Nuclear Engineering and Design 322 (2017) 577–590

Contents lists available at ScienceDirect

Nuclear Engineering and Design

journal homepage: www.elsevier.com/locate/nucengdes

Numerical simulations for determination of minimum representative bundle size in wire wrapped tube bundles

Landon Brockmeyer [a],*, Lane B. Carasik [a], Elia Merzari [b], Yassin Hassan [a]

[a] Texas A&M University, Department of Nuclear Engineering, 3133 TAMU, College Station, TX 77843, USA
[b] Argonne National Laboratory, 9700 Cass Ave, Lemont, IL 60439, USA

HIGHLIGHTS

- A comparison between RANS and LES is made for a 19 pin wire-wrap domain.
- Bundles containing 19, 37, 61, and 91 pins are compared.
- Subchannel mass exchange is the primary metric of comparison.
- Subchannel behavior is found to be a function of distance from nearest wall.
- Minimum recommended bundle size for modeling and simulation is 37 pins.

ARTICLE INFO

Article history:
Received 23 November 2016
Received in revised form 10 June 2017
Accepted 26 June 2017

Keywords:
Wire-wrapped fuel rod
Bundle size
Verification

ABSTRACT

When constructing an experiment or simulation for flow through a wire-wrapped fuel rod bundle, scientists may utilize a smaller bundle than design in order to minimize material or computational costs. Small bundles may not capture the required flow physics experienced by larger bundles. This paper compares the flow fields through wire-wrapped rod bundles of 19, 37, 61, and 91 pins and investigates the ability of each to capture the relevant physics of a larger bundle. For model verification, the SST k-ω and elliptic blending k-ϵ RANS models were compared against an LES simulation of the 19 pin domain, finding both RANS turbulent models capable for the given geometry. The central subchannel transverse velocity and inter-channel mass exchange for each bundle was compared, revealing a strong dependence of inter-channel mixing on the bundle size. Furthermore, analysis of the inter-channel mass exchange for subchannels at a varying distance from the surrounding shroud revealed than the mass exchange as a function of height is strongly tied to distance from the wall, with a slight adjustment in magnitude for the bundle size. The asymmetrical aspect of the wall effect was observed, revealing that the outside 2 or 3 rings of subchannels experience a large deviation from the characteristic subchannel behavior, but the central subchannels of the 37, 61, and 91 pin bundles are largely isolated from the asymmetric wall effect. Based on these findings the authors recommend a 37 pin bundle as the minimum surrogate for a larger bundle, and 61 pins as the preferred bundle size.

1. Introduction

A common fuel arrangement for Sodium Fast Reactor designs is a hexagonal array of wire wrapped fuel rods. The helically wound wires redirect coolant to neighboring subchannels and encourage mixing. The increased mixing of the coolant aids heat transfer and decreases temperature peaking in hot channels. The wire-wrappers provide structural support and separate the rods. These wires reduce flow-induced vibrations that may result in mechanical failure of the fuel cladding. However, wire-wrappers contribute an additional source of pressure drop through the bundle compared to bare rods or rods with different supporting structures.

Prototypical Sodium Fast Reactors (SFRs) typically contain bundles of up to 271 rods. Experiments and computational studies commonly utilize 19, 37, or 61 pin bundles in order to simplify the geometry and decrease material and computational costs. However, care must be taken to ensure that the results gathered from smaller bundles are pertinent to larger bundles and capture the desired information. This motivates our current study and will

---

* Corresponding author.
E-mail address: brockmeyer.landon@gmail.com (L. Brockmeyer).

http://dx.doi.org/10.1016/j.nucengdes.2017.06.038
0029-5493/

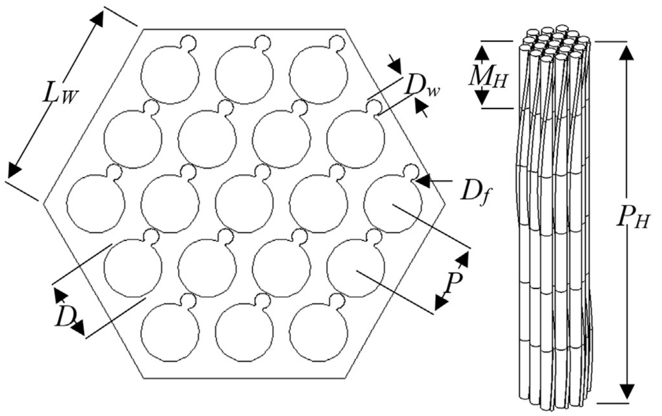

Fig. 1. Geometric meaning of characteristic parameters.

be a dominant focus of provided work. For reference, an example wire-wrapped fuel rod geometry is given in Fig. 1.

Computational Fluid Dynamics (CFD) has recently become a popular tool for SFR core modeling and design. Ahmad and Kim (2005), and Gajapathy et al. (2007) began using Reynolds Averaged Navier Stokes (RANS) turbulence models in the mid-2000s to observe and contrast 3-D flow fields for bare and wire-wrapped fuel rods. Ahmad & Kim observed a strong rotational flow in the outer subchannels following the direction of the wire wrappers, and a periodic behavior of high transverse flow in the interior subchannels. A recirculating flow was observed to follow the wire-wrapper in the interior subchannels. Gajapathy similarly noted the periodic transverse flow behavior. The RANS models agreed well with experiment for pressure drop and friction factor.

Following these earlier studies are a variety of publications utilizing RANS turbulence modeling to model different wire-wrap configurations. A variety of flows with various Reynolds numbers, pitch to pin diameter ratios, helical pitch to pin diameter ratios, and shroud size to pin diameter ratios have been modeled by Sreenivasulu and Prasad (2009), Natesan et al. (2010), and Jeong et al. (2015) with 7, 19, and 37 pins respectively. Raza & Kim modeled a 19 pin configuration using circular, rhomboid, and hexagonal wire cross sections (Raza and Kim, 2008). They found that the flow field retains its overall structure, but the circular wire produces less turbulent kinetic energy (Raza and Kim, 2008). Hamman & Berry modeled 3 pin-wire connections, including a chamfered connections, submerging the wire into the pin, and square connection of the wire to the pin. The simplifications result in pressure drop differences of up to 20% (Hamman and Berry, 2010). Fischer was the first to model the wire-wrapped fuel rod bundle using Large Eddy Simulation (LES), providing more detailed flow resolution for a 7 pin bundle (Fischer et al., 2007). Fischer's LES results agree with the RANS modeling of Ahmad & Kim, providing confidence in RANS' ability to capture the flow physics.

Direct Numerical Simulation (DNS) of the geometries of interest is not possible at the time of writing due to the large computational expense. However, Ranjan performed DNS on a simplified geometry to observe in great detail the flow behavior as it passes over the wire (Ranjan et al., 2011). The geometry consists of a pin attached to a wall in a channel with angled flow. The results indicate that a separation region develops on the leeward side of the wire. This region shows large deviations from the law of the wall behavior. Thus RANS models that utilize wall functions may not accurately model the flow near the wire. Merzari et al. (2012) utilized the same geometry with LES and RANS to observe the effect of pin-wire contact modeling on flow behavior. The geometry near the base of the wire was shown to have little effect on flow behavior as long as no flow passes beneath the wire. The RANS results of Merzari agree with the LES results of Fischer, again adding confidence to the use of RANS for this geometry.

The works of Gajapathy et al. (2009), Rolfo et al. (2012), and Pointer et al. (2009) are most relevant to the present study. Each observe velocity profiles in rod bundles as a function of bundle size. Gajapathy used a high Reynolds k-ε model, as implemented in Star-CD 2001, with wall functions to model 7, 19, and 37 pin bundles. The results for velocity distribution agree well with experimental measurements of Lorenz et al. (1974), and the calculated friction factors agree with an established empirical correlation (Novendstern, 1972). As this is an earlier study, the mesh is comparatively coarse and no grid convergence study was possible. Rolfo et al. (2012) used the standard k-ε turbulence model as well as the second moment closure (SMC) model with wall functions to model turbulent flow through wire-wrapped fuel rod bundles of 7, 19, and 61 pins. A 271 pin bundle was modeled using standard k-ε as well. A few different wire-pin contact models were tested. The strong secondary swirling of the flow around the outer subchannels was observed to be limited to the edge region, with little effect on the inner subchannels. The author found that the number of fuel pins does not have a large influence on the flow features, and that the inner subchannels are homogenous regardless of bundle size. Pointer et al. (2009) utilized a RANS turbulence model with wall functions to model bundles of 7, 19, 37, and 217 pins. The 7 pin bundle RANS model was compared to an LES simulations and found to give comparable results for cross-flow. With increasing bundle size, the importance of bulk swirling was observed to decrease, and the flow field was found to increase in complexity. A fundamental difference in flow behavior is observed between 19 and 37 pin bundles.

The purpose of this paper is to compare the flow behavior of subchannels for bundles of sizes 19, 37, 61, and 91, and to determine their capability to predict the flow behavior of larger bundles. This study differs from the others previously mentioned in that it carries out an extensive mesh convergence study and a comparison to LES results. The turbulence modeling does not utilize wall functions, which may fail to accurately capture near-wall behavior. Further, the analysis focuses on direct comparison of subchannel mass exchange and transverse velocity profiles over a variety of locations in order to gather a quantitative understanding of the differences in flow behavior. The results focus on transverse velocity and subchannel mixing rather axial velocity effects in order to focus on the mixing mechanics of the wires. Quantifying the inter-channel mixing is one of the ultimate goals of modeling the wire-wrapped fuel rod bundles.

2. Methodology

The computational domain consists of a 19 rod wire-wrapped fuel rod bundle in a hexagonal lattice surrounded by a hexagonal shroud. The length of the modeled domain (M_H) is one-sixth of a helical pitch. Due to the periodic nature of the wire-wrapped bundle, one full pitch (P_H) is composed of six identical axial segments. In reality each wire will form a helical contact with the pin around which it is wrapped. The wire will make point contact with its six neighboring pins as it completes a full revolution. Point and line contact result in meshing singularities. The domain must be adjusted to avoid these singularities while also considering the effect of these adjustments on the flow behavior. In the present study, the wire is attached to the wrapped pins by small fillets. This modification has been shown in literature to have little effect on the flow structure (Rolfo et al., 2012), and similar modifications to the base of the wire have supported this observation (Hamman and Berry, 2010) (Merzari et al., 2012). To avoid point