CFD Investigation of Thermal-Hydraulic Characteristics in a SFR Fuel Assembly

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Abstract. The wire effect on three-dimensional flow field and heat transfer characteristics in a helically wrapped fuel assembly mock-up of an SFR have been investigated through a numerical analysis using the commercial CFD code, CFX. In this study, complicated and separated flow phenomena in the fuel assembly without wire spacer and with wire spacer were captured by a RANS flow simulation with the SST turbulence model, and by the vortex structure identification technique based on the critical point theory. It is concluded that the wire spacers locally induce a tangential flow by up to about 13 % of the axial velocity. The tangential flow in the corner and edge sub-channels is much stronger than that in the interior sub-channels. The flow with a high tangential velocity is periodically rotating in a period of wire lead pitch. The cross flow due to the wire spacer can achieve to enhance heat transfer characteristics up to about 50 %.

Key Words: CFD, SFR fuel assembly, Wire spacer

1. Introduction

The wire effect on three-dimensional flow field and heat transfer characteristics in a helically wrapped 7-pin fuel assembly mock-up of an SFR (Sodium-cooled Fast Reactor) have been investigated through a numerical analysis using the commercial CFD (Computational Fluid Dynamics) code, CFX.

The SFR system has a tight package of the fuel bundle and a high power density. The sodium material has a high thermal conductivity and boiling temperature than the water. That can make core design to be more compact than LWR (Light Water Reactor). The fuel assembly of the SFR system consists of long and thin wire-wrapped fuel bundles and a hexagonal duct, in which wire-wrapped fuel bundles in the hexagonal duct has triangular array. The main purpose of a wire spacer is to avoid collisions between adjacent rods. Furthermore, a vortex induced vibration can be mitigated by wire spacers. The wire spacer can enhance a convective heat transfer due to the secondary flow by helically wrapped wires.

In this study, complicated and separated flow phenomena in the 7-pin fuel assembly without wire spacer and with wire spacer were captured by a RANS (Reynolds-Averaged Navier-Stokes) flow simulation with the SST (Shear Stress Transport) turbulence model.

2. Numerical Analysis Methodology

2.1. Test Section

A numerical study of the 7-pin fuel assembly was carried out in the sodium boiling and fuel failure propagation test loops (SIENA) installed at PNC's Oarai engineering center. The geometric parameters of the 7-pin fuel assembly are summarized in Table I. [1] Fig. 1 shows a schematic of the test section and an cross sectional view of the fuel assembly with wire spacers. As shown in Table I and Fig. 1, an electrically heated 7-pin bundle was centered in a hexagonal duct, with a 23.6 mm flat-to-flat distance inside. The heated pins were 6.5 mm in diameter with 0.55 mm cladding thickness, arranged in a triangular array with a pin pitch of 7.9 mm, and had a 450 mm heated length. 7 pins of 6.5 mm in diameter were wrapped by wire spacers of 1.3 mm in diameter with a wrapping lead of 264.8 mm. The pitch-to-diameter ratio (P/D) was 1.22.

2.2.Test Section of Numerical Analysis

The present CFD investigation was carried out over the full-scale experimental facility of SIENA's 7-pin fuel assembly. Fig. 2 shows the test section of the numerical analysis and duct wall surface with red color on the heated location of the hexagonal duct. To understand heat transfer characteristics due to wire spacer, the numeric analysis of the 7-pin fuel assembly without wire is also conducted. In case of the CFD analysis without wire, the pin diameter of geometric parameters is modified to 6.629mm for satisfying same hydraulic diameter. The pin diameter without wire is larger than that with wire. Fig. 3 shows sub-channel area fraction with axial position from inlet region. Sub-channel area fraction value is axially fluctuating because helically wrapped wire spacers periodically pass through certain sub-channels.

TABLE I: GEOMETRIC PARAMETERS OF TEST SECTION

Geometric parameters	**Value**
Number of pins	7
Pin diameter	6.5 mm
Pin pitch	7.9 mm
Pitch to diameter ratio	1.22
Pin axial length	1317 mm
Heated length	450 mm
Heat flux distribution	Uniform
Duct inner flat-to-flat distance	23.6 mm
Wire spacer diameter	1.3 mm
Wire lead pitch	264.8 mm
Cladding thickness	0.55 mm

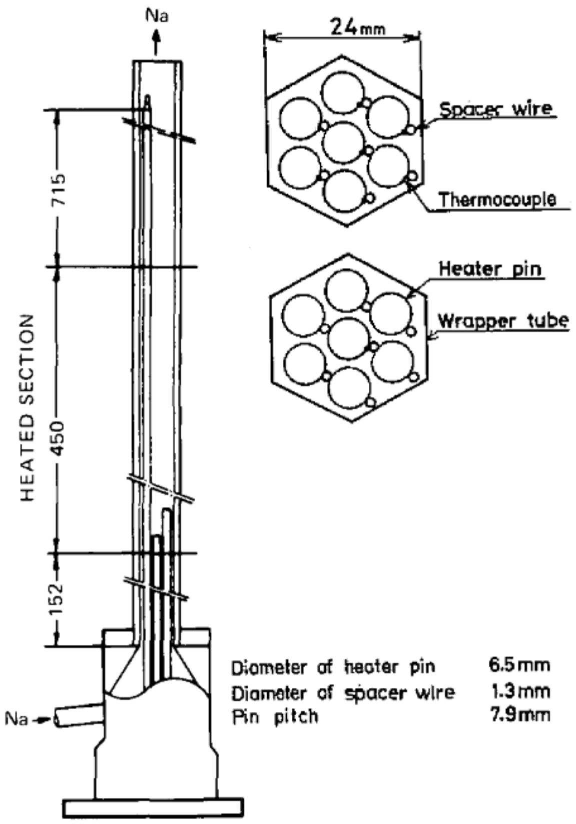


FIG. 1. Schematic of the test section [2]

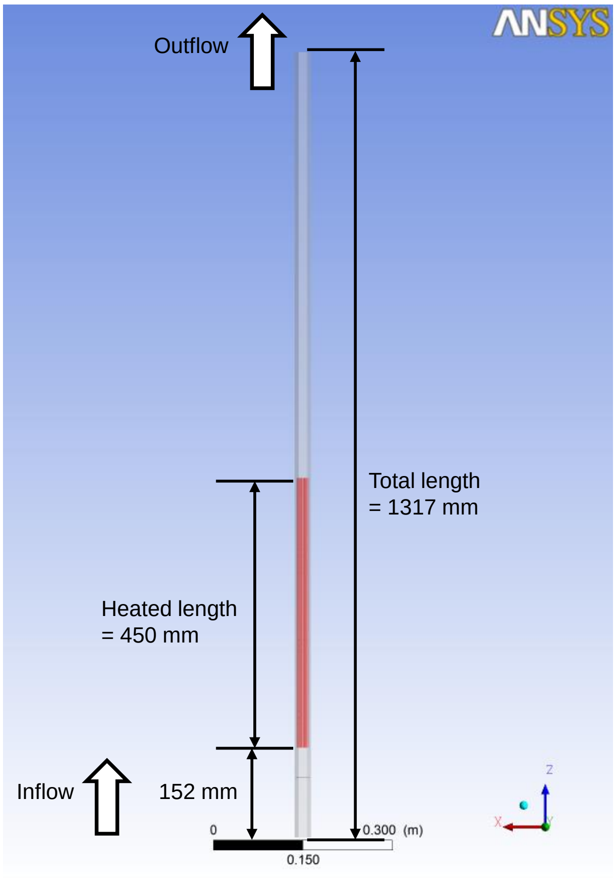


FIG. 2. Numerical test section

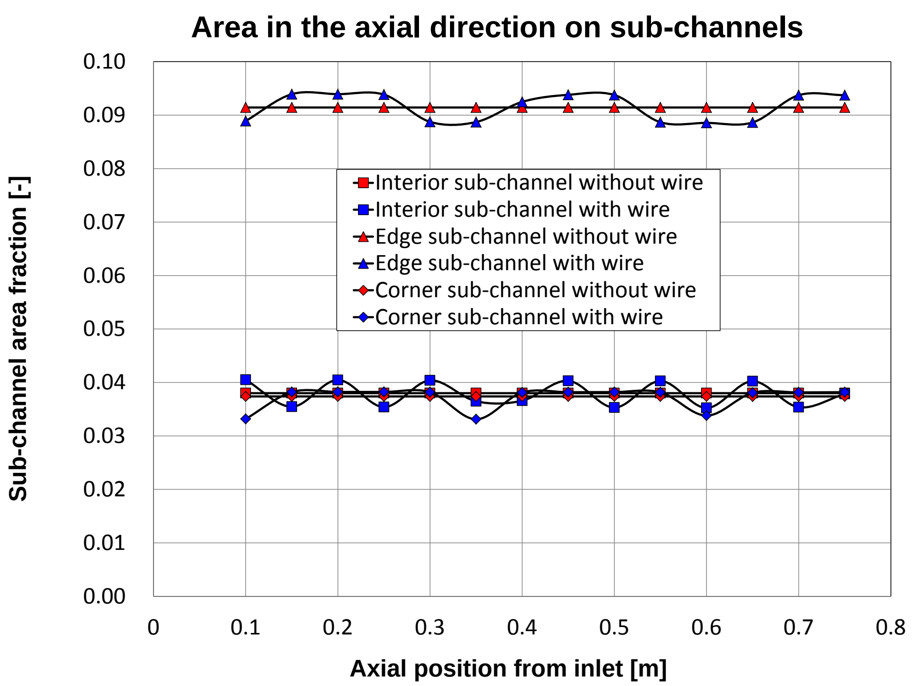
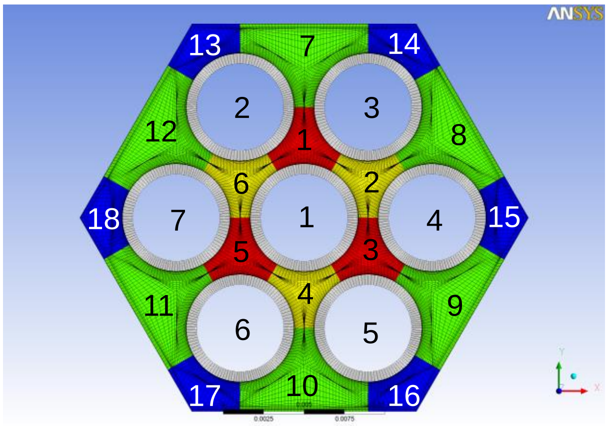


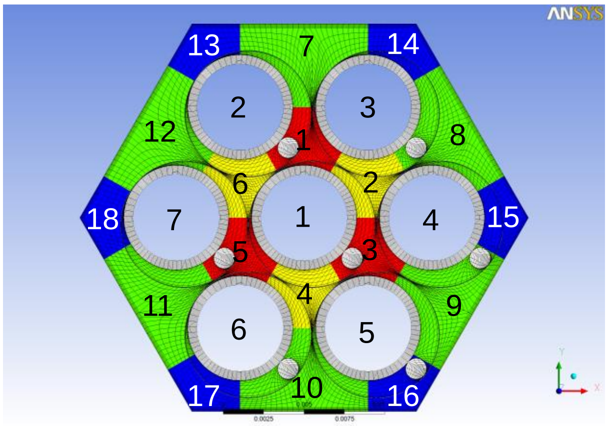
FIG. 3. Sub-channel area fraction with axial position from inlet

2.3.Test Section of Numerical Analysis

Fig 4 shows the cross sectional view with grid distribution, which is divided into interior (red and yellow color), edge (green color), and corner (blue color) sub-channels. All sub-channels are numbered 1 through 18 in a clockwise and radial direction. Figs. 4 (a), (b) are the 7-pin fuel bundles without wire spacers and with wire spacers, respectively. Both computational grid systems of the 7-pin fuel assembly are composed of hexagonal meshes. As shown in Fig. 4, all fuel bundles are numbered 1 through 7 clockwise. Compared to other studies [3-6] with a trimmed shape at the interface between pin surface and wire surface, this RANS based flow simulation is carried out without any trimmed shapes in this study.



(a) Without wire



(b) With wire

FIG. 4. Cross sectional view with grid distribution

Table II describes the computational grids system. The computational grid system is divided into two regions: a fluid part and a structure part. The total number of computational grids in the system was approx. 2.78×10^6 cells.

TABLE II: COMPUTATIONAL GRID SYSTEM

7-Pin	Cells	Nodes	Elements
Fluids	1,583,790	1,646,330	1,583,790
Structures	1,192,100	1,341,340	1,192,100
Total	2,775,890	2,987,670	2,775,890

Table III describes the computational boundary condition of the CFD analysis. The inlet and outlet are defined with various velocities, a temperature of 556.25 K, and a relative pressure of 0 Pa. The inner cladding domain of the heated section has a constant heat flux of 660198 W/m^2. The outer claddings and wire spacers are defined with no slip condition, conservative interface flux, and smooth roughness. The duct wall is applied under no slip and adiabatic conditions.

TABLE III: COMPUTATIONAL BOUNDARY CONDITION

Boundary domain	Condition	Value
-Inlet	-Constant velocity [m/s]	1.3059
		1.6685
		2.1711
		2.6995
	- Temperature [K]	556.25
-Outlet	-Relative pressure [Pa]	0
-Inner cladding	-Constant heat flux [W/m^2]	660198
-Rod & wire outer	-No slip (Smooth wall)	-
-Duct Wall	-No slip (Adiabatic)	-

3. Numerical Analysis Results

3.1.CFD Validation with Correlations

Friction factor correlations such as the Rehme model [7], Engel et al. model [8], and Cheng and Todreas simplified model [9] have been widely used for the wire-wrapped fuel bundle. Each friction factor is calculated through above correlations. Fig. 5 depicts a comparison of the CFD analysis results with friction factor correlations of the Rehme model, Engel et al. model, and Cheng and Todreas simplified model in various ranges of Reynolds number. As shown in Fig. 5, the Cheng and Todreas model has a good agreement with the CFD.

A thermal energy from a fission of the fuel pins is transferred to the coolant by the convection. In case of SFR, the coolant is sodium which has higher transfer coefficients than other fluid. However, for many fluids, including water, Pr (Prandtl number) lies in the range from 1 to 10. For gases, Pr is generally about 0.7. For sodium, the Prandtl number is very small, generally in the range under 0.01. [10] This means that the mechanisms of conductive heat transfer dominate over those of momentum transfer in sodium. Typical Peclet numbers for normal operation are from 150 to 300 in the fuel assemblies. Borishanskii et al. [11] and Graber et al. [12] proposed the following correlations. Fig. 6 depicts the Nusselt number of the CFD analysis results with different Pr_t (turbulent Prandtl number) in various range of Peclet number. Pr_t is calculated by SST turbulence model. Based on the calculated Prt value and certain Pr_l (laminar Prandtl number) value in a certain condition, the Pr value is decided. As shown in Fig. 6, the CFD analysis results with Pr_t of 0.02 have a good agreement with Borishanskii et al. model and Graber and Rieger model. The increase of the Pr_t leads to the decrease of heat transfer as shown in Fig. 6. Nusselt number of the 7-pins with wire spacer is about 50 % higher than that without wire spacer. The wire spacer enhances the heat transfer characteristics.

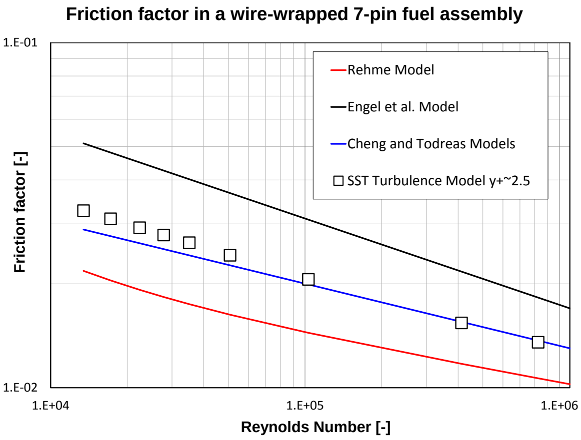


FIG. 5. Comparison of the CFD results with friction factor correlations in various range of Reynolds number

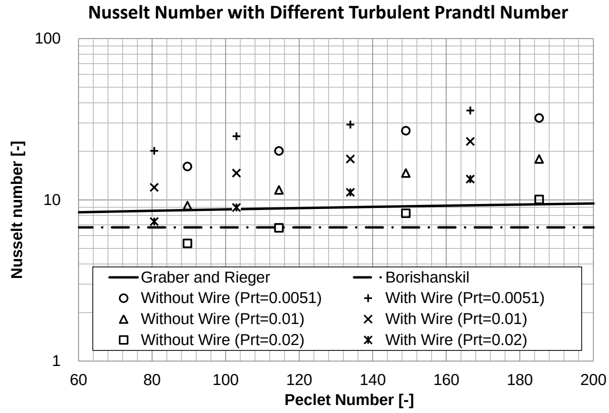
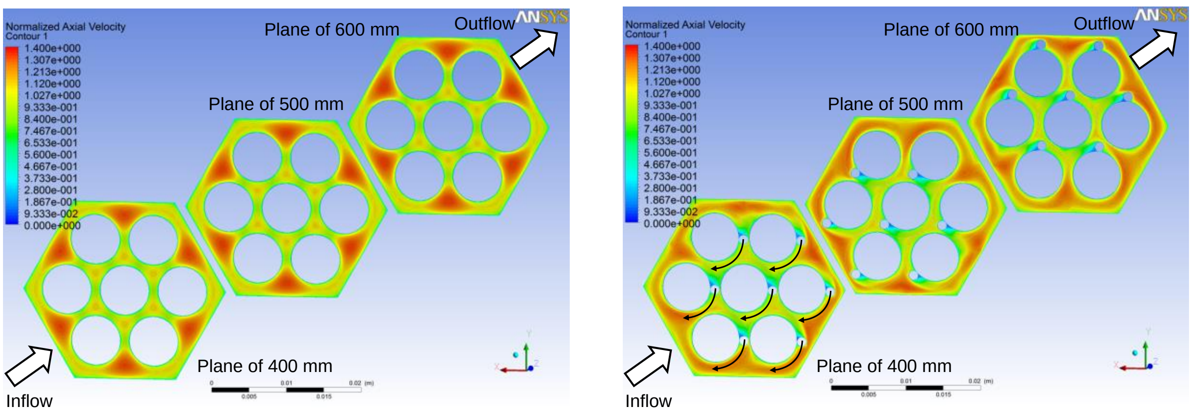


FIG. 6. Heat transfer comparison of correlations and the CFD results with different Prt in various range of peclet number

3.2.CFD Analysis Results

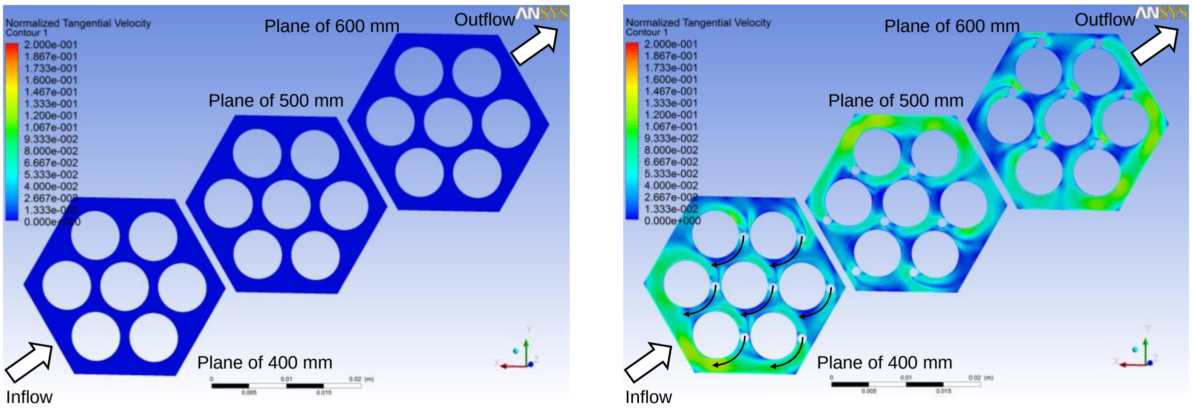
The three-dimensional flow field with Prt of 0.02 has been investigated at a Peclet number of about 1.8×10^3. Fig. 7 shows the axial velocity distribution normalized by inlet velocity on the planes of 400, 500, and 600 mm, which are perpendicular to the axial direction. Figs. 7 (a) and (b) are without wire, and with wire, respectively. Both of axial velocities on the edge and corner sub-channels are higher than that on the interior sub-channels. In case with wire, wake regions due to helically wrapped wire spacers are developed nearby the suction surface of wire spacers.



(a) Without wire (b) With wire

FIG. 7. Normalized Axial velocity distribution

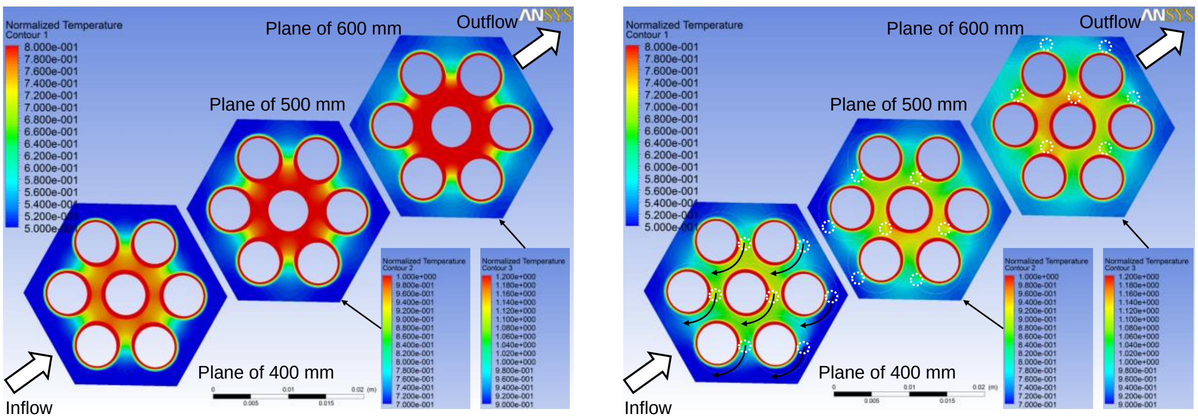
Fig. 8 shows the tangential velocity distribution normalized by inlet velocity on the cross sectional planes of 400, 500, and 600 mm axial position. Figs. 8 (a) and (b) are without wire, and with wire, respectively. The wire spacers induce a tangential flow by up to about 13 % of the axial velocity. The tangential flow in the corner and edge sub-channels is much stronger than that in the interior sub-channels. The flow with a high tangential velocity is periodically rotating in a period of wire lead pitch.



(a) Without wire (b) With wire

FIG. 8. Normalized tangential velocity distribution

Fig. 9 shows the normalized temperature distribution by inlet temperature on the cross sectional planes of 400, 500, and 600 mm height with local range contour. Figs. 9 (a) and (b) are without wire, and with wire, respectively. The peak temperature of 7-pins with wire is located at the connected interface region between center-pin and wire, and helically rotating with wire spacer. The region with peak temperature is corresponding to the wake region due to wire spacer in Fig. 7. As shown in Fig. 9, heat transfer in case with wire spacer is significantly enhanced because of the tangential flow due to wire spacer. Fig. 10 depicts the normalized temperature averaged in each sub-channel area with axial position from inlet. The temperature of the interior sub-channel with wire is lower than that without wire. However, the temperature of the edge and corner sub-channel with wire is almost higher than that without wire. Those phenomena due to the wire spacer make the strong cross flow over the interior, edge, and corner sub-channels. As it has been mentioned before, the tangential flow due to the wire spacer can achieve to enhance heat transfer characteristics up to about 50 %.



(a) Without wire (b) With wire

FIG. 9. Normalized temperature distribution

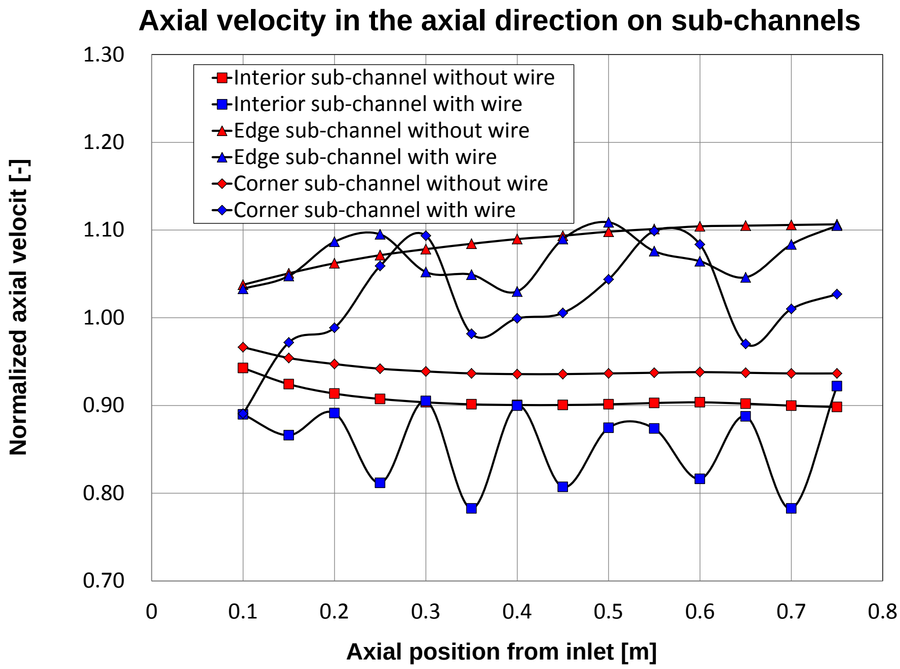


FIG. 10. Normalized axial velocity on the sub-channels along axial position from inlet

4. Conclusions

The wire effect on three-dimensional flow field and heat transfer characteristics in a helically wrapped 7-pin fuel assembly mock-up of the SFR have been investigated through a numerical analysis using the commercial CFD code, CFX. Complicated and separated flow phenomena in the 7-pin fuel assembly without wire spacer and with wire spacer were captured by the RANS flow simulation with the SST turbulence model.

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