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Original Paper

Research of liquid-solid two phase flow in centrifugal pump with crystallization phenomenon

Liu Dong, Wang Ya-yun, Wang Ying-ze, Wang Chun-lin and Yang min-guan

School of Energy and Power Engineering
Jiangsu University, Zhenjiang , 212013, China

Abstract

Particle Image Velocimetry combined with developed image processing method is adopted to study the liquid-solid two phase flow in the centrifugal pump impeller with crystallization phenomenon. The tracer particle is used to follow the liquid phase, which has the diameter between 8 to 12μm. The crystal particle precipitates from the sodium sulfate solution does change the wavelength of the laser, and which has great laser scattering characteristics . The diameter of the crystal particle is larger than 20μm. Through calculating the diameter of the particles in the image, the tracer particle and the crystal particle can be distinguished. By analyzing the experimental result, the following conclusion has been obtained. During the delay period, there is not any crystal particle and the pump performance has not been changed. As the crystallization process begins, the crystal nuclei appears from the supersaturation solution and grows larger with temperature decreasing, which has the tendency of moving towards the pressure side. The characteristics of liquid-solid two phase flow with crystallization phenomenon in the pump are obtained according to analysis of experimental results, and some guiding advices are presented to mitigate the crystallization phenomenon in pump impeller.

Keywords: Centrifugal pump, crystallization phenomenon, PIV, image processing method

1. Introduction

Crystallization is a process that solid particle precipitates from salt aqueous solution which mainly consist of natrium and kalium ions. As the crystallization phenomenon happens in the transportation process, crystal particle will be adsorbed on the inner wall of pipeline and pump, which has a negative impact on relevant equipment operations and even causes severe economic losses[1]. Centrifugal pump is an important fluid transportation device, used extensively in chemical industry, and the crystallization problem is common. When the crystal particles are generated in the solution, pump efficiency declines gradually and then drops abruptly. The study on liquid-solid two phase flow with crystallization phenomenon in the pump is important to thoroughly solved the problem mentioned above.

Research on this kind flow begins from fifty's of the last century. Some achievements have been made by Yang[2], they make primary analysis on crystallization phenomenon during the alkali reclaim process of paper making in pipes. In their paper, experimental researches on different periods of crystallization process were done, diameter distribution of crystal particles was obtained through image processing, and the effect of crystal particle on the flow field was also analyzed. Attentions also have been focused on certain pump configuration and specific application cases such as pulp production process[3]. Further researches lie in innovation and improvement of pump structure and mechanical seal for coping with crystallization and its adverse consequences[4.5,6]. Gao[7] measured this kind two phase flow field in a vortex pump , the crystal particle velocities were obtained by Phase Doppler Particle Analyzer, they found the particle velocity gradient of peripheral component varied with the pump discharge.

Those studies are meaningful in revealing potential relation between transport property and pump performance, and helpful in pump performance improvement. However, in the sense of fundamental mechanism and definition of decisive factors for crystallization, the results are relatively fewer. In this paper, the influence of temperature has been experimentally investigated in the liquid-solid two phase flow in a centrifugal pump. We believe this study can help not only to improve the performance of centrifugal pump transporting salt aqueous solution but also to understand fundamental mechanism of this liquid-solid two phase flow.

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Corresponding author: Liu Dong, Associate Professor, liudong@ujs.edu.cn

2. Experimental set-ups

2.1 Experimental Device

The basic parameters of centrifugal pump are as follows: design discharge $Q=20m^3/h$,head H=10m, rotational speed n=1450rpm,blade number Z=5. The experimental system is shown in figure.1. In this paper, PIV will be applied to measure the flow field, which has been widely used in measuring the internal flow in the pump[8,9] . For the PIV measurement, pump is made of organic glass, and the frequency converter is used to start the pump. Inlet and outlet of the pump were equipped with pressure transducer. Discharge was measured by electromagnetic flowmeter, rotational speed and power were obtained by torque indicator. The flow rate is controlled by outlet valve. To generate different temperature condition, the heating resistors are installed in the container.

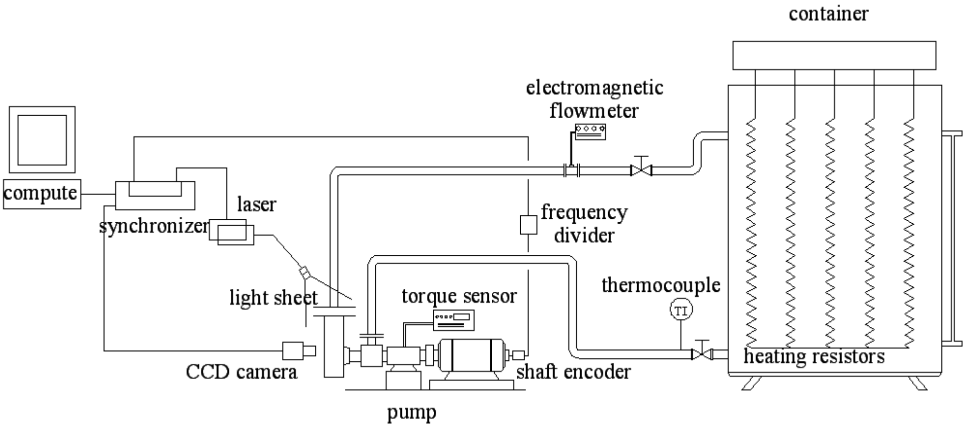
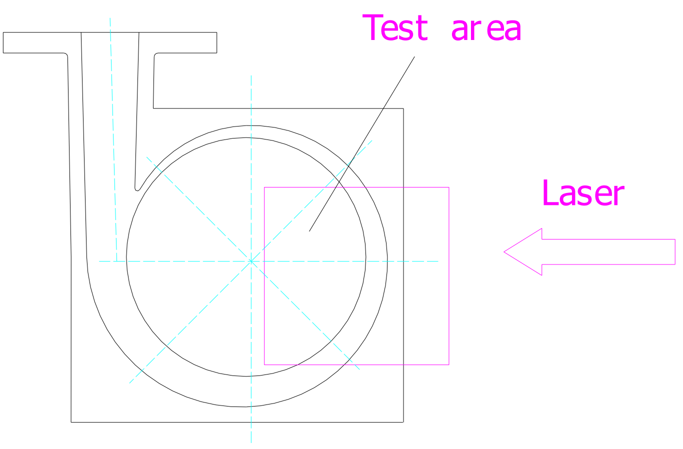


Fig. 1 Experimental system

The PIV hardware consists of a 120 mJ/pulse Nd:YAG laser (532 nm wavelength), laser light sheet optics, a CCD camera (resolution: 1280 x 1024 pixels) equipped with a 60 mm Micro lens (Nikon) and a data acquisition system consisting of a PC and a frame grabber card . The laser beam is formed into a 0.2 mm thick light sheet using a combination of cylindrical and spherical lenses. The CCD camera is mounted on a 3-D traverse with a translation accuracy of ±0.1 mm in each direction, and has its focal axis perpendicular to the plane of the laser light sheet to acquire flow images. Pair of single exposure image frames is required to enable cross correlation data processing. The image pair acquisition and processing is done using the INSIGHT 5.0 offered by TSI .The image pair acquisition is synchronized to the impeller rotation using an axes encoder and a frequency divider. The arrangement of optical path and the model pump is presented in Figure 2.



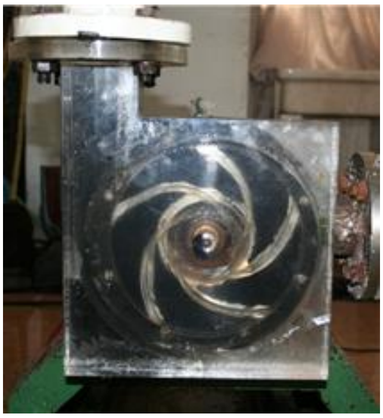


Fig. 2 Configuration of PIV optical path and the model pump

2.2 Synchronization Problem

To ensure the synchronization, two additional hardwares are needed, one is the shaft encoder, the other is frequency dividing circuit. This allowed a large number of instantaneous samples to be obtained at the same circumferential position of the impeller in order to calculate ensemble averages.

The shaft encoder is LEC-S1 optical encoder, which generates signals as the impeller rotation, and then triggers the synchronizer. The synchronizer in turn sends a signal to the data acquisition system, which will fires the laser and acquires the images by the CCD camera. The shaft encoder used in the experiment generates 500 pulse signals per circuit. The speed of test pump is 1450 rpm and the working frequency of the CCD camera is 8 frames per second. The pulse signals from shaft encoder are larger than the frequency of CCD camera. So the signals should be divided before sending to synchronizer. The basic principle is to ensure the frequency of signals to be the same as the CCD working frequency .

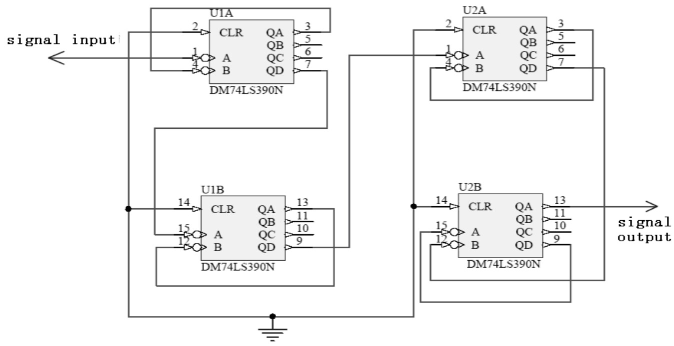


Fig. 3 Sketch of frequency dividing circuit

The first step of design of frequency dividing circuit is to choose an appropriate frequency multiplier coefficient m. The details are shown as follows:

Choosing a frequency multiplier coefficient m satisfies the following formula.

$$(500 \times 1450)/(60 \times m) \le 3.75$$
$$m \ge 3212$$

To consider the complexity of the frequency dividing circuit, we choose m=10000. The signals send from the shaft encoder are divided into 10000(5*2*5*2*5*2*5*2) , which realized by two 74LS390 decimal counter. The concrete circuit shows in figure 3.

2.3 Image Processing

During the experiment, many crystal particles precipitate from solution, it is hard to distinguish the crystal particles from the images. However, the crystal particles are larger than the tracer particles, so its scattering light is stronger. With the technology of image processing, we can get distributing graphs of crystal particles and tracer particles respectively, then two phase velocity field can be obtained by software insight5.0.

Based on the image processing software developed by YANG[10], diameter of all the particles can be calculated, and then the crystals particles and the tracer particles could be distinguished. Supposed an intermediate value according to the different diameters between the solid and tracer particle, and then consider those bigger than the value as crystal particles, and the smaller ones as the tracer particle of the liquid phase. Save the different particles into different images, in this way separation of the two phase particles are completed.

3 . Results and discussions

The experimental medium is supersaturation sodium sulfate solution, hollow glass microsphere with good flow following ability and the light scattering characteristics was added as seeding particles, and the diameter is between 8 and 12 micron. During the process, valve in the outlet pipe is used to adjust the flux of system and the solution is heated up to 40℃ by constant temperature heating container. The experiment is done to measure the liquid-solid two phase flow with crystallization phenomenon during the temperature decreasing, velocity and size distribution of crystal particles were measured when the temperature is 40℃ and 34℃.

3.1 Crystal size distribution at different temperatures

The pump keeps working four hours at the temperature of 40℃ under designed operating condition, no crystal particle appears in the solution during this period, and the crystallization process is in delay period, so the flow field does not changed obviously. After four hours, some crystal particles are appeared in the pump. Figure.4 show the size distributions of crystal particles when temperatures is 40℃. Temperature is proved to be one of the decisive factors influencing crystallization process. The diameters of the most majority of crystal particles are smaller than 50 μm as temperature is 40℃. Because of lower phase change driving force, crystallization nuclei form and grow gradually in supersaturation sodium sulfate solution. Crystal structure is not stable and is characterized by collision among crystal particles, breakup resulted by particles' collision with solid boundary. Figure 5 shows the size distributions of crystal particles when temperatures is 34℃, the Crystal particles keep growing when temperature declines. Diameters of some crystal particles can be as large as 100μm when the medium temperature reaches 34℃. And nearly half number of particles is larger than 50μm. From this ,we can conclude that with decline of temperature , supersaturation increases, which accelerates the crystal particle's growth. During this process, crystal particle experiences accumulation, breakup and aging. Stable crystal configuration is finally realized in the flow field.

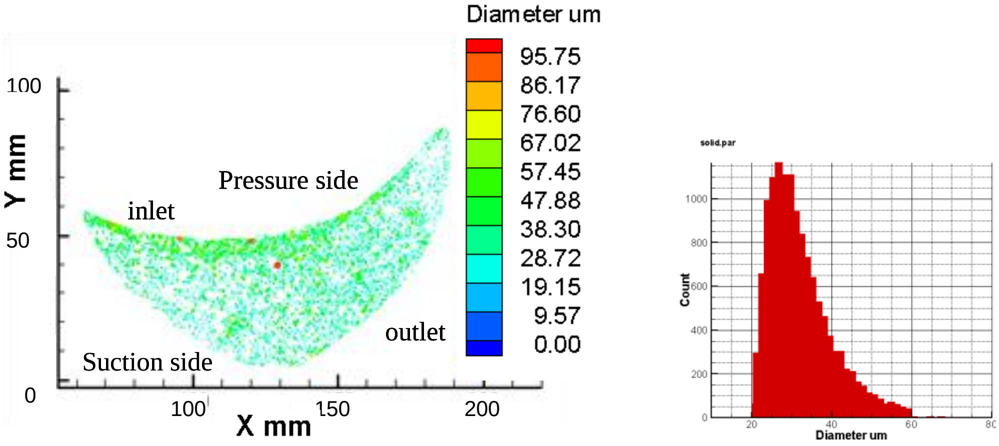


Fig. 4 Size distribution of crystal particles at 40℃

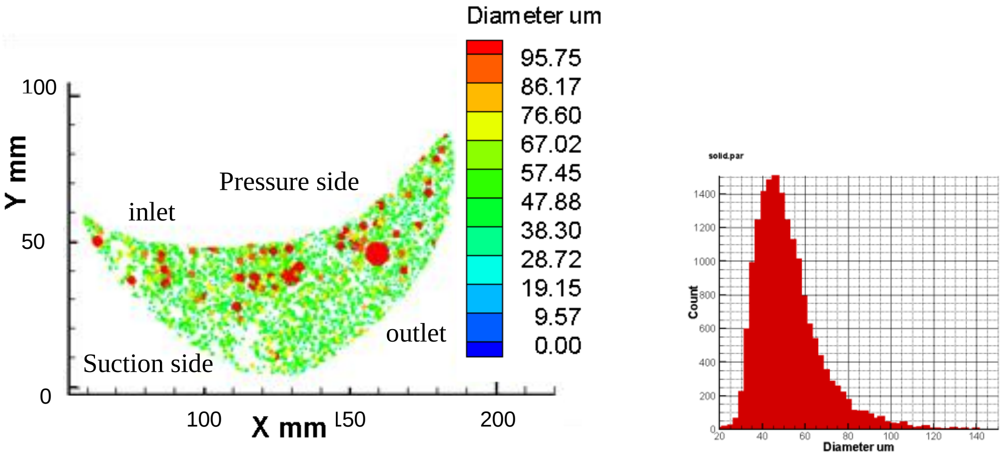


Fig. 5 Size distribution of crystal particles at 34℃

It can be found from Figure.5 that large crystal particles gather near the pressure side. Crystal particles in the flow passage are subjected to shear force coming from surrounding fluid and the strong shear force existing in boundary layer can separate smaller particles with crystal particles they attached to. Those small particles will join the growing crystal particles. At low velocity zone near pressure side, smaller shear force is imposed on the particles. Near the blade pressure side, relative velocity of liquid phase is smaller and consequent shear force is smaller. With the same driving force for crystal particle' growth, particles here are easier to grow up.

3.2 Relative Velocity Distribution

Figure 6 shows the velocity distribution during delay period, after the delay period, a large number of crystal particles appear in the solution, and they become larger as the temperature decreasing.

The result in figure 7 shows that the velocity of two phases. In radial direction of the impeller, the velocity near pressure side increases gradually, but decreases gradually near the suction side. Relative velocity of both phases on pressure side is less than that on suction side because of the rotational action of impeller, but there are some differences between liquid and crystal particles at impeller outlet. The relative velocity of crystal particles is a little larger than that of liquid phase. These conclusions are because of low concentration and small particle size in the solution at 40℃ , at this temperature condition the particle size is between 20 and 60 µm, and most are under 30 µm. Therefore the crystal particles have little influence on liquid flow field.

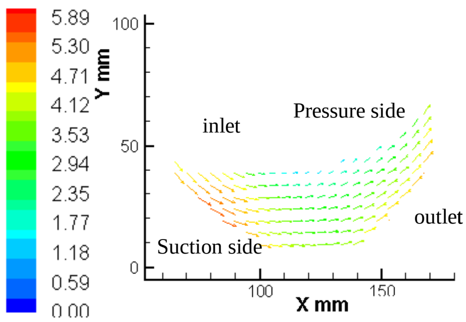
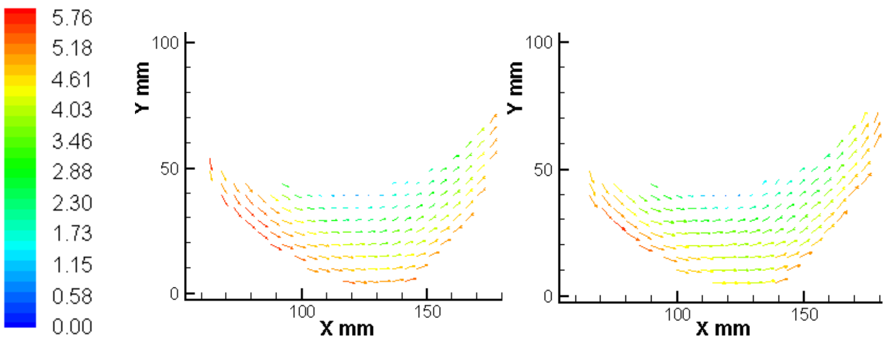
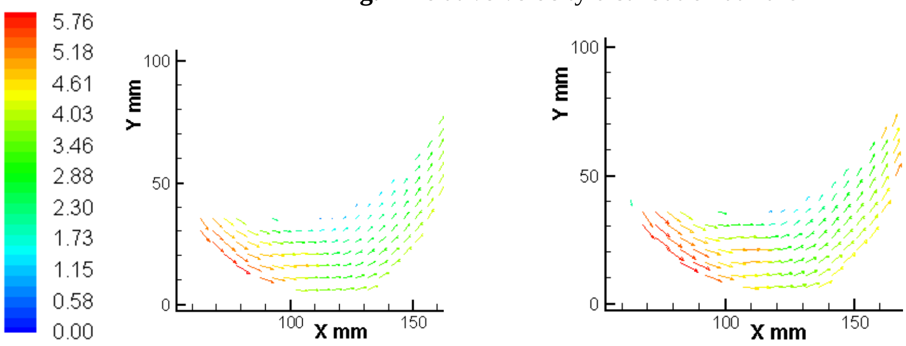


Fig. 6 Velocity distribution during delay period



(a) Liquid phase (b) Crystal phase

Fig. 7 Relative velocity distribution at 40℃



(a) Liquid phase (b) Crystal phase

Fig. 8 Relative velocity distribution at 34℃

Figure 8 shows the relative velocity distribution when the temperature is 34℃. At the inlet of impeller, the velocity of crystal particle is smaller than that of liquid phase. At the outlet, the velocity of crystal is larger than that of liquid. From inlet to outlet, the crystal particle has the tendency of moving towards pressure side.

The crystal particle velocity in figure 7 and figure 8 show that the bigger particles at 34℃ move to working surface obviously and the main deposition region is the middle area of pressure side. There are two main reasons: one is a low velocity region in this area, which is in favor of crystal growth, the other reason is the composite force of crystal particles is leaned to the working surface because of the high density of crystal.

3.3 Pump performance analysis

Figure.9 shows the pump performance curves at different working condition. At different temperature condition, the working performance of this pump has great difference. As the temperature decreases, the crystal particles grow larger, and the pump head decreases about 19% when the pump flow is 20 m^3/h. And the power increases as the temperature decreases. The efficiency of pump decreases from 48% to 30.5% as the temperatrue decreases.

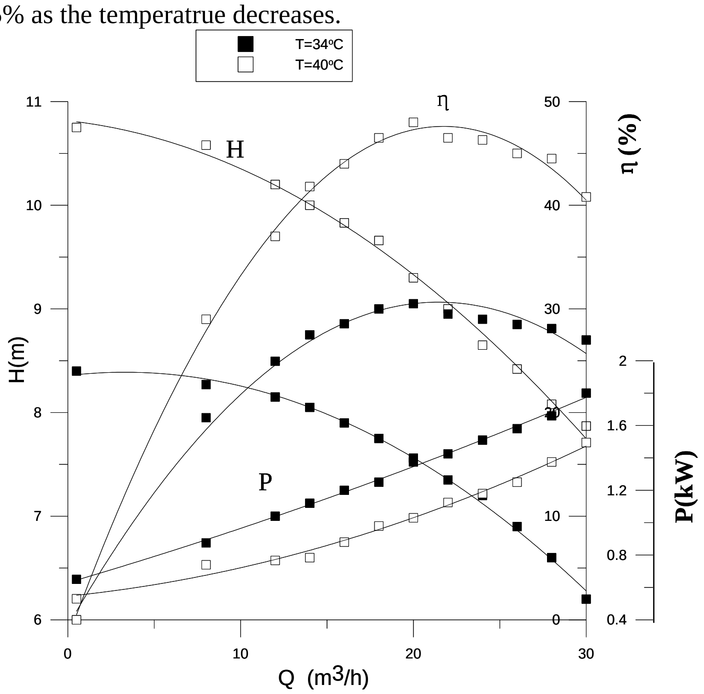


Fig. 9 Pump performance curve of different working condition

4. Conclusion

The liquid-solid two phase flow with crystallization phenomena in the impeller of centrifugal pump is studied by PIV. The conclusions are as follows:

1) There is no crystal particle appearing in the solution during the delay period, and the performance of pump does not change obviously.

2) As the temperature decreases, larger particle appears in the impeller, which gathers near the pressure side area.

3) Bigger particles move to pressure side obviously at 34℃.Because lower velocity is favor of crystal growth, the composite force of crystal particles is leaned to the pressure side.

4) The pump head and efficiency decreases as the temperature decreases, but the power increases when temperature is 34℃.

Acknowledgments

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