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Measurements of turbulent flow in a large-scale model of a 37-rod bundle

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ABSTRACT

The turbulent flow in the subchannels around an outer rod of a scaled up (12.9:1) model of a 60° section of the CANDU reactor 37-rod bundle with a pitch-to-diameter ratio of 1.149 was documented for three bulk Reynolds numbers (50,000, 100,000 and 130,000). Reported results include measurements of the mean axial velocity, the Reynolds stresses, the turbulent kinetic energy, the anisotropy tensor components, the integral length scale, the Taylor microscale, the Kolmogorov microscale, the wall shear stress, the friction factor and the characteristics of the gap vortex street forming in the vicinity of a rod-wall gap. In general, normalised turbulence properties showed some weak dependence on Reynolds number, whereas the normalised Strouhal number, convection speed and wavelength of the vortex street were insensitive to the Reynolds number. The gap vortex street was found to form fairly close to the rod-bundle inlet, which was fitted with an endplate. The objective of this work was to elucidate the effect of Reynolds number on the turbulence properties and the vortex streets that form in tightly-packed rod bundle flows. The reported measurements have been documented in sufficient detail to serve as a reliable database for the validation of computational fluid dynamics analyses of such flows.

1. Introduction

Like the cores of pressurized water nuclear reactors, the core of the CANDU nuclear reactor consists of channels containing bundles of fuel elements (rods), cooled by liquid coolant flowing axially in the interconnected subchannels formed by the rods. The performance of the reactor, as well as the temperatures of the coolant and the rod surfaces strongly depend on the turbulent flow structure in the subchannels, which in turn depends on the geometrical features of the rod bundle and to a lesser degree on the Reynolds number, when this is sufficiently large. An important geometrical parameter of rod bundles is the pitch-to-diameter ratio P/D. A large number of experimental studies over several decades (including those by Trupp and Azad, 1975; Hooper, 1980; Krauss and Meyer, 1998; Guellouz and Tavoularis, 2000; Baratto et al., 2006; Choueiri and Tavoularis, 2014, 2015) have shown that the structure of flows in “tightly packed” rod-bundles and other channels that contain narrow passages (“gaps”) between open subchannels is drastically different from that in flows in pipes and other simple channels and even flows in rod bundles with $P/D \gtrsim 1.2$ (Meyer, 2010). Flows in channels with narrow gaps give rise to quasi-periodic vortex streets, which, in rod bundles, form networks of vortices that extend throughout the cross-section and dominate intersubchannel heat and mass transfer (Tavoularis, 2011). A good knowledge of the characteristics of these vortices and the general features of turbulent flow in rod bundles is essential for the accurate prediction of reactor performance under design, off-design and postulated accident conditions.

A number of analytical studies have been conducted to predict the effect of gap vortex streets on the velocity distributions in rod bundles. Chang and Tavoularis (2005) simulated numerically the formation of coherent vortices and predicted their effect on the flow structure in a set-up similar to the one used by Guellouz and Tavoularis (2000). In a later study on that same geometry, Chang and Tavoularis (2012) performed a comparative analysis between RANS (Reynolds-Average Navier Stokes), URANS (Unsteady RANS) and LES (Large–Eddy Simulations) simulations and concluded that, although LES yielded the most accurate results, URANS results were also fairly accurate, while RANS simulations were the least accurate. Chang and Tavoularis (2007) successfully simulated a turbulent isothermal flow in a 60° sector of a CANDU 37-rod bundle by separating the coherent fluctuations from the non-coherent fluctuations and resolved the first numerically while modelling the latter.

Evidence of coherent vortex streets has been reported in compound rectangular channels connected by slots, eccentric annular flows and flows in tightly packed rod bundles. In these geometries, a strong spanwise velocity gradient on either side of the narrow gap introduces flow instability near the inflection points of th spanwise velocity profile that generates a street of counter-rotating vortices, appearing alternately on each side of the gap. In the case of tightly packed rod bundles, such as the CANDU rod bundle, which contains multiple interconnected subchannels, the different gap vortex streets form a vortex network

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(Tavoularis, 2011), which synchronizes cross-stream exchange between the subchannels adjacent to the narrow gaps. Several studies have found that the stream exchange tended to be quasi-periodic with a relatively low frequency, and so passage of coherent vortices could be detected from the spectrum of the cross-velocity fluctuations in the narrow gap regions, where the effect of the coherent vortices would be more pronounced.

An overall assessment of the available literature on rod bundles indicates that measurement remains the most reliable approach for examining the complex flow and heat transfer phenomena that are present in such flows and for determining accurate values of various properties, particularly in novel configurations. At the same time, it is acknowledged that advances in CFD (Computational Fluid Dynamics) analysis and computational power during the last decade have made numerical simulation a valuable tool that complements experimental work and permits a time and cost effective comparative evaluation of alternative rod-bundle designs and operating conditions. For CFD results to be reliable, they need to be validated against measurements. Such validation, however, should not be confined to predictions of the mean flow distribution, but extend to turbulence parameters and large-scale phenomena, such as vortex networks. Very few of the many available experimental studies of rod bundles report sufficient details to serve as benchmarks for meaningful CFD validation. In particular, most past experiments fail to document inlet conditions, which are essential specifications for the numerical simulation of developing flows. For example, CFD predictions of gap vortex streets are known to be sensitive to inlet conditions (Chang and Tavoularis, 2012); for a tightly packed rod bundle of relatively short length, auch as the 37-rod CANDU rod-bundle, one would like to know the starting location of vortex streets, as this would affect the overall thermalhydraulic performance of the device. Moreover, most available experimental studies have been performed at Reynolds numbers which are typically an order of magnitude smaller than values in operating nuclear reactors (~ 500, 000), and one would like to be able to estimate the uncertainties caused by Reynolds number mismatching.

The present work aims at contributing to the available experimental database on turbulent flows in tightly packed rod bundles, while also addressing some relevant issues that have not in the past received sufficient attention. Experiments were conducted in a large-scale, geometrically realistic model of the 37-rod bundle of the CANDU nuclear reactor, equipped with a realistic endplate at the inlet. Because of the large size of the apparatus, errors due to geometrical imperfections and limitations in spatial resolution of the measuring instrumentation were kept at relatively low levels. Flow properties upstream of the inlet have been measured to serve as boundary conditions in CFD analyses using the present results for their validation. Particular effort was made to document the characteristics of a representative gap vortex street, including the location along the rod-bundle where it first became detectable. An important contribution of this work is the documentation of Reynolds number effects on the turbulence properties and the gap vortex street characteristics.

2. Apparatus and measurement procedures

2.1. Experimental apparatus

The experiments were conducted in the large-scale rod bundle facility shown in Fig. 1 and described in detail by Rind and Tavoularis (2012) and Don, 2016. Air was drawn into a centrifugal blower through an intake contraction with a contraction ratio of 16.25, containing polypropylene air filter sheets, which captured 85% of particles larger than 1 μm. The discharge of the blower was connected to a wide-angle diffuser through a rubber coupling to reduce vibrations. The diffuser contained five perforated plates that broke down large-scale motions from the blower and caused pressure drop, which prevented flow separation from the walls. It led to a 1875 mm long, 1645 mm high and

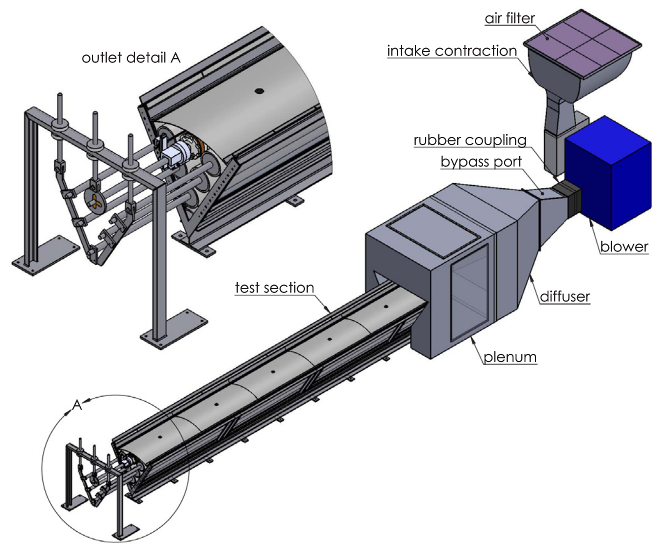

Fig. 1. Rod-bundle facility.

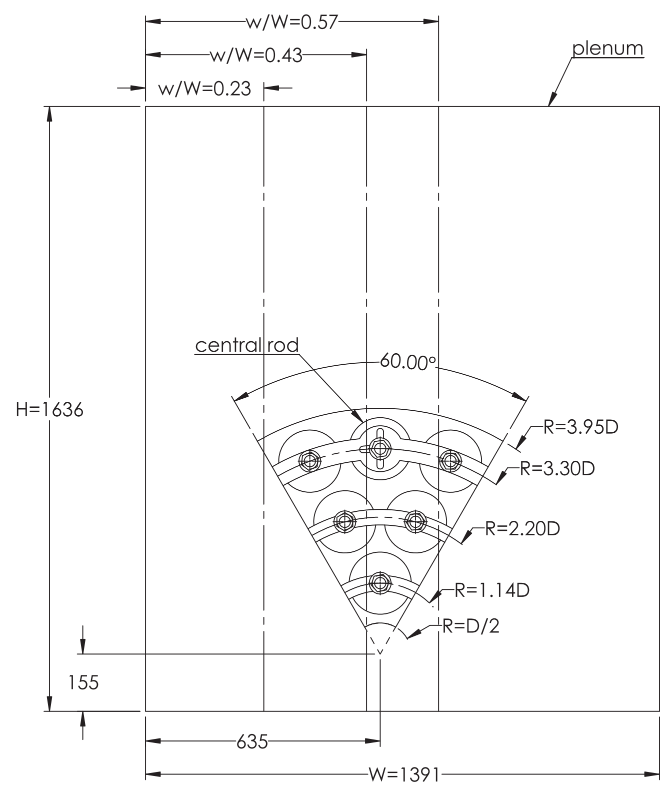

Fig. 2. Test section inlet with endplate viewed from the plenum interior; dimensions are in mm and the rod diameter is D = 168.3 mm.

1391 mm wide plenum, which contained a honeycomb and an additional perforated plate.

The test section, viewed from the plenum interior, is shown in Fig. 2. The test section was a geometrically scaled up (12.9:1) model of a 60° section of the CANDU 37-rod bundle. It consisted of six rods and a one-sixth segment of a rod, which were models of CANDU fuel elements. Each rod was a piece of a Schedule 40 pipe, with a nominal outer diameter D = 168.7 mm, a diameter uncertainty of 0.4 mm and a nominal length of 6100 mm. Consequently, the present rod length-to-diameter ratio was 36.2, which is slightly smaller than the value of 38.2 in the CANDU rod bundles. The test section hydraulic diameter was D_h = 73.6 mm, which, because of the increased wetted surface