Measurement of transient supercritical fluid velocity using infrared pulse laser with high-speed camera

by

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ABSTRACT

The characteristics of the supercritical fluid had been investigated by many researchers in 1960's to develop the fossil power plants. However, for the development of nuclear power reactor including fission and fusion plants, the much more precise characteristics should be investigated. There were very few visualization study on the forced convection heat transfer of the supercritical fluid, because of the difficulty of the experiment. The density variation of the supercritical carbon dioxide under forced convection heat transfer were visualized, using shlieren and shadowgraph technique.

With analyzing the serial shleiren images, the movement of the image pattern were detected. With assuming that the density variation wave is the same with the fluid velocity, the movement denotes the fluid velocity. This means that the density variation pattern was taken as the tracer of the fluid flow.

In this study, the frame straddling technique was applied to the high-speed camera capturing, with infrared pulse laser. The camera speed was 250Hz, while the pulse laser illuminated double pulse with 125Hz. The double pulse was controlled to be the frame straddling condition. The pulse interval of the double pulse was set to be 0.48ms. By shortening the interval, the density pattern variation decreasing between the two images. Therefore, the higher accurate velocity distributions can be measured using the frame straddling technique. The velocity distributions are taken with every 8ms, (125Hz). The transient phenomena in the supercritical heat transfer are evaluated using the measured data.

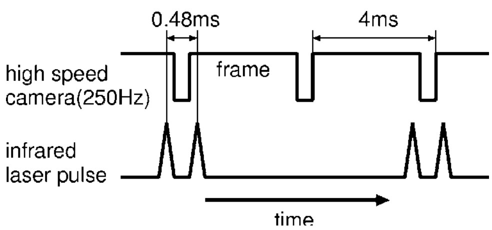


Fig. 1 Frame Straddling

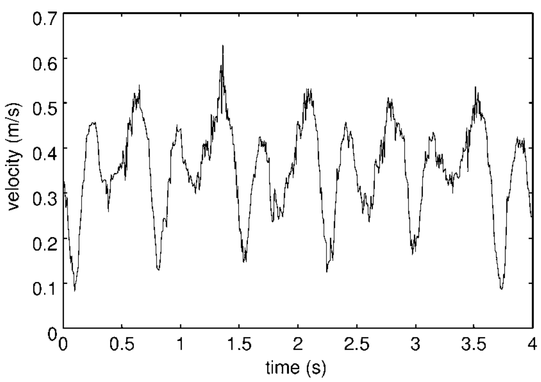


Fig.2. Velocity fluctuation measured by PIV (125Hz)

1. Introduction

To improve the thermal efficiency for the steam cycle, the supercritical steam turbine was used for many fossil-fired power plants. However, in the nuclear power plants, the steam pressure was remain sub-critical, because of the material and economical reasons. The advanced supercritical water cooled nuclear reactor (SCWR) will be one of the candidates of the next generation reactor (Oka and Koshizuka, 2000). To develop the SCWR, the knowledge of supercritical fluid is needed. The characteristics of the supercritical fluid had been investigated by many researchers in 1960's to develop the fossil power plants. For the supercritical fluid, the thermal property varies rapidly with temperature and pressure near the critical point (Dickinson and Welch, 1958). An increase in heat flux has the effect of diminishing the enhancement of heat transfer (Yamagata te al, 1972). The heat transfer is affected by the influence of huge buoyancy (Weinberg, 1972). Lots of numerical analysis for these phenomena were also carried out (Koshizuka et al., 1995). There are lots of the visualization study for the stagnant heat transfer, which shows the boiling like phenomena near the critical point.

However, there were very few flow visualization study on the forced convection heat transfer of the supercritical fluid because of high pressure and temperature. The flow condition under the natural convection was quite different from that under the forced convection. This is required to solve the theoretical problem such as a pseudo-boiling phenomenon.

In the previous study, the visualization for the supercritical carbon dioxide under forced convection heat transfer had been carried out. The density variation inside the heated test channel was visualized using schlieren and shadowgraph technique (Sakurai et al., 2000, Ota et al., 2001). In the visualization, the schlieren images were obtained by the 15 mW He-Ne probing laser with 632 nm of the wavelength and the high-speed camera with 1000 frames per second. With assuming the density wave to be the same with the fluid velocity, the movement of the image pattern denotes the fluid velocity. This means that the density variation pattern was taken as the tracer of the fluid flow. However, the time interval between the two images are too large (1ms) to detect the pattern tracking correctly. To get the fluid velocity with higher accuracy, it is necessary to shorten the time interval to decrease the image pattern distortion.

In this study, the frame straddling technique was applied to the high-speed camera capturing, with infrared high frequency pulse laser. Using this technique, the time interval can be controlled to be 0.01 to 1ms. Also, in the image analysis, the noise removal technique was applied, considering the noise and signal points in the image. The images are analyzed only with the signal points. The intensity variation at signal point is considered to be the density variation wave,

2. Experiment

Carbon dioxide was used as the supercritical fluid, although water will be used as a coolant in actual nuclear power plant. For the Carbon dioxide, critical point is 31°C and 7.4MPa. Comparing with water whose critical point is 374°C and 22.1MPa, it can be treated very easily. The features of supercritical CO_2 are similar to that of supercritical water.

2.1 Experimental Setup

The forced convection of the supercritical carbon dioxide was visualized. The test facility was composed of the main loop and the test section as shown in Fig. 1. The design pressure and temperature of the

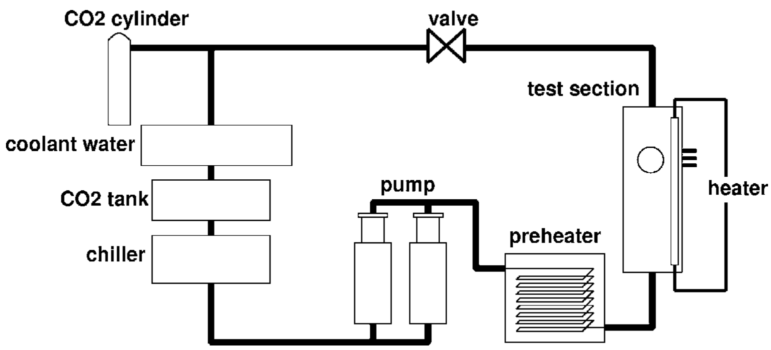
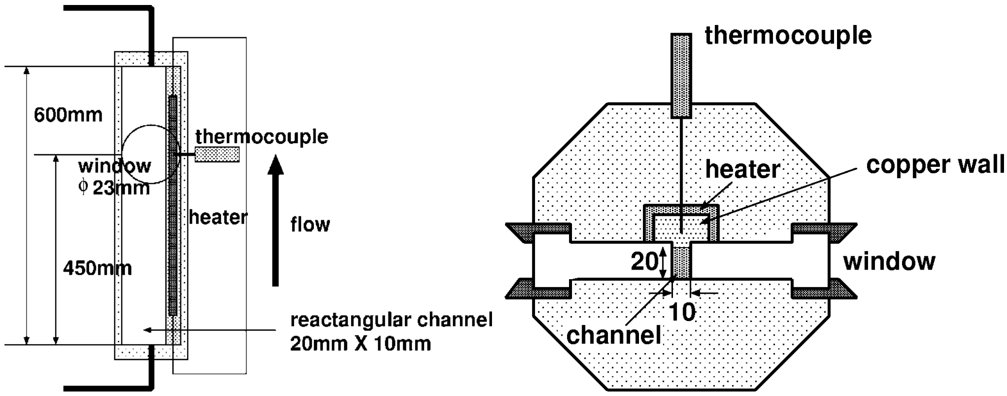


Fig.1 Test Loop for supercritical Carbon dioxide (15MPa, 100°C)



(a) Side View (b) Cross-section

Fig.2 Schematic of the test channel

facility are 15MPa and 100°C, respectively. The liquid phase carbon dioxide was stored inside the main tank, which was cooled and liquefied by the chiller. The double diaphragm pumps pushed up the fluid to be required pressure. The frequency of these pumps were 81 rpm. With controlling the pump stroke, the flow rate can be controlled from 0 to 50g/s. The pressure of the loop was controlled by the control valve with a feedback electronic control formula. The temperature of the fluid was controlled by the pre-heater, from 20 to 80°C.

2.2. Test section

Figure 2 shows the side and top view of the test section. The test channel was rectangular channel whose cross-section was 20x10mm. The one side wall (10 mm) was uniformly heated by copper block. The vertical length of the test section was 1200 mm and that of the heated section was 600 mm. The super critical fluid flowed upward. The circle view window with 23 mm diameter was settled at 3/4 downstream of the heated test channel. The view windows consist of ULE glass whose thermal expansion is negligible small. The view window size was larger than that of the test channel, so that the heater area were clearly visualized. The flow temperature were measured directly from thermocouples at the entrance, middle and the exit of the test section.

2.3 Experimental condition

The parameters for the visualization experiment are the fluid pressure(P), inlet fluid temperature(T), flow rate(q) and heat flux(Q). In the supercritical fluid, the density varies continuously with increasing the temperature. There is no gap of the density, which is quite different from the sub-critical fluid. The sub-critical fluid shows the liquid/gas phase change with spontaneous density variation. Although the density varies continuously, there is a peak of the gradient of the density variation. This point is called as the pseudo critical point, which may be corresponding to the boiling point under sub-critical pressure.

The pseudo critical point of the carbon dioxide at 8.5MPa is 38°C. The experimental condition was near the pseudo critical point, i.e., P=8.5MPa, T=38°C, q=24g/s and Q=167kW/m^2. The selected parameters are almost similar to that of the previous studies. The movement of the fluid was complicated at these conditions. The Reynolds number was about 10,000.

3. Improved Technique

3.1. Visualization Technique

The images were obtained by shadowgraph technique with infrared pulse laser and high-speed camera. The thermal plume with relatively large density variations and the crowd of higher density fluid were visualized near the heated wall. In order to detect the transient flow field, the high reputation pulse laser should be used as the illumination. Also to detect the velocity distribution using PIV technique, the frame straddling illumination was preferable.

However, there are not so many lasers are available with high reputation rate with the potential of frame straddling. Normal PIV Nd:YAG Laser can generate the pulse only with 30 Hz. High frequency pulse laser can generate up to 10 kHz, however, frame straddling is difficult. Therefore, in this study, the infrared pulse laser (Oxford, HSI-0500) is used. The wavelength of the laser is 808 nm, which can be detected usual CCD array. The peak power is 200 W. The maximum pulse reputation rate is 500 Hz. In each pulse reputation, up to 4 pulse can be illuminated. This means, the frame straddling illumination can be generated up to 500 Hz.

In this study, the specification of the high-speed camera is 250 frames per second with 512x480 pixels. The timing chart of the frame straddling is shown in Fig. 3. The timing of laser and the shutter of the camera is synchronized, and a pulse is emitted just before the shutter of camera closes and immediately after the it opens. Thereby, the images are obtained at short time interval. The time interval between the

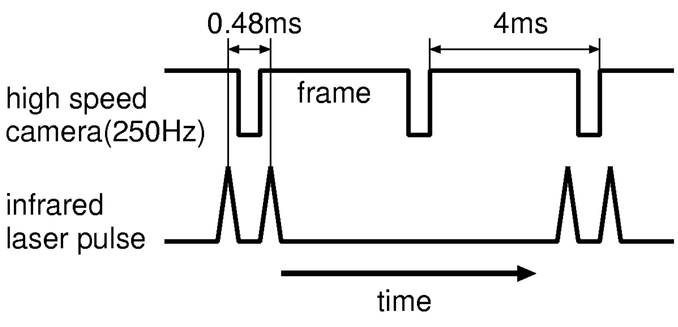


Fig.3 Timing chart for Frame Straddling

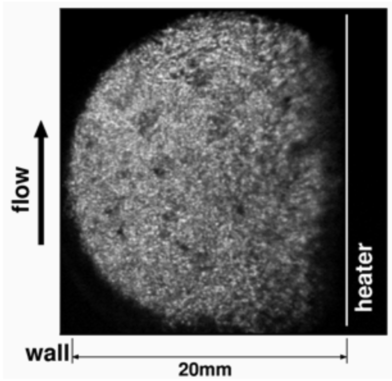


Fig.4 Sample of image captured by infrared laser and high-speed camera

two pulses is set to be 0.48 ms, which can be varied from 0.01 to 1 ms. The pulse duration for one pulse is 0.02 ms, i.e., 4 mJ/pulse. Though the image pattern distortion would be small by shorter time interval, cross-correlation method needs a few pixels movement.

The illumination pass through the windows, showing the bright and dark whose intensity is proportional to the 2nd order gradient of the density variation, i.e. shadow graph technique.

3.2 Image Analysis Procedure

Figure 4 shows the images captured with frame straddling technique using a infrared pulse laser for case.1. The circular area denotes the view window with 23mm in diameter. The vertical region at the right hand side is the copper heater. An Infrared laser passed through the flow field and dark and bright pattern was captured by a high-speed camera. The intensity distribution expresses density variation distribution through the light passage. The fluid flows upward direction. The image size is 512 x 480 pixels(1 pixel = 0.057 mm). In the image, the heater surface is shown as white line. The left side is the other side wall of the rectangular channel, whose width is 20mm.

In the visualized movie, a dark fluid cloud moves upward periodically. The cloud was considered to be a hot fluid bubble (lighter fluid bubble). In this cloud the refractive index is different from these at around area. It is thought that the density inside the cloud is much lower than that of main flow. Although there are no phase change in the supercritical condition, the non-equilibrium of the fluid was observed, because of the larger density gradient ($d\rho/dT$).

The movement of the image patterns between the two serial images was calculated using the cross-correlation method. As shown in Fig. 4, there are lots of dark points in both images. The dark points are the dirt on the window, causing the noise on the images. These points are called as noise points in this study. The others does signal points. The intensity hardly varies at noise points. While, the intensity varies frequently at signal points because of density variation. Then, the image is divided into signal and noise points using the intensity temporal variation information. When the standard deviation of the intensity variation exceeds the threshold, the point is considered to be signal. The dirt points and the background area in Fig.4 are treated as noise points. The images are analyzed using cross-correlation method with only signal points. Let f and g be the first and second image, respectively. The cross-correlation function, $R(p,q)$ will be expressed as follows,

$$R_{(p,q)} = \frac{\sum k_{(i,j)} k_{(i+p,j+q)} f_{(i,j)} g_{(i+p,j+q)}}{\sqrt{\sum k_{(i,j)} k_{(i+p,j+q)} f^2_{(i,j)} * \sum k_{(i,j)} k_{(i+p,j+q)} g^2_{(i+p,j+q)}}}, \quad (1)$$

where *k(i,j)* is the flag function for signal/noise points.
(*k*=1 at signal / *k*=0 at noise)

4. Results and Discussion

Figure 5 shows the instantaneous vector map obtained from the two serial images using cross-correlation method with noise removal. The time interval between the images are kept 0.48ms. The vectors in Fig. 5 shows the movement of the density variation. In the analysis, 32x32 interrogation area was used. The distance between the vectors is 16 pixels(= 0.89 mm). The heater exists at the right side of the image.

With assuming that the density variation moves with the fluid velocity, the vector shows the two-dimensional velocity distributions. Since the shadowgraph image is the projection of the density variations through the light passage, the velocity is the projectional averaged velocity in the channel. Also, the area close to the heater can not be detected, because the intensity near the heater is almost black, i.e., the huge density variation.

In the previous study (Ota et al., 2001), the continuous laser was used for illumination with camera shutter of 1/10,000s. The image resolution was 256x240 for 1000Hz. Also, the time interval between the two images was 1 ms. In this study, using the frame straddling technique, the time interval reduced to be 0.48 ms, with higher image resolution (512x256) and short illumination pulse (0.02ms = 1/50,000s)

The image resolution was improved. Because the shorter time interval between the two images, the tracking error can be reduced, Also, the shorter illumination period, the images are more clear. Then, the higher accurate velocity vectors can be obtained.

Figure 6 shows the average vector map in case.1. The 1,000 vector maps during 4 second are averaged to get the map. Averaging the vectors, the horizontal velocity is almost zero. Then, almost all vectors go in vertical direction. In Figure 6 vertical velocity decreases with increasing the distance from the heated wall, resulting in almost zero at the other sidewall. From the video image, the fluid near the wall also flew upward, the zero vector near the wall was caused by the background noise. Although background noises were removed as noise point in cross-correlation method, there still existed noise points treated as signal

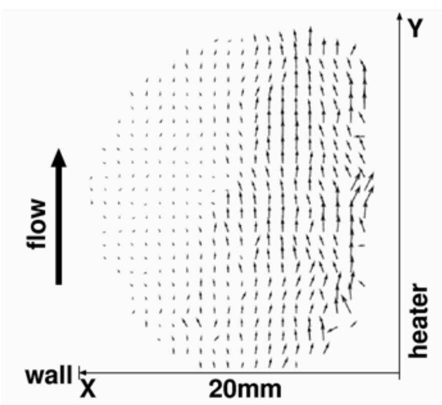


Fig.5 Instantaneous Vector Map

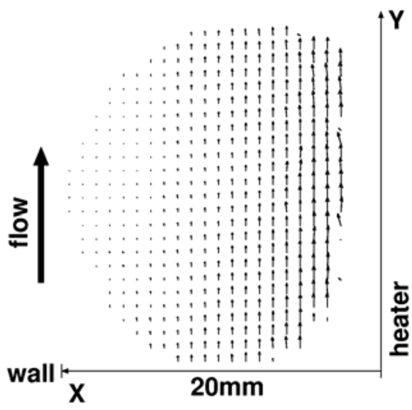


Fig.6 Averaged Velocity distributions

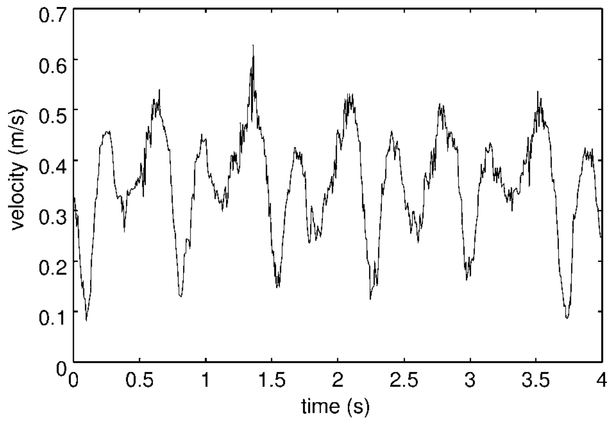


Fig.7 Velocity fluctuation inside the plume (3mm from wall)

point. The criteria for the elimination of error from signal should be much more improved. It will be the next topic to improve the algorithm for such noisy images.

The instantaneous velocity distributions were taken in every 8ms (1/125s). Then, the transient velocity distributions can be shown in animation. During 8ms, the cloud moved about 4mm, (1/5 of the view window size). So, the cloud tracking in the image analysis was difficult, However, the dark cloud movement can be seen in the velocity animation.

The temporal velocity variation at the location of 3mm from the heated wall is shown in Fig.7. Because the diaphragm pump pushed up the fluid in 81rpm, i.e., 1.2Hz, the velocity varies with the pump frequency. The visualized flow was the pulsed flow field. The area near the heater moves continuously upward. However, the difference between the maximum and minimum velocity was about 400mm/s (80% of maximum velocity). Although the pulsation may also affect on the velocity distributions, the plume and cloud of the hot fluid moves rapidly caused by the huge density gradient. The transient flow field should be more precisely evaluated.

5. Conclusion

The visualization study on the supercritical fluid heat transfer was carried out. The infrared pulse laser illuminated the flow field with synchronizing the high speed camera. The frame straddling technique reduced the image distortion between the serial images, resulting in the high accurate velocity information. Also, the noise reduction technique on the image analysis was applied. The transient velocity distributions of the supercritical in the heated channel were clearly obtained.

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