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DEVELOPMENT OF SUB-CHANNEL ANALYSIS TOOL FOR TRU FUEL FABRICATION

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ABSTRACT

The development of the fast reactor (FR) cycle is being preceded to utilize plutonium and trans-uranium (TRU) in Japan. In the fabrication process, it is considered that a fuel pin spirally-wrapped with a thin wire is laid horizontally. Then cooling air flows vertically into the gap of the pin bundle so as to suppress the temperature increase due to decay heat. From the view point of the safety assessment during the fabrication, a thermal hydraulic analysis method would be an alternative way to investigate the maximum temperature and the temperature distribution of the fuel pins. A numerical tool has been developed in the present study. A sub-channel method is applied considering a numerical resolution and a computational cost. Using the developed tool, the benchmark analysis of the mocked up experiment done by Nuclear Development Corporation has been carried out. It is demonstrated that we obtain a good agreement between the mocked up experiment and the numerical result. A sensitivity analysis has also been carried out to enhance the cooling efficiency.

1. INTRODUCTION

A low decontaminated fuel in which a trans-uranium (TRU) is included is to be planed in a development of Japanese Fast Breeder Reactor (FBR) cycle for the purpose of reducing a long-lived and highly radioactive waste. In addition to an avoidance of radioactive contamination of personnel, an effective cooling manner during the fabrication will be required because the fuel has a decay heat.

A schematic of the TRU fuel fabrication and its cooling image is pictured in Fig. 1. In the current status of fabrication planning (Itoh et al., 2008), it is considered that a fuel pin with a thin spirally-wrapped wire is laid horizontally and was assembled into a fuel bundle shape firstly. Then the fuel bundle will be inserted in a wrapper tube. As in Fig. 1, air flows into a gap of the fuel bundle vertically from the bottom of the bundle during the fabrication. It is noted that the Fuel Assembly with Inner Duct Structure (FAIDUS) (Mizuno et al., 2004) is to be planed in the TRU fuel bundle. Hence no fuel pin region exists for the inner duct as seen in the upper right side of Fig. 1.

In order to establish the effective cooling system, the authors have drawn up both experimental and numerical works especially from an engineering design's viewpoint (Itoh et al., 2008).

As a numerical tool for engineering design, the following terms should be necessary as:

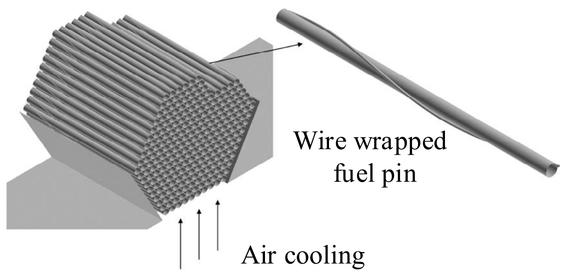


Fig. 1 Schematic image of TRU fuel bundle and its cooling

- ✓ Temperature distribution of cooling air and each cladding
- ✓ Multi-dimensional effect due to spirally-wrapped wire
- ✓ Low computational cost

The TRU fuel bundle consists of more than 200 fuel pins (for instance, 255 fuel pins are considered in the present study). Furthermore the geometrical configuration of the gap space between the fuels is quite complicated because of the wrapped wire. Therefore, a numerous computational mesh is required in case of a multi-dimensional thermal-hydraulics simulation resulting in a huge computational cost. On the other hand, the multi dimensional effect cannot be predicted by a flow network simulation method like a plant dynamic code though it achieves a quite low computational cost.

A sub-channel analysis method has been established to investigate a thermal-hydraulics phenomenon in a fuel bundle with a comparative low computational cost by using a specified control volume. Accordingly, sub-channel analysis method only has a potential to satisfy the criteria for the engineering tool mentioned above. On the other hand, it has been established for a vertically located fuel bundle in general and there is no empirical background of an applicability and/or capability of the method on a horizontal laid fuel bundle.

In the present paper, a sub-channel analysis method, which is specified to the TRU fuel bundle, has been developed. Benchmark analyses have been carried out to investigate the applicability of the present method. A sensitivity analysis has also been examined to enhance the cooling efficiency.

2. DEVELOPMENT OF SUB-CHANNEL ANALYSIS TOOL

In a sub-channel analysis method, a specific control volume is taken into account inside a pin bundle as shown in Fig. 2.

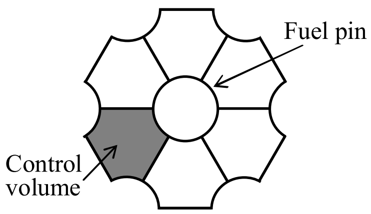


Fig. 2 Specified control volume

Conservation equations of mass and unknown variable ϕ are described in integral form as:

$$\frac{\partial\langle\rho\rangle}{\partial t}+\frac{1}{\Delta V}\int_{Aff}\rho\mathbf{u}\cdot\hat{\mathbf{n}}dA=0, \tag{1}$$

$$\frac{\partial}{\partial t}\langle\rho\phi\rangle+\frac{1}{\Delta V}\int_{Aff}\rho\phi\mathbf{u}\cdot\hat{\mathbf{n}}\,dA =-\frac{1}{\Delta V}\int_{Aff}\mathbf{J}\cdot\hat{\mathbf{n}}\,dA-\frac{1}{\Delta V}\int_{Afs}\mathbf{J}\cdot\hat{\mathbf{n}}\,dA+\langle\rho S\rangle. \tag{2}$$

Here, ρ, $\mathbf{u}$ and $\hat{\mathbf{n}}$ mean the density, the velocity in vector form and the normal unit vector respectively. ΔV, A and S are the volume, the surface area and the source and/or sink term respectively. The subscripts Aff and Afs represent the fluid-fluid and the fluid-solid interaction areas in the control volume. $\langle\ \rangle$ denotes the intrinsic volume average and is defined as:

$$\langle\phi\rangle=\frac{1}{\Delta V}\int_{Vf}\phi_f dV \tag{3}$$

As concerns a numerical scheme, the first order Euler and the first order up-wind method are applied to the time marching term and the convection term respectively. The Incomplete LU Bi-Conjugate Gradient (ILUBCG) method is used for solving the Poisson equation of pressure.

Since inlet and outlet boundary conditions are required at the cross-flow direction in the present study, additional control volumes are embedded as shown in Fig. 3. The red and green boxed regions reveal the control volume for the horizontal and vertical momentum conservations respectively. Besides, dummy cells (blue boxes in Fig. 3) are introduced to enlarge the control volume of the vertical momentum conservation (green boxed region).

In general, a sub-channel analysis method requires constitutive correlations, such as a flow resistance especially in cross-flow direction, a heat transfer coefficient between cladding surface and working fluid and a mixing factor due to turbulence, because of the specific control volume arrangement.

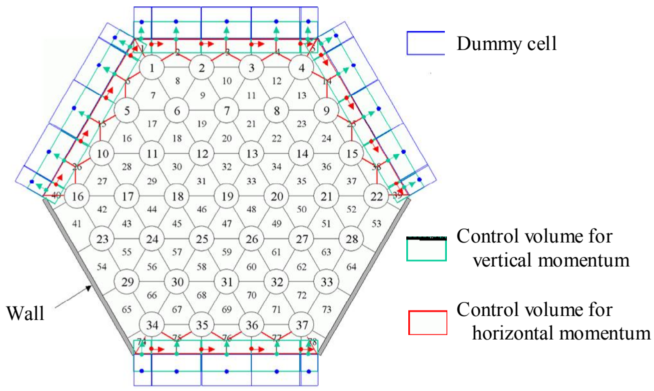


Fig. 3 Additional control volume for boundary condition

It is easily expected that the constitutive equations play an important role for a predictive accuracy of sub-channel analysis.

For instance, the flow resistance through the cross-section can be evaluated based on the Distributed Resistance Model (DRM) in case of wire-wrapped fuel pin bundle (Ninokata et al., 1987). In that model, the E-function $E(\omega)$, which is defined in the following equation, is adopted to add an effect of the wire on the flow resistance.

$$E(\omega)=\frac{f_G}{f_G^{\omega}}, \tag{4}$$

where, f_G is the friction factor of pin bundle without the wire (bare pin bundle). f_G^{ω} means the friction factor of wire-wrapped pin bundle with attached angle ω. In the original DRM model, the E-function was obtained based on the experiment (Suh et al., 1987). However, the fuel pitch divided by the cladding outer diameter (so called P/D) in the experiment was 1.21. On the other hand, the P/D of the TRU fuel bundle is approximately 1.10. This is attributed the fact that a dense fuel pin arrangement is to be planned in the TRU fuel.

The authors have elucidated the influence of the P/D on the E-function by numerical examination and have modified it for P/D=1.10 so as to enhance the predictive accuracy of the present method (Takata et al., 2008). It is noted that the applicability and the modification, if necessary, of the existent heat transfer correlations for triangular rod bundle (for instance, Grimison, 1937; Zukauskas, 1972) is also of importance for the code development. The numerical examination of the heat transfer coefficient has been ongoing (Manabe et al., 2008).

3. NUMERICAL ANALYSIS OF TRU FUEL BUNDLE

In the numerical investigation of the TRU fuel bundle, the benchmark analyses of the mocked up experiment done by the authors (Itoh et al., 2008) have been carried out firstly to clarify the applicability of the developed tool. Then the sensitivity analysis has carried out so as to enhance the cooling performance.

3.1 Analytical Conditions

Figures 4 and 5 show the geometry of the test apparatus and the cross sectional view of the bundle respectively. The mocked up bundle consists of 255 dummy fuel pins in which an electric rod heater is installed in the pin to duplicate the decay heat. The total length of the bundle is approximately 2,000mm and the uniform heating is added 1,000mm in length as shown in Fig. 4.

In the test apparatus, the both ends of the bundle are covered up by the support plate as well as the lower half of the horizontal side. It is noted that the test bundle has 5mm clearance at both horizontal walls as shown in Fig. 5. This clearance is set up temporarily taking into consideration the installation of the wrapper tube after the fuel bundle assembly.

The air inlet is located at the bottom of the apparatus and its dimension is 111mm in depth and 1,000mm in width that corresponds to the heating zone. The cooling air flows into the bundle vertically upward.

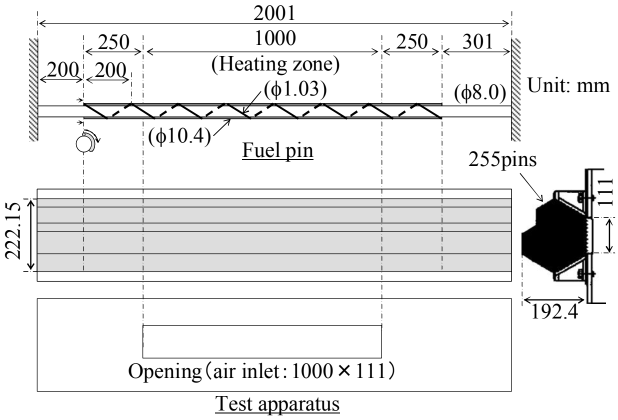


Fig. 4 Geometry of test apparatus

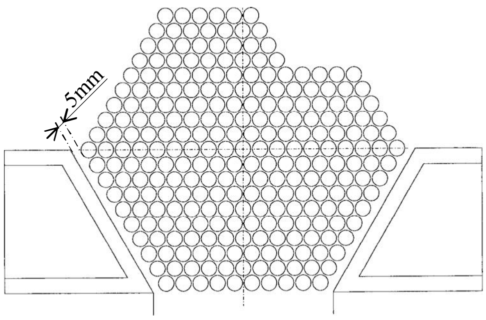


Fig. 5 Cross sectional view of bundle

In the analysis, the axial direction of the bundle is divided into 123 meshes. The thin wire that is wrapped spirally to the fuel pin is assumed to be put horizontally at each node. The axial mesh size is approximately 16.7mm at the heating region, which corresponds to the 1/12 of the wrapped pitch.

In the preliminary analyses (Takata et al., 2008), it has been demonstrated that the thermal conductivity in the fuel cladding affects the temperature distribution considerably. Hence, multi-dimensional thermal conductivity is applied to the present analysis as in Fig. 6. The cladding is segmented into 2 meshes in radial direction, 6 meshes in circumferential direction and 123 meshes in axial direction. The nodalization both in circumferential and axial direction coincides with that of the control volume inside the bundle.

As concerns a boundary condition, a constant heat flux is embedded on the inner surface of the cladding (see Fig. 6) so that the total heat generation is equal to approximately 10W per pin. With regard to the coolant (air), a uniform and constant inlet velocity of 1.0m/s (24°C) is set. A free-slip and an adiabatic condition is applied to the support plate. Table 1 summarizes the analytical condition. Steady state simulation has been carried out both in the benchmark and sensitivity study.

In the benchmark of the experiment, the default configuration mentioned above is applied firstly. Then an influence of heat transfer due to natural convection at the outermost fuel pins is discussed. As concerns the sensitivity study, the influence of the cooling air leakage through the clearance between the fuel assembly and the horizontal support (see Fig. 5) has been investigated by changing the clearance size.

Table 1 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 [°C]

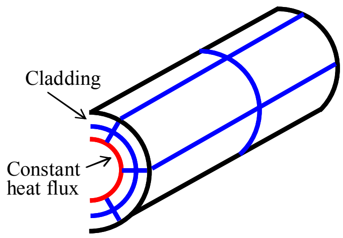


Fig. 6 Nodalization of fuel cladding

3.2 Results of Benchmark Analysis

Figure 7 shows the temperature distribution of the coolant at the outer surface and the cross section along the axial direction. As seen in Fig. 7, the high temperature region appears near the both ends of the heating zone. Since the flow resistance through the axial direction is smaller than that through the cross flow direction, the coolant flows easily into the axial direction. Consequently, the cooling air spreads widely along to the axial direction and the maximum temperature appears near the both ends of the heating zone.

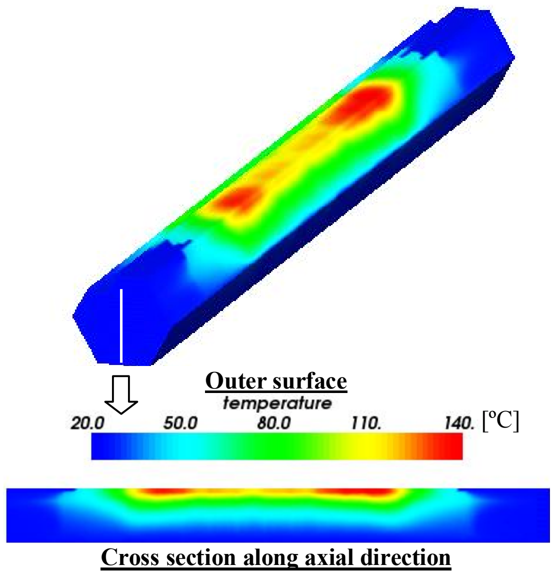


Fig. 7 Temperature distribution of coolant

As in Fig. 7, a periodical local maximum of the coolant temperature is obtained as well as an asymmetry temperature distribution. This is attributed the fact that the flowage of the cooling air is affected by the spirally-wrapped wire as shown in the topside of Fig. 4. Accordingly it is demonstrated that the present method has an advantage to investigate the multi-dimensional effect of the wire with a reasonable computational cost.

The velocity and temperature distribution of the coolant at the center of the heating zone is indicated in Fig. 8. The clearance between the fuel assembly and the support plate is quite wide (5mm) comparing with the gaps between the fuels (approximately 1.1mm that is same as the thin wire diameter). Consequently, a large amount of the coolant leaks from the clearance resulting in a less coolant at the topside of the assembly. Therefore, the highest temperature is investigated at the topside.

It is easy expected that the cooling performance will improve as the flow resistance at the clearance increases. The influence of the clearance will be discussed later.

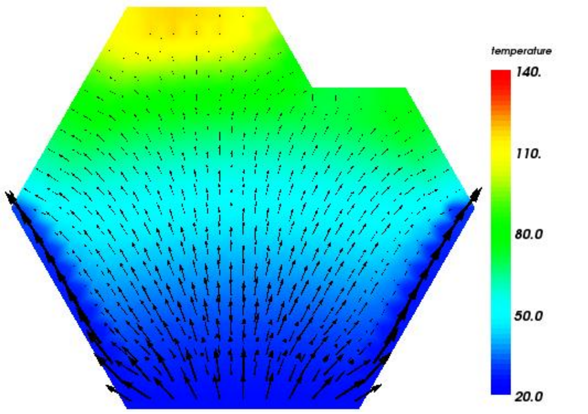


Fig. 8 Velocity and temperature distribution of coolant at the center of heating zone

Figure 9 shows the comparison of the cladding temperature increase between the analysis and the experiment at the center of the heating zone. The measurement location is also indicated in Fig. 10.

Except the topside (9th and 10th layers), an excellent agreement is achieved. In the present method, the outermost fuel pins are directly connected to the outlet boundary as shown in Fig. 3 and heat transfer due to convection is only taken into consideration at those computational cells. However, almost no cooling air flow is investigated in the analysis (Fig. 8) resulting in a very small amount of the heat transfer to the cooling air.

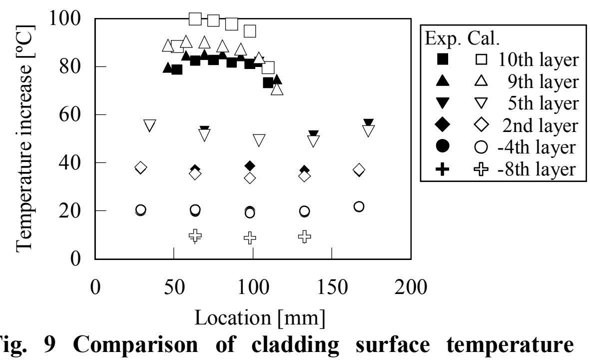


Fig. 9 Comparison of cladding surface temperature increase (default)

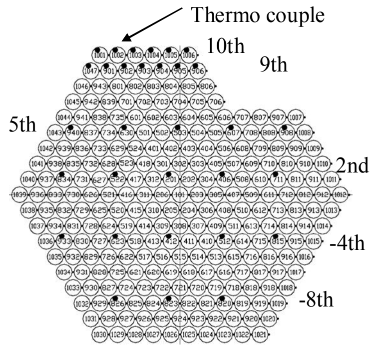


Fig. 10 Location of temperature measurement (cladding surface)

On the other hand, a large opening exists above the test apparatus. Accordingly, a heat transfer due to natural convection might take place in addition to the convective heat transfer in the experiment.

In order to investigate the influence of the heat transfer due to natural convection on the cladding temperature, an additional heat transfer correlation, which is applied to a horizontally located plate (Fishenden, 1950), is implemented into the outermost fuel pins including the obliquely-laid pins as;

$$Nu = 0.14 Ra^{1/3}. \tag{5}$$

Here, *Nu* and *Ra* are the Nusselt number and the Rayleigh number respectively. The fuel pin diameter is set to a characteristic length in Eq. (5). The computational result is shown in Fig. 11. A quite good agreement is obtained even at the topside of the bundle.

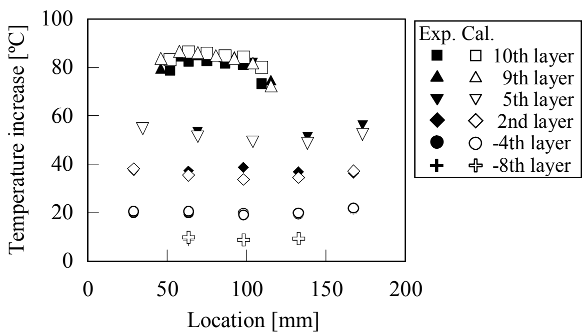


Fig. 11 Comparison of cladding surface temperature increase (considering natural convection heat transfer at outermost fuel pins)

In the benchmark analyses of the mocked up experiment, a quite good agreement is achieved between the analysis and the experiment when one considers the heat transfer due to natural convection at the outermost fuel pins. Therefore, it is concluded that the present method has an applicability to investigate the thermal-hydraulics in the TRU fuel fabrication.

However, it may also be said that the heat transfer due to natural convection is not necessary when one takes the efficient cooling performance into account.

3.2 Sensitivity Study

As mentioned in Sec. 3.2, the clearance between the fuel assembly and the support plate arranged in the experiment (5mm) will deteriorate the cooling performance. In practice, the treatment of the clearance is one of the main issues from the design assessment’s point of view (Itoh et al., 2008).

Hence, a simple assumption of the clearance plugging is considered as shown in Fig. 12 to estimate the influence of the clearance on the cooling performance.

In Fig. 12, it is noted that the clearance of approximately 1.1mm is still assigned because of the thin wire. It is also noted that no heat transfer due to natural convection is considered in the sensitivity analysis because more air flow is perspective at the topside of the bundle. Another numerical condition is same with the benchmark analyses.

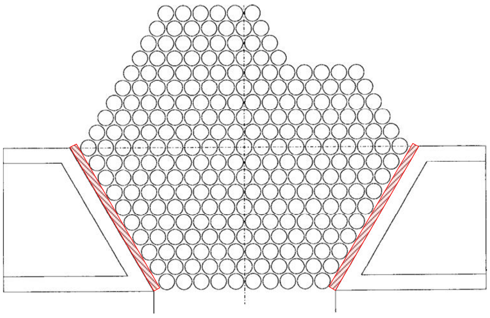


Fig. 12 Plugging of clearance

The computational results of the coolant temperature distribution and the velocity distribution are indicated in Figs. 13 and 14 respectively.

Comparing with Fig. 7, the coolant temperature decreases considerably and the high temperature region diminishes. However, the leakage through the clearance still remains as seen in Fig. 14.

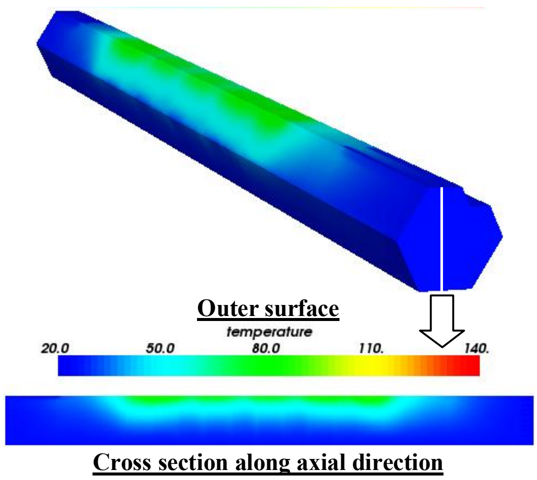


Fig. 13 Temperature distribution of coolant (1.1mm clearance)

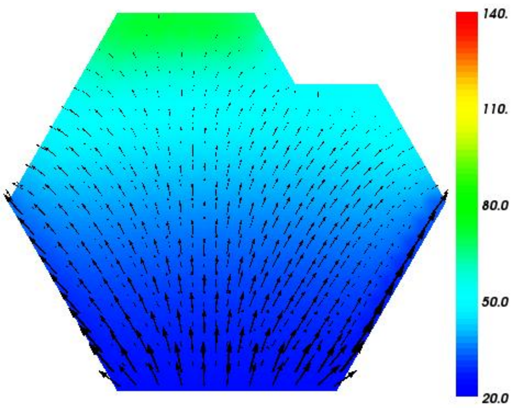
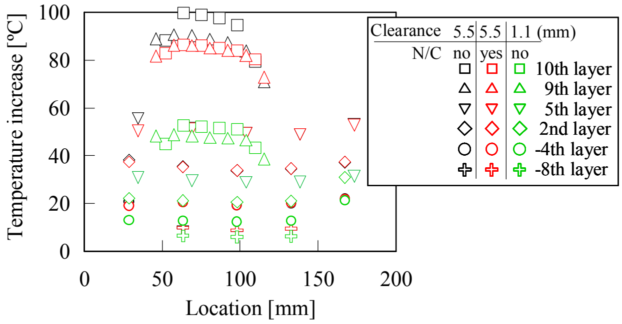


Fig. 14 Velocity and temperature distribution of coolant at the center (1.1mm clearance)

Figure 15 reveals the comparison of the cladding temperature increase at the center between the analyses. When the clearance is reduced from 5mm to 1.1mm, the cladding temperature that is located above the support plate (higher than 2nd layer) decrease significantly. For instance, it drops approximately 15ºC at 2nd layer and more than 30ºC at 10th layer if the natural convection heat transfer is not taken into account in both cases.



N/C: Natural convection heat transfer

Fig. 15 Influence of clearance (cladding surface temperature)

As a result of the sensitivity study, it is demonstrated that the treatment of the clearance affects the cooling performance significantly. In the present study, the leakage through the clearance still remains although the size of the clearance changes from 5.5mm to 1.1mm. An efficient plugging manner is required so as to enhance the cooling performance.

It is also demonstrated that the developed tool is useful to investigate the cooling performance. Currently, the similar experiment as in Fig. 12 has been conducted by the authors. Consequently, a mature numerical examination of the developed tool will be carried out in the near future as well as the modification of the heat transfer correlation in order to enhance a predictive accuracy.

4. CONCLUSIONS

As a numerical tool for engineering design to evaluate a thermal-hydraulics behavior during a fuel fabrication in which trans-uranium is included (TRU fuel), a sub-channel analysis method has been developed specified for a horizontally allocated fuel pin bundle.

The benchmark analyses have been carried out to investigate the applicability of the present method to the TRU fuel fabrication. The sensitivity analysis of the clearance between the fuel assembly and the horizontally allocated support plate has also been examined numerically.

As a result of the benchmark analyses, it is concluded that a good agreement is achieved when the heat transfer due to natural convection is assumed at the outermost fuel pins which are allocated next to the outlet boundary. This is attributed the fact that the coolant air leaks through the clearance and almost no coolant flows appear at the topside of the bundle in the experimental condition.

In the sensitivity analysis, the clearance is reduced from 5.5mm to 1.1mm. As a result, it is demonstrated that the size of the clearance affects the cladding temperature significantly especially at the topside fuel pins which are laid above the support plate.

It is concluded that the developed method has an applicability to investigate the thermal-hydraulics phenomena in the TRU fuel fabrication and to establish an efficient cooling system during the fabrication.

In the future work, the authors are planning to have additional benchmark analyses in which the influence of the clearance and the transient trend of the temperature without the cooling air have been quantified experimentally. Furthermore, the code development has been continued in terms of the transient analysis and the modification of the empirical correlation used in the analysis so as to enhance a predictive accuracy.

In the modification of the empirical correlation, numerical experiment with a multi-dimensional CFD is an alternative way as well as the enlarged-partial model (Hishida, et al., 2008). Further experimental observation of the enlarged-partial model has also been conducted to understand the thermal-hydraulics phenomenon in the TRU fuel bundle and to contribute the upgrading of the numerical tool in the future work.

ACKNOWLEDGEMENTS

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NOMENCLATURE

A	surface area	[m^2]
f_G	friction factor of bare pin bundle	[-]
f_G^{ω}	friction factor of wire-wrapped pin bundle	[-]
Nu	Nusselt number	[-]
$\hat{\mathbf{n}}$	normal unit vector	[-]
Ra	Rayleigh number	[-]
S	source and/or sink term	
u	velocity of vector form	[m/s]

Greek Letters

ϕ	unknown valiable	
ΔV	volume of cell	[m^3]
ρ	density	[kg/m^3]

Subscripts

Aff	fluid-fluid interaction
Afs	fluid-solid interaction

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