

POD-Based Reduced-Order Prediction of Pressure Drop in 217 Wire-Wrapped Pin Bundles

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1. Introduction

Wire-wrapped fuel assemblies used in sodium fast reactors exhibit strongly three-dimensional flow structures generated by the interaction between the coolant, fuel pins, and helical spacer wires. High-fidelity computational fluid dynamics (CFD) can resolve these structures and predict assembly pressure loss, but repeated CFD calculations over a broad range of operating conditions remain computationally demanding. A reduced-order model (ROM) that preserves the dominant characteristics of the CFD solution is therefore attractive for design studies, sensitivity analyses, and rapid evaluation of off-design conditions.

Proper Orthogonal Decomposition (POD) [1,2] constructs an optimal low-dimensional basis from a set of full-order snapshots and represents a new solution using only a small number of modal coefficients. In this study, an integrated framework combining parametric geometry generation, automated CFD mesh construction, and POD-based ROM is applied to two 217-pin wire-wrapped bundles: the CEA bundle analyzed by Cadiou et al. [3] and the PELICAN test bundle [4]. CFD and POD predictions of the bundle pressure drop are compared with available correlations and reference data to assess the accuracy and practical applicability of the proposed approach.

2. POD-Based Reduced-Order Modeling

Steady CFD solutions obtained at different inlet flow rates were used as snapshots. For each field variable, the spatial values were arranged as a snapshot vector, and the ensemble mean was subtracted before constructing the snapshot matrix. POD modes were then extracted from the mean-centered snapshots using singular value decomposition. The modes were ordered according to their singular values so that the leading modes retained the dominant spatial variation contained in the CFD database.

For a new operating parameter μ , the flow field q is approximated by the mean field and a truncated expansion of r POD modes:

$$q(x; \mu) \approx \bar{q}(x) + \sum_{i=1}^m a_i(\mu) \phi_i(x) \quad (1)$$

where ϕ_i is the i -th POD mode and a_i is its modal coefficient. Modal coefficients were evaluated for the snapshot cases by orthogonal projection and interpolated with respect to the inlet flow parameter. The reconstructed pressure field was subsequently post-processed using the same inlet-to-outlet pressure-drop definition as the CFD solutions. Six CFD cases covering the prescribed inlet-flow range were used to construct and assess each ROM.

This non-intrusive procedure does not modify or project the governing equations. Consequently, once the snapshot database and POD basis have been generated, predictions at additional parameter values require only coefficient interpolation and field reconstruction rather than a new CFD simulation.

3. CFD Analysis of 217-pin bundles

The CFD database was generated for two geometrically different 217-pin wire-wrapped bundles. The CEA bundle has a pin diameter of 9.7 mm, a wire diameter of 1.1 mm, a pin pitch of 10.8 mm, and a wire lead pitch of 180 mm. The PELICAN bundle uses smaller pins and a longer wire lead pitch, with a pin diameter of 6.35 mm, a wire diameter of 1.016 mm, a pin pitch of 7.366 mm, and a wire lead pitch of 266.954 mm. The two configurations therefore provide a useful test of whether the same CFD-to-ROM procedure can reproduce pressure-loss behavior for substantially different bundle geometries.

The pin arrangement was generated by a Python program based on the ring topology of a hexagonal assembly. Once the number of rings or pins and the pin, pitch, wire, and duct dimensions are specified, the program automatically creates the pin centers and wire paths. Fig. 1 illustrates the progressive construction of the hexagonal ring arrangement up to the 217-pin configuration.

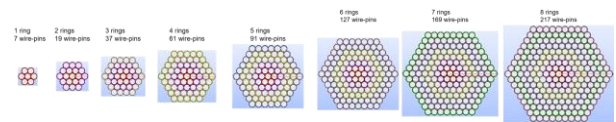


Fig. 1. Parametric generation of hexagonal pin rings using the Python geometry program.

The main geometric parameters of the two bundles are summarized in Tables 1 and 2.

Table 1. Geometric data of the CEA 217-pin bundle [3]

Geometric parameter	Size [mm]
Pin diameter	9.7
Wire diameter	1.1
Pin length (heating part)	800
Pitch	10.8
Wire pitch	180
Gap (distance between pin and wall)	1.1

Table 2. Geometric data of the PELICAN 217-pin bundle [4]

Geometric parameter	Size [mm]
Pin diameter	6.35
Wire diameter	1.016
Pin length (heating part)	1524
Pitch	7.366
Wire pitch	266.954
Gap (distance between pin and wall)	1.016

The automated meshing procedure first creates a body-fitted background mesh around the pin array and subsequently introduces the helical wires using OpenFOAM mesh-generation and mesh-modification utilities. This strategy avoids manually constructing the complex wire-pin intersections and can be applied to assemblies with different ring numbers and geometric dimensions. Fig. 2 shows the resulting hybrid mesh for the 217-pin bundle. Cells in the main flow direction are elongated to limit the total cell count, while local resolution is retained around the pins and wires where the velocity gradients and form losses are concentrated.

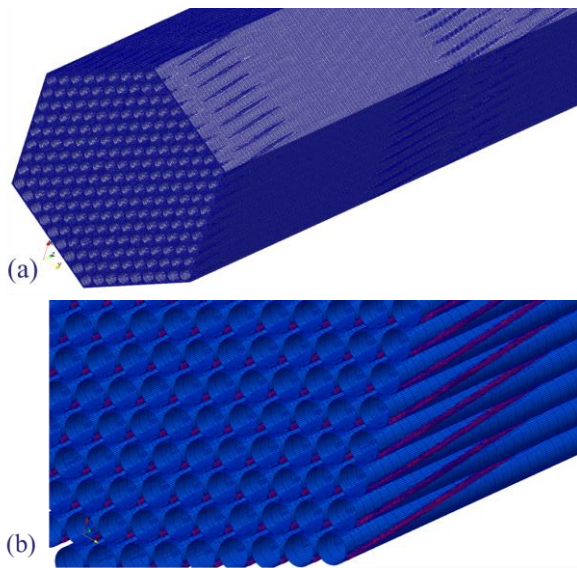


Fig. 2. Hybrid mesh of the 217-pin wire-wrapped bundle generated by the automated meshing procedure: (a) assembly-scale mesh and (b) local mesh around pins and wires.

Steady CFD calculations were performed using the *simpleFoam* solver over six inlet-flow conditions for each bundle, employing the $k-\omega$ SST turbulence model with a wall function. Due to the extreme wire-to-pin diameter ratio, generating a massive computational mesh is inevitable for wire-wrapped pin bundles. Consequently, the computational meshes employed in this study consisted of 37,676,137 cells for the CEA 217-pin bundle and 54,408,196 cells for the PELICAN 217-pin bundle. A formal mesh sensitivity study was omitted since the validity of the CFD results was assessed by directly comparing the predicted pressure drops under various inlet flow conditions with an established empirical correlation. For the convergence criteria, the calculations were deemed converged when the residual of the pressure equation decreased by four orders of magnitude.

The pressure drop was evaluated between common upstream and downstream sections so that the full-order CFD and reconstructed POD fields could be compared consistently. The computed velocity distribution for the CEA bundle is presented in Fig. 3. The spacer wires periodically deflect the predominantly axial flow and generate a helical secondary-flow pattern around the pins. This wire-induced redistribution is a principal source of momentum exchange, coolant mixing, and bundle pressure loss.

The geometrically resolved CFD solutions serve two purposes in the present study: they provide the full-order reference for comparison with available pressure-drop data, and they form the snapshot database from which the POD basis and parameter-dependent modal coefficients are obtained.

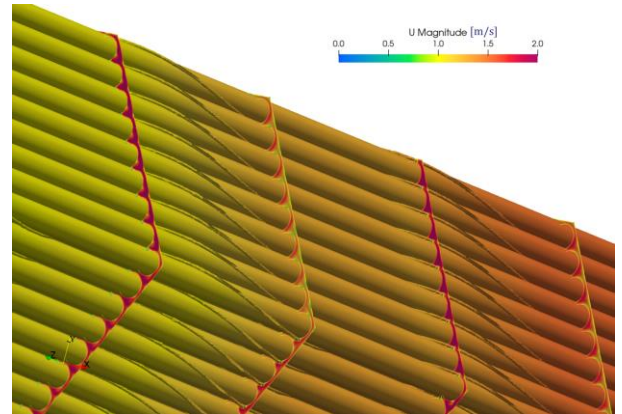


Fig. 3. CFD-predicted velocity distribution in the CEA 217-pin wire-wrapped bundle.

4. Results and Discussion

Figs. 4 and 5 compare the pressure drops obtained from the UCTD correlation [5], reference calculations or measurements, the present CFD simulations, and the POD-ROM reconstructions. For the CEA bundle, the CFD results reproduce the nonlinear increase in pressure drop with mass flow rate and remain close to the Cadiou et al. results over the investigated range. The POD predictions follow the CFD trend, including the strong

increase at the upper end of the flow range, demonstrating that interpolation of the retained modal coefficients preserves the global pressure-loss response.

For the PELICAN bundle, the CFD and POD results likewise exhibit the expected nonlinear dependence on volumetric flow rate. The ROM points remain close to the corresponding CFD curve despite the markedly different pin and wire dimensions of this bundle. The comparison indicates that the proposed workflow is not tied to a single assembly geometry; rather, an independent snapshot basis can be constructed and used efficiently for each design.

Small differences among the correlation, reference data, and CFD results become more visible at the highest flow conditions. These differences reflect the sensitivity of wire-wrapped bundle pressure loss to geometry representation and flow modeling. The purpose of the ROM, however, is to reproduce the selected full-order model. Its close agreement with the CFD pressure-drop trend confirms that the reduced representation and modal-coefficient interpolation introduce only limited additional deviation within the sampled parameter range. Because reconstruction requires no additional CFD solution, the method is suitable for repeated parametric evaluations after the initial snapshot-generation cost has been incurred.

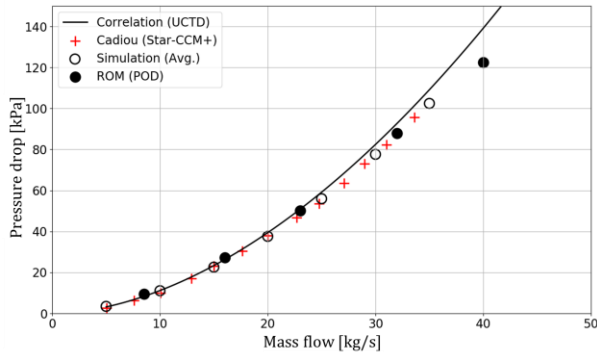


Fig. 4. Pressure drop as a function of mass flow rate for the CEA 217-pin bundle: comparison of correlation, reference calculation, present CFD, and POD-ROM results.

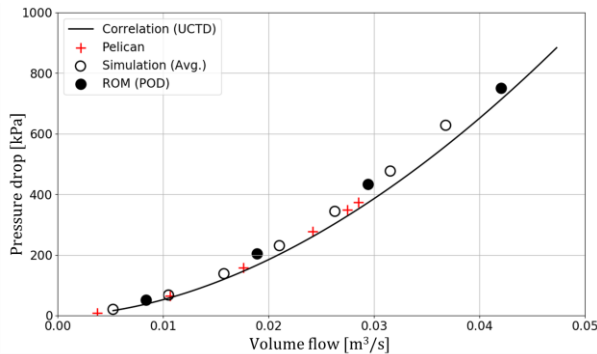


Fig. 5. Pressure drop as a function of volumetric flow rate for the PELICAN 217-pin bundle: comparison of correlation, experimental data, present CFD, and POD-ROM results.

5. Conclusions

A POD-based non-intrusive reduced-order modeling framework was developed for rapid prediction of the thermal-hydraulic behavior of 217-pin wire-wrapped bundles. Parametric Python geometry generation and an automated OpenFOAM meshing procedure were used to construct the CEA and PELICAN bundle models, and six steady CFD solutions at different inlet-flow conditions were used as snapshots for each configuration.

The full-order calculations reproduced the nonlinear pressure-drop characteristics and the wire-induced three-dimensional flow pattern. The POD-ROM reconstructions closely followed the CFD pressure-drop trends for both mass-flow-rate and volumetric-flow-rate parameterizations, while also remaining consistent with the available correlations and reference data. These results demonstrate that POD can retain the dominant parametric response of geometrically resolved wire-pin-bundle CFD solutions and can provide additional operating-point estimates without repeating the full CFD calculation. The proposed framework is therefore promising for rapid SFR assembly design assessment and parametric analysis. Future work will quantify field-wise reconstruction errors, optimize snapshot selection, and extend the method to coupled velocity and temperature predictions under unsteady conditions.

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