Programmable Mesh Generation Strategy for Flow Analysis of Wire-pin Bundles

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1. Introduction

Due to the high heat transfer coefficient of the coolant used in liquid metal reactors such as SFR (sodium fast reactor), the diameter of the fuel rod (pin) becomes very small, and a wire is wrapped around the pin for structural integrity of the pin to prevent bending or vibration of the pin.

Many experiments [1, 2, 3] have been conducted on the thermal hydraulics of the wire-pin bundle, and various sub-channel analysis codes based on the experimental data have been developed and used for the design of the core of a liquid metal reactor [4, 5, 6].

Application of turbulence-resolved computational fluid dynamics (CFD) to predict flow characteristics in a wire-wrapped fuel bundle becomes more and more popular. But it still requires a lot of manpower because of a mesh generation problem. Representative geometric parameters of a wire-wrapped fuel bundle for generating a mesh to be used for a flow simulation are fuel pin diameter (D), wire diameter (d), and pin length (L). In general the ratio of the parameters based on the wire diameter d:D:L is approximately1:10:1000. In order to geometrically resolve the circular circumference of the wire, more than 10 nodes are required. If isotropic mesh elements (cells) are used for a mesh of a 217 wire-pin bundle, the mesh size exceeds 200,000,000. Modern HPC (high-performance computer) can handle the size of the mesh for CFD. But it is not efficient economically. If characteristics of a channel flow is considered, cells elongated in an axial direction can be used to reduce the mesh size without noticeable deterioration of numerical accuracy. Jeong et al. [7] And Cadiou et al. [8] have used block meshes to carefully control the size of the meshes for flow simulations in large bundles. A block mesh generation for a large bundle is topologically complicated so it requires big human hours.

In this study, a programmable mesh generation strategy is developed to automatically generate a hybrid mesh for flow simulations in large bundles.

2. Methods and Results

2.1 Mesh Generation for wire-wrapped fuel bundles

In order to optimize mesh size and resolution especially for a large wire-pin bundle, directional hybrid mesh generation is adopted in this study. In spanwise or radial direction of the bundle, unstructured mesh type is used but structured mesh topology is used in axial or streamwise direction by extruding the spanwise mesh.

Fig. 1 is a schematic of the programmable hybrid mesh generation composed of 2 steps, which are wire-pin CAD and background mesh generation processed by a python program utilizing SALOME [9] functionalities and wire-part mesh generation processed by a shell program utilizing OpenFOAM [10] utilities

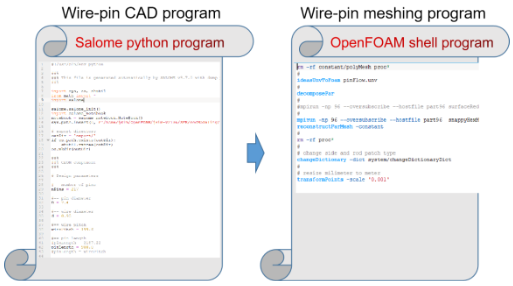

Fig. 1. Schematic of the programmable mesh generation for a wire-wrapped fuel bundle.

During the first step of the hybrid mesh generation procedure, the geometry of a wire-pin bundle is modeled automatically on the SALOME GUI. Fig. 2 shows screen shots of geometry modeling.

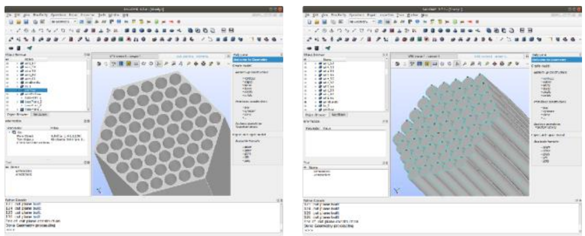
Fig. 2. Automatic drawing of a wire-pin bundle and auto-generation of a pin mesh using the SALOME-python program.

Current wire-pin bundles have a topological similarity which is ring-based pin arrangement in a hexagonal channel. The ring topology is programmable in a python code. When a user of the python code specifies the number of rings or the number of wire-pins, the python code automatically generates the geometry of a wire-pin bundle. Fig. 3 shows wire-pin arrangement along with the number of rings.

The developed python program can generate hybrid mesh for pin bundle with wires, which is called a background mesh. The background mesh is imported to OpenFOAM mesh generator snappyHexMesh and the shell program utilizes OpenFOAM utilities to generate a mesh including wires and modify the mesh for possible corrections.

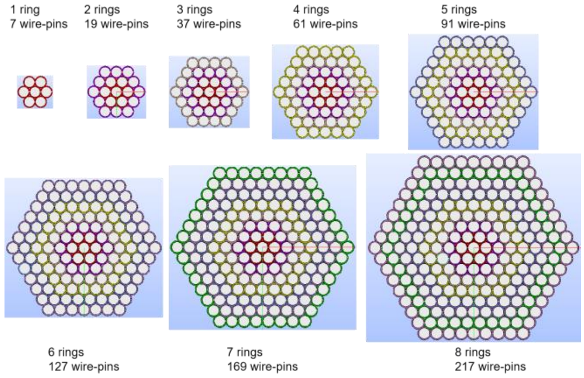

Fig. 3. Automatic wire-pin ring generation by the python program running on the SALOME GUI.

Fig. 4 shows the procedure of the hybrid mesh generation schematically.

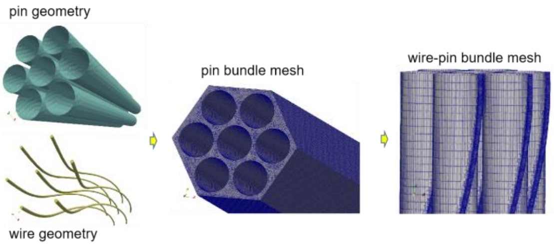

Fig. 4. Procedure of a wire-pin mesh generation

A wire wrapping around a fuel pin contacts the pin on a line. If this is correctly modeled, a mesh around the corner near the contact line becomes too acute. Another option is to make surface contact between a pin and a wire. Fig. 5 shows an elliptical shape of a wire

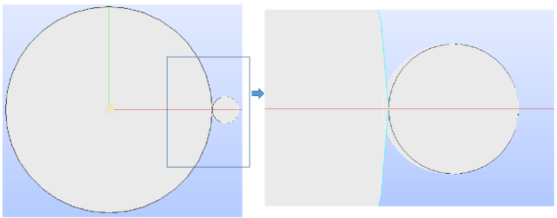

Fig. 5. Modeling of point-contact and surface-contact between a pin and a wire.

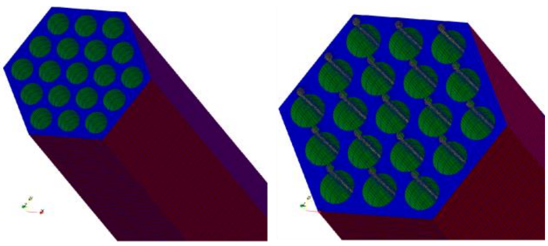

Fig. 6. A mesh for 19 wire-pin bundle generated by the programmable meshing strategy.

Fig. 6 shows a hybrid mesh generated for a 19 wire-pin bundle, where a surface contact between pins and wires were adopted.

The proposed mesh generation procedure is applicable to any number of rings and any size of pin and wire geometries. The procedure was applied to generate a hybrid mesh for 217 wire-pin bundle as shown in Fig. 7. It is seen that mesh cells near pins are elongated in the axial direction to reduce the size of the mesh.

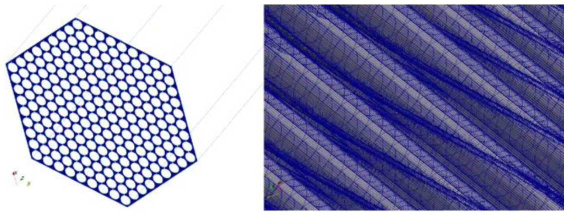

Fig. 7. A mesh for 217 wire-pin bundle generated by the programmable meshing strategy

2.2 Flow Simulation for a Mesh Test

To test a generated mesh for a turbulence-resolved simulation of a wire-wrapped pin bundle, two 217-pin bundles were chosen, which are the fuel assembly of PGSFR designed by KAERI [7] and CEA fuel assembly simulated by Cadiou et al. [8] Table 1 is the geometric parameters of KAERI 217-pin bundle.

Table 1. Geometric data of the KAERI 217-pin bundle

Gemetric parameter	Size [mm]
Pin diameter	7.4
Wire diameter	0.95
Pin length (heating part)	900
Pitch	8.436
Wire pitch	199.6
Gap (distacen between pin and wall)	1.03

The number of the mesh cells for the KAERI 217-pin bundle is 38,490,082 (74 % of the cells is hexahedron).

For the simulation of the turbulent flow in the KAERI 217-pin bundle, SimpleFoam in the OpenFOAM package was used with k-e turbulence model. For the current mesh tests, only cold flow without heat transfer was considered. As boundary conditions for the simulation, constant flow rate at inlet and constant pressure at outlet were used.

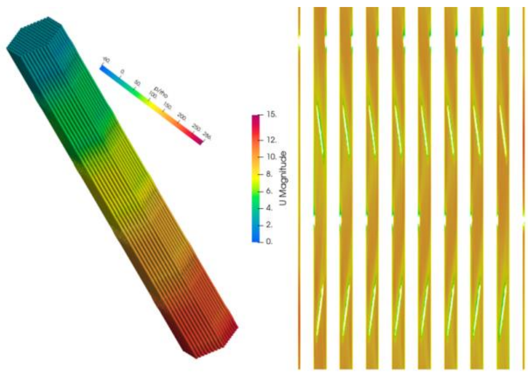

Fig. 8. Pressure and velocity distributions from the simulation of KAERI 217-pin bundle.

Fig. 8 shows pressure (left) and velocity (right) distributions from the simulation of KAERI 217-pin bundle. The convergence of the numerical solutions on the generated mesh was controlled by using limited convective schemes. It took about 350 iterations to get a 3-order reduction of the pressure equation residual.

The pressure gradients along the wire-pin channel depending the inlet flow rate were compared in Fig. 9. It clearly shows that the pressure drop along the channel increases with an increased flow rate.

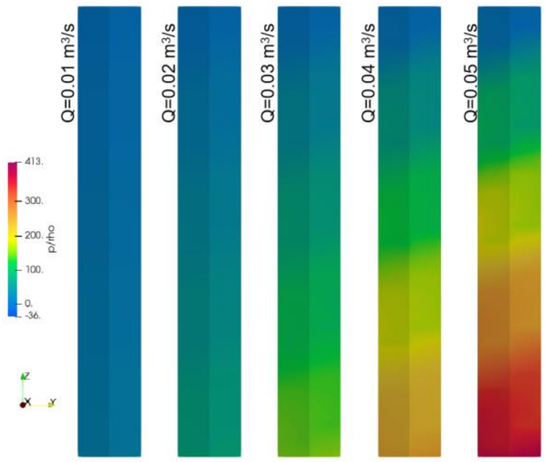

Fig. 9. Pressure distributions on the channel wall of the KAERI 217-pin bundle depending on a flow rate.

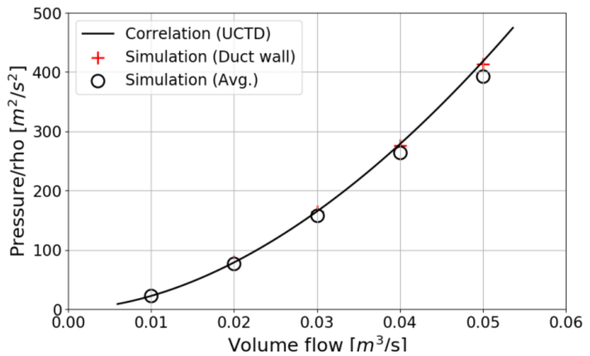

Fig. 10. Comparison of pressure drop along with volume flow for the KAERI 217-pin bundle

Pressure drop of the flow channel can be calculated by differencing inlet and outlet pressures. The inlet pressure can be obtained by a point-probing or a area averaging on the inlet patch. In Fig. 10 the calculated pressure drop divided by liquid sodium density at 475 ºC was compared with UCTD (upgraded Cheng-Todreas detailed) correlation [11]. If inlet pressure at the channel wall is used, the pressure drop exactly matches the correlation. But there exists a minor discrepancy in the pressure drop if the area-averaged inlet pressure is used.

CEA fuel assembly [8] was modeled and the same procedure for mesh generation was applied. Table 2 is the geometric parameters of CEA 217-pin bundle.

Table 2. Geometric data of the CEA 217-pin bundle [8]

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

The number of the mesh cells for the CEA 217-pin bundle is 37,676,137 (74 % of the cells is hexahedron). In this case, constant mass flow with a liquid sodium density at 475 ºC was applied at the inlet. And the pressure drop resulting from the current simulation was compared with the UCTD correlation and results of star-CCM+ by Cadiou et al. [8] In Fig. 11, only the area-averaged pressure at inlet was used for the comparison. The current results exactly match star-CCM+ results by Cadiou et al. at every condition of the inlet mass flow.

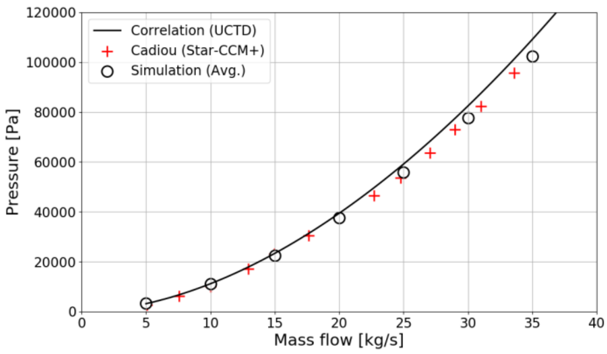

Fig. 11. Comparison of pressure drop along with mass flow for the CEA 217-pin bundle [8]

3. Conclusions

A mesh generation procedure based on an open-source CAD (SALOME) and a CFD tool (OpenFOAM) has been developed for a turbulence-resolved simulation of a wire-wrapped fuel bundle. The process of the mesh generation was fully automated by the developed python and shell programs. From the mesh test, it seems that the generated meshes are acceptable to be used for a prediction of pressure drop along the channel of wire-wrapped fuel bundles.

ACKNOWLEDGMENTS

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