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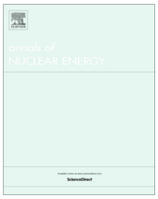

Estimation of appendage pressure-loss coefficients for fuel rod bundles using computational fluid dynamics

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ABSTRACT

The thorium fuel cycle is attracting increased attention in nuclear industries worldwide due to its intrinsic proliferation resistance and the greater abundance of thorium than uranium. Under an R&D program, Canadian Nuclear Laboratories (CNL) is studying a new bundle design fuelled with thorium. This paper presents an application of computational fluid dynamics (CFD) to determine the fuel-bundle appendage pressure-loss coefficients (*k*-factors) that are generally used in subchannel thermal-hydraulics codes such as ASSERT-PV (the Canadian subchannel code). In the CFD simulations, the ASME best practise guidelines were used to the extent possible for reducing uncertainties and user-effects. The results showed that the use of a well calibrated CFD model could potentially reduce the turnaround time in the development of new fuel assembly components. The predicted *k*-factor for the new fuel bundle design is in line with the currently used value for the CANDU bundles.

1. Introduction

The rod bundle design for thorium fuel is currently under the conceptual stage at Canadian Nuclear Laboratories (CNL), and is based on the CANFLEX[1] fuel bundle (Inch et al., 2000). The CANFLEX bundle is a 43-element CANDU1 fuel bundle with two different rod diameters: small-diameter rods for the outer and intermediate rings, and large-diameter rods for the inner ring and the centre element. Spacing devices (appendages) include bearing pads and spacer pads. Even though appendages cause pressure losses in the reactor core, they contribute towards integrity and spacing of fuel rods, turbulence enhancement to improve fluid mixing in the subchannels and reduction of hot spots on the fuel elements. Therefore, they are deemed to be an important component of any fuel bundle configuration and their effects on the fuel performance must be accurately modeled. It should be pointed out that the “appendages” in CANDU bundles play a similar role as the “spacers” in light water reactor designs or in other fuel assemblies.

The ongoing development of the thorium fuel bundle design evaluated twenty core concepts that involved different types of thorium-based fuels, pertinent details have been discussed in Colton and Bromley (2016). Amongst the twenty, the current investigation focussed on the design with 35 rods, in two rings, with appendages and a large, central displacer rod as shown in Fig. 1. The detailed design features will continue to evolve as a result of ongoing design analysis based on the thermalhydraulics testing and physics calculations. The primary task in the early stages of the design evolution comprises of optimising the fuel bundle geometry. Traditionally, this has been carried out using the subchannel code ASSERT-PV (Rao et al., 2014), which has been developed and qualified for the CANDU rod bundles and its variants.

As in any other subchannel codes (such as FLICA, COBRA, VIPRE), ASSERT-PV employs empirically derived loss coefficients (*k*-factors) to quantify the resistance of any particular appendage to fluid flow, including bearing pads and spacer pads. These appendages act as flow obstructions in the fuel bundles and therefore increase the pressure losses due to form drag and skin friction (Avramova, 2007). Thus, the use of correct values of the *k*-factors for the appendages are vital to the predictive capabilities of the subchannel approach as they affect the prediction of the subchannel flow distribution and pressure drop.

Because of the specifics in the new bearing pad configuration employed between the unique centre displacer rod and the neighbouring ring elements, there is an increased uncertainty in modelling the bearing pad effect using the empirically derived *k*-factor values. In general, *k*-factors for simple geometries are calculated from the flow resistance handbook (Idelchik, 1986), while for the complicated ones (e.g. rod bundles), they are based

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[1] CANDU and CANFLEX are trade-marks or registered trade-marks of Atomic Energy of Canada Limited in Canada and other countries.

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Notations

ASME	American Society of Mechanical Engineers	M	Million
CAD	Computer Aided Design	p	Pressure, Pa
CANDU	CANada Deuterium Uranium	ΔP	Pressure drop for blocked and unblocked, Pa
CFD	Computational Fluid Dynamics	PCD	Pitch Circle Diameter
CNL	Canadian Nuclear Laboratories	RANS	Reynolds-Averaged Navier–Stokes
D	Rod diameter, mm	SST	Shear Stress Transport
GCI	Grid Convergence Index	ω	Specific dissipation rate, s^{-1}
k	Turbulence Kinetic Energy, $m^2 s^{-2}$	v	Fluid velocity, $m s^{-1}$
k	Pressure loss coefficient in Eq. (1)	ρ	Density, $kg m^{-3}$

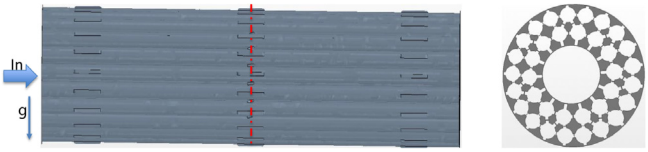

Fig. 1. Fluid domain and cross-section of the rod bundle for thorium fuel along with 35 rods and appendages (pressure tube not shown).

on the flow-resistance experiments. The major problems associated with conducting experiments arise from high operational costs and availability of loops that can operate at the desired flow conditions.

Alternatively, computational fluid dynamics (CFD) can be utilised as an evaluation tool for modelling the spacing devices of arbitrary geometric complexity. CFD solves fundamental equations governing the fluid flow and heat transfer at the computational cell level thereby reducing empiricism to a large extent. CFD has recently been used by several investigators (Avramova, 2007; Blyth et al., 2016; In et al., 2014; Chang et al., 2016) to calculate the spacer loss factors for the light water fuel assembly. However, the use of CFD for estimating the pressure-loss coefficients for the CANDU rod bundle geometries is limited, except for a study by Banas et al. (1992).

The objective of the current study is to determine appendage pressure-loss coefficients or k-factors using CFD for the bearing pads between the displacer rod and ring elements in the new rod bundle design for thorium fuel. The k-factor determined using CFD would be used in the ASSERT-PV subchannel code to optimise the fuel rod bundle geometry. A commercial CFD code, Siemens STAR-CCM+ by CD-Adapco v 9.02.007 was used for this analysis. The scope of the simulations was limited to an unheated single fuel bundle (495.3 mm) subjected to single–phase fluid flow.

2. CFD modelling

In this section, the CFD modelling approach for the CNL proposed thorium fuel rod bundle is discussed.

2.1. Geometry and computational mesh

The computational domain was built to the specified dimensions listed in Table 1. The resulting fluid domain can be seen in Fig. 1. Due to the complexity of the geometry, solid CAD model was developed in Solid Edge and imported into STAR-CCM+. The fluid domain was extracted from the solid CAD model in STAR-CCM+ and was subjected to meshing. To prevent negative volumes in the volume mesh, the resulting fluid domain model was subjected to several surface mesh quality checks to ensure the extracted CAD model was water tight with no pierced faces. As an unheated rod bundle was considered for the current study, the fuel sheath was not included in the computational domain. The overall volume mesh was developed using the trimmer model that results in structured mesh with hexahedral cells. Individual mesh controls were used to capture the geometric features of the bearing pads and spacer pads on the fuel rods.

Table 1
Selected dimensions for developing the CAD model of the thorium fuel bundle.

Parameter	Dimension
Length of the fuel bundle	495.30 mm
Outer ring PCD	87.68 mm
Inner ring PCD	61.50 mm
Outer ring fuel rod diameter, # of rods	11.47 mm, 21
Inner ring fuel rod diameter, # of rods	11.47 mm, 14
Displacer rod diameter (centre ring), # of rods	42 mm, 1
Bearing pad dimensions at the displacer rod (L × W × H)	31.75 × 2.5 × 3.7 mm

To capture the turbulence in the boundary layer and the flow separation induced at the bearing pads and spacer pads, dense mesh along with five prism cells was used in a boundary layer. As most of the turbulence models are not valid near the wall, wall functions were employed to model the turbulence behaviour at the wall. It is crucial to satisfy the constraints implicit in this treatment; therefore, the mesh was developed such that the wall y^+ for the first node point away from the wall was in the range of $0.5 \leq y^+ \leq 2$.

Due to the lack of solid sheath in the model, the trimmer mesher was used instead of polyhedral cells. As can be seen in Fig. 2, the growth of the mesh cells, especially between the inner and the outer ring, was set to "medium" primarily to capture the secondary flows in the subchannels. The same approach could have

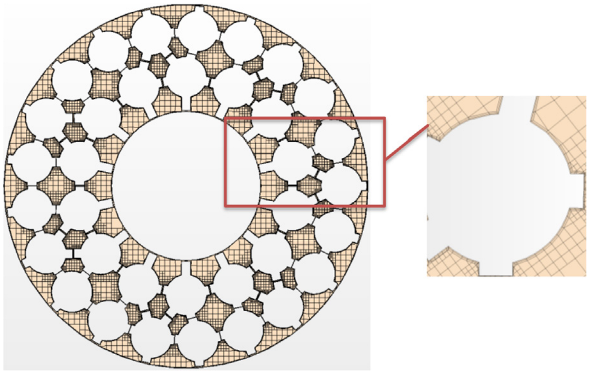

Fig. 2. Mesh on a cross section of the fuel rod bundle.