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To cite this article: A V Chinak et al 2018 J. Phys.: Conf. Ser. 1105 012071

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Measurement of velocity profiles in multicomponent flows

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Abstract. A study of velocity profiles in a flow of a multicomponent flow of a guar polymer-based gel in a flat channel was performed. The method of planar shadow image velocimetry was used. It has been demonstrated that a flattening of the velocity profiles in the central part of the flow and an increase in the velocity gradient in the near-wall zone is observed for the cases if such components as fibers and proppant are included in the flow and their concentrations are increased.

1. Introduction
Multicomponent gel-based flows are widely used in various industrial applications, for example, in mineral production. Therefore, it is necessary to know the rheology, hydraulics and structure of such flows. Commonly gel flows have an essentially non-Newtonian rheological behaviour. To meet various fluid performance requirements, solid particulates and fibers can be added. Also, such gels can contain a suspension of gas bubbles due to high viscosity. For this reason, the flows exhibit low optical transparency, which makes it difficult to use optical methods, such as digital tracer anemometry (PIV-Particle Image Velocimetry). The presence of fibers makes the use of probe methods impossible due to fast settling on projecting parts.

There is a sufficient number of papers focused on rheological study of guar gels [1–4], including crosslinked ones [5]. When studying crosslinked gels, a "sliding" phenomenon can be observed, which involves a high fluid velocity gradient near the wall. Sliding is a negative effect that has a significant influence on the accuracy of measurements of the rheological properties of fluids. Actually, the phenomenon is a common for guar polymer-based crosslinked gels [6]. It leads to underestimating the measured viscosity as compared to the actual viscosity. Studying the velocity profiles of gel flows will allow us to avoid this error.

In view of this, difficulties in studying the hydrodynamic flow parameters and rheology arise, and we are faced with the task of creating scalable and relatively simple methods for non-destructive diagnostics of such flows.

2. Experimental setup
The proposed method is based on observing and measuring the velocity of objects that had "sharp" images, i.e. those in the measuring range of an optical system with a small depth of field (DOF). A similar method was used previously in [7] for analysis of bubble flows. Testing was performed in the
Hele-Shaw flow in a flat channel with a cross-section of 10 x 200 x 1000 mm. The flow was formed between the walls of the flat channel. The thickness of channel walls was 20 mm. One of the walls was transparent and made of Plexiglas, the other one was made of metal. A camera with a lens was attached to a positioning stage connected to a flat channel, opposite a light source. The method of shadow illumination was used. Illumination of the flow was arranged in a frontal manner, through a plug made of Plexiglas with a diameter 16 mm that was screwed into the metal wall of the channel. The end of the plug was polished and located in the same plane as the internal surface of the channel wall. A force-cooled white-color LED array of 32 x 32 mm in size with a power of 100 W, and a light flux focusing lens was used to provide lighting. The gel flow contains contrast particles, such as micro-bubbles, sand particles, and fibers. Upon entering the DOF zone of the optical system, the contrast particles form a "sharp" image. Velocity profiles were measured using the optical system consisting of the Nikon J4 high-speed camera and the Canon MP-E 65 mm lens. According to the calibration, the depth of field of this type of system is about 0.25 mm. The design of the experiment is depicted in figure 1.

Before the experiment start, the positioning stage was adjusted in such a way so that the internal wall of the transparent front panel of the channel was in the focus of the camera. In addition, calibration imaging of an object with known linear dimensions was performed. In this experiment, the gauge scale was applied directly onto the transparent plug that was temporarily installed instead of the one through which the source projected light during experiments. The distance on that the camera position should be shifted in the air in order to change the position of measuring volume in the fluid was obtained by the calibration procedure. In this procedure the DOF was moved from one wall with a contrast marked point to another one which was marked t.

In the course of the experiment, the coordinating device with the camera was gradually moved towards the channel by increments of 0.25 or 0.5 mm. The refractive index for the gels under study was measured using the modified Abbe IRF-22 refractometer. The measured relative refractive index for gel is almost the same as the relative refractive index for water and equals 1.335 ± 0.0002. The frame rate was selected in such a way so that the same object would come into the camera's field of view at least 3–4 times. Therefore, the frame rate depends on the flow velocity and magnification of the optical system. The conducted experiments provided satisfactory results at frame rates of 400 and 1,200 frames per second.

The exposure during imaging was selected in such a way that the histogram for each frame would fully fit in the range of 0–255. Two rounds of imaging lasting 3 seconds (1,200 frames in each) were performed at each point.

In the experiments the Polilastic Acid polymer (density 1200 kg/m³, length 6 mm, diameter 12 mkm) was used as tested fibers [8]. Proppant is a ceramic spheres with mean particle diameter of ~0.6
mm and the density 3600 kg/m³. Base fluid is borate fluid with 4.8 kg/m³ guar loading. According to [3] the base fluid is shear-thinning and its apparent viscosity can be estimated using unmodified Coxe–Merz rule. Also values of the apparent viscosity for a solution with a guar gum concentration 5 g/l were presented in [3]. It was shown that the apparent viscosity changes in the range of 0.1÷0.5 Pa*s for shear rates varied from 0.1 to 100 s⁻¹.

### 3. Experimental results

An example of processing images for a baze fluid and for a baze fluid with fibers and a high concentration of proppant is shown in figure 2. The following steps were performed while image processing: 1 — images were converted in Grayscale format, 2 — adjustment of brightness levels procedure was carried up, 3 — gradient field was found, 4 — gradient field was binarized. We can see that the particles that are not in the lens focus are not displayed on the resulting binary image. Thus, upon further correlation processing of images, we obtain the velocity of objects that are in the focus of the camera. In the experiments presented, the frame rate was 400 frames per second.

The size of the experiments presented was 768 x 288 pixel. According to the calibration measurements, the spatial resolution was 221.4 points per mm. After the processing and binarization of images, a correlation image analysis was performed. The normalized cross-correlation function has the following form:

\[
R(i, j) = \frac{\sum_{k=1}^{B_x} \sum_{l=1}^{B_y} (I_a(k, l) - \bar{I}_a)(I_b(k + i, l + j) - \bar{I}_b)}{\left( \sum_{k=1}^{B_x} \sum_{l=1}^{B_y} (I_a(k, l) - \bar{I}_a)^2 \sum_{k=1}^{B_x} \sum_{l=1}^{B_y} (I_b(k + i, l + j) - \bar{I}_b) \right)^{0.5}}
\]

where \( I_a \) and \( I_b \) is sequential binary frames, \( B_x \) and \( B_y \) are the frame sizes in the X and Y directions.

Examples of two sequential binary frames as for a baze fluid and for a baze fluid with fibers and a high concentration of proppant which were obtained using previously described algorithm are shown on figure 3. A correlation analysis is used to calculate the cross correlation of sequential binary frames (figure 4) and find the position of the correlation function maximum. Once the correlation function is calculated, correlation level filtering is performed. If the correlation function maximum is lower than a certain value (~0.7–0.9), this result is rejected and is not taken into account when calculating the mean. Based on the peak position of the correlation function, the displacement components of objects dX and dY are calculated. Then, using the calibration images and frame rate information, the velocity components of objects are calculated. After this, the mean velocity across the entire array of frames is calculated.

The processing of images in the case of a high proppant concentration was performed in an similar way. The brightness of illumination is of significant importance for cases with high proppant concentrations. It is caused by rather high degree of image coverage by nontransparent particles.

Examples of velocity profiles measured in a flat channel are shown on the figure 5. In the presented experiments, the superficial velocity of the fluid was 0.14 m/s, according to calibration procedure which was performed at first.

Measurements were conducted for different concentrations of components: 1 — base fluid; 2 — base fluid and fiber with volume fraction of 0.2%; 3 — base fluid and fiber with a volume fraction of 0.4%; 4 — base fluid, fiber with a volume fraction of 0.4% and proppant with a volume fraction of 6%. The diagrams show estimates of measurement errors. We can see that the error can reach 23% value in near-wall position in the high velocity gradient region (0.33 mm). Father away from the wall, the error for the most part does not exceed 5–10%. Increasing the concentration of fibers in gel results in an increase in the velocity gradient near the wall and a flatter profile in the flow core.

To increase the accuracy of velocity profile measurements in the near-wall area, one should reduce the error caused by DOF. To do this, optical systems with a smaller DOF should be used.
Figure 2. An example of an image processing sequence. a — base fluid and fiber with a volume fraction of 0.2%; b — base fluid, fiber with a volume fraction of 0.4% and proppant with a volume fraction of 8%. 1 — image in Grayscale format, 2 — image after adjustment of brightness levels, 3 — illumination gradient field, 4 — binarized illumination gradient field.

Figure 3. Two sequential frames after preliminary processing: a — base fluid and fiber with a volume fraction of 0.2%; b — base fluid, fiber with a volume fraction of 0.4% and proppant with a volume fraction of 8%.
Figure 4. Cross correlation function of sequential frames: a — base fluid and fiber with a volume fraction of 0.2%; b — base fluid, fiber with a volume fraction of 0.4% and proppant with a volume fraction of 8%.
Figure 5. Distribution of gel flow velocity in the channel cross-section. The distance from the channel wall is shown along the x-axis. 1 — base fluid; 2 — base fluid and fiber with a volume fraction of 0.2%; 3 — base fluid and fiber with a volume fraction of 0.4%; 4 — base fluid, fiber with a volume fraction of 0.4% and proppant with a volume fraction of 6%.

4. Conclusions
An approbation of the method for measuring flow velocity profiles of optically low-transparent gels has been performed. Guar-based non-crosslinked linear gel was used as a base fluid system. As the next part of the work, fluids with additives of fibers with volume fraction up to 0.4% and additives of proppant up to the volume fraction of 12% were studied. It has been demonstrated that the method can be applied successfully for characterization of both pure and highly concentrated gels.

The influence of components concentrations on the shape of the velocity profile has been studied. It was demonstrated that an increase in fiber and proppant concentrations results in the flattening of velocity profiles (a decrease in the central part of the flow and an increase in the near-wall one). The applicability of proposed method was proven, considering the said concentration range of solid additives. However, further optimization of optical conditions (increasing the frame rate and improving the quality of illumination) would extend concentration range of components for testing in the long term.

References
[1] Aderhold J, Davydov V Yu, Fedler F, Klausing H, Mistele D, Rotter T, Semchinova O, Stemmer J and Graul J 2001 J. Cryst. Growth 222 701
[2] Chenlo F, Moreira R and Silva C 2010. Journal of Texture Studies 41 396
[3] Torres M D, Hallmark B and Wilson D I 2014 Food Hydrocolloids 40 85
[4] Patel S P, Ranjan G and Patel V S 1987 International Journal of Biological Macromolecules 9 314
[5] Oblonšek M, Šostar-Turk S and Lapasin R 2003 Rheol Acta 42 491
[6] Goel N, Shah S N, Yuan W-L and O’Rear E A 2001 J. Appl. Polym. Sci. 82 2978
[7] Ahuja A, Singh A 2009 Journal of Rheology 53 1461
[8] Bröder D, Sommerfeld M 2007 Measurement Science and Technology 18 2513
[9] Shalagina A, Fu D 2015 Treatment Fluid. Patent WO 2015160275