



Evaluation of existing correlations for the prediction of pressure drop in wire-wrapped hexagonal array pin bundles



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HIGHLIGHTS

- Wire-wrapped bundle friction factor data and correlations thoroughly collected.
- Three methodologies proposed for identifying the best fit correlation.
- 80 out of 141 bundles selected as database for evaluation.
- The detailed Cheng and Todreas correlation identified to fit the data best.

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ABSTRACT

Existing wire-wrapped fuel bundle friction factor correlations were evaluated to identify their comparative fit to the available pressure drop experimental data. Five published correlations, those of Rehme (REH), Baxi and Dalle Donne (BDD, which used the correlations of Novendstern in the turbulent regime and Engel et al. in the laminar and transition regimes), detailed Cheng and Todreas (CTD), simplified Cheng and Todreas (CTS), and Kirillov (KIR, developed by Russian scientists) were studied. Other correlations applicable to a specific case were also evaluated but only for that case. Among all 132 available bundle data, an 80 bundle data set was judged to be appropriate for this evaluation. Three methodologies, i.e., the Prediction Error Distribution, Agreement Index and Credit Score were principally used for investigating the goodness of each correlation in fitting the data. Evaluations have been performed in two categories: 4 cases of general user interest and 3 cases of designer specific interest. The four general user interest cases analyzed bundle data sets in four flow regimes – i.e., all regimes, the transition and/or turbulent regimes, the turbulent regime, and the laminar regime. The three designer interest cases analyzed bundles in the fuel group, the blanket and control group and those with $P/D > 1.06$, for the transition/turbulent regimes. For all these cases, the detailed Cheng and Todreas correlation is identified as yielding the best fit. Specifically for the all flow regimes evaluation, the best fit correlation in descending order is CTD, BDD/CTS (tie), REH and KIR. For the combined transition/turbulent regime, the order is CTD, BDD, REH, CTS and KIR. In the turbulent regime alone, the order is CTD, BDD/REH, CTS and KIR. In the laminar regime, the order is CTD, CTS, KIR and BDD/REH. For fuel assemblies, the order is CTD, BDD, REH, CTS and KIR. For blanket and control assemblies, the order is CTD, CTS, KIR, REH and BDD. For bundles with $P/D > 1.06$, the order is the same as that for the fuel group. Three supplemental evaluations have been performed, one being the 80 bundle set in the transition and/or turbulent regimes with 8 added CFD simulation results. The other two are based on the appropriate set of 109 bundles covering all flow regimes and 108 bundles covering the transition/turbulent regimes, respectively. In these supplemental evaluations the correlation order is CTD, CTS/BDD, REH and KIR for the CFD results added case; CTD, REH, BDD, CTS and KIR for the 109 bundle case and REH, CTD, BDD, CTS and KIR for the 108 bundle case. Several shortcomings were found in the most recently published evaluation for the best fit correlation by Bubelis and Schikorr. The twenty-two bundle set evaluated by Bubelis and Schikorr is reexamined by the methodologies in this study, resulting in the correlation order of REH, CTD, CTS, BDD and KIR.

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Nomenclature

A	axial average flow area
A_r	projected area of wire in a subchannel
D	rod diameter
D_e	equivalent hydraulic diameter
D_w	wire diameter
f	Darcy friction factor, if no subscript means bundle average value
H	wire lead length
L	axial length
N	number of each kind of subchannel in the bundle
N_r	number of pins in the bundle
P	rod pitch
ΔP	pressure drop
P_w	wetted perimeter
Re	Reynolds number, if no subscript means bundle average value
Re_L	laminar to transition boundary Reynolds number
Re_T	transition to turbulent boundary Reynolds number
V	axial velocity
W	edge pitch parameter defined as $(D + \text{gap between rod and bundle wall})$
X	flow split parameter for each subchannel defined as (V_i/V_b)
ρ	coolant density
μ	dynamic viscosity
θ	angle which the wire makes with respect to vertical axis
Ψ	intermittency factor
Subscripts	
i	1, 2, 3 or b denote interior, edge, corner subchannel type, or bundle average, respectively
f	denotes friction
L	denotes laminar flow regime
T	denotes turbulent flow regime
Tr	denotes transition flow regime
Superscript	
'	denotes equivalent bare rod values (without considering wire)

1. Introduction

1.1. The wire-wrapped rod bundle configuration

Use of helically wound wires around fuel and control rods is typically selected for tightly packed hexagonal rod arrays, frequently referred to as an “assembly” or “bundle”. Wrapped wire following a helical pattern functions as a spacer maintaining the gap between adjacent rods while importantly also enhancing coolant mixing between adjacent subchannels. Fig. 1 illustrates a 37-pin wire-wrapped assembly with the standard single wire per rod wrapped at the same wire start position (designated as the wire-to-pin configuration) including conventional subchannel definitions and key geometrical parameters. Alternate configurations with multiple wires have been designed and tested but are not considered in the evaluations of this paper.

Sodium-cooled fast reactors (SFRs) have recently received renewed interest and have been proposed as one candidate concept for Generation IV reactors. The French ASTRID (Varaine et al., 2012) reactor is such a design using wire-wrapped fuel pins tightly spaced in hexagonal bundles. The exact pin and wire wrap

geometry of the ASTRID bundle design has not yet been published. The 600 MWe Traveling Wave Reactor-Prototype (TWR-P), a pool-type, sodium-cooled fast reactor (Hejzlar et al., 2013) also uses wire-wrapped fuel rod assemblies. The fuel pin diameter, P/D and H/D for the TWR are 8.35 mm, 1.141 and 29.94, respectively. Wire-wrapped bundle geometry is also of potential application in fuel bundles of other current unique reactor designs. These include the reduced-moderation pressurized water reactor (RMWR) design for which two design variants – a heterogeneous and a seed-and-blanket core – have been explored. For these variants the fuel array has a P/D from 1.08 to 1.11 while the blanket array parameters are from 1.03 to 1.06 (Shelley et al., 2003; Hibi et al., 2000). An additional unique design is the accelerator-driven sub-critical reactor system (ADS) of which the latest version is the Multipurpose Hybrid Research Reactor for High-tech Applications (MYRRHA), with a preliminary P/D selection of 1.3 or 1.4 (De Bruyn et al., 2011).

Pressure drop across the bundle is a key design value for the performance of the wire-wrapped rod assembly. Pressure drop across a length L is calculated by the following equation,

$$\Delta P = f \left(\frac{L}{D_e} \right) \left(\frac{\rho V^2}{2} \right) \quad (1)$$

where f , the (Darcy) friction factor, is a function of Reynolds number (Re) and bundle geometrical parameters, normally dimensionless ones, such as P/D , H/D . In order to characterize the pressure drop behavior of wire-wrapped rod bundles, 132 experiments on bundles with the wire-to-pin configuration and a wide range of geometrical parameters have been performed over the last six decades. During this period about 10 correlations for friction factor were developed for design application and calibrated based on different sets of experimental data.

1.2. The objective of this paper

This paper will evaluate these correlations based on this available data base and will provide recommendations for their use by general users and designers. The essential step is to identify the questions these users would like to have answered and then select the appropriate set of experimental bundles (the data base) upon which the evaluation of correlations to answer these questions should be based. These questions and appropriate databases are as follows:

- For the general user, what is the relative performance of existing correlations over the broadest range of bundle geometries and flow regimes for which experimental results exist?

For this case we assess the available correlations against 80 bundles selected from the total available 132 experimental bundles. These 80 bundles cover the full range of geometry and all flow regimes – laminar through turbulent. Of the 132 test bundles, 74 were performed by Rehme (1967). Rehme's bundles have a geometry of five P/D ratios combined with five H/D ratios, and each combination has three bundles with different pin number (except one, the $P/D=1.343$ and $H/D=8.33$ set, i.e., the Rehme41 configuration, includes only two bundles). To avoid undue influence of any systematic uncertainties in his experimental database, we have selected 25 bundles, one for each of the sets of P/D and H/D , to represent Rehme's experimental results. Our 80 bundle assessment group is composed of these 25 Rehme bundles plus 55 test bundles performed by other investigators which will be identified in the next section.

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