Large-scale flow structures and their role in mass transfer rate enhancement behind an orifice

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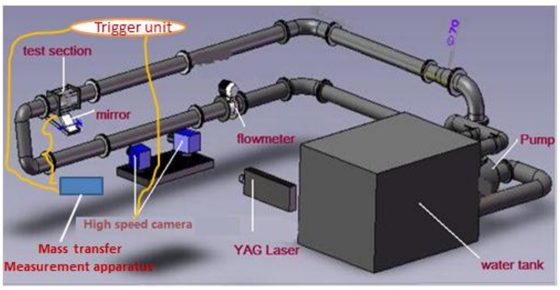
Abstract Mass transfer rate of several positions at the wall and turbulent flow field behind an orifice in a circular pipe are measured simultaneously by means of limiting current technique and stereo-particle image velocimetry respectively. Proper orthogonal decomposition is implemented to extract the large-scale coherent structures of the flow field, and mass transfer rate time series are decomposed into multi-scale components by wavelet transform. It is found out that mean wavelet energy spectrum distributions of large scale flow structures and large scale components of mass transfer rate are quite similar, moreover, they have large common cross wavelet power and in-phase complex angle and high conditional correlation, which strongly suggests the important role of the large-scale coherent structures in mass transfer rate enhancement behind an orifice.

Introduction

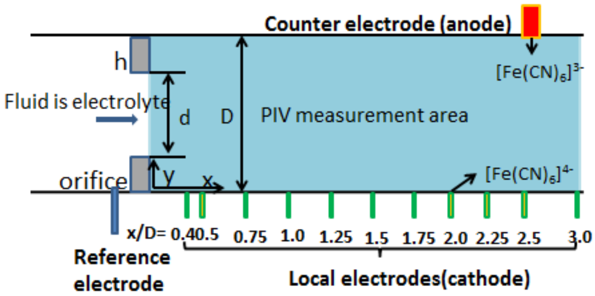
Although many researches have already been done from either the view point of flow field or mass transfer rate enhancement behind an orifice, few of them are devoted to the relationship of flow field and mass transfer rate. This is partly because of the difficulties encountered in the simultaneously detailed measurement of flow field and mass transfer rate. With the development of time-resolved particle image velocimetry, turbulent flow field can be measured with a relatively high temporal resolution and spatial resolution comparable to numerical simulation, which offers the possibility to assess the relationship between flow field structure and mass transfer rate experimentally.

Experimental set-ups

The experimental system encompasses a time-resolved stereo-particle image velocimetry [1] flow field measurement system and a mass transfer rate measurement system based on limiting current technique [2]. The flow field measurement system and the mass transfer rate measurement system are synchronized by an external trigger, and the sampling frequency of both systems is set at 1k Hz. The flow field up to about 3 pipe diameter downstream and mass transfer rate at several locations at the pipe wall are measured as shown in figure 1(b).



(a) sketch of the whole system



(b) enlarged test section

Fig.1 Overview of the experimental system

Results and discussions

Proper orthogonal decomposition is implemented to extract the large-scale coherent structures of the flow field, and the processes are similar to [3]. The most two dominant large-scale structures of flow field are extracted, the vertical flapping and the compression and expansion structure [4], whose dynamical information are contained in their POD reconstruction coefficients. Wavelet transform is already at our disposal for the multi-scale analysis [5], which is employed to decompose the mass transfer rate time series and POD reconstruction coefficients of the large-scale coherent structures into multi scales. Both the mean wavelet energy spectra and the Fourier spectra of the of the vertical flapping structure and the mass transfer rate at x/D =1 is shown in figure 2 as an example, from which it can be seen that, wavelet spectra are much smoother than their Fourier counterpart, and in the low frequency (large scale) region, the spectrum distribution of vertical flapping structure and mass transfer rate is very similar to each other, nevertheless the slopes of the two wavelet spectra at high frequency differs very much, which is probably because the small scale components of mass transfer rates are determined by some small scale structures in the vicinity of the wall. If the large scale coherent flow structures can affect the mass transfer rate at the wall, there must be relationship in some way between mass-transfer rates measured at different locations with relatively large distance. On one hand cross wavelet transform [6] can be used to assess the relationship between two mass transfer time series measured simultaneously at different locations with relatively large distance, figure 3 shows the cross wavelet transform of mass transfer rate at the

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1st and the 4th electrode with a distance about 0.6D (D is the pipe diameter) as an example, the colour of the contour plot represents cross wavelet amplitude, and the directions of the arrows represents the phase relationship of the two mass transfer time series, if the arrow points right, the two time series are in phase, for a detailed description of the meaning of cross wavelet transform, refer to [6]. It can be concluded that in the frequency region of 1~10Hz, which is actually the frequency region of the large-scale flow structure, the two mass transfer time series have large common cross wavelet power and in-phase complex angle, that is to say, they change coincidently in the frequency region of large scale flow structures. On the other hand, we can reconstruct the large-scale components of mass transfer time series and calculate the correlation of their large-scale components, which we call the conditional correlation. The large scale components of mass transfer time series at the 1st and the 2nd electrode are shown in figure.4 as an example, from which it can be seen that the large scale components of the two mass transfer time series change almost coincidently, moreover, the no time lag conditional correlation reaches above 90% though the correlation is actually less than 10% if we consider the original two mass transfer time series.

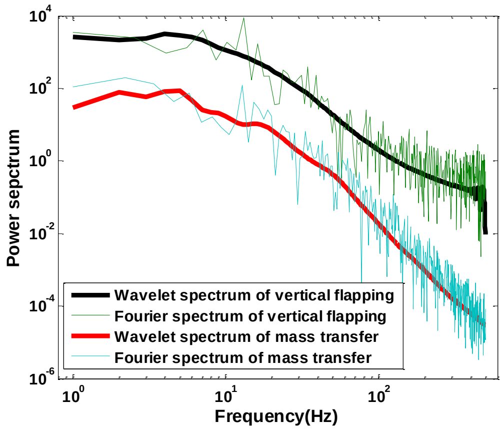

Fig.2 Comparison of mean wavelet spectrum of vertical flapping structure and mass transfer rate

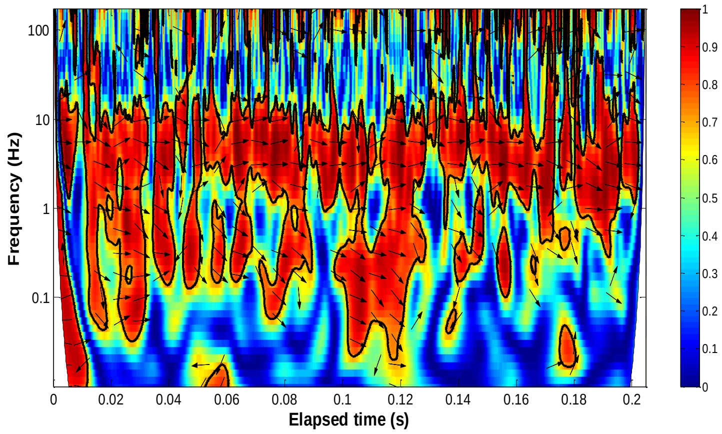

Fig.3 Cross wavelet transform of mass transfer rate at the first and the fourth electrode,

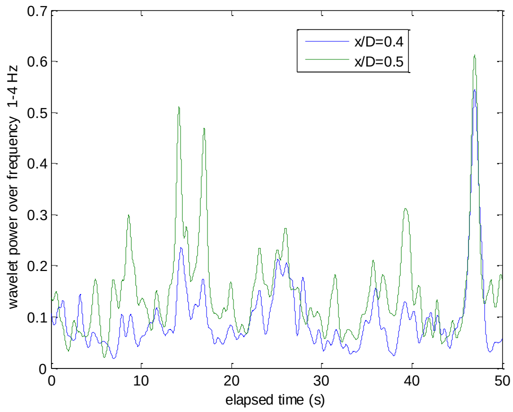

Fig.4 large scale component of two mass transfer time series

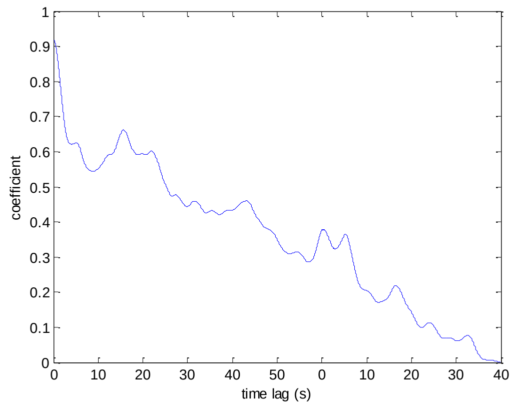

Fig.5 correlation of the two large scale mass transfer in fig.4

Conclusions

Detailed flow field and mass transfer rate at several positions are measured simultaneously behind an orifice in a circular pipe. Two dominant large scale structures are extracted by proper orthogonal decomposition, the vertical flapping and compression and expansion. Dynamical properties of the large scale flow structures and mass transfer rate time series are decomposed into multi-scale components by wavelet transform. The similar mean wavelet spectrum distribution of large flow structures and mass transfer rate suggests that those large scale flow structures are probably the driven force of the mass transfer enhancement. Meanwhile, large common cross wavelet power with in phase complex angle and very high conditional correlation of mass transfer time series at different positions with large distance proves the role of large scale flow structures in mass transfer enhancement behind an orifice.

References

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