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学 位 論 文 名		Development of Image Analysis Methods for Flowing Soap Films as a Two-Dimensional Turbulence and Analysis of the Effects of Polyethylene Oxide on the Flow 二次元乱流としての流動石鹸膜を用いた乱流画像解析法の構築と乱流へのポリエチレンオキシド添加効果の解析

論文の内容の要旨

The turbulence is the most complicated, the most troublesome and the most common flow in fluids dynamics. Therefore, the turbulence has been discussed in various areas, and was tried to be inhibited in industries. For instance, it is known that minute amounts (20-30ppm) of long chain molecules reduce the drag forces in turbulences, which is called drag reduction [1]. This phenomenon is used to improve the energy efficiency in various industrial areas such as the transport of crude oil. This phenomenon was investigated by Toms, and the mechanism of this effect has been a long-standing issue. The interaction between the polymers and the walls of the container, or the turbulent flow itself and the polymers are the main problem for the mechanism of the drag reduction. However, a complete explanation of the phenomenon has not been reported yet. In order to approach the drag reduction effects more simply, turbulence study on flowing soap films as a two dimensional (2D) turbulence is useful. Since flowing soap films show the flow information by reflecting the illumination light, the variation of the turbulence by polymer additives can easily be seen on the interference pattern of the film.

In this thesis, single-image analyses are proposed to quantify flowing soap films as a 2D flow by analyzing the optically reflected interference pattern. Besides, the effects of polymers on the films are quantified by these image analysis methods [2].

The power spectrum $\langle I_G^2(k_x) \rangle$ of the interference patterns is obtained by calculating the intensity of the green channel of the image. The power spectrum shows the scaling law $\langle I_G^2(k_x) \rangle \sim$

k_x^α in the spatial frequency k_x , the scaling exponent α is $-5/3$. This value was predicted by a theoretical research in order to describe the thickness fluctuations of the film. Indeed, the intensity of green channel of the image is related to the thickness of the soap film, that is why, the scaling exponent of the power spectrum of the interference image is consistent with that of the thickness fluctuations [1,2].

The velocity fluctuations are quantified by two methods which analyze the interference pattern. In the first analysis, the curvatures of the interference patterns are calculated. The thickness, the vorticity and the streamlines are related to each other. Besides, the thickness is related to the interference patterns, thus the interference pattern can be related to the streamlines [3]. That is why, the curvature of the interference patterns can be related to the velocity fluctuations by definition. The velocity distribution which is derived from the curvature histogram $P(\kappa)$ can be fitted by the distribution function $P(\kappa) = A_1 \exp\{-A_2(\kappa)^\gamma\}$. In the second analysis, the velocity is connected to the thickness with the equation $h=Q/(VW)$, where h is the thickness, Q is the flow rate, V is the velocity and W is the apparatus constant. Besides, the thickness is related to the intensity of the image, thus the velocity is calculated from the intensity. In this method, the distribution function of the velocity fluctuations is obtained as $P(V - \langle V \rangle) = A_1 \exp\{-A_2(V - \langle V \rangle)^\gamma\}$, where $\langle V \rangle$ is the mean velocity.

Long flexible polymer, polyethylene oxide ($M_w=4,000,000$), is added to the soap solution ranging from 0 to 30ppm in order to see the effects of polymers on the flow. The vortex seen as the interference patterns becomes long and thin by polymer additives. The variation of the flow is analyzed by the image analysis, the thickness fluctuations and the velocity distribution are calculated. The scaling exponent α of the power spectrum of the image is changed from $-5/3$ to -1 . The velocity distribution becomes narrower as seen the decreasing of the value γ . Indeed, these variations were mentioned by the theoretical and experimental work using laser Doppler velocimetry (LDV).

These original image analyses can quantify the turbulence and the effect of polymers from the interference pattern. With this method, the turbulence was visualized and quantified really simply. This method suggests the possibility to analyze complex fluids. That is, the flowing soap films consists of surfactant bilayers, thus the polymer is inside the sandwich structure of the bilayer. Similar confined complex systems can be seen in the nature. For instance, the cell membranes are made by surfactant bilayers that contain proteins. Synovial fluid is also non-Newtonian very thin 2D fluids, which contains biological polymers like a hyaluronic acid. Thus, the investigation of the effects of polymers in flowing soap films has a full of probability to concern not only fluids dynamics but also biological issues.

- [1] H. Kellay et al., *Rep. Prog. Phys.* **65**, 845 (2002)
- [2] R. Hidema et al., *Exp. Fluids*. in press (2010)
- [3] P. Vorobieff et al., *Phys. Fluids*. **11**, 2167 (1999)