the unit at various mix-door angles obtained from the color image analysis with a time averaging procedure. It is observed with the mix-door angle of $\theta=1/4$ that the distribution from fluorescein sodium spreads around the unit corner where

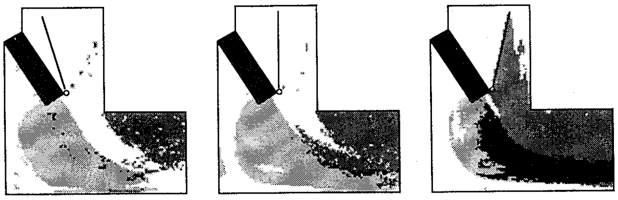

Fig. 6 Visualization of flow mixing by image analysis (▒ Rhodamine B, ▨ Fluorescein sodium, ■ Rhodamine B + Fluorescein sodium)

the flow is separated, whereas that of the rhodamine B appears downstream of the heater core where the flow is recirculating. The expected highly turbulent nature of areas is confirmed by the velocity distribution of Fig. 5. No diffusion distributions are observed near the entrance regions of the main and heater flows. Common areas for the two fluorescent dyes are seldom observed in the flow field, suggesting that the main flow and the heater flow behave almost individually. A similar result of flow mixing is observed at the mix-door angle $\theta=2/4$. However, the diffusion distribution of the main flow has increased, especially near the separation region downstream of the corner and near the boundary of main and recirculating flow regions. This is attributed to reducing contraction effect of mix-door. The diffusion distributions of heater flow near the recirculating flow region move to the main flow side because of an increase in flow rate on heater flow side. An increase in the flow mixing region is observed at the boundary of main flow and recirculating flow region. The diffusion distribution changes noticeably as the mix-door angle increases to $\theta=3/4$. The diffusion distribution of the main flow spreads to the mix-door and into the recirculating flow region downstream of the heater core. This is in consequence of turbulence in the decelerating flow with separation on the mix-door, as shown in the velocity distributions. The diffusion distribution shrinks in size and moves to the main flow side due to an increase in flow rate on the heater flow side. Conseqently, the flow mixing region of main and heater flows increases in size especially along the boundary of main and heater flows and covers a recirculating region downstream of the mix-door. This increase in the mixing region is attributed to an intrusion of the main flow into the recirculating flow, because the change of the diffusion distribution of the heater flow is similar to that at other mix-door angles. The changes in the diffusion distributions with mix-door angle are largely contributed by the presence of the separating region downstream of the mix-door, that promotes the turbulent mixing between the main flow and the heater flow.

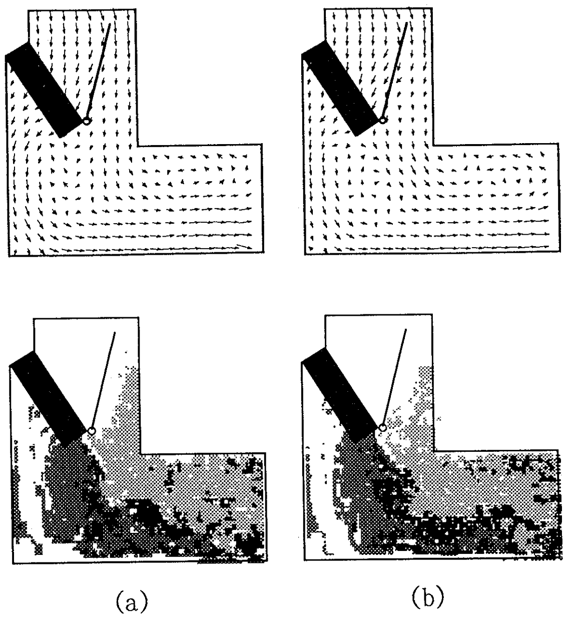

Fig. 7 Variance of combined images and velocity distributions

3.3 Instantaneous flow mixing observations

Figure 7 shows instantaneous velocity and diffusion characteristics for the flow mixing process at the mix-door angle $\theta=3/4$, where the intense flow mixing occurs between the main and heater flow. It is found from the diffusion distributions that the boundary between the main and heater flows moves vigorously, when observing the diffusion distributions at 1/30 sec interval. Typical results are shown as Fig. 7(a) and (b), where the boundary moves toward the heater flow and then back towards the main flow, respectively. Here, the time interval between these two images is 0.2 sec. It is seen from the velocity distributions that the main flow develops to the heater flow side (Figure 7(a)), while the main flow moves to the exit of the unit (Figure 7(b)), which agrees closely with the variation of the diffusion distributions. Therefore, the enhanced flow mixing at this mix-door angle is due to an increase in the momentum transfer between the main and heater flow, caused by an increase in turbulence in a decelerating main flow.

3.4 Temperature distributions in prototype unit

Figure 8 shows the distributions of temperature efficiency $T_\eta[=(T-T_i)/(T_h-T_i)]$ measured in a prototype unit at various mix-door angles, (where T is a measured temperature, T_i the air temperature at the unit entrance (=15°C), and T_h the water temperature at the heater core (=80°C)). The measurements are made by traversing a thermocouple probe in the center plane of the unit. It is noted that the height of the unit entrance (B=200 mm) and the main flow

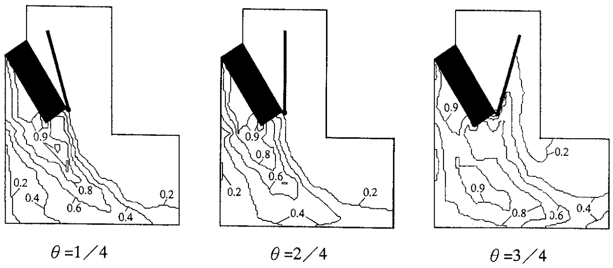

Fig. 8 Temperature distributions in prototype unit

velocity ($U=1.0$ m/s), so that the Reynolds number $Re(=UB/\nu)=1.4\times10^4$.

The temperature distributions at small mix-door angles $\theta=1/4$ and 2/4 are similar. A high temperature region is formed just downstream of the heater core which diffuses along the unit wall toward the exit. These observations of the temperature distributions agree closely with the diffusion distributions of flow mixing measured in the scaled unit, as seen in Fig. 6. On the other hand, the temperature distribution at $\theta=3/4$ shows an indication of intense mixing between the main and heater flows. The temperature diffuses across a wide area which covers not only in the separating flow region downstream of mix-door, but also downstream of the unit corner. This result suggests an enhanced flow mixing at this mix-door angles and in close agreement with the observation of the diffusion distribution in the scaled model unit. The present visualizing technique of flow mixing is able to characterize the temperature distribution in the unit, which suggests applicability of this technique in unit design.

4. Conclusions

The flow mixing in an air conditioning unit for automobiles is studied in a water tunnel at various mix-door angles by visualizing the flow mixing process and measuring simultaneously the velocity distributions by particle imaging technique. The results can be summarized as follows.

(1) The diffusion characteristics of the main and heater flow are visualized by a laser induced fluorescence with two color dyes and processed by a color image processing with an operation between the RGB images to extract diffusion distributions at the mixing region.

(2) The observation of the flow mixing in the unit is made at various mix-door angles using the present visualization with color image analysis. The results indicate that an enhanced flow mixing appears at the mix-door angle $\theta=3/4$.

(3) The instantaneous measurement of flow mixing at this mix-door angle indicates that the decelerating main flow near the mix-door interacts vigorously with the recirculating region of the heater flow in the mixing chamber. This encourages flow mixing.

(4) The diffusion distributions of the main and heater flow at various mix-door angles measured in a scaled model unit are well reproduced in the temperature distribution measured in a prototype unit, suggesting the usefulness of this technique for studying the flow mixing for the unit design.

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