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On flow structures associated with large wall mass transfer coefficients in orifice flows

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ABSTRACT

In this study, the turbulent flow field is simultaneously measured by stereoscopic particle image velocimetry (SPIV) and the wall mass transfer coefficient using the limiting diffusion current technique (LDCT). SPIV measurements of the flow field behind an orifice in a round pipe are performed in the cross and longitudinal sections. One-point linear and quadratic stochastic estimations are employed to calculate the conditional average of the flow field associated with the large wall mass transfer coefficient. The results suggest that the counter-rotating vortex pairs play an important role in the large wall mass transfer coefficient. The flow structures associated with a large wall mass transfer coefficient in the cross sections are found to be similar to the flow structures enhancing the wall heat transfer obtained by a theoretical analysis and numerical study in literature.

1. Introduction

The heat and mass transfer behind orifices is of considerable theoretical and engineering importance, as this phenomenon appears widely in a variety of engineering applications. Consider, for example, the problem of pipe walls thinning in nuclear/fossil power plant pipelines. Such wall thinning is mainly caused by flow-accelerated corrosion (FAC), which is common in carbon steel pipes, where the wall's iron ions diffuse into the turbulent bulk flow through the oxide layer coating the wall's surface [1]. Although FAC is affected by many factors—such as flow field, water chemistry, and temperature—the rate at which walls thin in nuclear/fossil power plant pipelines is generally considered to be the result of a mass transfer phenomenon driven by the concentration gradient of the iron ions on wall surfaces and in the bulk flow [1]. Indeed, a popular area of study within FAC research is determining what kinds of flow structures enhance the mass transfer coefficient at the wall (hereafter referred to as the "wall mass transfer coefficient"). However, this topic involves a basic and difficult problem—that is, the necessity of simultaneously measuring the concentration field (or, equivalently, the wall mass transfer coefficient) and the velocity field in wall-bounded flows.

The present paper focuses on flow structures associated with large wall mass transfer coefficients at high Schmidt numbers (larger than 1000) behind circular orifices in round pipes. Our study is conducted in relation to an actual instance of pipe-wall thinning that caused a very serious accident at the Japanese Mihama Nuclear Power Plant in 2004 [2]. Although this study only deals with mass transfer, it is possible to use the Chilton–Colburn analogy to consider a relation between wall mass transfer and wall heat transfer; thus, this study could also be of some value when discussing structures associated with wall heat transfer.

Orifice flow is a typical, separated, internal flow that includes extremely complex flow separation, reattachment, and redevelopment processes. A separated internal flow may be encountered in many practical situations—such as in the immediate vicinity of valves, orifices, nozzles, and boiler tube gags as well as in sudden changes of the pipeline diameter, and it may also exist in the region adjacent to electrochemical cell inlet ports. Hence, it is widely believed that the characteristics of flow structures associated with large wall mass transfer coefficient should exist in many flow fields. Previous research relating to the characteristics of heat/mass transfer in separated internal flows has mainly concentrated on two findings: the peaked, streamwise distribution of heat/mass transfers downstream of sudden pipe changes and the empirical relation between the peak heat/mass transfer values, the Reynolds number, and the Prandtl/Schmidt number [3–5].

With the development of supercomputers, a number of numerical simulations of turbulent mass transfers at solid boundaries have been reported in recent years [6–9]; there is a comparative lack of experimental research regarding turbulent mass transfers

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at solid walls—particularly in the case of separated internal flows. For example, Yamagata et al. have measured the wall mass transfer coefficient behind an orifice in a circular pipe using the benzoic acid dissolution method in a water flow [10]—a method that allowed them to measure the mass transfer at the Schmidt number under conditions that were similar to the actual operating conditions of the pipeline. Their results indicate that, because of flow turbulence, the Sherwood number behind the orifice reaches its maximum value within an area of 1–2 pipe diameters from the orifice; that value then decreases gradually downstream. This trend agrees qualitatively with the features of pipe-wall thinning data; moreover, although their Schmidt number greatly differs from the value we obtain in our mass transfer study wherein the electrochemical method is used [11], the distribution of the wall mass transfer coefficient agrees qualitatively well. The different orifice to pipe diameter ratios (β ratios) and the thicknesses of orifice plates are believed to be responsible for the discrepancies. Utanohara et al. report that the profile of the measured FAC rate can be well correlated with the profile of the root mean square of the wall shear stress, as was predicted by LES [12]; their flow field results, as predicted by RANS and LES, were validated by their LDV data.

Furthermore, some researchers have used the naphthalene sublimation method to measure the wall mass transfer coefficient of flows behind orifices and have discussed the mechanism involved in asymmetric pipe-wall thinning in relation to the combined effect of swirling flow and orifice bias [13,14]. In this respect, the naphthalene sublimation method allows the measurements of mass transfer coefficients in air flows at low Schmidt numbers. In addition, some researchers have studied the effects of swirling flow on mass and momentum transfers downstream of a pipe with elbow and orifice [15]. More specifically, they have used the plaster dissolution method to measure the distribution of the wall mass transfer coefficient downstream of the orifice and have explained why the pipe-wall thinning rate is not uniformly distributed when there is swirling flow upstream of the orifice plate [15]. This nonuniform distribution of pipe-wall thickness in the circumferential direction of the pipe greatly accelerates pipe breakdowns in the industry. In addition, proper orthogonal decomposition (POD) has been applied to analyze the large-scale energetic turbulent structures responsible for nonuniform thicknesses within pipe walls [16]; such findings greatly contribute to our understanding of the nonuniform distribution evident in the Mihama Nuclear Power Plant pipe that is herein evaluated.

Despite the considerable amount of research conducted, interactions between the underlying flow structures at a solid boundary and the associated turbulent heat/mass transfer are still not well understood because of the various obstacles involved in simultaneously measuring velocity and concentration fields close to a solid boundary. The present study is a continuation of our previous work relating to the characteristics of a flow field [17] and that relating to the relationship between a flow field and mass transfer at a wall [11]. Although we have already shown that a strong relation exists between fluctuations in the wall mass transfer coefficient and velocity components, it is still difficult to say what kind of flow structures are responsible for enhancing the wall mass transfer coefficient just by looking at the contour plot of the spatial–temporal correlation of the wall mass transfer coefficient and the flow field. This objective can be fulfilled by using the conditional average technique. More specifically, we can conditionally average the flow field when the wall mass transfer coefficient is large. However, a conventional conditional average is not practical if we are using the time-resolved PIV measurements, which require huge amounts of computer memory and other computational costs. Fortunately, stochastic estimation is able to calculate the conditional average with much less data. stochastic estimation is the approximation, or estimation, of a random variable in terms of other random variables [18]; Adrian first proposed of its application to extract coherent motion in turbulent flows [19]. Since then, it has been widely used in the community of fluid dynamics (for example, [20–22]), where the velocity field or pressure has been mostly used to perform stochastic estimation. Indeed, the accuracy of stochastic estimation has been tested many times in many different flows, always with almost unreasonable success [23]. Therefore, in this study, we use stochastic estimation to estimate the conditional average of the flow field when a very large wall mass transfer coefficient appears; this, thus, enables us to focus on the structures associated with large wall mass transfer coefficients. To the best of our knowledge, this is the first study to use a wall mass transfer coefficient in the stochastic estimation of flow field structures.

2. Experimental setup

The problem of pipe-wall thinning is not directly discussed here; instead, we consider the pipe-wall thinning problem as a wall mass transfer phenomenon in which ferrous ions from the carbon steel wall transfer into the bulk flow. This consideration is consistent with a theoretical consideration that views pipe-wall thinning in relation to corrosion [24]. For this study, LDCT was used to measure the wall mass transfer coefficient. For a detailed discussion of LDCT, please refer to [11] and the references therein. In LDCT, we used a polarized condition wherein an adequately large voltage was applied to an electrochemical cell in which the current was controlled by the rate of the wall mass transfer coefficient and wherein the concentration of the reactant was always zero at the surface of the test electrode. The measured electric current was therefore proportional to the mean rate of the mass transfer over the test electrode.

Fig. 1 shows a sketch of the SPIV in both cross and longitudinal sections. A three-electrode system was employed in the chemical reaction [11], which used a small cathode to measure the local wall mass transfer coefficient, a much larger anode, and a reference electrode. The local electrodes acting as the cathode in the electrochemical reaction are depicted as small yellow dots in Fig. 1; note that, to clarify the test section, only some of the local cathodes are shown in the figure. The cathodes for measuring the local wall mass transfer coefficient are circular and have diameters of 1 mm. The anode is much larger than the local cathode and is a circular ring (with a thickness of 1 cm) mounted flush against the pipe wall, as shown in Fig. 1. In our former study [11], we determined the location of the maximum mean wall mass transfer coefficient to be $x_{max} \approx 2R$.

We made two types of simultaneous measurements, as indicated by the laser sheet in Fig. 1. Note that, only some laser sheet locations are shown to clarify the figure. We simultaneously measured the flow field in the longitudinal section and the wall mass transfer coefficient at the location of the maximum mean wall mass transfer coefficient x_{max} ($x/R = 2.0$) just as we did in the previous study [11]. Additionally, we simultaneously measured the flow field and the wall mass transfer coefficient of three cross sections at x/R = 1.8, 2.0 and 4.0, respectively. Therefore, in this study, we discuss flow structures based on both the longitudinal and cross sections, as shown in Fig. 1.

The viscosity of the working fluid was measured by a viscometer, and its density ρ was calculated by the equation $\rho = m/V$, where m and V are the mass and volume of the working fluid, respectively. The Reynolds number based on the pipe's diameter and mean velocity was 25,000, and two temperatures of the working fluid (T = 283 K, 298 K) were measured, which correspond to two Schmidt numbers (2770 and 1600). All other experimental conditions were similar to those in our previous study [11].