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Flow blockage analysis of a channel in a typical material test reactor core

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ABSTRACT

The course of the partial and total blockage of a channel in the IAEA 10 MW MTR pool type research reactor core (IAEA-TECDOC-233, 1980. IAEA Research Reactor Core Conversion from the use of high-enriched uranium to the use of low enriched uranium fuels Guidebook.) without scram is investigated. The analysis is performed with the best estimate code RELAP5/MOD3.3. The interaction of the obstructed channel and its adjacent channels has been taken account of. Results indicated that even when the flow channel has been totally blocked, there is still no boiling occurrence, and the fuel temperature is low enough to maintain its integrity. This work indicates that the consideration of the conjugate heat transfer in the obstructed channel during this transient is very important.

1. Introduction

The safety analysis of the research reactor usually entails the simulations of several selected cases within two broad categories of accidents, namely, reactivity insertion accidents (RIA), and loss of flow accidents (LOFA). In the transient simulations, it is customary to consider the situation with or without scram event, called protected transients and unprotected transients. Much research has been done on LOFA with scram (Bokhari and Mahmood, 2005; Hamidouche et al., 2004; Mariy et al., 2003; Mohamed et al., 2007). The applicable accident sequences are those anticipating failures of reactor scram in occurrences, such as primary pump failure, valve failure, or pump unavailability due to loss of electrical power. Most analysis had been done with single channel models, such as hot channel, average channel, and bypass channel, without considering the interaction between channels. Adorni et al. (2005) carried out an analysis of the partial and total blockage of a single fuel assembly in an MTR type research reactor. Each channel of the core was simulated individually in order to assess the thermal-hydraulic effect of the flow blockage on the intact channels, without the consideration of the interaction between the obstructed channel and its adjacent channels.

In the eighties, a safety-related benchmark problem for an idealized generic 10 MW MTR light-water pool-type reactor has been defined (IAEA-TECDOC-233, 1980). This benchmark was specified under the conversion program of the research reactor cores from highly enriched uranium (HEU) to low enriched uranium (LEU) cores. It covers large steady state neutron kinetics and thermal-hydraulic calculations and a wide range of hypothetical dynamic accidental scenarios. Much research has been done based on this benchmark problem (Kazeminejad, 2006; Hamidouche et al., 2004; Mohamed et al., 2007), however, little work has been done to investigate the blockage of a coolant channel because of the swelling of the fuel or some other incidents, which may occur and damage the integrity of the fuel in the lifetime of the research reactor. In the present paper, the partial (95%) and total (100%) blockage of a channel in an assembly in the IAEA 10 MW research reactor without scram was investigated by RELAP5/MOD3.3. A multi-channel model was applied by RELAP5 to take account of the interaction of the obstructed channel and its adjacent channels.

2. Configuration of the core

The core of the IAEA 10 MW MTR type research reactor (IAEA-TECDOC-233, 1980) is cooled and moderated by a forced downward circulation of light water. The core configuration is depicted in Fig. 1 and the detailed specifications of the core are given in Table 1. There are 21 MTR Standard Fuel Assemblies (SFA, 1–21) and 4 Control Fuel Assemblies (CFA, 22–25) (Fig. 1(a)). The core is reflected by graphite, which is represented by G, on the two opposite sides and surrounded by light water which is represented by W. The standard fuel assemblies contain 23 standard plates whereas the control fuel assemblies contain 17 standard plates with special regions to receive the 4 fork type absorber blades. The arrangement of the fuel plates in an assembly is depicted in Fig. 1(b).

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Nomenclature

L	length of the channel
Tcil	inner side temperature of the clad on the left
Tcir	inner side temperature of the clad on the right
Tcenter	temperature on the centerline of the fuel plate
Tcol	outer side temperature of the clad on the left
Tcor	outer side temperature of the clad on the right
Tf	temperature of the coolant
Tfuel	temperature of the fuel plate
y	axial position from the inlet
Y	nondimensional length, $Y = y/L$

3. Modeling

3.1. Modeling for the blockage of a channel

It is important to consider the interaction between the reactor's cooling loop and the core's kinetics during the blockage of a channel. However, as our attempt here is to investigate the flow blockage in a channel, only 9 channels and fuel plates were modeled. The combination of the fuel heat conduction and the fuel-coolant heat convection were considered. The power and coolant mass flow were given as the initial conditions. The power distribution and the total mass flow were supposed to be constants in the transient, which was conservative, because the feedback of kinetic was not considered (Adorni et al., 2005). Nodalization for RELAP5 is depicted in Fig. 2. The left boundary was the boundary of channel 1. The right boundary was assumed to be adiabatic, because only half of the plate was considered (Fig. 2(a)). The fuel plate and the channel were divided into 21 nodes along the flow direction (defined as y direction), and the fuel plate was divided into 13 nodes along the radial direction (defined as x direction) (Fig. 2(b)).

Since the power was assumed to be averagely distributed in the fuel plates in the current study, channel 3 was chosen arbitrarily to carry out the partial and total flow blockage simulations. With a chosen RELAP5 motor valve component (Fig. 2(a)), the phenomenon is simulated by changing the position of the valve stem (RELAP5/MOD3.3, 2001).

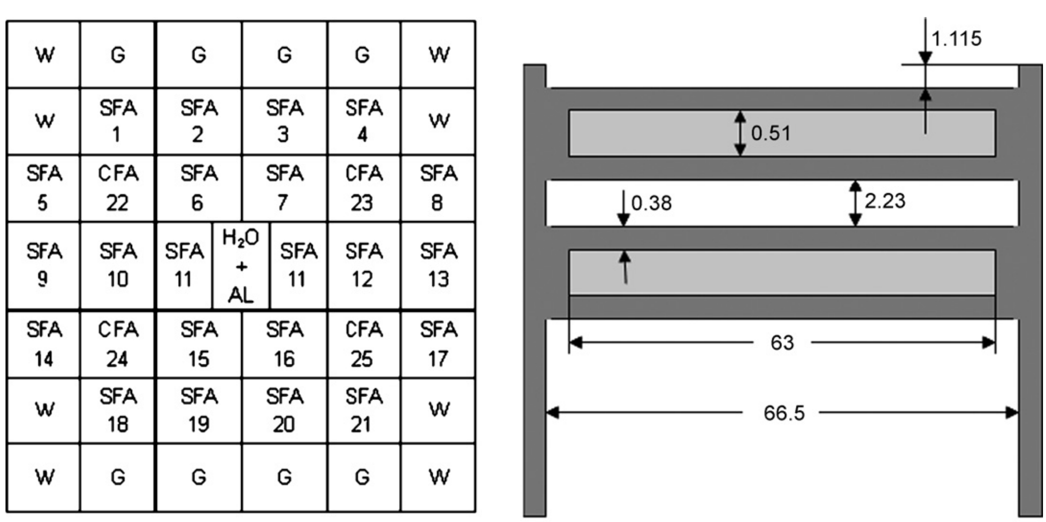
Table 1
The operating conditions of the IAEA research reactor benchmark problem

Core material	
Nuclear fuel	MTR
Fuel element	Plate type clad in Al
Coolant	Light water
Moderator	Graphite-light water
Core thermal-hydraulics	
Fuel thermal conductivity (W/cm K)	1.58
Cladding thermal conductivity (W/cm K)	1.80
Fuel specific heat (J/g K)	0.728
Cladding specific heat (J/g K)	0.892
Fuel density (g/cm^3)	0.68
Cladding density (g/cm^3)	2.7
Radial peaking factor	1.4
Axial peaking factor	1.5
Engineering peaking factor	1.2
Inlet coolant temperature (°C)	38.0
Operating pressure (bar)	1.7
Fuel assembly dimensions	
Length (cm)	8.00
Width (cm)	7.60
Height (cm)	60.0
Number of plates/fuel SFA/CFA	23/17
Plate meat (mm)	0.51
Width (cm) active/total	6.30/6.65
Height (cm)	60.0
Water channel thickness (mm)	2.23
Plate clad thickness (mm)	0.38

3.2. Validation of the computational model

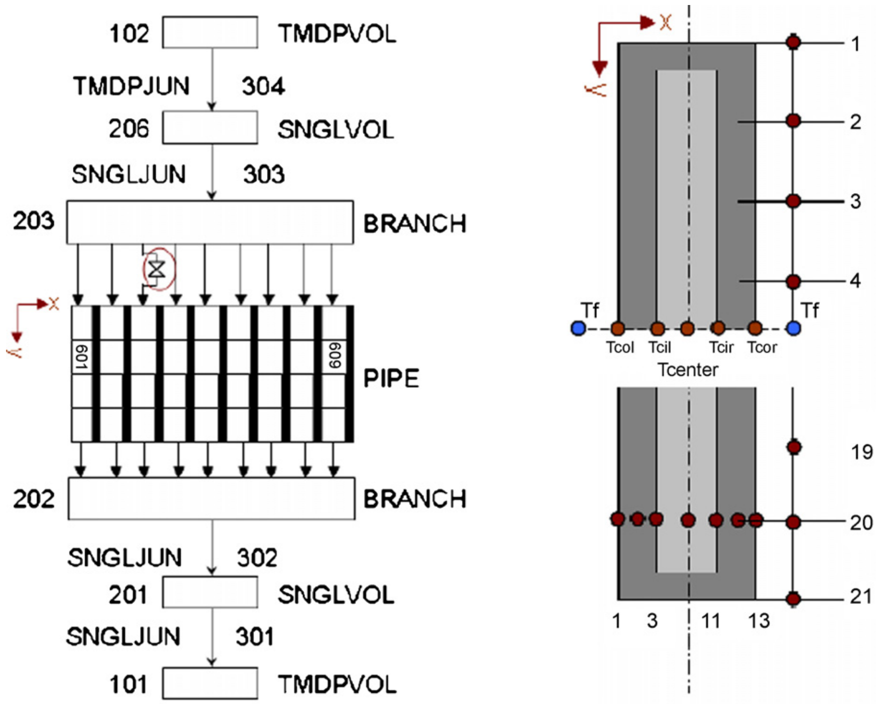
Because there are no measured or calculated results of the blockage of a channel in the core of this type reactor, so in order to validate the computational model, the Fast Loss Of Flow Accident (FLOFA), which is defined in IAEA TECDOC-643 (1992), is taken to be simulated here for the model validation. The core power is initiated at 12 MW, where a 1.2 overpower factor is included. The flow decay is modeled as an exponential decrease with time constant of 1.0 s ($\exp(-t/1.0)$). The reactor scrams when the mass flow decrease reaches 85% of its initial value. It is supposed that the reversal regime begins and an upward natural circulation flow begin to set up at 15% flow. This transient is described in Table 2.

Calculated results were presented and compared in Table 3. It can be drawn that the FLOFA could be well simulated with



(a) (b)

Fig. 1. Benchmark core configuration. (a) The configuration of the core (b) the arrangement of the fuel plates.



(a) (b)

Fig. 2. The sketch of the adopted nodalization for RELAP5 code. (a) The RELAP5 model (b) the nodalization in the fuel plate and channel.

RELAP5/Mod3.3 under this node system. Fig. 3 gives out the parameters transient during this accident.

4. Results and discussions

The analyzed cases are divided into two categories: those who investigate the effect of the partial blockage of one SFA channel when the obstruction is up to 95% of nominal flow area; and those who concern a total blockage of one cooling channel of the same SFA. The transient simulation begins as the channel obstruction is initiated, after 500 s of the steady state calculations. The main initial and boundary conditions are summarized in Table 4.

Table 2
Main benchmark leading characteristics of FLOFA

Transient key parameters	FLOFA
Initial power (MW)	12.0
Coolant flow direction	Downward
Loss of flow decay periods (s)	1.0
Scram setting point	85% of nominal core coolant flow rate
Delay time before scram (s)	0.2
Shut down reactivity ($/s)	−10.0/0.5

Table 4
Main initial and boundary conditions

Transient key parameters	Partial blockage (95%)	Total blockage (100%)
Total core power (MW)	10	10
Total mass flow rate (kg/s)	1000	1000
Flow direction	Downward	Downward
Blocked channel	3	3
Steady state duration time before transient (s)	500	500
Transient duration time (s)	9.5	10
Scram	Disabled	Disabled

Table 3
Code validation based on the FLOFA

	RELAP5/3.3/XJTU	/AEA[a]	RELAP5/3.2/UPISA[b]	RETRAC-PC/LAS[c]	PARET/ANL[c]	COSTAX-BOIL/JEN[c]	RELAP4/Mod5 /JAERI[c]	COBRA III-C /Interatom[c]
Peak temperature (°C)								
Fuel	95.35(0.37)	92.75(0.368)	NA	91.20(0.391)	90.3(0.371)	95.4(0.37)	NA	91.9(0.363)
Clad	92.52(0.37)	88.27(0.374)	92.58(0.400)	88.45(0.394)	87.5(0.371)	93.9(0.37)	97.1(0.40)	89.3(0.363)
Coolant	60.23(0.45)	59.46(0.41)	59.50(0.504)	60.05(0.481)	60.3(0.446)	59.3(0.43)	58.1(0.48)	56.4(0.460)
Temperature at 15% of flow (°C)								
Fuel	59.70(1.94)	58.29	NA	58.61(1.437)	58.5(1.9)	NA	NA	NA
Clad	59.36(1.94)	57.78	NA	58.33	58.2	NA	95.2(10.0)	NA
Coolant	46.82(1.94)	47.01	46.70	45.93	46.5	NA	49.3(10.0)	NA

Quantities between parentheses indicate time in seconds of parameter occurrence. NA: data not available.
AEA: Atomic Energy Authority (Egypt); UPISA: University of PISA (Italy); ANL: Argonne National Laboratory (USA); LAS: Laboratoire d' Analyse de Surete (Algeria); JEN: Junta de Energia Nuclear (Spain); JAERI: Japan Atomic Energy Research Institute (Japan); Interatom: (Germany).

[a] Mohamed A. Gaheen et al. (2007).
[b] Tewfik Hamidouche et al. (2004).
[c] IAEA-TECDOC-643 (1992).

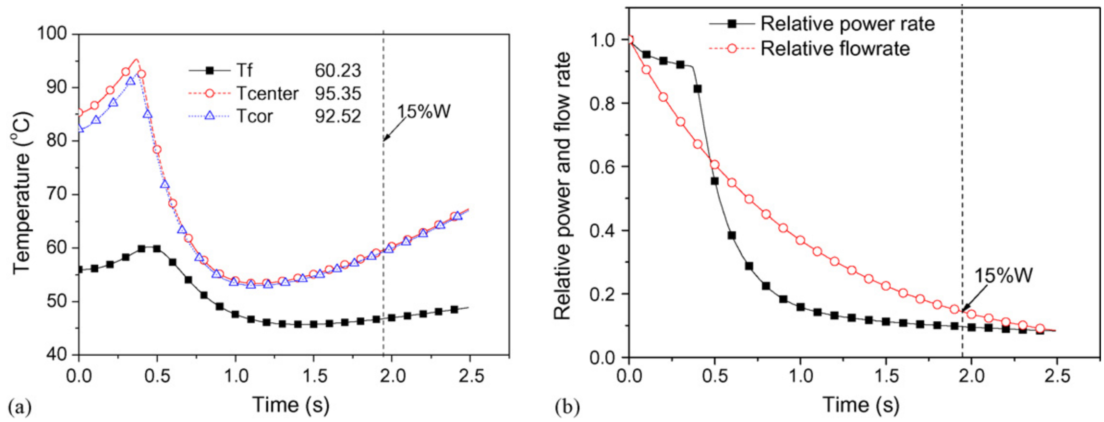


Fig. 3. Parameters transient during FLOFA. (a) Temperatures (b) relative power and flow rate.

4.1. Partial blockage of a channel

Results obtained from RELAP5/MOD3.3 calculations for a 95% obstructed SFA channel is described in this section. Based on the assumption that the total mass flow of the investigated SFA was constant, the mass flow in channel 3 decreased because of the obstruction, while the mass flow in other channels increased, especially in the two adjacent channels (2 and 4) (Fig. 4). The increments of the mass flow in the two adjacent channels were the same. The obstruction resulted in the sharp increase of the temperature in channel 3, as shown in Fig. 5. As a given condition, the temperature at the entrance ($Y=0$) was constant. The temperatures at the mid-height ($Y=0.5$) and at the exit ($Y=1$) were sharply increased. The exit coolant temperature was higher than the temperature on the outer side of the clad and the temperature on the centerline of the fuel, which meant that the heat was transferred from the fluid to the fuel.

Figs. 6–9 show the stable temperature field after the transient. In Fig. 6, the solid points represent the temperature of the fluid,

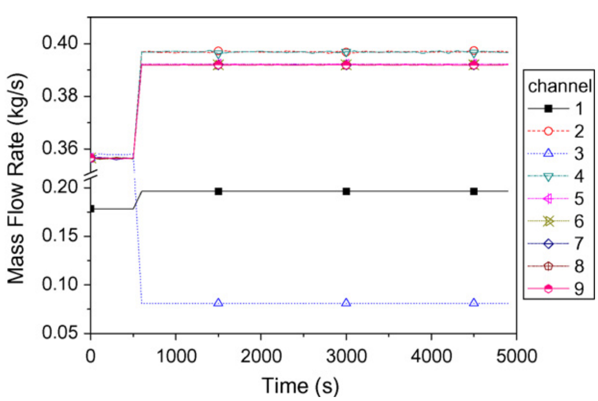


Fig. 4. The mass flow rate in different channels.

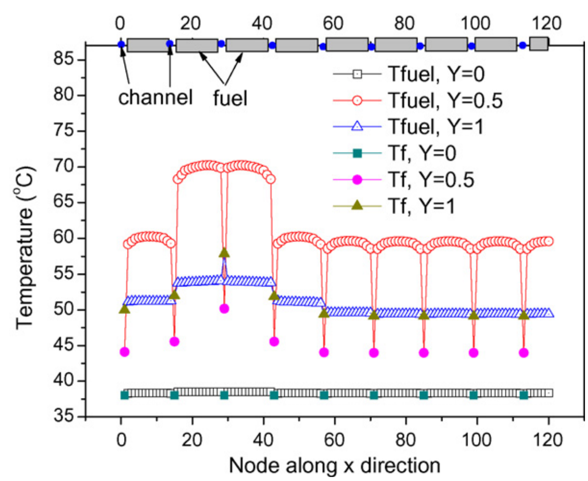


Fig. 6. The temperature variation along the radial direction.

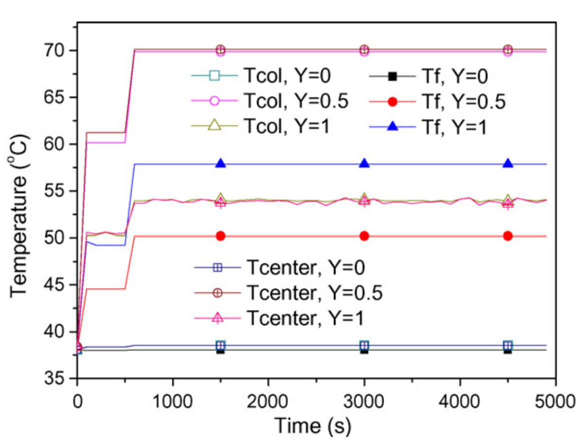


Fig. 5. The temperature variation of the fuel and coolant in the obstructed channel.

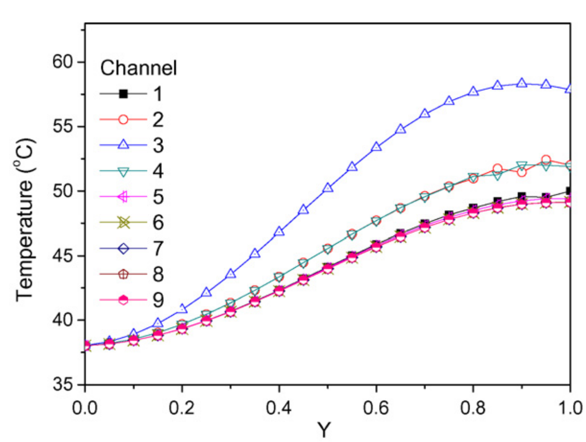


Fig. 7. The temperature of the coolant in different channels.

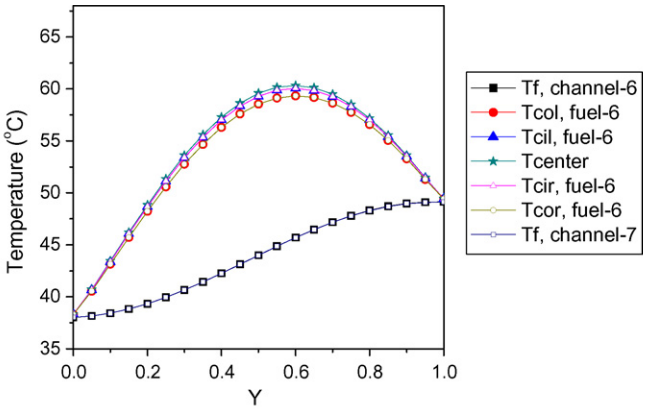


Fig. 8. The temperature field of a fuel plate under symmetrical cooling condition (fuel plate 6).

and the hollow points represent the temperatures of the fuel elements. It can be seen that the coolant temperature of channel 3 was higher than that of any other channels, and the coolant temperatures in channels 2 and 4 were almost the same and higher than that of any other intact channels. Moreover, the temperatures of fuel Plates 2 and 3 were higher than any one of other plates. This is because the obstruction of channel 3 resulted in the loss of coolant flow, which leaded to the decrease of the Reynolds number, heat was not transferred by turbulent convection but by laminar convection in this channel. So the convective heat transfer coefficient in this channel decreased, thus heat generated in fuel Plate 2 mainly transferred into channel 2, while heat generated in fuel Plate 3 mainly transferred into channel 4. This fact can also be found in Fig. 7. What worth more attention is that, at the outlet of channel 3, the temperature of the coolant had been higher than the temperature of the fuel clad (Figs. 5, 6 and 9). It reveals that, in the lower part of the channel, heat was transferred back to the fuel Plates 2 and 3 from the coolant in channel 3, which also limited the temperature increasing of the coolant. So the maximum temperature is reached at the upper part, instead of at the exit (Fig. 7). Also, it could be found that some fuel plates were symmetrically cooled (Fig. 8) and others were asymmetrically cooled (Fig. 9). Under the symmetrically cooling condition, the temperature distribution of the fuel was symmetrical along the centerline, although it is not the truth under the asymmetrically cooling condition.

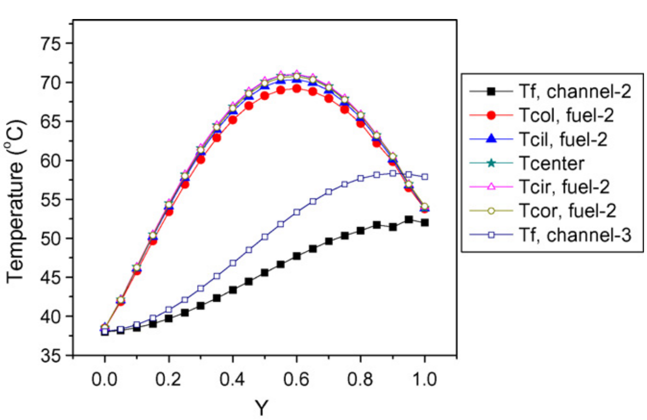


Fig. 9. The temperature field of a fuel plate under asymmetrical cooling condition (fuel plate 2).

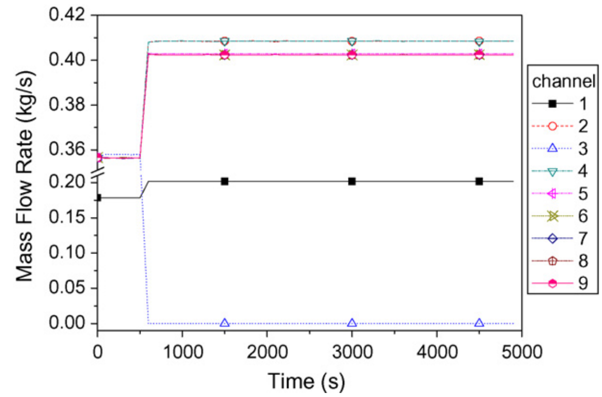


Fig. 10. The mass flow rate in different channels.

4.2. Total blockage of a channel

Figs. 10–15 give out the RELAP5 calculation results of a totally blocked SFA channel. The results are more or less the same compared to the partial blockage mentioned above. The major difference is the temperature field of the obstructed channel and its adjacent fuel plates.

After the transition, the trend of the mass flow rate distribution (Fig. 10) was the same as that under 95% blockage (Fig. 4). However,

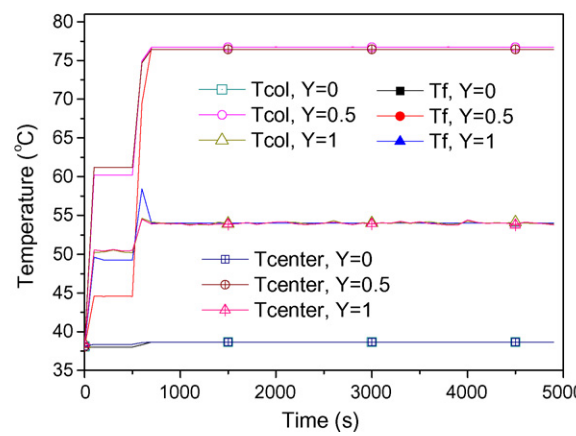


Fig. 11. The temperature variation of the fuel and coolant in the obstructed channel.

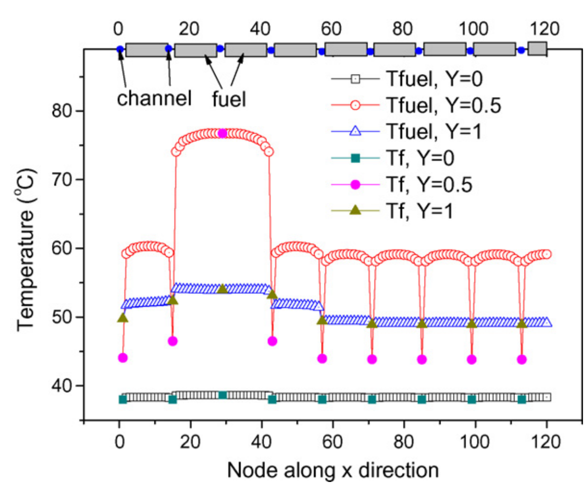


Fig. 12. The temperature variation along the radial direction.

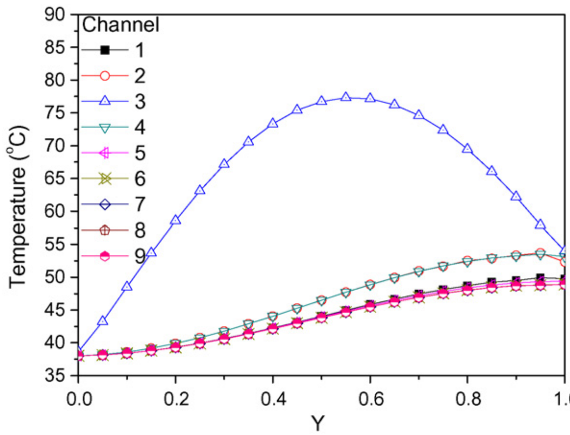


Fig. 13. The coolant temperature of the calculated channels.

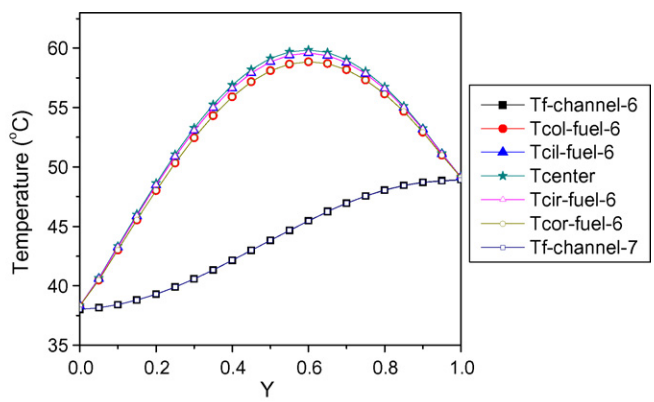


Fig. 14. The temperature field of a fuel plate under the symmetrical cooling condition (fuel plate 6).

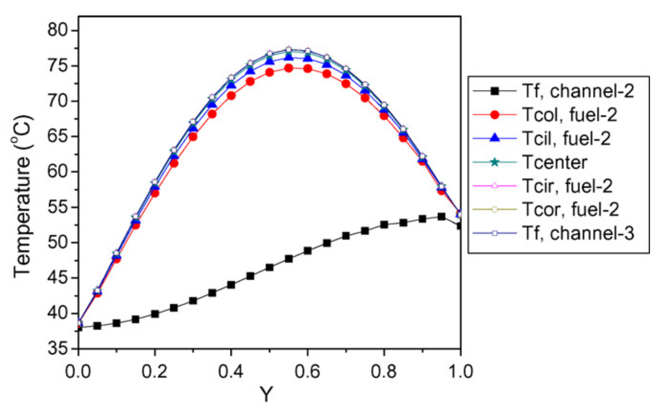


Fig. 15. The temperature field of a fuel plate under the asymmetrical cooling condition (fuel plate 2).

the temperature variation depicted in Fig. 11 was quite different from what depicted in Fig. 5. It could be found that the temperature of the coolant in the obstructed channel was almost the same as the temperature of the adjacent fuel elements (Figs. 11 and 12).

The reason is that in the totally obstructed channel 3 there was only slight natural convection heat transfer, thus the coolant temperature got close to the outer clad temperature of the fuel Plates 2 and 4. Moreover, from Fig. 13, it can be found that the location of the maximum temperature moved upstream to almost where the power crest located. It is very different from the results depicted in Fig. 7. The temperature field under full blockage (Fig. 14) has almost no difference from that under 95% blockage (Fig. 8) when the fuel plate was symmetrically cooled. Furthermore, under the asymmetrical cooling condition (Fig. 15), the temperature of the coolant in the obstructed channel was almost the same as the outer clad temperature of fuel Plate 2 on the right. Almost all the heat generated in fuel Plate 2 were dissipated to channel 2 just as mentioned before, which resulted in a great increment in the maximum temperature although no boiling occurred.

In fact, the phenomenon of the blockage of a channel is a 3D problem of thermal-hydraulic coupled with kinetic. However, the RELAP5 code adopted here is just a 1D thermal-hydraulic analysis with the point kinetic model, which is much conservative. The 3D kinetic model with CFD techniques will do help to fully understand this phenomenon.

5. Conclusions

Enlarged commercial exploitation of the nuclear Research Reactors (RR) has increased their safety consideration. In this article, the limiting safety margins were explored using the best estimate code RELAP5/MOD3.3. The transients considered are the partial and total blockages of one cooling channel of a single fuel assembly in the IAEA 10 MW MTR core. To take the interaction between the heat convection in the channel and the heat conduction in the fuel plate into consideration, 9 channels and 9 fuel plates were modeled. The results demonstrated that because the heat transfers to its adjacent channels, no boiling occurs even when the channel was totally blocked. However, the given power distribution and initial condition may lead to highly conservative predictions that are away from what could be expected. However, this analysis has outlined the importance to consider the impact of the adjacent channels on the obstructed channel, especially for such type of research reactors. For fully understanding the phenomenon, the interaction of the core dynamic should be considered, and the 3D kinetic calculations should be used. Furthermore, it is very valuable to adopt the CFD tools, such as FLUENT, CFX, to analyze the 3D thermal-hydraulic phenomena in the obstructed channel, with detail consideration of the variation of the thermophysical properties of water.

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