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Fast Reactor Fuel Pin Behavior Analyses in a LOF Type Transient Event

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In order to evaluate integrity limiting parameters of fuel pins during fast reactor core transient events, such as fuel center line temperature and cladding maximum temperature, fuel pin behavior calculations were made using the fast reactor fuel pin performance code CEDAR. The temperature histories of fuel pins during a loss of flow (LOF) type transient events was calculated based on Ross & Stoute type gap conductance model and constant gap conductance model, which is used in a core transient calculation code like HIPRAC.

The calculated maximum temperatures of cladding and adjacent coolant channel were lower in the case with Ross & Stoute type model than in the case of constant gap conductance model due to the dynamic change of gap conductance of former case. It is indicated that core transient calculations with constant gap conductance give conservative cladding and coolant temperatures than that with Ross & Stoute type gap conductance model which is thought to be realistic.

Keywords：Fast Reactor, Mixed Oxide Fuel, Transient, Gap Conductance, Ross and Stoute, CEDAR

LOF 型過渡事象における高速炉燃料ピン挙動解析

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燃料中心温度や被覆管最高温度のように、過渡事象時の高速炉燃料ピンの健全性に影響する因子を評価するため、燃料解析コード"CEDAR"による照射挙動評価を実施した。冷却材流量低下型(LOF)の過渡事象時における燃料ピンの温度履歴を、２通りのギャップコンダクタンスモデル（Ross&Stoute 型のギャップコンダクスタンスモデルおよび一定のギャップコンダクタンスモデル）に基づき計算した。後者のギャップコンダクタンスモデルは、炉心過渡計算コード"HIPRAC"で用いられているモデルである。

被覆管最高温度と被覆管周辺の冷却材温度は、Ross&Stoute モデルではギャップコンダクタンスの時間変化を考慮することにより、一定のモデルを用いる場合よりも低く計算された。これより、一定のギャップコンダクタンスモデルによる炉心過渡計算では、現実的な Ross&Stoute モデルを用いる場合よりも、被覆管と冷却材温度の評価結果は保守的になることが示された。

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1. Introduction

In fast reactor core transient events, fuel centerline temperature and cladding maximum temperature are integrity limiting parameters of fuel pins. In reactor design studies, fuel and cladding temperatures during reactor core transients are evaluated using calculational tools, such as HIPRAC1),2) in which the core neutronics analysis is based on the point-kinetics and thermal hydraulic calculation is based on multi-channel model with simplified heat transfer equations to calculate fuel, cladding and coolant temperatures2). On the other hand, fuel pin performance codes are available to calculate these temperatures with detailed thermo-mechanical models. The fast reactor fuel pin performance code CEDAR3) is a typical tool for analyses of fuel pin behavior including temperatures in a fuel pin with detailed models such as a Ross & Stoute type fuel-cladding gap conductance model4), thermal expansions of fuel and cladding, their mechanical deformations and compositions of gaseous phase in a fuel pin, whereas HIPRAC applies constant fuel - cladding gap conductance through a calculation of single channel without analyses of fuel pin mechanical behavior and gas composition in a fuel - cladding gap.

It is worth to evaluate fuel pin performance during the fast reactor core transient event using a fuel in performance code applying power histories obtained by a reactor core transient calculation code such as HIPRAC and to look into the deference of temperatures between simplified and detailed calculations. The result will show the margin of temperatures calculated by simplified model in a reactor core transient code.

2. Evaluation method

The JSFR 1500MWe core5),6) with oxide fuel is selected for the transient calculation. Initiator of the core transient in the present study is a flow rate decrease of the primary circuit as a typical loss-of-flow type transient. Major characteristics of the core and a reactor system modeling are found elsewhere.1),5) Transient fuel pin behavior calculations were made using CEDAR code. The fuel pin specifications of JSFR core is indicated in Table 1 5) and the histories of fuel pin power and coolant flow rate were taken from HIPRAC calculation results1) as indicated in Fig.1. CEDAR code calculated the temperatures of fuel, cladding and coolant. For (U,Pu) oxide fuel pins, two kinds of calculation are made using CEDAR code changing the fuel-cladding gap conductance model. One is with Ross & Stoute type gap conductance model, and the other is with constant gap conductance which is identical with HIPRAC calculation of simplified model. These two results are compared to understand the difference between detailed modeling and simplified modeling. For Ross & Stoute type gap conductance model, fuel and cladding thermal expansions are predominant factors to determine the fuel to cladding gap width during transient. In the present study, thermal expansion correlation of austenitic steel is applied to the cladding tube on the assumption that the modified type 316 stainless steel (PNC316) is used for cladding material.

To investigate the contribution of minor actinide, identical calculation was made with Ross & Stoute type gap conductance model. Minor actinide(MA) content was set to 5% in heavy metal (HM) as a sensitivity study and the MA content was considered in the fuel thermal conductivity. The result was compared with that of (U,Pu) oxide fuel.

3. Results of calculation and discussions

3.1 Calculation results of (U,Pu) Oxide fuel pins

At first, a benchmark calculation was made to compare the results of CEDAR code and a core safety analysis code using a model case of LOF type transient in which the power and flow rate histories are different from those in Fig.1. Figure 2 shows the average fuel temperature history for the case of constant gap conductance. A solid line indicated the average fuel temperature by CEDAR code.

At the time = 0 (sec), flow rate reduction starts and fuel temperature becomes gradually high since heat removal reduces due to coolant flow rate reduction outside of the fuel pin.

At about two second, reactor scram occurred by low flow rate signal of reactor protection system. Then, fuel temperature goes down with time due to the rapid reduction of reactor power and fuel pin power after the reactor scram.

The result of CEDAR code agrees well with that of core safety analysis code indicated by closed circles in the figure.

This benchmark calculation was followed by analytical calculation using the power and flow rate histories in Fig.1. Figure 3 shows calculated fuel centerline temperatures and fuel - cladding gap conductances. The broken line shows the temperature with constant gap conductance and the solid line shows one with Ross & Stoute type fuel-cladding gap conductance model. The values of gap conductance are equal to each other at the beginning of the transient, time=0, and Ross & Stoute type gap conductance decreases during the transient. This is due to the change of thermal expansions of fuel and cladding, which results in the change of fuel cladding gap width or fuel-cladding contact pressure. Before the scram, the gap conductance decreases mainly due to the increase of cladding thermal expansion. After the scram, it decreases mainly due to the decrease of fuel thermal expansion because of fuel pin power and fuel temperature decrease. As a result, fuel temperature of the Ross & Stoute type gap conductance case is higher than that of constant gap conductance case after the reactor scram, since heat transport from fuel to cladding is less in the former case than in the later case. This mechanism also affects the cladding and coolant temperatures.

Figure 4 shows the calculated cladding and coolant temperatures, Ross & Stoute type gap conductance case of a solid and constant gap conductance case of a broken line. Before 20 seconds, cladding and coolant temperatures of the Ross & Stoute type gap conductance case are lower than those of constant gap conductance case, whereas they reverse each other after 20 seconds. This behavior is explained as follows;

When transient starts, low gap conductance in Ross & Stoute type gap conductance case gives less heat transfer from fuel to cladding and coolant than that of constant gap conductance case. This results in lower cladding and coolant temperatures in Ross & Stoute type gap conductance case in comparison with constant gap conductance case. After certain time, more residual heat remains in the fuel of Ross & Stoute type gap conductance case due to the low heat transfer from fuel to cladding. Then heat transfer from fuel to cladding becomes larger in case of Ross & Stoute type gap conductance than in case of constant gap conductance case.

As a result, cladding and coolant temperature changes in Ross & Stoute type gap conductance case are benign. As simplified constant gap conductance is applied to core safety calculations, such simple model includes some margin to cladding and coolant temperature in the evaluation results. This also means that, if Ross & Stoute type gap conductance model is applied to core safety calculations, that gives wide design window due to benign temperature change.

3.2 Contribution of minor actinides

The calculation result of 5%(in HM) MA bearing fuel pin is shown in Fig.5. Obtained temperature history was similar to that of the (U,Pu) oxide fuel pin. The temperatures of MA bearing fuel pin were slightly higher than that of (U,Pu) fuel pin. But in terms of a comparison between Ross & Stoute type gap conductance model and constant gap conductance model, simplified constant gap conductance includes some margin to cladding and coolant temperature in the evaluation results, even in a case of MA bearing fuel.

4. Conclusions

Temperature histories of a fast reactor oxide fuel pin during a LOF type transient event were calculated using a fuel pin performance code CEDAR. Ross & Stoute type gap conductance model and constant gap conductance model used in a core transient calculation code like HIPRAC were applied. The calculated maximum temperatures of cladding and adjacent coolant channel were lower in the case with Ross & Stoute type gap conductance model than in the case of constant gap conductance model due to the dynamic change of gap conductance of former case. It is indicated that core transient calculations with constant gap conductance give conservative cladding and coolant temperatures than that with Ross & Stoute type gap conductance model which is thought to be realistic. This is concluded to MA bearing oxide fuel pins as well as (U,Pu) oxide fuel pins.

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Table 1 Core and fuel specifications of the large scale JSFR

Items	Breeding Core	Break Even Core
Nominal full power (MWe/MWt)	1, 500/3, 570	←
Coolant temperature [outlet/inlet] (℃)	550/395	←
Primary coolant flow (kg/s)	18, 200	←
Core height (cm)	100	←
Axial blanket thickness [upper/lower] (cm)	20/20	15/20
Number of fuel assembly [core/radial blanket]	562/96	562/ −
Envelope diameter of radial shielding (m)	6. 8	←
Fuel cladding outer diameter (mm)	10. 4	←
Fuel cladding thickness (mm)	0. 71	←
Number of fuel pin per assembly	255	←
Wrapper tube outer flat-flat width (mm)	201. 6	←
Wrapper tube thickness (mm)	5. 0	←

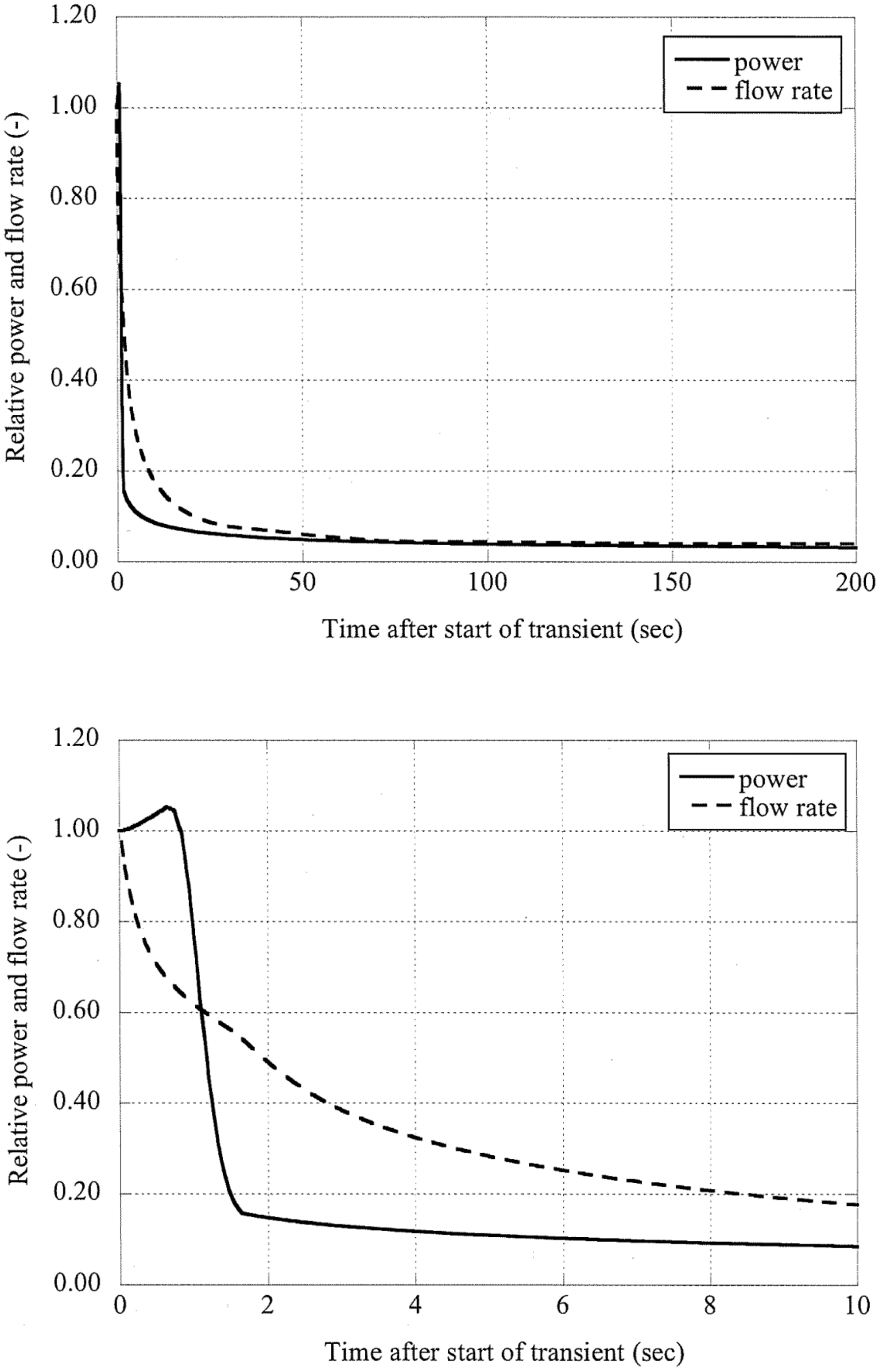

Fig.1 Histories of fuel pin power and coolant flow rate

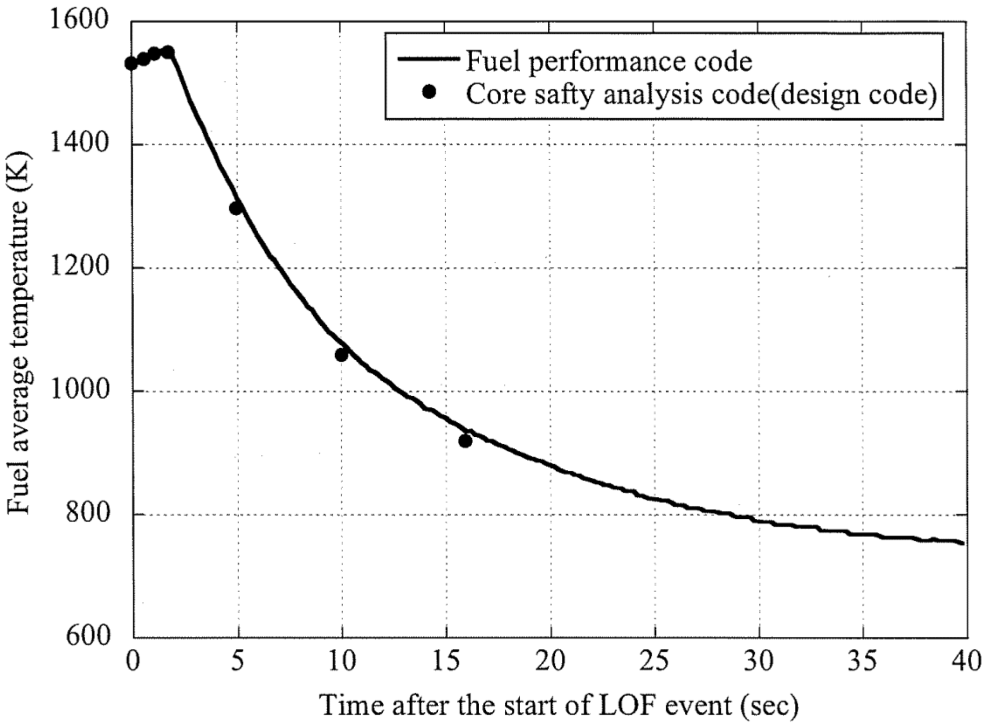

Fig.2 An example of fuel transient calculation (LOF type event)

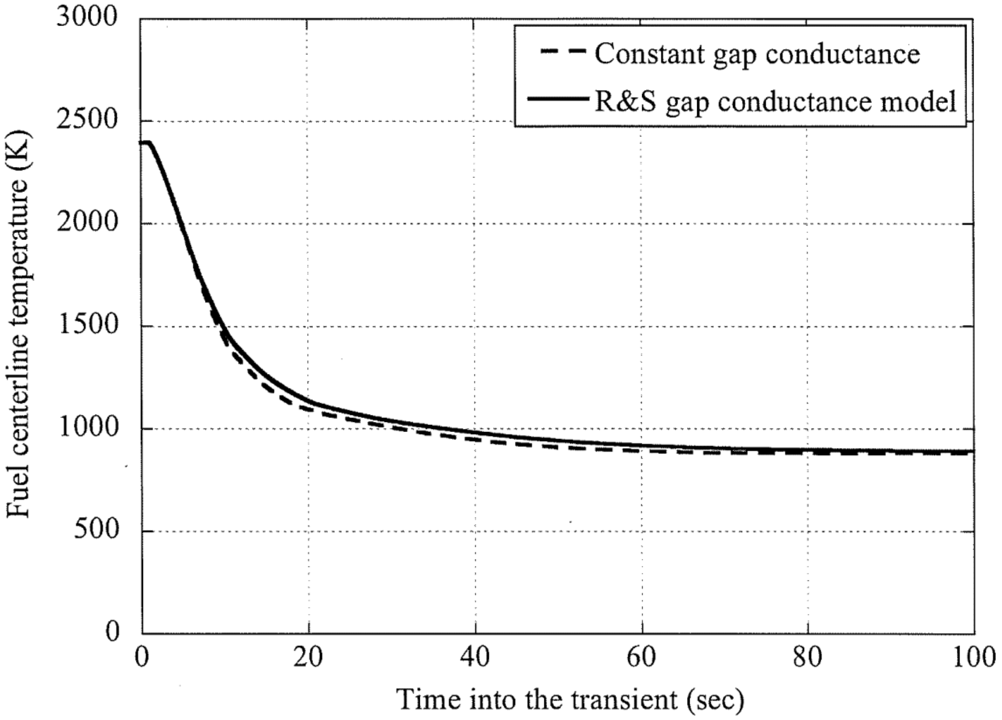

Fig.3(a) History of fuel centerline temperature

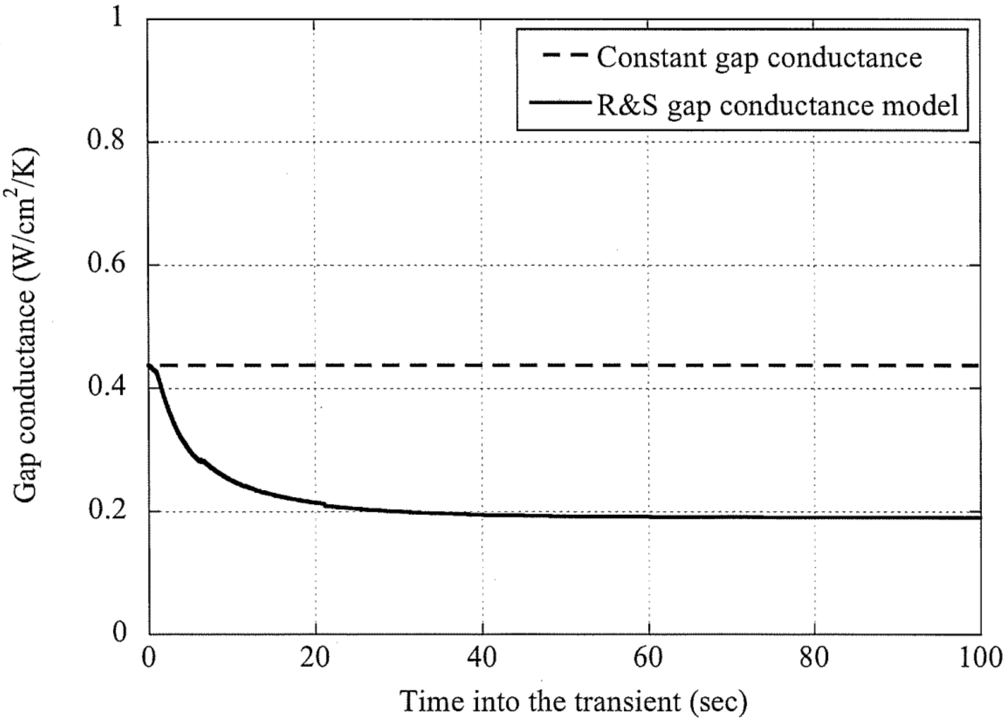

Fig.3(b) History of gap conductance

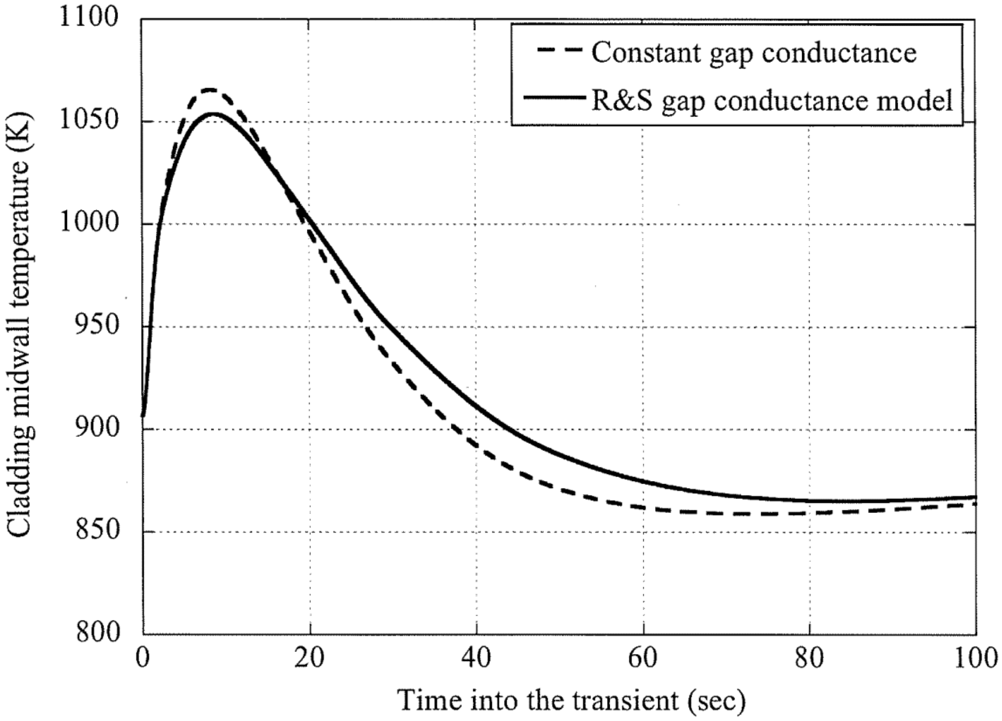

Fig.4(a) History of cladding midwall temperature

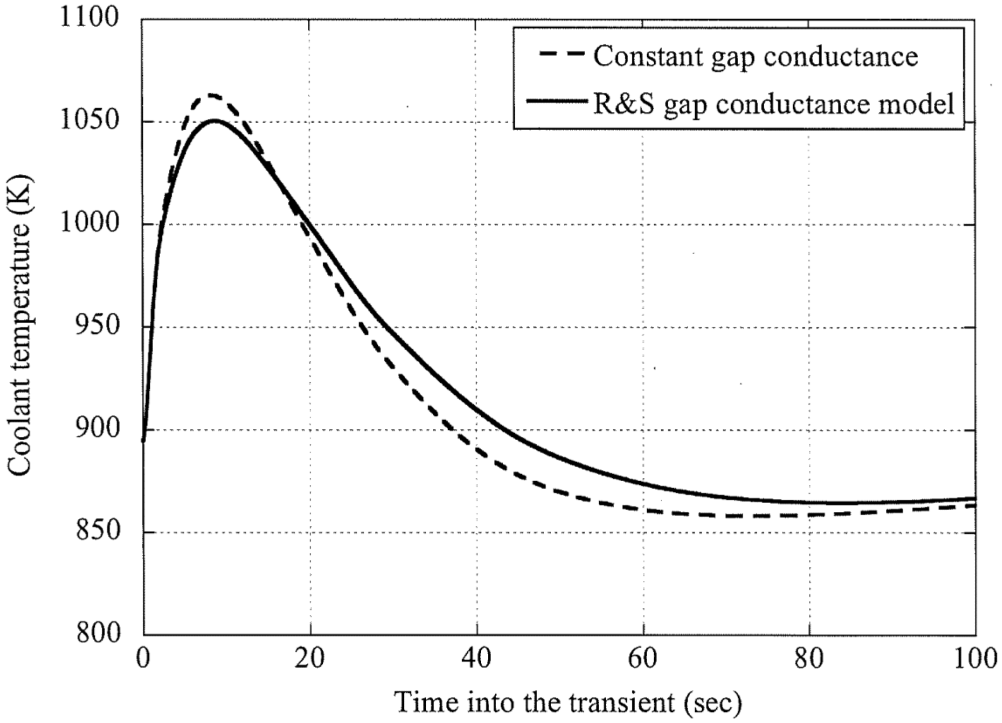

Fig.4(b) History of coolant temperature

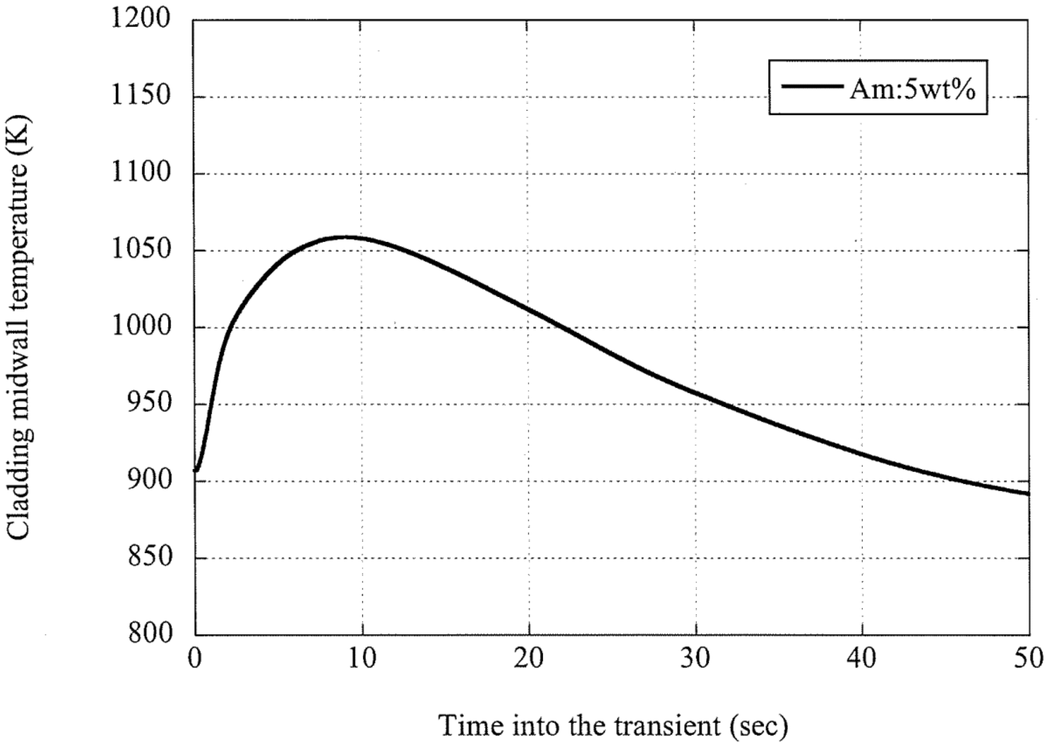

Fig.5(a) Cladding midwall temperature as a function of the time into the transient (R&S gap conductance model)

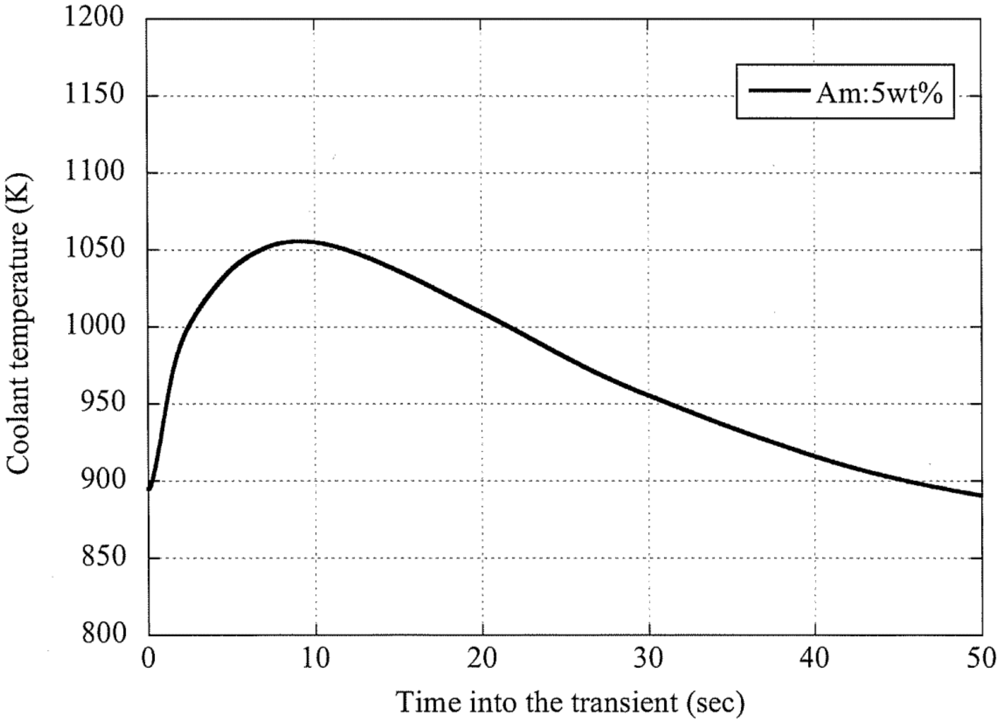

Fig.5(b) Coolant temperature as a function of the time into the transient (R&S gap conductance model)