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Feasibility Test of Commercial CFD Code for Thermal-Hydraulic Analysis of Wire-wrapped Fuel Pin Bundle in SFR

Chiwoong Choi [a*], Haeyong Jeong [b], and Kwiseok Ha [a]
[a]*Korea Atomic Energy Research Institute, 989-111, Daedeok-daero, Yuseong-gu, Daejeon, 305-353, South Korea*
[b]*Sejong University, Nuclear Engineering Department, Neungdong-Ro, Gwangjin-Gu, Seoul, 143-747, South Korea*
[*]*Corresponding author: cwchoi@kaeri.re.kr*

1. Introduction

The Korea Atomic Energy Research Institute (KAERI) has designed a prototype Gen-IV Sodium-cooled Fast Reactor (PGSFR) with a wire-wrapped fuel bundle. The wire wraps have been the most popular to date, mainly because fabrication is relatively easy and inexpensive. Moreover, it has higher resistance to vibration [1]. Owing to the wrapped wire in a bundle, a swirling flow is generated in the subassembly. Basically, this swirling flow enhances the heat transfer and increases the pressure drop. Therefore, various correlations of pressure drop and heat transfer have been proposed.

In this study, we conducted a numerical analysis of a wire-wrapped 7-pin rod bundle to evaluate feasibility of commercial CFD code, ANSYS-CFX. Various parameters including turbulent models for numerical approach were tested. Various numerical analyses of wire-wrapped fuel bundles have been carried out. One of the major difficulties in the numerical approach is a grid generation of the interface between a wire and rod, because the point connectivity and higher scale deviation of a wire and rod can easily increase the number of meshes. The general way to handle this problem is a simplification of the wire-rod interface [2]. In this study, the wire configuration effect is also studied with a no-wire case and simplified wire geometries. In addition, low Prandtl number like liquid metal has different characteristics in a heat transfer modeling [9]. Therefore, the effect of a turbulent Prandtl number was studied. This work describes a numerical approach to a wire-wrapped fuel rod bundle, which can be a good guide for CFD usage of a future work.

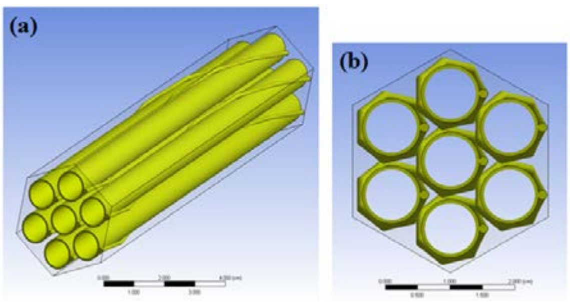

Fig. 1 Computational Domain of the Wire-wrapped 7 Fuel Pin Subassembly: (a) 3D View and (b) Cross-sectional View

2. Computational Conditions

7 fuel pin bundle is defined as computational domain as shown in Fig. 1. The materials of coolant and cladding are sodium and HT9. Fuel part is not modeled. The detailed design parameters are described in Table 1. In addition, Fig. 2 shows a detailed schematic of the fuel rod and wire. The wire contact distance, S_w, is the length penetrating the clad. Basically, the wire will be firmly contacted with the clad surface. As shown in Table 1, the wire diameter is the same as the gap between two fuel rods. However, it is unavoidable in the modeling of the wire to ignore a singular contact point between the wire and cladding. Therefore, an intersected wire and rod are arbitrarily generated.

Table 1 Geometrical Parameters of Wire-wrapped Fuel Pin

Design variables	Value
Fuel rod pitch, P [mm]	10.5
Fuel rod diameter, Dr [mm]	9
Wire pitch, H [mm]	204.9
Wire diameter, Dw [mm]	1.5
Gap of duct, g [mm]	0.2
Wire contact distance, Sw [mm]	0.2, 0.1, 0.05, 0.025
P/Dr	1.167
H/(Dr+Dt)	22.767
Cladding thickness, δclad [mm]	0.56

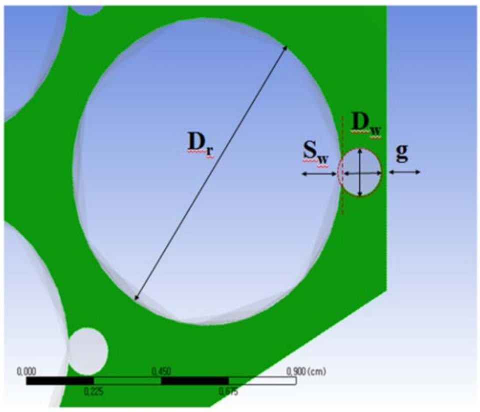

Fig. 2 Schematics of Fuel Rod and Wire

The boundary conditions for the conjugated heat transfer analysis are described in Table 2. The inlet region is defined with a uniform velocity and constant temperature of 650 K. The outlet is defined with a constant ambient pressure, i.e., zero static pressure. Since only the cladding part was modeled, a uniform heat flux condition is applied on the inner cladding wall surface. All solid surfaces are considered as no slip adiabatic boundaries.

Table 2 Boundary Conditions

	B. C.	Remarks
Inlet	Constant inlet velocity Constant inlet temperature	U_{in} = Various m/s T_{in} = 650 K
Outlet	Constant outlet pressure	P_{out} = 0 Pa
Outer wall	No slip Adiabatic condition	U_{wall} = 0 (No heat loss)
Fuel rod surface	No slip Constant heat flux	U_{wall} = 0 q" = 200 kW/m^2
Rest surfaces	No slip Interface condition	U_{wall} = 0

3. Results

3.1 Pressure Drop

Fig. 3 shows the friction factors for seven different turbulent models: K-epsilon, RNG-K-epsilon, LRR-RSM, QI-RSM, K-Omega RSM, K-omega, SST models. The highest friction factors are evaluated for omega-based models including the SST model. And lowest friction factors are evaluated for RSM type models. The friction factors for the K-E based models show middle between omega-based and RSM turbulent models.

Cheng and Todreas proposed turbulent transitional Reynolds number as shown in Eq. (1) [4].

$$\mathrm{Re}_T = 10000 \cdot 10^{0.7(x-1)} \tag{1}$$

where, x is a ratio of pin diameter and pitch. The transitional Reynolds number is about 13081. In this analysis, except first data point, all results were included in fully turbulent region.

Bubelis and Schikorr reviewed the existing correlations of friction factor in a wire-wrapped fuel bundle and proposed a new correlation [3]. Currently, the widely used friction factor correlations are Cheng

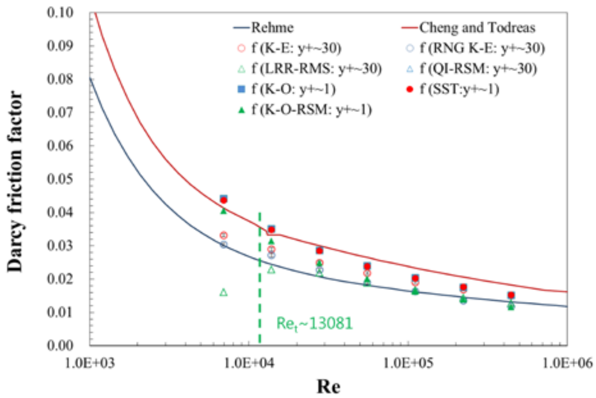

Fig. 3 Friction Factor with Different Reynolds Numbers for Different Turbulence Models

and Todreas [4] and Rehme [5]. Both correlations are defined with y, which indicate the ratio of wire pitch and rod diameter. Therefore, the two correlations have dependency of wire wrapping design. These two correlations are compared with different turbulent models in Fig. 3. For this fuel pin bundle design, the Cheng and Todreas' correlation indicates the higher friction factor than the Rehme's correlation. Except RMS model for higher Re condition, all results are show the friction factors are between two correlations.

A no wire case and three different wire configurations with S_w were also tested (Table 1). Fig. 4 shows the wire configuration effect on the pressure drop. The SST model is used as a turbulence model for this analysis. It is intuitively obvious that the wire acts like an additional friction loss component. The wire is wrapped on the fuel rod surface. Therefore, a flow swirl is generated through the wire, which can add an additional pressure drop component. As the S_w value is decreased, the friction factor is slightly increased, which means that the actual wire configuration can make a slightly higher pressure drop. Hamman and Berry's work indicates similar results with different wire configurations [2]. In other words, the wire can increase the frictional loss owing to an increased surface area and flow distortion.

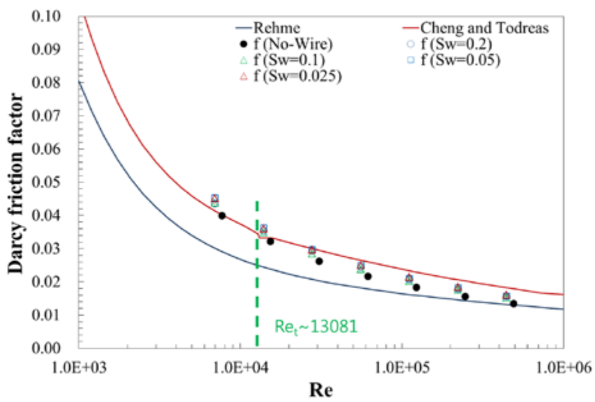

Fig. 4 Wire Configuration Effect on Friction Factor in SST Model

3.2 Heat Transfer

Mikityuk reviewed the heat transfer correlations for a tube bundle [6] and reported that Graber and Rieger [7] and Ushakov [8] show good predictions. These correlations are defined as follows:

Graber and Rieger's correlation

$$Nu = 0.25 + 6.2x + \left(0.032x - 0.007\right) Pe^{0.8-0.024x} \tag{2}$$

Ushakov's correlation

$$Nu = 7.55x - 20x^{-13} + \frac{3.67}{90x^2} Pe^{0.56+0.19x} \tag{3}$$

Mikityuk's correlation

$$Nu = 0.047\left(1 - e^{-3.8(x-1)}\right)\left(Pe^{0.77} + 250\right) \tag{4}$$

These correlations are defined with Peclet number and x. The Nusselt numbers (Nu) evaluated from the numerical results are compared with these three correlations. Fig. 5 shows the turbulent model effect on Nu, which indicates that the turbulent model dependency is increased as increasing Pe. The SST shows highest Nu and RNG-K-Epsilon model shows lowest Nu. Generally, K-Epsilon Based model shows poor estimation due to neglecting a viscous sublayer. The CFD results under-estimated and over-estimated for lower and higher Pe, respectively comparing with these correlations.

The wire effect on the convective heat transfer was also investigated in the same way as the pressure drop analysis. Fig. 6 shows Nu for different wire configurations. As shown in Eqs. (2) - (4), there is no convective heat transfer correlation with parameters related to a wire as in the pressure drop correlations. In other words, the heat transfer correlations for a bundle have no y parameter. However, the numerical results show a difference between the no-wire and wire cases. The wire-wrapped bundle shows a higher Nu than the no-wire case. Intuitively, a swirling flow through a wire can enhance the heat transfer. In addition, a wire itself can have a fin effect. A larger S_w means a larger contact area between the cladding and wire, and thus the thermal resistance can be reduced, which means an enhancement of the heat transfer. With the exception of an S_w of 0.2, the wire configuration effect on the heat transfer is negligible in this analysis.

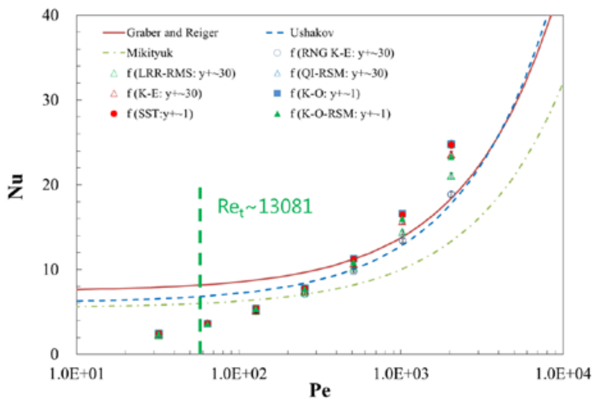

Fig. 5 Nusselt Number with Peclet Number for Different Turbulence Models

3.2 Turbulent Prandtl Number, Pr_t

A turbulent Prandtl number (Pr_t) can be defined as a ratio of diffusivities of momentum and energy. Based on a Reynolds analogy, the Pr_t becomes constant, which is acceptable in a numerical analysis of most turbulent flows with Prandtl number (Pr) over unity. However, experimental observations shows that this classical Reynolds analogy in a small Pr such as a liquid metal fails to correctly predict the local heat transfer [9].

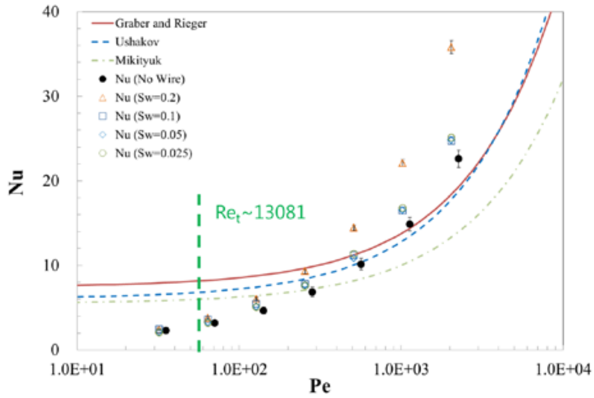

Fig. 6 Wire Effect on Convective Heat Transfer for SST Model

The major observations for the Pr_t can be summarized as follows:

- Pr >1 (air, oil, water, etc.) the Pr_t seems to constant and independent of the Re and Pr.
- The influences of Pr and Re both increase with a decrease in Pr and Re.
- Pr_t increases with a decrease in Pr and Re.

Bricteux et al. studied numerical approaches for a low Pr (liquid metal) and high Re. They compared the LES and DNS results with Reynolds' [10], Kays' [11] and Weigand et al.'s [12] Pr_t correlations. These correlations can be defined as follows:

Reynolds' correlation

$$\Pr_t = \left(1+100Pe^{-0.5}\right)\left(\frac{1}{1+120\,\mathrm{Re}^{-0.5}}\right) \tag{5}$$

Kays' correlation

$$\Pr_t = 0.85+\frac{0.7}{Pe_t} = 0.85+\frac{0.7}{\Pr\frac{\varepsilon_M}{\nu}} \tag{6}$$

Weigand et al.'s correlation

$$\Pr_t = \frac{1}{2\Pr_{t\infty}}+0.3Pe_t\sqrt{\frac{1}{\Pr_{t\infty}}} -\left(0.3Pe_t\right)^2\left[1-\exp\left(\frac{1}{0.3Pe_t\sqrt{\Pr_{t\infty}}}\right)\right] \tag{7}$$

where, $\Pr_{t\infty} = 0.85+\dfrac{100}{\Pr \mathrm{Re}^{0.888}}$

Their results showed that Kays' correlation predicted a reliable temperature profile. In a general approach using Reynolds analogy, the turbulent Prandtl number is constant at 0.85. It is failed to apply Kays' correlation on this CFD analysis due to too higher eddy-viscosity near the wall. However, calculations with different turbulent Prandtl numbers for a wire-wrapped fuel bundle were conducted to check the sensitivity, as shown in Fig. 7. A constant Pr_t of 2 and 100 and a

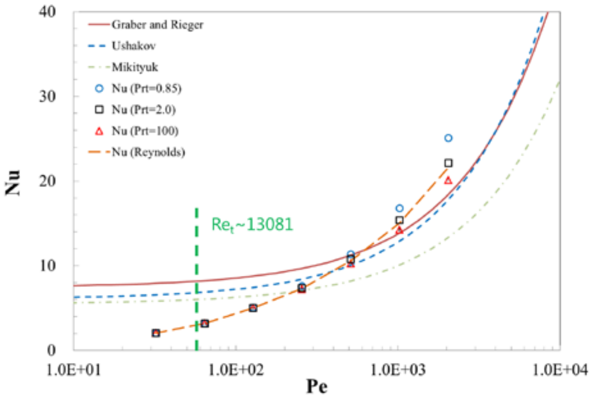

Fig. 7 Nusselt Number with Different Turbulent Prandtl Number for SST and S_w=0.025

Reynolds's correlation were applied. When increasing Pr_t, Nu is decreased and this dependency becomes stronger at a higher Pe. The Reynolds' correlation, defined as a function of Re, shows a similar Nu with the Pr_t = 2 case. As shown in Eq. (7), the Reynolds correlation has no dependency of near wall position. However, as Bricteux et al. reported, Kay's correlation has a spatial dependency from a wall, and therefore can show a better prediction. Although the geometry has an influence on the Pr_t, these correlations were developed for only simple geometries. Therefore, an appropriate Pr_t for a wire-wrapped fuel bundle is necessary for a better prediction with a numerical approach.

3. Conclusions

The numerical analyses of wire-wrapped 7 pins are conducted using ANSYS-CFX to check the feasibility of the CFD tool in thermal-hydraulic phenomena in a wire-wrapped fuel pin bundle. Typical turbulent models are applied to check the dependency of model selection on the pressure drop and heat transfer on the wire-wrapped fuel rod. In short, the omega-based model shows the highest pressure drop and heat transfer. Comparing the existing correlations, the pressure drop results represent acceptable values with certain ranges. However, the heat transfer is highly over-estimated especially higher Pe.

It is not avoidable to simplify the interface between wire and fuel rod, because this geometrical complexity results in huge computational load. Thus, different wire configurations and a no-wire case were selected as the test geometries to estimate the sensitivity of the wire geometry. Compared to a no-wire case, a wire creates a higher pressure drop and heat transfer due to a swirling flow. However, there is no existing heat transfer correlation with wire design parameters. By reducing the wire contact area, the pressure drop slightly increased, but the heat transfer was reduced. Since a reduced contact area increases the frictional area, the thermal resistance is increased. The wire configuration is more sensitive during the heat transfer.

The turbulent Prandtl number (Pr_t) was considered in this study, and existing Pr_t correlations were compared with the numerical results. The dependency of Pr_t showed only a higher Pe number range, and Nu decreased, which indicates approaching to compared correlations. This part is not fully covered yet. For example, the appropriate heat transfer correlation for a wire-wrapped bundle is necessary for a better prediction of the heat transfer. This study started from the fundamental part to evaluate the feasibility of the ANSYS-CFX tool for a thermal-hydraulic analysis of a wire-wrapped fuel pin bundle. The smallest fuel pin group, 7 pins, was used, and thus it is also necessary to extend to a larger number of fuel pins. This work can provide a good guideline for CFD approaches related to a wire-wrapped fuel rod bundle.

REFERENCES

[1] A.E. Walter and A.B. Reynolds, Fast Breeder Reactors, Pergamon Press, pp.295-298 (1939)

[2] K. D. Hamman and R. A. Berry, A CFD M&S Process for Fast Reactor Fuel Assemblies: Experiments and CFD Code Applications to Nuclear Reactor Safety, Idaho National Laboratory, INL/CON-08-14131 (2008)

[3] E. Bubelis and M. Schikorr, Review and proposal for best fit of wire-wrapped fuel bundle friction factor and pressure drop predictions using various existing correlations, Nuclear Engineering and Design, Vol 238, pp. 3299-3320 (2008)

[4] S. K. Cheng and N. E. Todreas, Hydrodynamic models and correlations for bare and wire-wrapped hexagonal rod bundles-bundle friction factors, sub-channel friction factors and mixing parameters, Nuclear Engineering and Design, Vol. 92, pp. 227-251 (1986)

[5] K. Rehme, Pressure drop correlations for fuel element spacers, Nuclear Technology, Vol. 17, pp. 15-23 (1973)

[6] K. Mikityuk, Heat transfer to liquid metal: Review of data and correlations for tube bundles, Nuclear Engineering and Design, Vol. 239, pp. 680-687 (2009)

[7] H. Graber and M. Rieger, Experimentelle Untersuchung des Warmeubergangs an Flussigmetall (NaK) in parallel durchstromten Rohrbundeln bei konstanter und exponentieller Warmeflussdichteverteilung, Atomkernenergie Vol. 19, pp. 23-30 (1972)

[8] P. A. Ushakov, A. V. Zhukov and N. M. Matyukhin, Heat transfer to liquid metals in regular arrays of fuel elements, High Temperature, Vol. 15, pp. 868-873 (1977)

[9] Handbook on Lead-bismuth Eutectic Alloy and Lead Properties, Materials Compatibility, Thermal-hydraulics and Technologies, OECD/NEA Nuclear Science Committee Working Party on Scientific Issues of the Fuel Cycle Working Group on Lead-bismuth Eutectic, OECD/NEA (2007).

[10] L. Bricteux, M. Duponcheel, M. Manconi, and Y. Bartosiewicz, Numerical Prediction of Turbulent Heat Transfer at Low Prandtl Number, J. Physics: Conference Series, Vol. 395, 012D44 (2012)

[11] A. Reynolds, The prediction of turbulent Prandtl and Schmidt numbers, Int. J. Heat Mass Transfer, Vol. 18, pp. 1055-1069 (1975)

[12] W. M. Kay, Turbulent Prandtl Number – Where Are We? , Trans. Of the ASME, Vol. 116, pp. 285-295 (1994)

[13] B. Weigand, J. Ferguson and M. Crawford, An Extended Kays and Crawford turbulent Prandtl number model, Int. J. Heat Mass Transfer, Vol. 40, pp. 4191-4196 (1977)