Reconstruction of three-dimensional particle trajectories in flows through curved circular tubes

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Abstract. An automated technique is described for reconstructing three-dimensional trajectories of tracer particles in curved circular ducts. Individual particles are tracked in real time by a rotating camera under computer control. A digital imaging system enables the computer to locate the particle, adjust the speed of rotation, and store position and calibration data. By viewing the tube from approximately orthogonal directions, three-dimensional information on the position of the particle is obtained. Its precise location is calculated by tracing rays from the camera to the interior of the tube. This technique yields detailed three-dimensional position and velocity data along a trajectory.

1 Introduction

Fluid flows through curved circular tubes have received much attention because of their importance in engineering design applications and their role in the formation of atherosclerotic lesions in large blood vessels. For small curvatures, the steady flow possesses a secondary motion in which the fluid near the middle of the tube moves towards the outer wall. Two counter-rotating vortices exist above and below the plane of symmetry, and as the fluid moves down the pipe, the fluid particles follow helical trajectories. Experimental and theoretical work by Dean (1928), Berger et al. (1983), and others have elucidated many aspects of the fully-developed and entrance flows. Questions still remain concerning multiple vortex states (Daskopoulos and Lenhoff 1989), flows in highly curved ducts (Bovendeerd et al. 1987), and time-dependent behavior described by Hamakiotes and Berger (1990).

Previous experimental work has primarily involved laser-Doppler anemometry (LDA) to obtain velocity field information. A number of studies were done by Agrawal et al. (1978) and Talbot and Gong (1983). Other techniques involved tracer materials to visualize the flow such as the work by L. H. Back et al. (1987, 1988) and Akiyama et al. (1985). Wall shear rates have also been measured by Choi et al. (1979). None of these studies, however, probed the full three-dimensional motion of a fluid element, and therefore could only reveal partial information on the vortex nature of flows through curved ducts.

In our lab, we have developed a flow visualization technique for real-time tracking of particles inside curved circular tubes. The apparatus consists of an automated position feedback system which monitors the locations of individual particles using a mobile camera under computer control. This approach has a number of advantages. Unlike velocity field measurements, three-dimensional position and velocity data along actual particle trajectories can be obtained. This technique can track particles with widely varying velocities, such as those occurring in the outer regions of the Dean vortices, which cannot be monitored if the camera is moving at a constant rate. It can also measure both positive and negative velocities, and is therefore well-suited for studying pulsatile flows. In this paper, we describe the apparatus, the preparation of the particles, the data acquisition system, and the trajectory reconstructions. Although this description directly pertains to the apparatus in our laboratory, the instrumentation can be easily adapted to other experimental needs.

2 Apparatus

The test section, shown in Fig. 1a, consists of a transparent curved circular tube in the form of a 270° bend with a 15" radius. The tube has an inner diameter of 1.5" and a wall thickness of 3/16". The test fluid, generally water, is circulated through the duct by means of a gravity feed system, and exits the test section through tubing that is gently bent under the entrance. Near-Poiseuille flow conditions are established at the inlet through a long straight section preceding the curved region. Small tracer particles are individually injected at controlled times and positions in the straight section, and detected over the full length of the curved tube by a camera located at the center. The temperature of the fluid is matched to room temperature and regulated to limit variations within the tube to less than ±0.1°C.
2.1 Preparation of particles

Accurate matching of the specific gravity of the particles to that of the surrounding fluid is achieved by mixing two miscible organic fluids, known as Cargille Heavy Liquids, which can be purchased in a wide range of densities. (The composition is proprietary.) Since their densities vary with temperature by about \(-10^{-3}\) g/cc/°C at 15°C–35°C, compared to about \(-2 \times 10^{-4}\) g/cc/°C for water, the mixture required to match densities is temperature dependent. Particles are formed by “flicking” a small quantity of organic fluid into a jacketed beaker containing water at the same temperature as the test fluid. This process forms a large number of small spherical droplets (about 0.5–2 mm in diameter) whose buoyancy can be easily observed. If the densities do not match, the mixture can be adjusted and the particle buoyancy tested again. A small quantity of Solvent Green 3 dye (Aldrich Chemical Company) is added to intensify the contrast between the particle and the surrounding fluid. This procedure enables the specific gravity to be matched to within 0.1%.

To inject the particles into the tube, the droplets and surrounding water are withdrawn from the beaker with a wide pipette and a large syringe. The pipette is inserted into a port in the tube, and particles are injected individually. Water must always surround the droplets to prevent adhesion of the organic fluids to the pipette walls. In order to accurately monitor the flow, we choose the smallest possible particles which can still be reliably tracked. This minimizes the terminal velocity in the case of a density mismatch, disruption by the particle of the flow, the distortion of a spherical droplet shape due to shear, corresponding reorientation effects and transverse motion to the streamlines. Internal circulation may exist although this was never detected by our apparatus.

2.2 Rotating camera and position feedback system

The particles are detected by a Pulnix CCD camera (Model TM 545) located at the center of curvature of the tube. As shown in Fig. 1a and b, the camera is mounted on a scissor jack and ball bearing table. A motorized arm under computer control drives the rotation of the platform supporting the camera, enabling the particle to always be in the field-of-view as it moves along the tube. The camera is aimed directly at the tube and at a mirror positioned rigidly above the tube to acquire the “direct image” and “mirror image”, respectively. By viewing the particle simultaneously from the side and the top, three-dimensional information on the particle position can be obtained.

The motorized arm consists of a motor/tachometer (Pittman GMT 9413-2) with an off-center shaft and a rubber tire for traction and vibration isolation. The radius of the tire, the rotation rate of the motor, and the length of the arm are matched to the velocity of the flow. In our apparatus, the tire has a diameter of 1 5/8” and is located 13” from the center of curvature. While a large range of rotation rates can be easily achieved, in practice the maximum rate is about 0.25 rad/s, corresponding to a flow with a Reynolds number of about 1,800. This is primarily due to software limitations in tracking which are discussed in Sect. 3. Fine control of motor speeds is achieved by a power amplifier circuit and a position feedback system involving the computer. The camera, mirror, motorized arm, and electronics are rigidly mounted onto a platform and rotate as a single unit.

To track, a position feedback system monitors the location of the particle and controls the rotation rate of the camera. This system consists of the camera assembly, described above, a personal computer with a 20 MHz 80386 processor and ISA bus (Everex), a frame-grabbing board with 512 x 480 pixel resolution (Imaging Technology PC-VISIONplus), a 12-bit analog and digital I/O board (Data...