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Measurement of Concentration of Sorbent Particles and Water Droplets in Hydration Desulfurization Reactor with PIV*

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Abstract: Vortexing limestone injection into furnace combined with calcium lime hydration in the downstream is the most promising technology for controlling SO_2 emission. Particle imaging velocimetry (PIV) is used to measure the gas-liquid-solid three-phase flow field in a reactor. By image processing based on newly developed software, the number concentrations of sorbent particles and water droplets are presented. The measuring results are very helpful for better understanding the desulfurization mechanism and optimizing configurational and operational parameters in the hydration reactor.

Key words: particle image velocimetry, desulfurization, particle, water droplet, concentration

Several flue gas desulfurization (FGD) technologies with high sulfur removal rate have been developed for controlling SO_2 emission from coal burning. However, they are difficult to be widely applied in developing countries because of high capital and operational cost. A new desulfurization technology, vortexing limestone injection into furnace combined with calcium lime hydration in the downstream, which has much lower capital cost and medium sulfur removal rate (about 80%), is suitable for SO_2 emission control in China. In a vertical hydration reactor, unreacted sorbent particles in the flue gas get in touch with water droplets sprayed from an atomizer and become water-lime droplets. They absorb rest SO_2 in the flue gas escaped from the furnace by gas-liquid ion reaction, which is faster than gas-solid reaction by more than one order of magnitude. Therefore, the sulfur removal rate and calcium utilization rate are improved substantively. So the capture rate of sorbent particles by water droplets is one of the most important parameters affecting sulfur removal rate. It is beneficial to better understanding the desulfurization mechanism and optimizing configurational and operational parameters in the hydration reactor to measure the number concentration of sorbent particles and water droplets, and thus the capture rate precisely.

But it is difficult to measure the capture rate with conventional instruments. With the rapid development of computer technology and photoelectric technology, PIV has been more and more used to measure flow fields of two phase or three phase flows[1-3]. That makes it possible to measure the concentration of water droplets and particles and the capture rate in the reactor.

In this paper the measuring method and results in the reactor column are reported. By image processing based on newly developed software, the number concentration of sorbent particles and water droplets are presented. The measurement results can be used for determining the capture rate between solid particles and liquid droplets.

1 Experiment

The measurements were conducted on a hydration column with 400 mm in diameter and 6 m in height with the flow map type PIV set made by Dantec Company. Glass windows are arranged on the three side walls of the column, two of which are for laser beam traveling, the other is for CCD photographing. There are two pieces of glasses sized as 2 000 mm × 200 mm on each wall. The schematic diagram of PIV measurement system on the hydration reactor is illustrated in Fig.1. The flue gas burdened with sorbent particles comes drown at the top of the reactor. The water droplets sprayed from the compressed air-aided atomizer come

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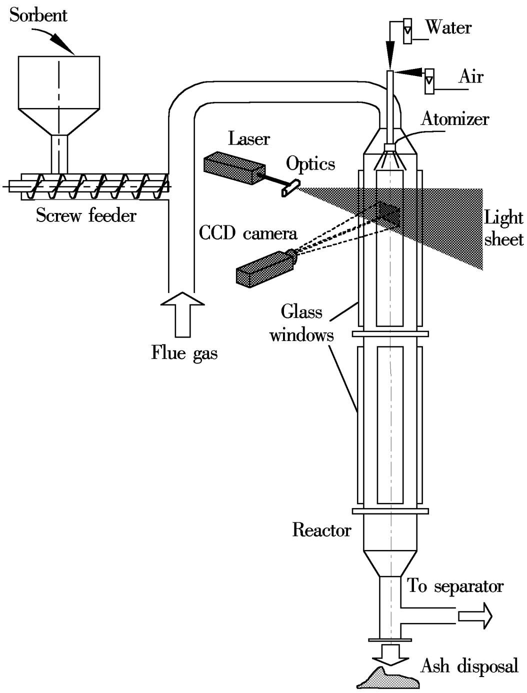


Fig.1 The schematic diagram of PIV measurement system on the hydration reactor

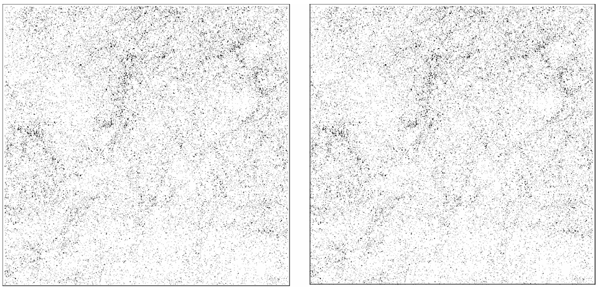
drown at the inlet of flue gas[4].

The PIV measurement system consists of the seeding particle generator, the laser emission system, the image recording system and the data processing system. Normally, the smoke generator is used to generate seeding particles for gas flow measurement. In present measurement very fine lime particles were used as the seeding. The laser emission system includes double-cavity resonator laser pulsing system made of two 50 mJ Nd-YAG lasers and a system of optics components. The laser beam from each of two lasers is converted to a light sheet with the thickness of 1 mm – 2 mm and with a certain expansion angle. The super-infra-red laser beam with wavelength of 1 064 nm is converted to the blue-green beam with wavelength of 532 nm with two stages of harmonic generators, which is in the more sensitive visible spectrum region. The image recording system consists of Kodak Megaplus ES1.0 CCD camera, PIV processor and a computer with related processing software. The data processing system consists of PIV 2000C processor and Flow Manager 3.11 software developed specially for the PIV by Dantec Co.[5]. The images recorded are processed based on cross-correlation and FFT-processing. The concentration measurement of solid particles and water droplets is a further development of PIV function based on its velocity measurement[6].

2 Results and Discussions

2.1 Gas flow measurement

Fig.2 shows two typical original camera frames captured by CCD camera at the same region of 110 mm × 110 mm under the axial gas velocity of 2 m/s and the



(a) (b)

Fig.2 Frames captured by CCD camera.(a) Frame A;(b) Frame B

lime feed rate of 3 kg/h near the inlet of the hydration reactor. The positions particles occupy appear as dark specks on a light background. Divided with the known time interval between the two images captured, the average particle displacement vectors are converted into a map of so-called raw velocity vectors as shown in Fig.3. It is obvious that there are several outliers, or called as erroneous vectors on the raw vector map

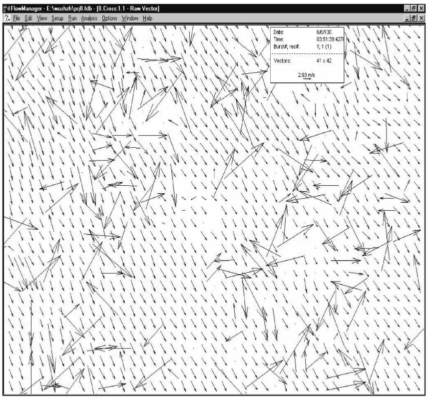


Fig.3 PIV raw vector map

because of noise caused by interference light. When validation algorithms are applied to the raw vector map, the outliers (false measurement) can be detected and removed (noise is reduced by the filters). Fig.4 illustrates a new validated vector map after moving average validation. Other parameters, such as streamlines and vorticity, can be derived from the measurements. The streamlines produced after further analysis are shown in Fig.5. It can be seen that there are some small local eddies near the expansive inlet of the reactor. The local turbulence is beneficial to capturing sorbent particles by water droplets.

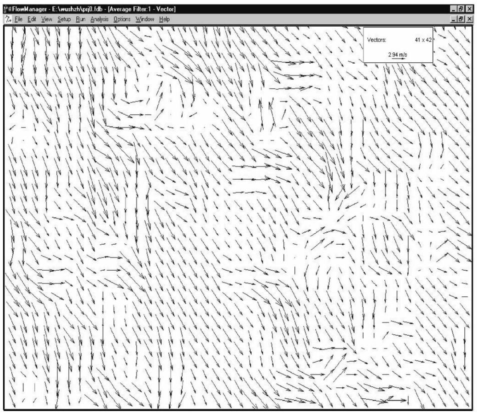


Fig.4 Vector after moving average validation

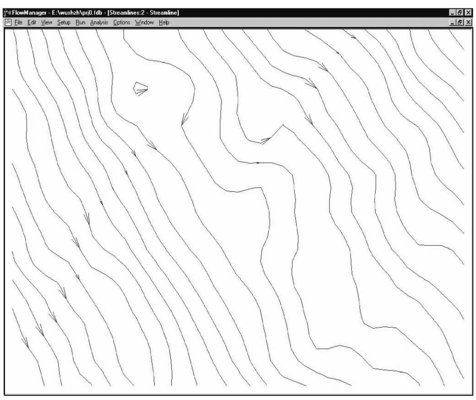


Fig.5 Gas streamlines

2.2 Sorbent particle concentration measurement

Sorbent particle concentration measurement and particle velocity measurement are conducted simultaneously. The number concentration of sorbent particles is obtained by means of detecting periphery of the specks on the frame captured by PIV CCD camera. About 30 to 40 frames are captured by CCD camera at each measurement position for about 20 s. The frames are processed with image recognition software developed secondly, and the quantity of particle image on the frame can be obtained. But the particle numbers calculated from each of those frames at the same position under the same conditions are not fully identical because of the fluctuation of feeding characteristics of the screw feeder and the other system parameters. So the time-average particle number on the interrogation area is given based on the root mean square deviation analysis of image processing result. In addition, the present measurement gives particle number in a two-dimension plane. In order to get particle number concentration N in the reactor, an assumption has to be made, i.e. all the particles are homogenously dispersed in the volume measured. Fig.6 gives the measured results of the sorbent particle number concentration distributions along the axial direction of the reactor under two axial gas velocities when the feed rate of the lime powder is 3 kg/h. The solid and dashed lines in Fig. 6 show the calculated particle number concentration distributions under the axial gas velocity of 1.6 m/s, 2.0 m/s, respectively. The solid and dashed curves are the measured results at two gas velocities. By comparison, it can be seen that generally, both of them are in good agreement, but the measured particle number concentration is a bit smaller than the calculated value. The reason is that there is a certain amount of fines less than 5 μm (22.9%) in the sorbent used. Very fine particles are difficult to be imaged or resulted in out of focus. Considered as noise, they are easy to be removed. Another reason for that is the actual photographed area is larger than the ideal area (100 mm × 100 mm) for PIV photographing, limited by the test rig.

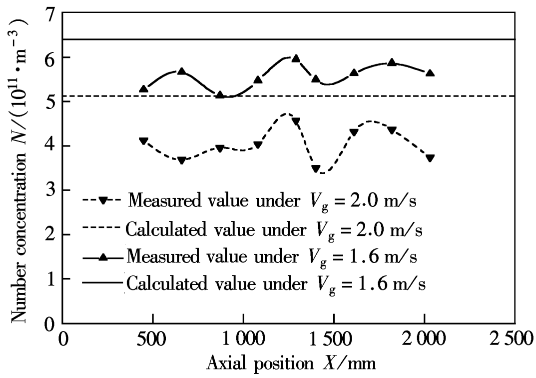


Fig.6 Sorbent particles concentration

2.3 Water droplet concentration measurement

The small size water droplet with small enough curvature radius has the similar optical characteristic to solid particle. It is practicable to adopt the same measurement method and image processing approach for water droplets as for solid particles. The water droplet concentration distributions along the reactor measured and calculated under the gas velocity of 2 m/s and two flow rates of sprayed water are illustrated in Fig.7. It shows that the water droplet concentration N rapidly declines along the reactor because of evaporation. The concentration at the position 1 300 mm away from the reactor inlet approaches zero, which means all the droplets almost vaporize there. The result is in good agreement with the measured gas temperature distribution along the reactor.

The measurement of capture rate of sorbent particles by water droplets cannot be carried out because of some PIV hardware problems encounter

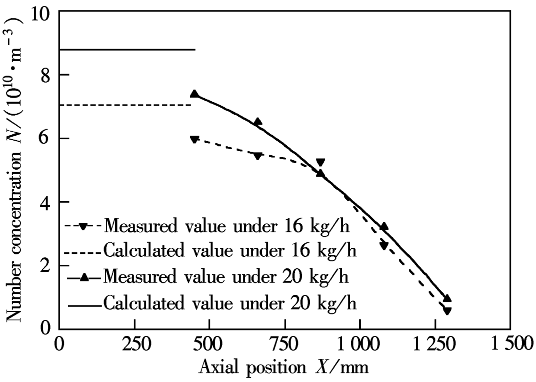


Fig.7 Water drops concentration

during the measurements. The intensities of the laser beams from the two lasers have substantial difference, which reduces the measurement accuracy. There are some difficulties with focusing of the CCD camera with its own modulation mechanism sometimes. A stepping motor for fine adjustment is mounted on the measurement system. After improvement the situation becomes better.

3 Conclusion

Particle image velocimetry is successfully used for not only measuring the gas flow field and particle velocity field in the hydration reactor, but also measuring the particle number concentration in the gas flow field by means of the image recognition software for the first time. PIV is also successfully used for measuring the number concentration of the water droplets with smaller size, which have the similar optical characteristics to solid particles. The measured results and calculated values are in good agreement. It builds solid base for measuring the capture rate of the particles by the water droplets in the gas-liquid-solid three-phase flow with PIV.

Measurement results indicate that evaporation of water droplets is rapid and finished in the distance within 1.3 m under the test conditions.

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增湿活化脱硫反应器中脱硫剂颗粒和雾化水滴数量浓度的 PIV 测量

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摘　要　炉内旋涡喷钙尾部增湿活化脱硫技术是控制燃煤 SO_2 排放最有发展前景的技术之一.采用先进的颗粒速度图像仪(PIV)测定了活化反应器内气液固三相流场.利用二次开发的软件,经过图像处理得到活化反应器内脱硫剂颗粒和雾化水滴数量浓度.研究结果对于深入理解活化反应器内浆滴促进脱硫机理、优化结构和运行参数具有重要意义.

关键词　颗粒图像速度仪，脱硫，颗粒，水滴，浓度

中图分类号　X511