Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 18-19, 2017

Effect of Transverse Heat Conduction on Plate Type Fuel Wall Heat Flux Distribution

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1. Introduction

In research reactors, plate type fuels have been widely used for realizing high neutron flux environment. The plate type fuel is generally fabricated by hot rolling layers of fuel meat and cladding together to form a thin plate[1]. Owing to its resulting cross section geometry being high in aspect ratio (width/thickness), there is a transverse distribution of generated thermal power which cannot be neglected. In conventional analysis, this distribution is directly used in constructing power peaking factor and a hot channel (or hot stripe) is formed to estimate thermal margins[2]. In the hot channel analysis method, it is assumed that the wall heat flux distribution is in direct relation with the power generation within the fuel meat. In reality, the heat generated from the fuel meat is not directly related with wall heat flux due to transverse conduction within fuel meat and surrounding cladding[3]. Also, in research reactor, the thermal margin such as ONB temperature margin is dependent on local wall heat flux distribution. Considering the above, the effects of the transverse heat conduction along the fuel plate width on the wall heat flux distribution are studied in this paper.

2. Methods and Results

In this section, analysis geometry, governing equation and assumptions applied in calculation are explained.

2.1 Analysis Geometry

In this study, geometry and operating conditions of a standard fuel element (SFE) of the IAEA 10 MW generic research reactor are used[4]. Figure 1 shows an analysis geometry where symmetric and insulated boundary conditions are used to simplify the problem. It is assumed that there is no heat transfer between the fuel plate and the side plate. The heat conduction inside the fuel geometry along the flow direction is also conservatively neglected which leads to a simple two-dimensional heat conduction problem. In this study, a finite volume method is utilized to numerically solve the governing equation on the region of interest. Figure 2 shows a discretized geometry where rectangular finite volumes are used.

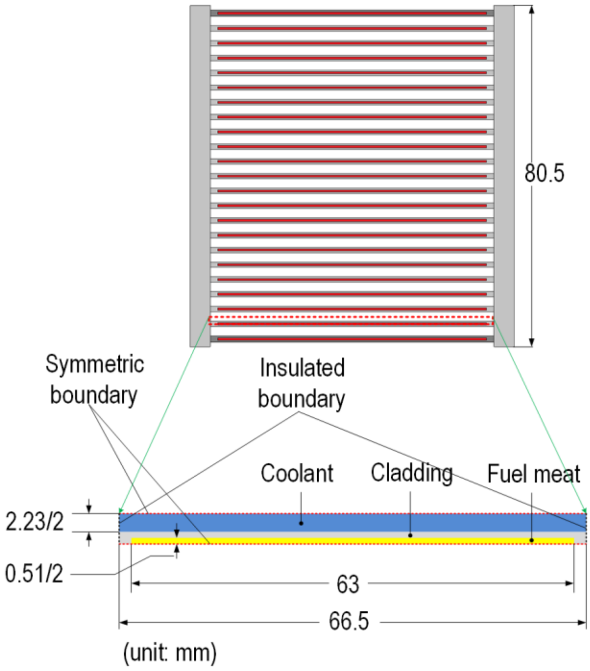


Fig. 1. Analysis geometry (not to scale).

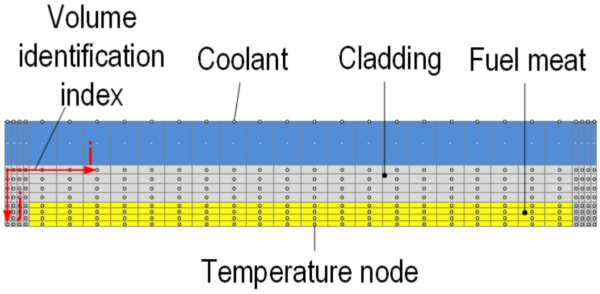


Fig. 2. Discretized geometry (not to scale).

2.2 Governing Equation

In order to obtain the temperature distribution of the fuel plate geometry, a transient two-dimensional heat conduction equation as shown in Eq. (1) is numerically solved for each finite control volume[5]. For the boundary between coolant and cladding wall, a convective boundary condition as described in Eq. (2) is used where Petukhov correlation is used for evaluating convective heat transfer coefficient[6]. A discretized form of governing equation is shown in Eq. (3) where an explicit time advancement scheme is used to update the temperature.

$$\rho c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) + \dot{q} \tag{1}$$

$$q'' = \mathrm{h}(T - T_\infty) \quad (2)$$

$$\left(\rho c_p \Delta V\right)_{i,j} \frac{dT_{i,j}}{dt} = \left(E_{in} - E_{out} + E_{generation}\right)_{i,j} \quad (3)$$

where, ρ is density [kg/m^3], c_p is heat capacity [J/kg-K], k is thermal conductivity [W/m-K], T is temperature [K], $\dot{q}$ is volumetric heat generation rate [W/m^3], q'' is wall heat flux [W/m^2], h is convective heat transfer coefficient [W/m^2-K], T_∞ is coolant bulk temperature [K], ΔV is finite volume [m^3], and E is heat generation rate for each finite volume [W], respectively.

2.3 Calculation Assumption

In this study, the calculation is carried out at the axial location where the thermal margin is at its minimum (a hot spot). In order to predict the location, an axial thermal margin distribution in terms of ONB temperature is evaluated using an analysis code TH_Calc Win (Thermal Hydraulic Margin Calculator for Plate-type Fueled Reactor Core for Windows) developed by KAERI[7]. TH_Calc Win solves one-dimensional governing equations of energy and momentum conservation for a single channel to quickly calculate the temperature and thermal margins of the plate-type fuel plate under normal operating condition. For estimating ONB margin, Bergles & Rohsenow correlation is used[8]. Figures 3 depicts estimated thermal margin with an applied axial power profile (33% control rod out case) taken from the literature[4]. Thermal hydraulic operating conditions of the fuel channel as summarized in Table I are used. A power peaking factor of 3.0 is assumed. From the calculation, it is seen that the minimum thermal margins exist just after the peak power location and this vertical position is selected as the analysis case. Due to lack of evaluation results, the transverse power peaking distribution is taken from the paper by Jo and Seo which deals with a similar fuel plate geometry (meat width= 62 mm)[3]. This distribution is normalized and used in 2D heat conduction calculation.

Table I: Operating Condition

Parameter	Value
Coolant inlet temperature	38 ^{o}C
Coolant inlet pressure	1.7 bar
Average coolant velocity	3.0 m/s
Core flow direction	Downward
Average heat flux	205.4 kW/m^2
Axial power peaking factor	1.4
Radial power peaking factor	2.1
Power peaking factor	3.0

Next, to apply the convective heat transfer boundary condition at the cladding wall, coolant velocity information is required. Since there is no analytic solution available for the turbulent flow regime, a CFD analysis is carried out on the channel geometry by solving Ω-based Reynolds Stress turbulence model[9]. Figure 4 shows a resulting transverse distribution of the coolant velocity averaged over the channel thickness which is used in the 2D calculation.

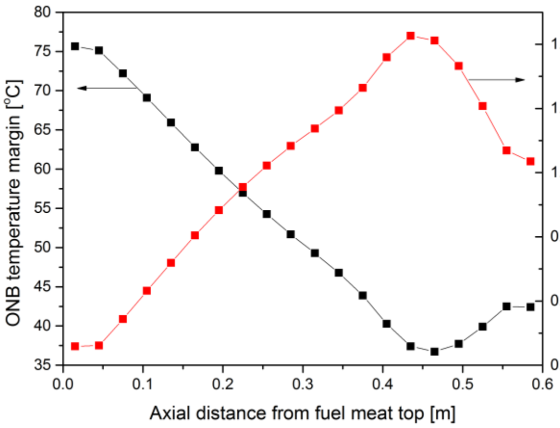


Fig. 3. Axial ONB temperature margin and power distribution.

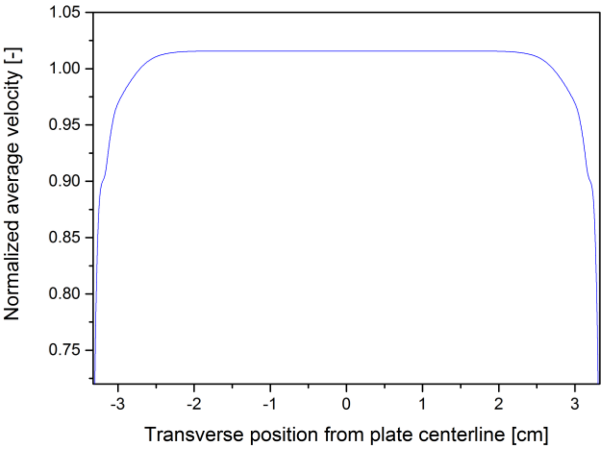
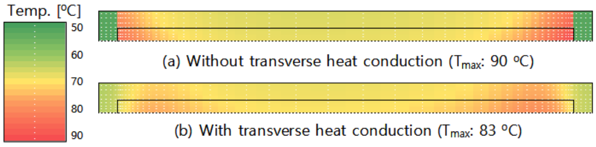


Fig. 4. Coolant velocity distribution in transverse direction.

2.4 Analysis Results

To obtain steady state solution, the 2D heat conduction equation (Eq. (3)) is continuously solved until maximum relative temperature difference between current and previous time step is smaller than 0.1%. From Fig. 5, it is seen that when the transverse heat conduction is considered, there's a noticeable decrease (about -7 ^{o}C) in the peak temperature value and the temperature distribution becomes more uniform. This smoothed out temperature distribution at the cladding surface also suppresses the wall heat flux peaking at the edge of the fuel meat (about -21%). In addition, the effect of the decreased flow velocity at the edge of the channel is evaluated to be minor (maximum temperature increase less than 1 ^{o}C). Lastly, the effect of the thermal conductivity deterioration (-50% assumed) from irradiation and burnup is analyzed which showed lower decrease (about -18%) in the maximum heat flux value than the previous case.



(a) Without transverse heat conduction (T_{max}: 90 °C)

(b) With transverse heat conduction (T_{max}: 83 °C)

Fig. 5. Fuel plate temperature distribution.

3. Conclusions

In this study, thermal analyses on the fuel plate geometry were carried out to see the effect of the transverse heat conduction on the wall heat flux distribution. A time explicit form of the finite volume method was utilized to numerically discretize and solve the geometry of interest. The analyses showed that the developed method can simulate thermal behavior of the fuel with given boundary conditions, but requires additional verification and validation to check the calculation accuracy. From the calculation results, noticeable decreases in the peak temperature and wall heat flux were observed when the transverse heat conduction is taken into consideration. The results also showed sensitivity on the thermal conductivity values. It is expected that the developed method can also be used to show conservativeness of the hot channel (stripe) analysis method currently used in the core thermal hydraulic design. However, to quantify the conservatism, entire thermal hydraulic correlations including ones for evaluating thermal margins need to be based on local phenomena in priori which will require a lot of effort.

REFERENCES

[1] G.M. Adamson, Jr., Fabrication of Research Reactor Fuel Elements, ORNL-TM-2197, Oak Ridge National Laboratory, 1968.

[2] Y. Nagaoka, B. Komukai, F. Sakurai, Nuclear Hot Spot Factor of JMTR-LEU Core, JAERI-M 92-042, Japan Atomic Energy Agency, 1992.

[3] J. Daeseong, S.C. Gyo, “Effects of Transverse Power Distribution on Thermal Hydraulic Analysis,” Progress in Nuclear Energy, Vol.81, p.16, 2015.

[4] IAEA, Research Reactor Core Conversion from the Use of Highly Enriched Uranium to the Use of Low Enriched Uranium Fuels Guidebook, Vienna, 1980.

[5] S.V. Patankar, Numerical Heat Transfer and Fluid Flow, Hemisphere Publishing Corp., Washington, D.C., 1980.

[6] B.S. Petukhov, “Heat Transfer and Friction in Turbulent Pipe Flow with Variable Physical Properties,” Advances in Heat Transfer, Vol.6, p.503, 1970.

[7] KAERI, TH_Calc Win (Thermal Hydraulic Margin Calculator for Plate-type Fueled Research Reactor Core for Windows) 1.0, Registration No. C-2017-001307, Korea Copyright Commission, 2017.

[8] A.E. Bergles, W.M. Rohsenow, “The Determination of Forced-Convection Surface-Boiling Heat Transfer,” Journal of Heat Transfer, Vol.86, p.365, 1964.

[9] ANSYS, Solver Theory Guide, Release 16.1, ANSYS, Inc., Canonsburg, PA, 2015.