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主 論 文 の 要 旨

論文題目　**Instantaneous Mass Transfer and Wall Shear Stress Measurement using Electrochemical Method and Their Relations to Turbulence Structures in Pipe Flow**
(電気化学的計測法に基づく円管乱流中の物質移行とせん断応力変動の計測及び乱流構造がそれらに与える影響に関する研究)

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論 文 内 容 の 要 旨

The transfer events above the wall in turbulence are important in many practical applications. This is especially paramount in engineering technologies as it is associated with energy dissipation, the heat transfer enhancement of heat exchangers, the flow accelerated corrosion, and the movement of coherent structures in the near-wall region. The transfer events in the near-wall region are mainly divided into three categories: heat transfer, mass transfer, and momentum transfer (wall shear stress).

Previously, studies have focused on the turbulence motion in the inner region, which was not random, and consisted of coherent structures. The large-scale events happening in the viscous sublayer have been studied in the experiment through the relationship between the wall shear stress and the velocity field (Hutchins et al., 2011). The importance of the large-scale streamwise structures in the near-wall region has now been clarified. The wall shear stress, as one of the transfer events in the near-wall region, has been studied as associated with the large-scale streamwise velocity structures in the log-region of the turbulent boundary layer. Based on previous studies, it is estimated that the mass transfer, as another transfer event in the near-wall region, may also be influenced by the large-scale streamwise velocity structures of the log-region. However, the quantitative analysis of the relationship between the mass transfer rate and the large-scale streamwise velocity structures was not thoroughly investigated.

Previously, wall shear stress was representative of the small-scale cycles in the near-wall region for the investigation of the influence of the large-scale streamwise structures in the log-region to the near-wall region. However, accurate wall shear stress fluctuations were difficult to obtain because of the spatial resolution, frequency response, and heat loss of the substrate of the wall shear stress probe. Benefiting from the similarities between the mass transfer and the momentum, the electrochemical measurement was applied in the present research to obtain the wall shear stress. There are two relationships between the mass transfer rate and the wall shear stress that correspond to the method of Hanratty and Campbell (1983) and the Chilton–Colburn analogy. These relationships can be satisfied to predict the time-averaged wall shear stress. However, a comparison between these two methods with respect to predicting the mean wall shear stress has not yet been made. In addition, there are few studies verifying predictions of wall shear stress fluctuations using the Chilton–Colburn analogy.

Although the large-scale streamwise velocity structures have been confirmed to have an influence on the small-scale cycles through a combination of velocity fields and wall shear stress, the other two velocity components (spanwise and wall-normal directions) were not thoroughly investigated. Moreover, the difference between very large-scale motions (VLSMs) and large-scale motions (LSMs) on the effect to the wall shear stress fluctuations has not been investigated yet.

Therefore, the previous studies and their insufficient investigations motivate the present research and make up the present dissertation to quantitatively and qualitatively investigate the relationship between velocity field and mass transfer (and wall shear stress) fluctuations.

In chapter 1, a literature review of turbulence structures is presented. Then, the previous studies of heat (and mass) transfer and wall shear stress is summarized, followed by the motivations and objectives of this dissertation.

In chapter 2, the diffusion-controlled electrochemical method is summarized. Benefit from the flush-mounted electrode, which is imbedded in the wall, this method does not disturb the flow field, that it increases a probability of measuring not only the mean value, but also the instantaneous value of the mass transfer rate or shear stress at a wall surface.

In chapter 3, the flow field and mass transfer rate in a straight pipe was measured simultaneously using particle image velocimetry (PIV) and an electrochemical method, respectively. Turbulence structures of length scales larger than 2.4R in the log-region were studied in relation to the mass transfer fluctuations in the near-wall region. Using the time-series contour, it was confirmed that the footprint of the large-scale turbulent structures in the log-region affects the near-wall region, which enhances the mass transfer rate. By comparing the two-point correlations of the streamwise velocity fluctuation and the mass transfer fluctuation, the mass transfer rate at the wall was observed to be related to the large-scale velocity structures in the log-region.

In chapter 4, the wall shear stress fluctuations were measured using an electrochemical method in pipe flow. Different with the traditional concept of electrode, the electrode for measuring the mass transfer rate is isolated in the electrode for developing the fully concentration boundary layer. The relationship between the mass transfer and the momentum transfer, that studied by Hanratty and Campbell (1983) and the Chilton–Colburn analogy (Chilton and Colburn, 1934), corresponding to the traditional electrode and the new designed overall electrode, are compared to each other with respect to the mean wall shear stress and the wall shear stress fluctuation. From the friction factor, it is found that both methods can accurately predict the mean wall shear stress. The wall shear stress fluctuations are compared via the probability density function and frequency spectrum, which indicate that both methods show similar features for the wall shear-stress fluctuations.

In chapter 5, PIV measurement and electrochemical measurement are applied simultaneously to study the relationship between wall shear stress events in the near wall region and the turbulence structures of VLSMs and LSMs, respectively. The conditional velocity field, based on the negative wall shear stress fluctuations, confirmed the existence of footprints of streamwise and wall-normal velocity components in the VLSMs. Furthermore, the pair of counter-rotating roll modes appears in VLSMs with length scale $\lambda_x > 3R$. However, in the LSMs with length scale of $0.6R < \lambda_x < 3R$, the counter-rotating vortex pair does not appear. In present pipe flow, the threshold of length scale $3R$ for generating the counter-rotating vortex pair is different with 1δ in the turbulent boundary layer (Marusic et al., 2010).

This dissertation concentrates on the investigation of the interaction between velocity field and transfer events above the wall. The PIV measurement is applied to obtain the velocity fluctuations of three components, the electrochemical method is used to obtain the transfer events which are mass transfer fluctuations and wall shear stress fluctuations above the wall. The simultaneous PIV measurement and electrochemical measurement are performed to quantitatively investigate the relationship between velocity field and mass transfer (and wall shear stress) fluctuations.