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Vortex shedding in a highly porous structure

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HIGHLIGHTS

- We investigate the flow in a continuous milli-reactor with highly porous inserts.
- Vortex shedding emerges from ligaments and interconnections of ligaments (nodes).
- Shedding frequencies are smaller behind nodes than behind ligaments.
- Smaller wake lengths are observed behind ligaments than behind nodes.
- Vortex shedding is identified as transport mechanism for mixing and heat transfer.

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ABSTRACT

Highly porous media (with a porosity $\geq 85\%$), like metal foams, fins or designed porous inserts are widely used in industrial flow applications. Motivated by the use of highly porous inserts in continuous chemical reactors, the time dependent behavior of flows through a highly porous structure is investigated experimentally and numerically for Reynolds numbers $Re_D=33$ and 330 (based on the ligament diameter and the bulk velocity). The experimental studies are based on the Particle Image Velocimetry (PIV), whereas the numerical studies are conducted by using the Large Eddy Simulation (LES) approach with the dynamic Lagrangian subgrid closure. The vortex shedding phenomena is observed for both values of Reynolds number. It is demonstrated that the length of the wake and the orientation of the shedded vortices are dependent on the position within the highly porous structure.

1. Introduction

Highly porous media are often found in industrial flow applications. Fins and metal foams are built in heat exchangers and their outstanding thermal properties lead to the use of highly porous media in continuous chemical reactors. In the chemical industry milli-reactors replace recently more and more classical batch reactors. These milli-reactors have a typical length scale of several millimeters and throughput of liters per minute. Smaller, more compact systems are favorable to large-scale batch reactors in terms of energy and resource savings and enhanced safety. A promising approach of a milli-reactor concept is a system with highly porous inserts. Hutter and Allemann (2010) and Hutter et al. (2011b,c) investigated mixing, residence time distribution and heat transfer in milli-reactors based on metal foams or designed highly porous inserts. These results suggest that milli-reactors with highly porous inserts are suitable for fast, exothermic and catalyst driven reactions. Besides the promising results of our milli-reactor less is known about the underlying physics and so design criteria are mainly missing.

The porous media can be considered as a complex bundle of tubes (Horton and Pokrajac, 2009), and so a generic model consisting of an array of braced cylinders was chosen to represent the milli-scale reactor. Porosity, pore and ligament sizes of the 3D arranged cylinder array agree with geometrical properties of a typical milli-scale reactor. As milli-scale reactors are tubular reactors, the 3D arranged cylinder array is confined in a duct to study end-wall effects. The required industrial throughput and ligament diameters in the millimeter range result in Reynolds numbers (based on the cylinder diameter D and the bulk velocity u_b) to be in $10 \leq Re_D \leq 300$ range. Flows around a single cylinder for this Reynolds number range exhibit the onset of vortex shedding and the transition from laminar to unstable, irregular vortex shedding. In the phenomena of vortex shedding vortices are formed directly behind the cylinder and shed off downstream. This

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phenomena was first described and analyzed by Bénard (1908) who pointed out its importance and von Kármán (1912) who introduced a model on the formation of the vortex street. Roshko (1954) defined first different shedding regimes.

Multiple cylinders configurations have been extensively studied and comprehensive reviews are given by Ohya et al. (1989) and by Sumner (2010) for two cylinder flows. The flow of multiple cylinder configurations is characterized by interactions of vortex shedding and shear layers of the different cylinders. Classification was undertaken in dependence on the arrangement of the cylinders to each other. The most simple arrangements are the tandem and the side-by-side configuration, in which two cylinders are for the first case parallel aligned to the flow and in the second case perpendicular to the flow. The most general arrangement for two cylinders is the staggered arrangement, in which two cylinders are arranged at an arbitrary angle to each other. For more than two cylinders Zdravkovich (1987) did further classifications. A further distinction considers the cylinder's aspect ratio (height to diameter ratio), where either end-wall effects can be neglected in the case of "infinite cylinders", or in the case of "finite cylinders" have to be taken into account. The different categorizations can cause interference, that were classified by Zdravkovich (1987) and Gu and Sun (1999). Originally Zdravkovich (1987) introduced two types of interference, namely the wake interference and the proximity interference. In wake interference one cylinder is partially or completely submersed by the wake of the other, like for instance in a close arrangement of the tandem or the staggered configuration. In the case of proximity interference, the two cylinders are located closely to another, but none of both is influenced by the wake of the other. Side-by-side configurations can exhibit proximity interference. Motivated by staggered configuration results (Gu and Sun, 1999) extended (Zdravkovich, 1987) classifications to three different interference types: wake interference, shear layer interference and neighborhood interference.

Most of these multiple cylinder studies content only two cylinders. Oengoren and Ziada (1998) and Iwaki et al. (2004) investigated vortex shedding in tube bundles. Ostanek and Thole (2012) considered several rows of short cylinders (height-to-diameter ratio=1) in staggered configurations, where wall effects influence the vortex shedding. Other experimental pin-fins studies with similar geometrical arrangements were performed by Ames and Dvorak (2006) and Ames et al. (2007). Numerical studies of pin-fins were conducted by Delibra et al. (2009, 2010). The effect of disordered single rows of cylinders on heat transfer was studied by Ambesi and Kleijn (2012). From these studies it is known that the frequency at which the vortices shed off (the shedding frequency) is dependent on the cylinder size. Smaller diameters imply larger shedding frequencies.

In contrast to previous studies addressed in literature, we investigate the geometry where cylinders are interconnected by nodes (so called 3D arranged cylinder array), which mimics flow conditions of the above described milli-reactor system. The velocity field measurements are performed for two values of Reynolds number, Re_D=33 and 330. These particular values of Reynolds numbers, when applied for a flow past a single cylinder, produce flow regimes with steady respectively unsteady wakes behind the cylinder. Combined experimental and numerical studies are used to provide detailed insights into flow dynamics (localized transient states, vortex shedding) in the 3D arranged cylinder array. These results can be used for validation of numerical models and can provide design criteria for the new generation of milli-reactors.

2. Methods

2.1. Water channel facility

Experiments were conducted in a water channel facility, Fig. 1. The 3D arranged cylinder array consists of a series of periodic units

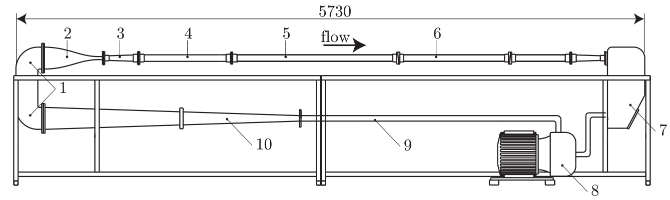

Fig. 1. Water channel facility. (1) Turning elbows, (2) nozzle, (3) diffuser, (4) nozzle, (5) entrance channel, (6) measurement section, (7) reservoir, (8) frequency controlled pump, (9) pipe, (10) diffuser.

and is inserted in the measurement section. The measurement section and the cylinder array are made of acryl glass to have optical access. A periodic unit of the cylinder array is schematically drawn in Fig. 2. It consists of round ligaments with diameters D of 1.77 mm and pore sizes d_p of 10.73 mm. The porosity ε is 93%. Milli-reactors have pore sizes d_p in the order of several millimeters and porosity $\geq 85\%$ and so the here considered geometry is an upscaled version, which mimics flow conditions found in milli-reactors. The array has a total length of 487.56 mm, which corresponds to 39 periodic units. The structure is build in a square channel of size length H=50 mm and axial length of 1000 mm. Upstream of the measurement section is an entrance channel with the same size length as the test section and a total axial length of 1500 mm. The entrance channel guarantees a fully developed duct flow which was laminar in the case of Re_D=33 and turbulent for Re_D=330 with a turbulence intensity of 5%. A nozzle and a diffuser in front of the entrance channel ensure smooth transition from the first nozzle with width 360 mm and height 30 mm. Originally the water channel facility was used to study flows over wavy walls in a channel with width 360 mm and height 30 mm (Guenther, 2001). Experiments were conducted at Re_D from 33 up to 330 with deionized water.

2.2. Experiments

Two dimensional Particle Image Velocimetry (2D PIV) was used to study flows through porous medium. Velocity fields were measured in (x_1, x_3)-planes in the middle of the channel at x_2/H=0.5, after the 29-th periodic unit, Fig. 2. This position far downstream guarantees fully developed, periodic flow conditions. An ensemble of 1000 image pairs was taken for all measurements by a CCD camera with a pixel resolution of 1344 $\times$ 1024 pixels^2 at a frame rate of 5 Hz. As light source a Nd:YAG dual pulsed laser was used. Deionized water was used as working fluid. The different refraction indices of water and acryl glass do not allow to measure velocities in the entire (x_1, x_3)-plane. However, the large optical access of the (x_1, x_3)-plane offers extensive measurements in the pores of the porous media. The water flow was seeded by hollow glass spheres of 10 μm in diameter (density: 1100 kg m^{-3}). The sizes of the field of view (FOV) of different measurements are given in Table 1. Dantec Dynamic Studio©'s was used to record and process the image pairs. First a background subtraction was applied on the recorded images to reduce noise. Adaptive cross-correlations with initial interrogation areas of 32 $\times$ 32 pixels^2 and final interrogation areas of 16 $\times$ 16 pixels^2 were applied to the pre-processed image pairs to determine velocity fields. At every cross-correlation step an overlap of 50% and window deformation were used to all interrogation areas. Spurious vectors are detected by a median filter and replaced by local interpolation. Detailed information about spatial resolutions of the different measurements are summarized in Table 1.

Sampling errors are evaluated by a bootstrap analysis. For every measurement, the spatio-temporal statistics are calculated from 800 randomly chosen velocity fields (out of 1000), and this procedure is repeated 350 times. A confidence level, which is defined by twice the