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Non-intrusive experimental investigation of flow behavior inside a 5 × 5 rod bundle with spacer grids using PIV and MIR

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A R T I C L E I N F O

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A B S T R A C T

The validity of the simulation results from computational fluid dynamics (CFD) is still under scrutiny. Some existing CFD closure models for complex flow produce results that are generally recognized as being inaccurate. Development of improved models for complex flow simulation requires an improved understanding of the detailed flow structure evolution with dynamic interaction of the flow multi-scales. Thus, the goal of this work is to contribute to a better understanding of presupposed and existent events that could affect the safety of nuclear power plants. The fundamental phenomena of fluid flow in rod bundles with spacer grids can be elucidated by using state-of-the-art measurement techniques. This study aims to develop an experimental data base with high spatial and temporal resolution of fluid flow velocity inside a 5 × 5 rod bundles with spacer grids. The full-field detailed data base is intended to validate CFD codes at various temporal-spatial scales. Measurements are carried out using dynamic particle image velocimetry (DPIV) technique inside an optically transparent rod bundle utilizing the matching index of refraction (MIR) approach. This work presents full field velocity vectors and turbulence statistics for a rod bundle under single phase flow conditions.

1. Introduction

Fluid flow around circular cylinders is one of the classical problems of fluid mechanics and has been well studied because of its common occurrence in many forms and in different applications. Cylinder-like structures can be found both alone and in groups in the designs for heat exchangers, cooling systems for nuclear power plants, offshore structures, power lines, struts, grids, screens, and cables, in both single and multi-phase flows. A complete understanding of the fluid dynamics for the flow around a circular cylinder includes such fundamental subjects as the boundary layer, separation, the free shear layer, the wake, and the dynamics of vortices. The flow field of multiple-cylinder configurations involves complex interactions between the shear layers, vortices and Karman vortex streets (Zdravkovich,1987). The problem is further complicated by the large number of configurations encountered in practice, resulting in different flow patterns, and by the effect of their interactions.

One of the applications of paramount importance in this study is fluid flow in fuel rod bundles of water nuclear reactors. In this type of nuclear reactor, optimum heat removal from the surface of fuel elements is the subject of many studies for researchers in order to determine reactor thermal margin and safety. In these reactors, the spacer grids which support the fuel assembly are used as an effective mixing device by attaching various types of flow deflectors. Several recent works are focused on the development of numerical simulations that predict the complex behavior of fluid flow close to grid spacers and between fuel assemblies.

The validity of the produced results from computational fluid dynamics (CFD) is still under scrutiny for several applications in real practical cases. Moreover, the existing models for multiphase flows produce results that are generally recognized as unreliable. Development of better models for multiphase simulation requires an improved understanding of the flow evolution with dynamic interaction of the flow multi-scales. Therefore, experimental data is urgently needed for validation of the CFD models.

In order to establish reliable design and performance criteria for tube bundle models, better velocity data is needed. Simonin and Barcouda (1988) conducted experiments using laser Doppler anemometry (LDA) within a specific tube arrangement. Although they gathered some velocity data in cross-flow over a tube bundle, the data points were limited and detailed velocity distributions, or whole flow field data was not available due to the nature of the LDA technique. Chang et al. (2008) used 2D-LDA measurements in a 5 × 5 rod bundle array scaled to be 2.6 times larger than the actual bundle size. This work focused on the performance and mixing characteristics of two kinds of spacers with turbulence enhancement vanes. The used spacer grids were of a typical split and swirl type for pressurized water reactors (PWR). The experiments were performed at a condition of Reynolds number of Re = 48,000 and pressure of 1.5 bar.

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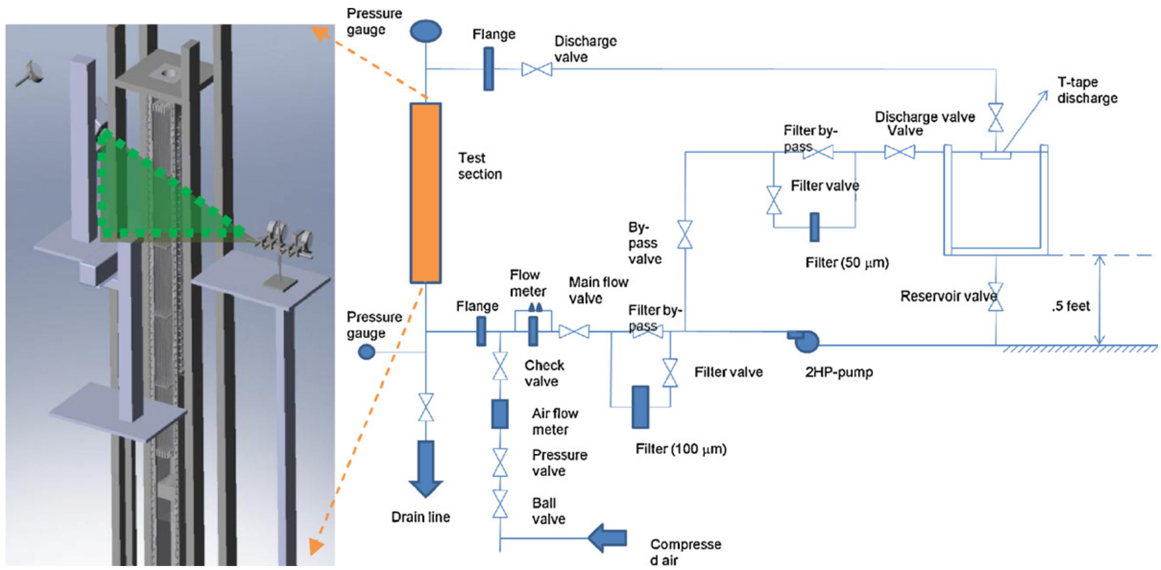

Fig. 1. Schematic diagram of the experimental hydraulic loop and test section.

They reported the velocity at various axial positions ranging from one hydraulic diameter to 16 hydraulic diameters. The reported accuracy of the velocity measurements is about 1.6%. However, the use of laser Doppler velocimetry (LDV) methods was restricted by the existence of invisible regions in fuel rod bundles and insufficient spatial resolution for the narrow gaps in rod bundles. Ikeda and Hoshi (2006) developed a miniaturized LDV system embedded in a fuel cladding. The rod-embedded fiber LDV can be inserted in an arbitrary grid cell instead of a fuel rod without disturbing the flow. They obtained flow velocity data in a 5 × 5 rod bundle typical of a PWR fuel assembly. Measurements were carried out for a central rod with a pitch-to-diameter ratio $P/D = 1.326$ with a hydraulic diameter, $D_h = 9.75$ mm. The Re number used was 57,000. The reported uncertainty in velocity data was 2.1%. In their work, the conditioning grid was without mixing vanes. They showed results of axial and cross flow velocity. The cross flow data indicated that positions close to the grid had velocities 40% greater than positions farther from the grid. The velocity fluctuations also increased as much as 100% at positions far from the grid compared to positions close to the grid. In the case of the axial-flow velocity, the mean flow velocity at $X = 3.1D_h$ was smaller than at $X = 20.5D_h$ and fluctuations were greater closer to the grid. It is found that for this type of grid the flow recovers after a distance of $X/D_h = 10$ for axial flow velocity. For the case of cross flow situations the fluctuations remain constant after $X/D_h = 10$ but the mean value of the velocity component decreases with distance from the grid. Mean cross flow velocity and turbulence in the fuel bundle are bigger near the spacer grid; recovery of mean flow velocity and a reduction in turbulence were observed downstream. These flow behaviors were assumed to be mainly due to the mixing vanes. The results indicate that the mixing vane effect has a strong influence to around $X = 10D_h$ downstream of the spacer grid. Conner et al. (2005) presents the experimental results of a 5 × 5 fuel bundle with spacer grids. Several spacer types typical of PWR's were tested in an air loop with fully heated rods. The work focuses on heat transfer measurements using a specially design thermocouple holder than can be moved axially inside the bundle. The Re number tested ranged from 15,000 to 37,000 based on the hydraulic diameter, $D_h = 11.77$ mm. The results were calculated based on temperature measurements at discrete positions inside the bundle. Conner et al. showed an improvement in the heat transfer after the spacer-grids but did not provide any explanation about the probable mechanism behind these improvements.

Yang and Chung (1998) have studied the influence of the spacer grids on the turbulent mixing within square sub-channel geome-

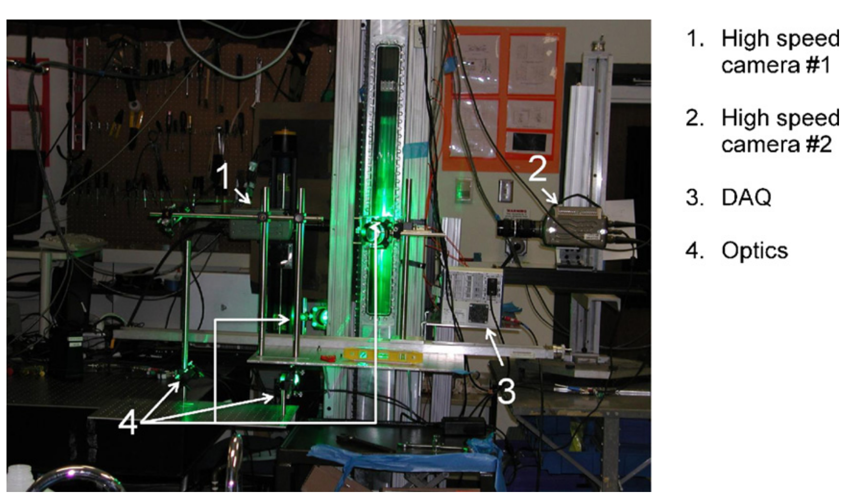

Fig. 2. Test section showing the optical arrangement and PIV system.