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Effects of cooling channel blockage on fuel plate temperature in Tehran Research Reactor

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Abstract In this study, the variation of the temperature distribution of the fuel plate in Tehran Research Reactor core was studied in case of coolant channels blockage. While the experimental method is not possible, both the analytical and simulation methods were used to obtain the more reliable data. The results show that one channel blockage will increase the fuel temperature to about 100%, but it does not lead to clad melt down still. With further calculation and simulation it is understood that if the coolant velocity drops to 90% of its nominal value, it may causes the clad melting down. At least two channels with complete blockage even at the positions far from the core center can also melt down the clad.

Key words Tehran Research Reactor (TRR), Coolant channel blockage, ANSYS11

1 Introduction

Tehran Research Reactor (TRR-5) is a reactor of the open pool type, with 5 MW of nominal power. The fuel is U_3O_8-Al alloy and the clad is stainless steel. The most important aspect in nuclear reactor designation is taking care about the human health. For nuclear reactors, the accidents that are not fully considered in the design process are called as Beyond Design Basis Accidents (BDBA)[1]. One of the major BDBAs that may occur in pool type reactors is coolant channels blockage due to some materials falling into the core[2]. Fuel melting down in OPAL and RSG-GAS reactors is an example of such accident[3]. The increased temperature damaged the fuel elements and the radioactive materials leaked into water. Therefore, for safety of the reactors, it is necessary to calculate the behavior of fuel and its components when the heat cannot be removed properly.

Such events cannot be examined experimentally, so calculations based on analytical and simulation methods shall be performed. Although the simulations may give results with uncertainties, they are helpful in complicated geometry[4]. In this paper we analyze and simulate the coolant channels blockage. ANSYS11 [5] was used in the simulation. The simulation is based on finite elements method. The calculation results are compared with the ANSYS results. The calculations and simulation were conducted under normal conditions first, before we could investigate temperature distribution of the fuel and clad under accident conditions.

2 Calculation method

The fuel plate has cubic rectangular geometry. Its specifications are given in Table 1. Normally, the coolant passes through every channel.

Table 1 The fuel plate and cooling channel specifications of TRR

Item	Value
Fuel thickness /m	0.0007
Clad thickness /m	0.0004
Fuel thermal conductivity /$W \cdot m^{-1} \cdot K^{-1}$	10
Clad thermal conductivity / $W \cdot m^{-1} \cdot K^{-1}$	18
Channel diameter /m	D=2b=0.0052
Coolant velocity /$m \cdot s^{-1}$	1.37
Inlet coolant temperature / ^oC	37
Outlet coolant temperature / ^oC	46

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Under steady-state condition, using the heat diffusion equation, $\nabla^2 T + q'''/K = 0$, one can calculate the maximum temperature at fuel center-line by:

$$T_{\max} - T_{\text{clad-in}} = q''' L^2/(8K_f), \quad (1)$$

where L, K_f and $T_{\text{clad-in}}$ are fuel thickness, fuel thermal conductivity and clad inside temperature, respectively. Solving the heat diffusion equation under the border conditions, we have:

$$T(x) = -q''' x^2/(2K_f) + q''' L^2/(8K_f) + T_{\text{clad-in}}$$
$$(-L/2 < x < L/2) \quad (2)$$

Considering the reactor power and the number of fuels (488 fuel plates), and using the "peaking factor 3" for the hottest channels, the volumetric heat source is $q'''_{\max} = 1.2\times10^9$ W/m^3.

Eq. (3) shows the heat transfer or film coefficient of water [6-7]:

$$h = Nu_D K/D, \quad (3)$$

where D is the channels diameter, K is the thermal conductivity, and Nu_D is the Nusselt number, which can be determined by [6-7]:

$$Nu_D = \frac{(f/8)(\text{Re}_D - 1000)\,\text{Pr}}{1 + 12.7\sqrt{f/8}(\text{Pr}^{2/3} - 1)}, \quad (4)$$

$$f = (1.82 \log \text{Re}_D - 1.64)^{-2}, \ \text{Re}_D = VD/v \quad (5)$$

Where V is flow velocity, and v and Pr (Parndtl number) are given in Table 2[6].

The maximum temperature at fuel center-line and clad was calculated at 99.8°C and 91.6°C, respectively. The results agree well with the data obtained from experimental measurements. The ANSS11 simulation gave the same results (Fig.1).

In a cooling channel blocked *completely*, there is no convectional heat transfer from the blocked side [8]. Ignoring the transient-state, after the system reach to the stable-state, the temperature distribution equation will be changed as Eqs.(6) and (7):

$$T_{\max} - T_{\text{clad-in}} = q''' L^2/(2K_f), \quad (6)$$
$$T(x) = -q''' x^2/(2K_f) - q''' L/(2K_f) + 3q''' L^2/(8K_f)$$
$$+ T_{\text{clad-in}}, \ (-L/2 < x < L/2) \quad (7)$$

The calculated temperature of the clad facing to the blocked channel was 169°C, and the ANSYS result was 168°C (Fig.2). These similarities can give more reliability to going on the further calculation for other situations like more than one channel blockage.

Table 2 v and Pr values for water[6]

Temperature/°C	v /(m^2.s^{-1}) ×10^{-7}	Pr
0.01	17.91	13.47
2	16.82	12.55
7	14.34	10.63
12	12.40	8.91
17	10.85	7.66
22	9.60	6.66
27	8.568	5.85
32	7.708	5.18
47	5.832	3.77
67	4.308	2.68
87	3.371	2.03
100	2.940	1.75
127	2.332	1.36
147	2.030	1.18
167	1.808	1.05
187	1.641	0.955
207	1.514	0.892
227	1.416	0.853
247	1.339	0.833
267	1.278	0.835
287	1.231	0.864
307	1.195	0.931
327	1.166	1.06
347	1.146	1.39
371	1.156	6.89
374	1.313	138.

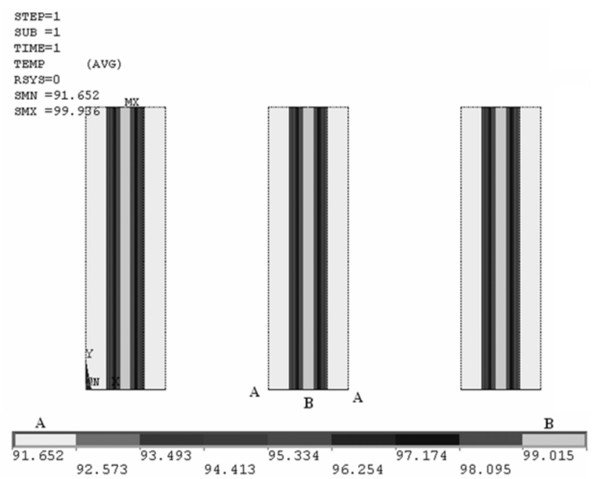

Fig. 1 ANSYS result for normal heat transferring.

To obtain more confident results of the temperature distribution, the thermal conductivity K and heat transfer h were considered as the functions of coolant temperature and velocity. As shown in Fig. 3 and 4, one can see that the variation of h is sensitive to the velocity and temperature of coolant. The importance of both velocity and temperature has been discussed in Ref. [9].

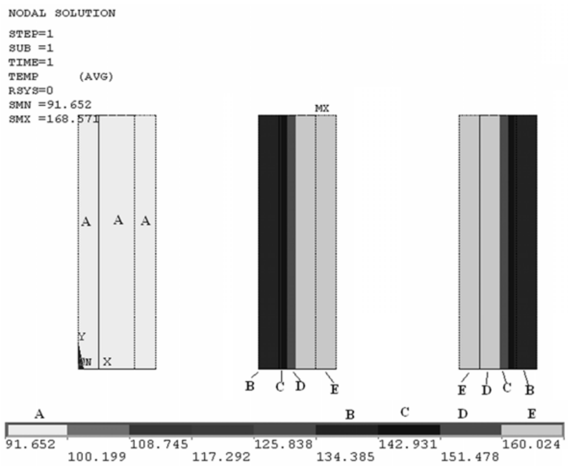

Fig. 2 ANSYS result for one channel blockage.

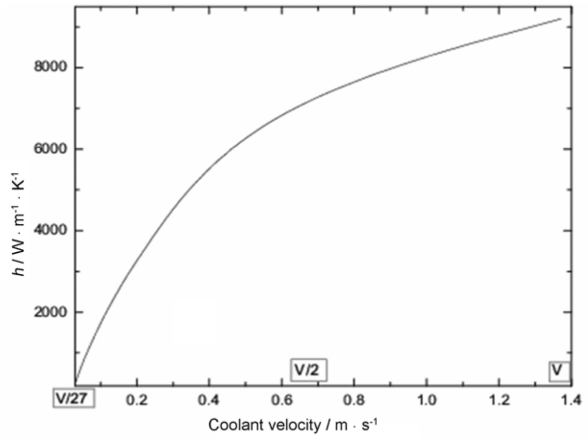

Fig. 3 Heat transfer *vs*. the coolant velocity.

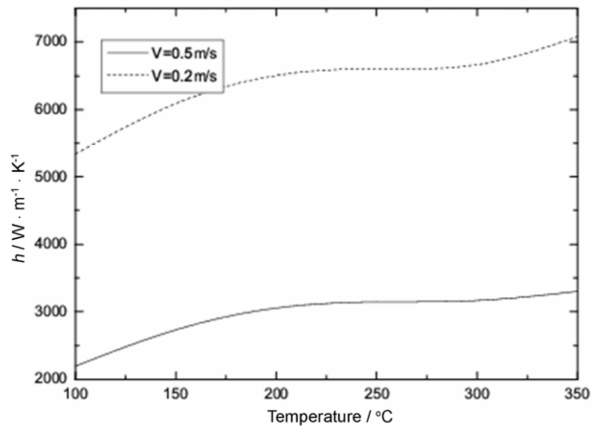

Fig. 4 Heat transfer *vs*. the coolant temperature.

In Fig.3, the heat transfer value increases with the coolant velocity. In the region where the coolant velocities are less than 0.5 m/s (nominal velocity of the coolant is 1 m/s), the h value increases rapidly. Therefore, when the coolant velocity drops down due to some partial blockage, we can expect more temperature increasing in the fuel components especially for the h value of less than 3000 $W \cdot m^{-2} \cdot K^{-1}$.

Fig. 4 shows the heat transfer of the coolant in different temperatures, which flows at 0.2 m/s (solid line) or 0.5 m/s (dashed line). One can see that a 250°C variation in coolant temperature for both velocities will change h value by only 50%. Therefore, h dependence to the coolant temperature is of less importance.

Fig.5 shows the maximum clad temperature as a function of coolant velocity. This is based on the assumption that the coolant phase does not change. The phase changes would cause less heat removal and clad melting finally. From Fig.5, in the region of low coolant velocities (V<0.2 m/s), the clad temperature exceeds the melting point. Therefore, only the coolant velocity near the designed value is safe for the fuel clad.

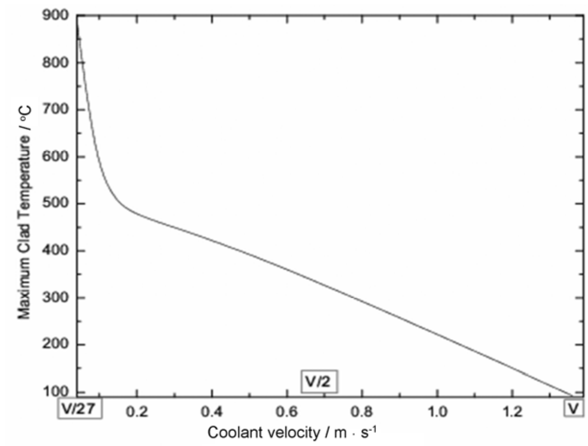

Fig. 5 Maximum clad temperature in terms of coolant velocity.

In complicated situations of partial or complete blockage of more than one channel, ANSYS 11 were used to get more reliable results. The complete blockage of two channels would cause the clad melt down. As shown in Figs. 6 and 7, very low film coefficient makes the situation the same as complete blockage. It can raise the fuel and clad temperature up to their melting points.

Fig. 8 shows that for the fuel elements located even far from the core center, a complete blockage of two channels would cause the fuel and clad melt down.

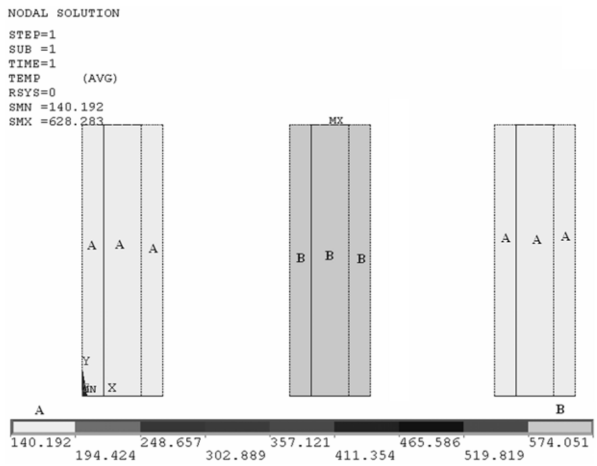

Fig. 6 Two channels blockage, h=1000W.m^{-2}.k^{-1}.

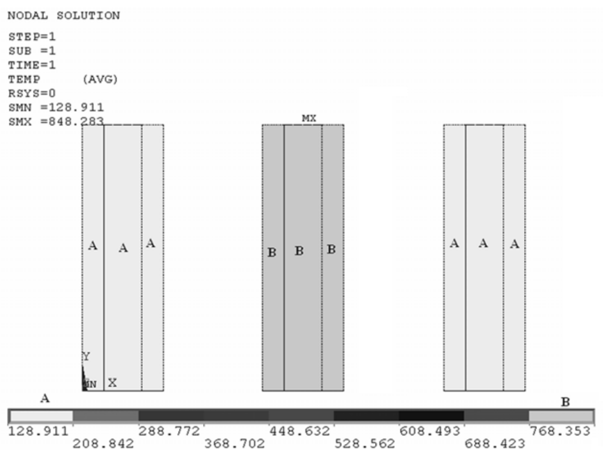

Fig. 7 Two channels blockage, h=500 W.m^{-2}.k^{-1}.

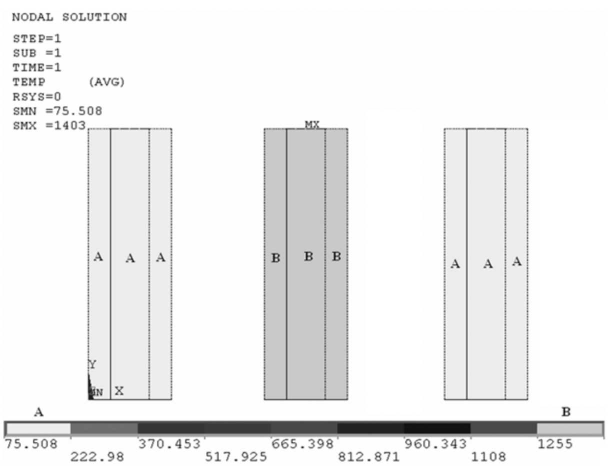

Fig. 8 Two channels complete blockage, q'''_{max} =4×10^8 W/m^3.

3 Conclusion

We have analyzed the fuel components temperature for cooling channel blockage, either complete (no heat convection) or partial (very low velocity flow), for TRR. The fuel and the clad melting points are about 1000°C and 650°C, respectively. The calculations and simulations show that one complete blockage of coolant channel would not harm the clad. More than one blocked channel can melt the clad in some conditions. The importance of such study has made the IAEA emphasize on such calculations for pool research reactors. These calculations also are helpful to determine the temperature distribution and coolant velocity in the case of increasing the reactor power up to its nominal value which is under study for TRR.

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