Development of heat transfer correlation in cross-flow direction of TRU fuel pin bundle with wrapping thin wire

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ABSTRACT

Trans-uranium (TRU) fuel has high decay heat because it contains Minor Actinide (MA). Therefore, it is important to establish an effective and practical cooling technology during the fabrication process. For the purpose, we have developed a heat transfer correlation in cross-flow direction of TRU fuel pin bundle. The correlation development process is divided into two steps. First, we investigated the thermal-hydraulics behavior, especially the relation between an angle (circumferential location with respect to the fuel pin) of wire attachment and heat transfer of a TRU fuel pin bundle system by two-dimensional thermal-hydraulic analysis. As a result, we found that the thermal-hydraulic property depends on the wire attachment angle of wire attachment. Second, in order to enhance a predictive accuracy, we implement the heat transfer correlation which we have constructed to the sub-channel analytical tool and perform a numerical simulation of the TRU fuel bundle system. We found that the thermal-hydraulic behavior in the present system is not sensitive to the heat transfer correlation consequently.

KEYWORDS

TRU fuel, thermal hydraulics, CFD, FLUENT, sub-channel analysis

1. INTRODUCTION

A low decontaminated fuel in which a TRU is included is planned to be used for Fast-Breeder Reactor (FBR) cycle system in Japan. When a TRU fuel pin bundle is fabricated, a fuel pin with a thin wire is wrapped to keep a distance between fuel pins and lay it transversely (Fig. 1). A TRU fuel has high decay heat because it contains Minor Actinide (MA), and we make air flow into the gaps vertically across the pin bundle to remove the heat. Therefore, it is important to establish an effective cooling technology in the fabrication process. For this purposes, we investigate the thermal-hydraulics behavior, especially in the cross-flow direction of a wire-wrapped fuel pin bundle.

In the previous study, we performed a two-dimensional thermal-hydraulics numerical analysis in the TRU fuel pin bundle system using FLUENT [1] and constructed the heat transfer correlation [2]. In those works, we supposed the bare bundle system for simplicity. However, in the actual situation, we attach a thin wire to fuel pins to keep distances between fuel pins. Therefore, it is important to study influence of the wrapped wires on the heat transfer of a TRU fuel pin bundle system. For that purposes, we perform a numerical analysis of the two-dimensional thermal-hydraulics analysis of an infinite staggered tube bank with a thin wire, which corresponds to a part of cross section of TRU fuel pin bundle system in the cross-flow direction (Fig. 1).

We also have investigated the heat transfer correlation sensitivity in the sub-channel analytical tool. We have developed the sub-channel analysis tool for TRU fuel pin bundle system The benchmark analysis has already been done and checked the applicability to investigate the thermal-hydraulics phenomena in TRU fuel fabrication [3]. The two dimensional analysis is done to improve the the sub-channel analysis tool. In the present work, we investigate the necessity of modification of the empirical heat transfer correlation. The existing sub-channel analysis tool uses the heat transfer correlation which is established for thermal-hydraulics analysis of gas cooling nuclear reactor [4]. Thus, we change the existent heat transfer correlation by the one which we constructed in the previous work [2], and checked the sensitivity of the correlation.

The contents of this paper are as follows. In section 2, we estimate the influence of an angle of wire attachment on thermal-hydraulics behavior in the TRU fuel pin bundle system. In section 3, we investigate the sensitivity of the heat transfer correlation in sub-channel code. The final section is devoted to the conclusions of the present work.

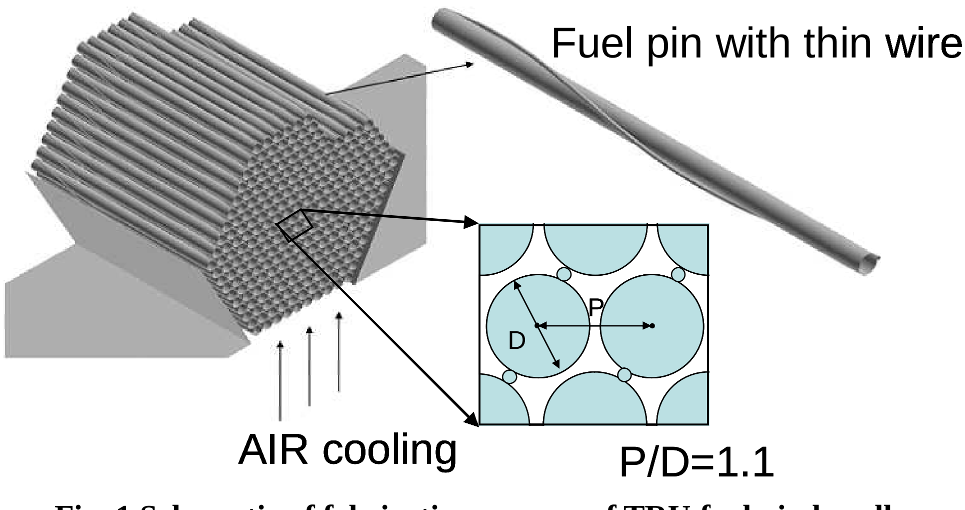


Fig. 1 Schematic of fabrication process of TRU fuel pin bundle

2. ESTIMATION OF INFLUENCE OF AN ANGLE OF WIRE ATTACHMENT ON THERMAL-HYDRAULICS BEHAVIOR IN THE TRU FUEL PIN BUNDLE SYSTEM

We perform a numerical calculation for an infinite staggered tube bank system with wire to investigate the thermal hydraulics properties by using the commercial CFD code FLUENT.

By doing the numerical calculation, we study the influence of an angle of wire attachment on the Nusselt number.

2.1. Analytical system

As an analytical system, we consider an infinite staggered tube bank system with wire in two-dimension (Fig. 2) which corresponds to a cross sectional surface of a part of TRU fuel pin bundle in a fabrication process in the cross flow direction (Fig. 1). In present TRU fuel pin bundle system, the thermal hydraulics behavior in the cross flow direction is more important than axial direction. Therefore, we consider a two dimensional system. Furthermore, a three dimensional system consists from two dimensional one in the axial direction. This system consists from two column and two rows of tubes with a wire. The fuel pitch divided by the pin diameter (so called P/D) is 1.1 (Fig. 1). All wires are attached to fuel pins in the same angle. An angle of wire attachment is defined as Fig. 3. All tubes and wires consist from SUS316. We suppose that all inside of tubes have the same heat flux (red circle of Fig. 2), and the heat transfer to outside of tubes. We send air into sub-channel from the bottom side (light blue region of Fig. 2) for cooling. The thermophysical properties of the each material are shown in the table 1. Furthermore, we impose the periodic condition on air flow, blue, green and pink line of Fig. 2, means that the same color connected each other. Now, we ignore the gravity for simplicity.

The height is 61.56 mm, the width 71.08 mm, the tube outer diameter 32.31 mm, the tube inner diameter is 27.89 mm (See Fig. 1). These sizes are different from an actual TRU pin. We use larger size to make convergence of the calculation better. However, the ratio of inner and outer diameter is the same as actual fuel pin.

We use an unstructured triangular cell, and the space of each cell is set to 0.1mm and total number of computational cell is about 400,000. A part of cell is shown in Fig. 2.

2.2. Analytical condition

We perform numerical analysis when an angle of wire attachment θ is 0, 10, 20, 30, 40, 50, 60, 70, 80, 100, 110, 120, 130, 140, 150, 160, 170 and 180. We do not need to consider when $180 < \theta < 360$ because of symmetry. We set the mass flow rate of air as 0.0071576 kg/s in all cases. This mass flow rate corresponds to Reynolds number 2,000 which is defined by

$$\mathrm{Re} = u_{\max} \frac{D}{\nu} \tag{1}$$

in the case of bare bundle. Here D is a tube diameter, $u_{\max}$ a maximum air velocity between gaps. ν is dynamic viscosity given by

$$\nu = \frac{\eta}{\rho} \tag{2}$$

where η is viscosity and ρ is density. We give 400W/m^2 heat flux to inside of all tubes (red circle in Fig. 2). We adopt RNG k-ε model as turbulence model, and enhanced wall treatment near-wall treatment, both of which are appropriate for present system [1]. And the convergence criteria are shown in Table. 2. We suppose that bulk temperature of fluid is 300K. Pressure-velocity coupling is SIMPLEC.

2.3. Method to obtain Nusselt number

In this subsection, we explain how to obtain the Nusselt number from the numerical analysis using FLUENT. We can obtain the value of T_{w}, T_{inflow} and T_{outflow} using FLUENT computation. Here, we define T_{w} as averaged temperature on the surface of the tube. And T_{inflow} is a temperature of fluid before flowing into a tube bank, T_{outflow} a temperature of fluid after flowing out of a tube bank. Here in this analysis, we use a mass flow rate averaged values defined by

$$T_{\mathrm{inflow}} = \frac{\int_{\mathrm{inflow}} GT}{\int_{\mathrm{inflow}} G}, \tag{3}$$

$$T_{\mathrm{outflow}} = \frac{\int_{\mathrm{outflow}} GT}{\int_{\mathrm{outflow}} G}, \tag{4}$$

respectively. Here G expresses mass flow rate and T temperature. The integral are performed along the lines which are expressed by the red line for inflow and blue line for outflow in Fig. 4 respectively. In addition, we define T_{m} as

$$T_{\mathrm{m}} \equiv \frac{T_{\mathrm{inflow}} + T_{\mathrm{outflow}}}{2}. \tag{5}$$

Now, we can obtain the averaged Nusselt number Nu_m of the present system by using the following relation,

$$Nu_{\mathrm{m}} = \frac{h_{\mathrm{m}} D}{k} = \frac{\phi D}{(T_{\mathrm{w}} - T_{\mathrm{m}})k}. \tag{6}$$

Here h_m is an average heat transfer coefficient, D a tube diameter, k a thermal conductivity of fluid, ϕ a heat flux on the surface of the tube.

2.4. Results and Discussions

In this subsection, we explain the calculational results. Fig. 5 and Fig. 6 show the contour of absolute value of flow velocity and temperature respectively at each angle of wire attachment. Fig. 7 shows the averaged Nusselt number as a function of an angle of wire attachment. In Fig. 7, "Wire included" means that heat flux ϕ in Eq. (6) is calculated so that the heat transfer area include the area of wire as follows

$$\phi = \int_{(\text{Area of tubes})+(\text{Area of wires})} q dA, \tag{7}$$

where q express amount of heat transfer and A is area of heat transfer area. Similarly, "Wire excluded" means that heat flux ϕ in Eq. (6) is calculated so that the heat transfer area does not include the area of wire as follows

$$\phi = \int_{(\text{Area of tubes})} q dA. \tag{8}$$

On the other hand, "Bare bundle" is the calculational result when we do not attach wires to fuel pins.

At first, we will explain the result in the case of "Wire included" in case of each θ value.

(i) $\theta = 0$

Nusselt number is near that of "Bare bundle". This is because the wires are located in the place where it does not interrupt the air flow. If we compare the distribution of the flow velocity of 0 degree with that of bare bundle, we can see that the existence of wire hardly change the distribution of the flow velocity (Fig. 8).

(ii) $0 < \theta \leq 30$
Nusselt number decreases as θ increases. It takes the minimum value when θ=30 because the wires stop the one-sided flow channel (See Fig. 5(d)).

(iii) $30 < \theta < 50$
Nusselt number increases as θ increases.

(iv) $50 \leq \theta \leq 70$
Nusselt number takes the value which is near that of bare bundle. This is because those wires are located around a stagnation point. For example, we compare the distribution of flow velocity of 50 degree with that of bare bundle, we find that the distribution of flow velocity is very similar to that of bare bundle (See Fig. 9).

(v) $70 < \theta \leq 90$
Nusselt number takes large value. If the θ approaches 90 degree, wires makes flow channel small and flow velocity becomes large, so that Nusselt number becomes very large. When θ = 90, it is impossible to perform the numerical calculation in two-dimensional analysis. Here in this work, we consider two-dimensional cross section in the cross flow direction. In actual TRU fuel pin bundle system is three-dimensional system and an axis direction exit. Therefore, the air flows go into the axis direction when the flow channel becomes small, and Nusselt number never takes extremely large value.

(vi) $90 < \theta \leq 150$
Nusselt number decreases as θ increases, and takes the minimum value in the case of θ=150. This is because the wires stop the one-sided flow channel as in the case of θ=30.

(vii) $150 < \theta \leq 180$
Nusselt number increases as θ increases. It takes the value which is near that of bare bundle.

Secondly, we will explain the result in the case of "Wire excluded". The results of "Wire excluded" is almost the same as those of "Wire included". The different point is that Nusselt number takes maximum value at θ = 170.

In the case of "Bare bundle", Nusselt number is 39.4. On the other hand, Nusselt number changes from 28.6 to 56.0 in the case of "Wire included". In other words, Nusselt number varies from -28% to 42% than that of "Bare bundle". Similarly, Nusselt number of "Wire excluded" varies from -20% to 29% than that of "Bare bundle".

We can conclude that the influence of wire on thermal-hydraulics properties is large and not negligible. Therefore, we have to take the influence of wrapped wire into consideration, in order to understand the thermal-hydraulics behavior of TRU fuel pin bundle system correctly. We will reflect the thermal-hydraulics properties, which we have obtained, to sub-channel analytical tool in the future, for example, as a function of wire attached angle.

Table 1. Thermophysical properties

Material	Density (kg/m^3)	Specific heat(J/kg/K)	Thermal conductivity (W/m/K)	Viscosity (kg/m/s)
SUS316	7970	450	13.5	
Air	1.225	1006.43	2.42×10^{-2}	1.7894×10^{-5}

Table 2. Convergence criteria

parameter	convergence
continuity	10^{-8}
x-velocity	10^{-6}
y-velocity	10^{-6}
energy	10^{-10}
k	10^{-6}
epsilon	10^{-6}

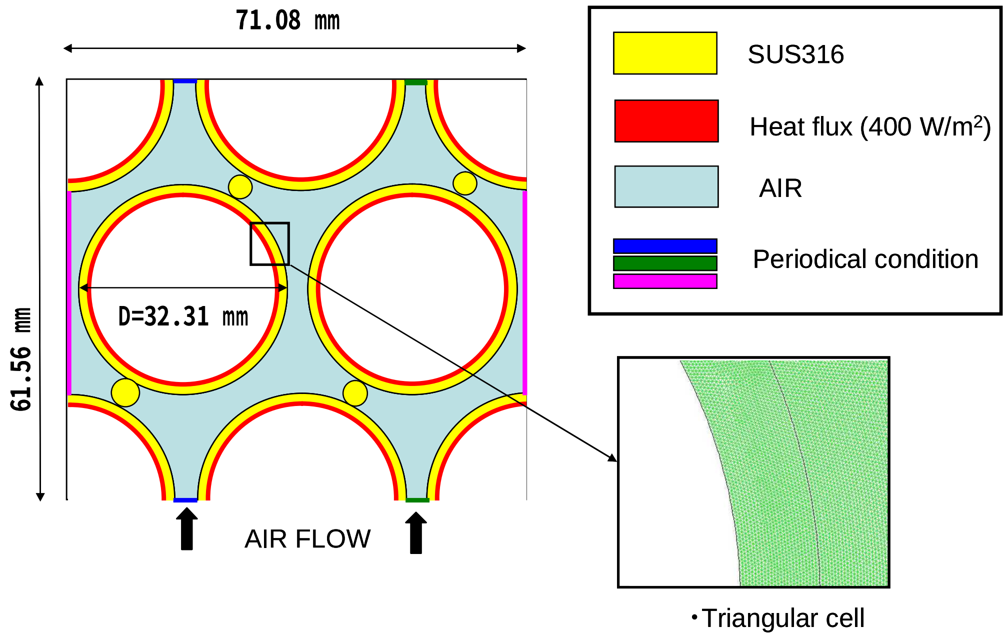


Fig. 2 Analytical system

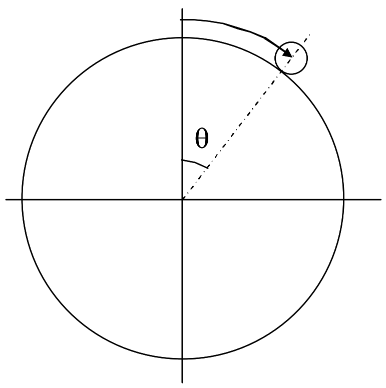


Fig. 3 Definition of an angle of wire attachment

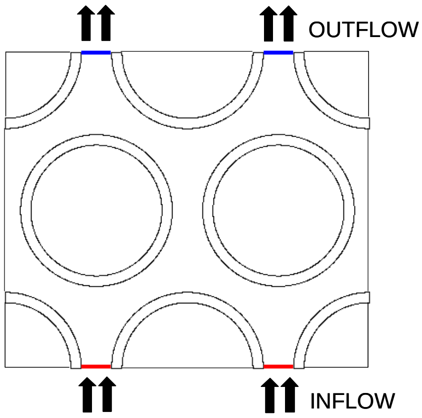


Fig. 4 Integral region for temperature

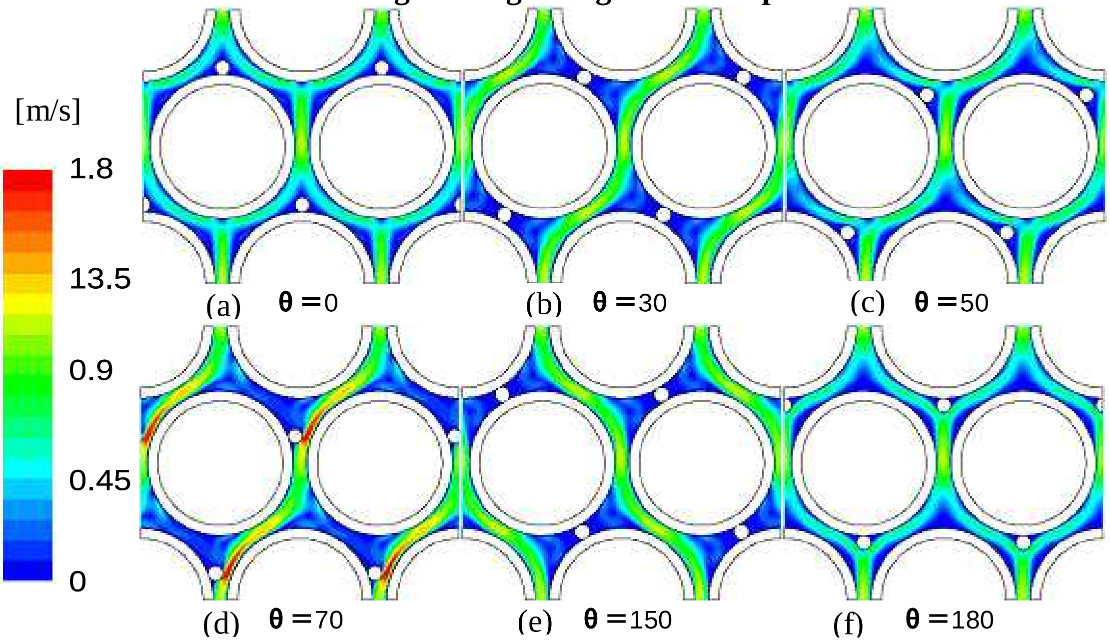


Fig. 5 Velocity distribution for each angle of wire attachment

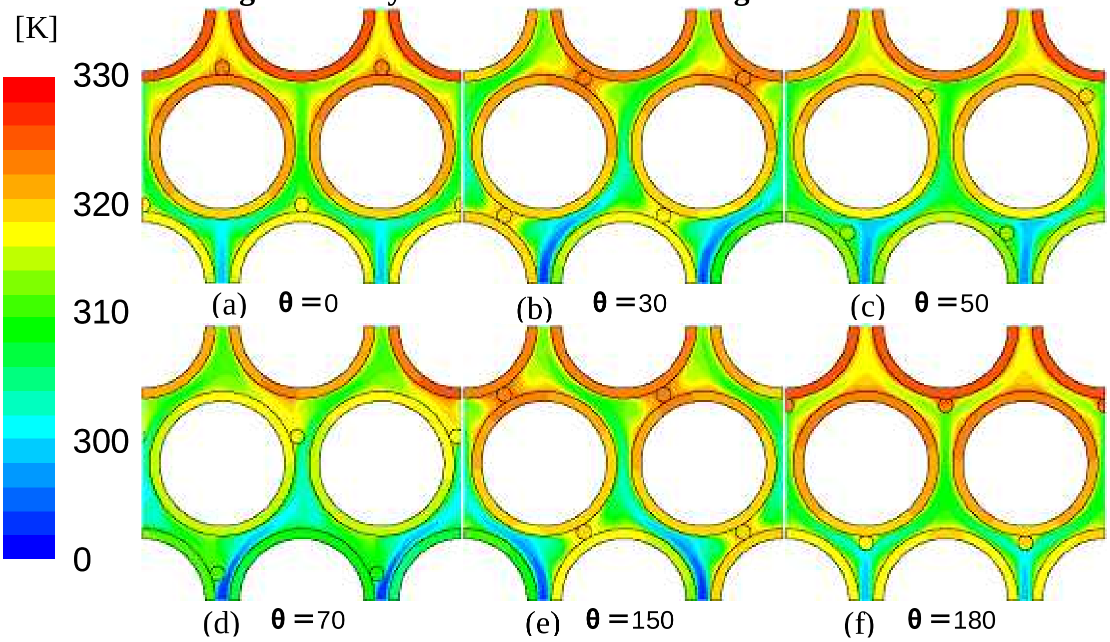


Fig. 6 Temperature distribution for some angle of wire attachment

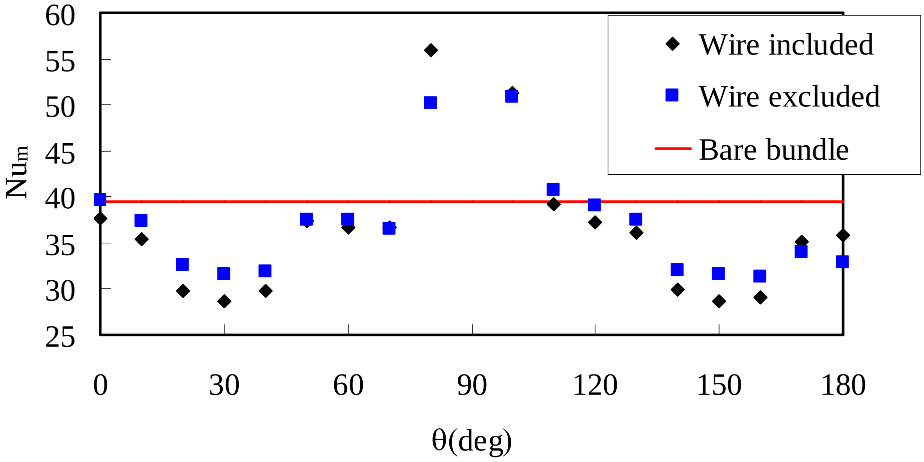


Fig. 7 Nusselt number for each angle of wire attachment

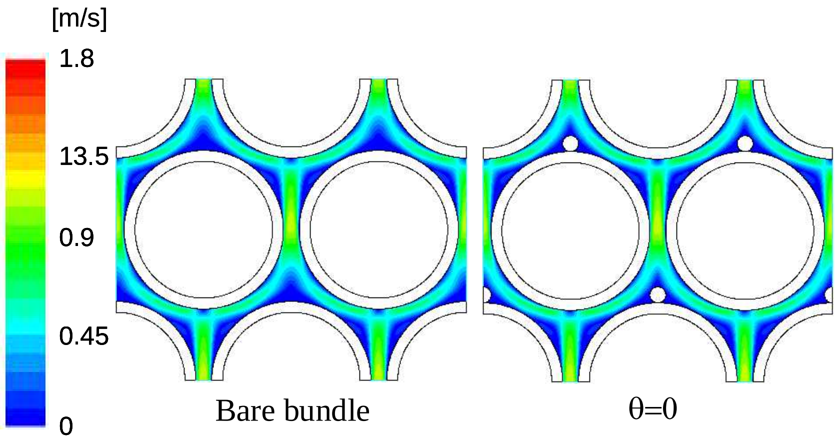


Fig. 8 Comparison of velocity distribution (Bare bundle and 0 degree)

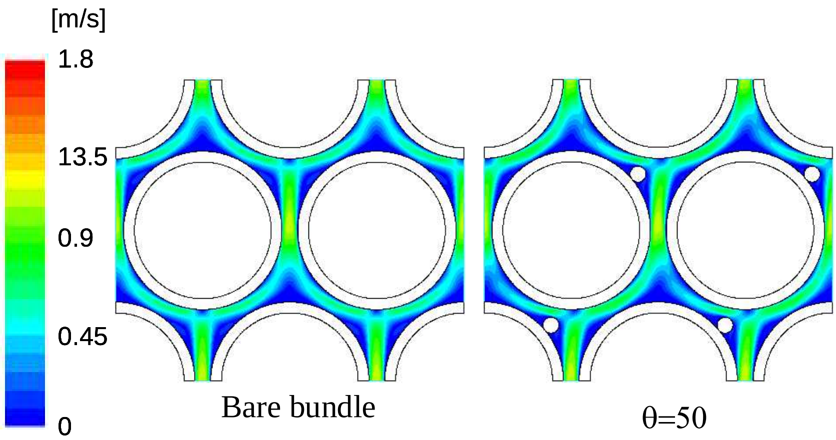


Fig. 9 Comparison of velocity distribution (Bare bundle and 50 degree)

3. DEVELOPMENT OF SUB-CHANNNEL ANALYSIS

In this subsection, we change the heat transfer correlation in sub-channel analytical tool, in order to investigate the necessity of modification of the heat transfer correlation. We implement the correlation equation which we have constructed [2] to existent sub-channel analytical tool and perform the numerical analysis to TRU fuel pin bundle.

3.1. Sub-channel analysis tool

We have developed the sub-channel analysis tool to investigate a thermal-hydraulics phenomenon in a horizontal laid fuel pin bundle. We can calculate the temperature distribution of cooling wire and each cladding. The advantage of this tool is that we can consider the multi-dimensional effect due to spirally-wrapped wire with a comparative low computational cost. The benchmark analysis has already been done and we have checked the applicability to the TRU fuel pin bundle on some analytical condition [3].

3.2. Heat transfer correlation

In the previous work, we constructed the heat transfer correlation using numerical calculation results [2] for TRU fuel pin bundle system. Fig. 10 shows Zukauskas and Grimison empirical correlation [5, 6], and our correlation

$$Nu_m = 0.66\,\mathrm{Re}^{0.53} \tag{9}$$

with calculational results obtained by two-dimensional analysis. On the other hand, the existent sub-channel code uses the smooth surface correlation which have been constructed for gas cooling nuclear reactor [3] and for system which $1.3 < P/D < 1.5$, whereas we assume the TRU pin bundle cooling system in fabrication process and $P/D = 1.1$. Therefore, we use Eq. (9) which was constructed for the TRU pin bundle system for applicability and sensitivity test.

3.3. Analytical condition

Fig. 11(a) shows TRU fuel pin bundle in the cross flow direction. TRU fuel pin bundle consists of 255 fuel pins (Fig. 11(a)) and both ends of the bundle is covered by the support plate in lower half part. The clearance between fuel assembly and support plate is 1.1 mm. additionally it is the Fuel Assembly Inner Duct Structure (FAIDUS) [7].

An electric rod heater is embedded in the pins to duplicate the decay heat. The total length of the fuel bundle is about 2,000 mm and we give uniform heat center part of fuel pin as shown in Fig. 11(b). We send air flow from air inlet located in the bottom of the apparatus. The depth is 111 mm and the width is 1,000 mm which corresponds to the heating zone. The diameter of each fuel pin is 10.4 mm. And the diameter of wrapped wire which is attached to each pin is 1.03 and pin pitch is 200 mm shown in Fig. 11(a).

The velocity of inlet air for cooling is 1.0m/s. Each fuel pin has 10 W heat generations. Main analytical condition is shown in Table 3.

3.4. Results and Discussions

Fig. 12(a) shows the comparison of the pin surface and coolant air temperature increase between the calculational result and experimental result in the cross section M (See Fig. 11(b)). For the heat transfer correlation, we use Eq. (9). Left side of figure express the results of the pin surface and right the coolant air. The measurement locations are shown by the black circles which indicate the location of Thermo couple in Fig. 11(a). The black diagrams express the experimental data and white ones calculational result. We can see that the sub-channel analytical tool underestimates the experimental data in all cases both in the case of pin surface and coolant air. Fig. 12(b) shows that the comparison of the pin surface and coolant air temperature increase between the calculational result and experimental result obtained by the existent sub-channel analysis tool which uses the smooth surface correlation. The calculational results of Fig. 12(a) and (b) are different numerically, however, they are almost the same. The marked different points are some of the results of 10th layer and 9th layer of pin surface temperature increase. Similarly, in other cross section B and M, we can not see particular difference between the results obtained by modified sub-channel tool and the existent sub-channel analysis tool results although we do not show those results here.

We conclude that the analytical result related to thermal-hydraulic behavior of TRU fuel pin bundle is not sensitive to the correlation adopted in sub-channel analytical tool. Therefore, we have to improve the other factor to enhance a predictive accuracy.

Table 3. Analytical condition

Number of fuel pin	255
Fuel pin (cladding) Outer diameter Thickness	 10.4 [mm] 0.7 [mm]
Wire Outer diameter Wrapping pitch	 1.03 [mm] 200 [mm]
Heat generation	10 [W/pin]
Inlet air velocity	1.0 [m/s]
Atmospheric temperature	24 [℃]

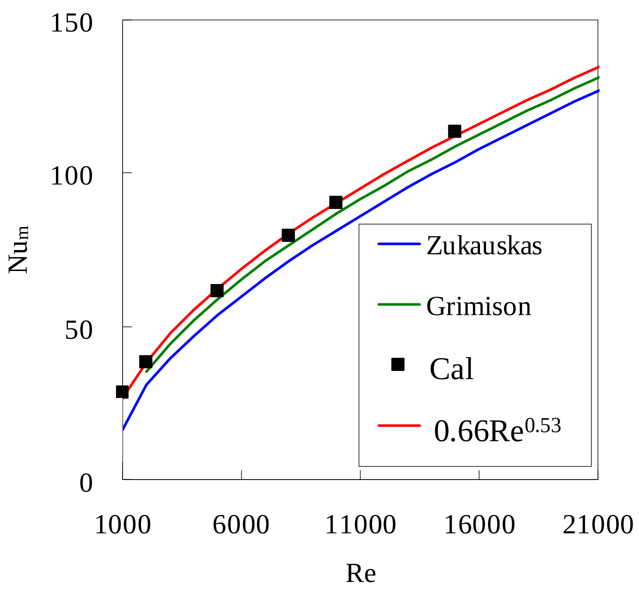
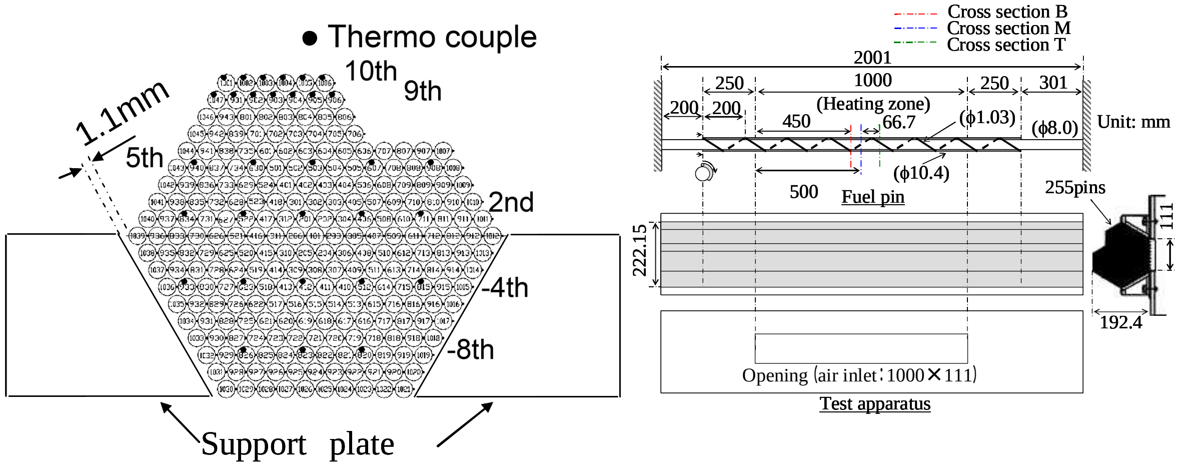
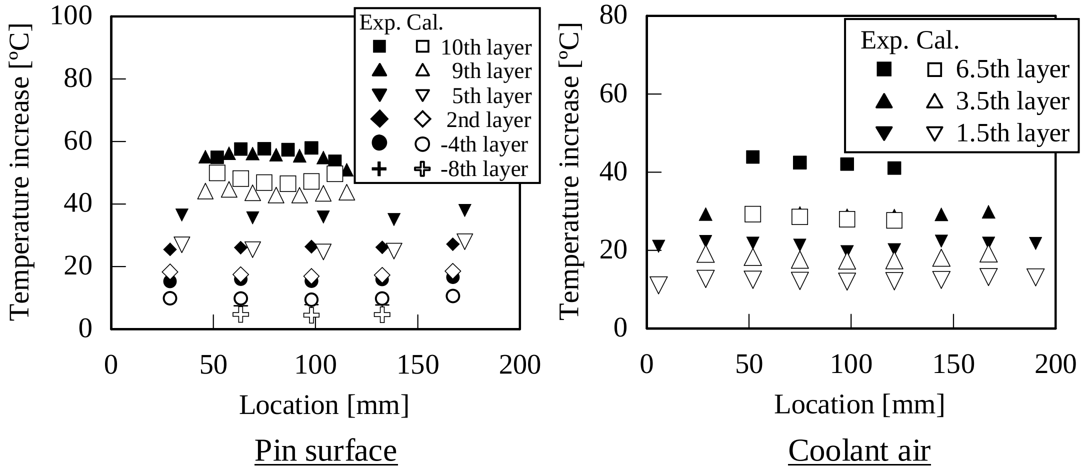


Fig. 10 Heat transfer correlation

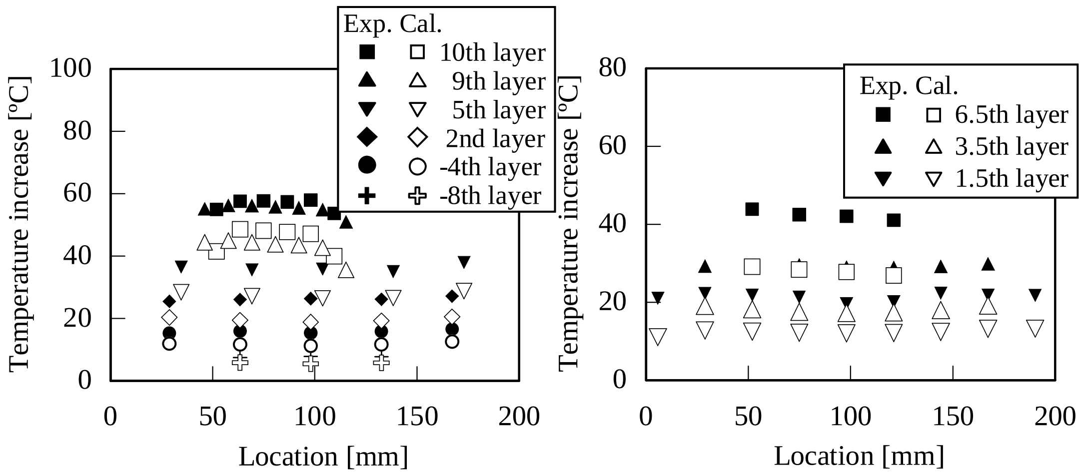


(a) Cross sectional view of apparatus **(b) Geometry of apparatus**

Fig. 11 Experimental apparatus



(a) Present sub-channel analysis [cross section M]



(b) Exsistent sub-channel analysis [cross section M]

Pin surface Coolant air

Fig. 12 Pin surface and coolant air temperature

4. CONCLUSION

We investigated the thermal-hydraulics behavior, especially the relation between an angle of wire attachment and heat transfer of a TRU fuel pin bundle system by performing two-dimensional analysis. As a result, we found that the influence of wire on thermal-hydraulics properties is large and not negligible. Therefore, we have to take the influence of wrapped wire into consideration in order to understand the thermal-hydraulics behavior of TRU fuel pin bundle system, correctly. We will reflect these results to sub-channel code in the future.

We investigated the sensitivity of heat transfer correlation. For that purposes, we implement the heat transfer correlation, which we have constructed, to the sub-channel code and perform a numerical simulation to see the influence of correlation on the thermal-hydraulics analysis in the TRU fuel bundle system. We found that the thermal-hydraulics behavior in present system is not sensitive to the heat transfer correlation consequently. In the future work, we plan to have additional benchmark analysis, for example, the sensitivity test of clearance. And we will develop sub-channel analytical tool for the transient analysis which the experiment has already done by authors, at the Nuclear Development Company.

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