学 位 論 文 内 容 の 要 旨

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学 位 論 文 題 名

CFD assisted quantitative flow measurement of Newtonian and non-Newtonian fluid flows
(ニュートン・非ニュートン流体に対する計算流体力学支援型の流体計測技術の開発)

Distributions of velocity, pressure are important to understand the fluid flows of practical importance such as flow over bluff bodies, industrial flows and environmental flows. Velocity distribution can be measured in three dimensions by PIV (Particle image velocimetry) but direct measurement of pressure distribution is still impossible. So, several counter techniques have been proposed for pressure estimation from PIV in literature. These techniques allow simultaneous measurement of velocity and pressure non-intrusively, which also enables the measurement of forces on immersed structures. However, estimated pressure field often suffers from errors propagated from uncertainty of velocity measurement. Error in pressure estimation depends on spatial and temporal resolution of measurement, domain size, aspect ratio and boundary conditions. Through past efforts, pressure estimation had been well investigated for transparent Newtonian fluids. However, in industries, opaque and non-Newtonian fluids are commonly in usage and these are inseparable from our daily needs. Existing pressure estimation techniques based on PIV measurement is not valid for opaque fluids and Non-Newtonian fluids and no study have been performed in this area. Present study is the first attempt to introduce the pressure estimation techniques for opaque Newtonian, opaque non-Newtonian and transparent non-Newtonian fluids. A novel irrotational correction framework is also proposed to provide curl free pressure field.

In chapter 1, background of research and basic theory is discussed followed by objective of the research work. In chapter 2, experimental arrangements and conditions are described. In chapter 3, a novel pressure estimation technique is discussed for opaque flows. PIV is substituted by UVP (Ultrasonic velocity profiler) for collecting velocity data due to its capability of measurement in opaque fluids. UVP can only give the velocity information in 1C-1D (one component- one dimensional) which added a new challenge of pressure estimation because 1C-1D data is insufficient to estimate pressure from Navier-Stokes or Pressure Poisson equations. So. a Unique filtering technique is developed by combination of FFT (Fast Fourier transform) and POD (Proper orthogonal decomposition) to determine unknown component of velocity from equation of continuity. This algorithm is demonstrated in milk flow.

In chapter 4, another pressure estimation algorithm is developed for transparent shear thinning fluids based on PIV measurements. Navier Stokes and pressure Poisson equation cannot be used directly for pressure estimation in these flows. So, momentum equations modified with rheological model are used. Power law and Carreau-Yasuda models are compared by estimating their capability of evaluation the 2D (two dimensional) distribution of viscosity field. This algorithm was tested for cylinder flow in steady and unsteady cases. It was found that the shear thinning property works against the momentum diffusion. In unsteady cylinder flow, it was found that for slowly developing vortices, the present algorithm works, but for separated wake flow it is invalid. Generally, in Newtonian fluids, the pressure Poisson equation is very useful for unsteady flows. But for shear thinning fluid it is invalid. So, a new pressure Poisson is derived for shear thinning fluids. However, this equation could not be utilized for pressure estimation because the spatial resolution of PIV is insufficient to solve new pressure Poisson equation which has four additional source terms consisting of viscosity derivatives. This open problem is addressed in next chapter. An error propagation from uncertainty of velocity to pressure is analyzed by linear precision propagation analysis to understand the specific role of shear thinning in error propagation. I have found that the error propagation increases with error in viscosity, which indicates that the selection of rheological models and parameters are extremely important.

In chapter 5, PIV is substituted by UVP for velocity measurement which can provide a better spatial resolution of velocity data. This also gives the advantage of its application in opaque fluid flows. So, a novel pressure estimation algorithm is developed for shear thinning opaque fluids using UVP. The new pressure Poisson equation for shear thinning fluids is solved for separated wake with UVP data to obtain pressure field. The alternating pattern of low-pressure regions in wake is successfully reconstructed which assures the good performance of algorithm. In parametric study, I have found that the Strouhal number decreases with Reynolds number increment which is opposite of Newtonian fluids.

In chapter 6, an irrotational correction method based on Helmholtz decomposition theorem is proposed for curl correction in estimated pressure from velocity data. It utilizes the curl correction characteristic of Laplacian operator. It is applicable in pressure fields estimated from Navier-Stokes and pressure Poisson equation. Present method is tested in analytical field and experimental data of PIV. It reduces the curl in significant amount and its capability of curl correction is insensitive to noise level. Although low resolution velocity data with high correlation error could lessen its performance of curl correction. The result of curl correction in PIV data showed that curl is reduced to almost zero and it encourages the refusal of velocity filtering techniques which often filter the information of true flow data. If Navier-Stokes is employed for pressure gradient estimation, present method can provide the error free pressure field without performing integration and saves the computational cost a lot.

In chapter7, conclusions and future directions are discussed.