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Estimation of Integrity of Shear Key and Reactor Vessel During A Severe Accident

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Abstract

In this work we estimated the integrity of the shear key and the reactor vessel around the key solving three-dimensional, steady-state heat conduction equations. The reactor shear key is of a rectangular fin (60.48cm´25.2cm´16.25cm) attached to the plate of 15.12 cm thickness. The problem domain covers the area 15 times the cross-sectional area for the fin. The constant heat flux boundary condition is applied to the inner wall. The heat flux is obtained by considering the natural convection of the molten debris pool within the lower head. Several boundary conditions are applied to the outer wall to simulate the external cooling. Results indicate that the film boiling at the bottom of the shear key raises the temperature of the region close to the melting point. Even though nucleate boiling may be maintained in the region, the heat flux at the outer wall is larger around the shear key and the critical heat flux (CHF) will be lower than that without the shear key. It is thus necessary to maintain nucleate boiling at the bottom of the shear key and ensure that the vapor be not stagnant underneath the key. Results also show that the partial exposure of the fin to the air has little effect on the temperature field of the shear key and the reactor vessel.

1. Introduction

During development of the basic design (Phase II) for the Korean Next Generation Reactor (KNGR), external cooling of the reactor vessel lower head was chosen as the severe accident management strategy, and is in the process of design optimization and licensing during Phase III. In fact, the in-vessel retention (IVR) concept was not considered during Phase I (1992 - 1994): decision of a reactor type and the conceptual design for the reactor vessel lower head. Thus, several issues surfaced while applying the IVR concept at a later stage of design, one of which is the integrity of the reactor vessel shear keys. The keys are installed to protect the reactor vessel from vibration by an earthquake as schematically shown in Figure 1. But the effect of the shear keys was not considered in previous studies. So far, thermal and mechanical analyses during a severe accident have been carried out as follows.

Theofanous et al. [1] estimated the integrity of the vessel during a severe accident by experiments on the natural convection in the molten pool and the critical heat flux on the outer vessel wall. Thermal and mechanical analyses of the reactor vessel were carried out especially concerning the metal layer focusing effect.

Park and Dhir [2] investigated the effectiveness of flooding the cavity of a pressurized water reactor (PWR) in preventing vessel melt-through in case of melting and relocation of the core material in the vessel lower head. Two-dimensional transient and steady-state analyses were carried out including heat loss by radiation to the upper regions of the reactor vessel and the unwetted portion of the vessel lower head. The effect of internal circulation in the molten core material on heat transfer at the bounding walls was determined by extending the correlations used in their study. Radiative heat transfer from the molten pool to surrounding structures was also included in the analysis.

Kim and Jin [3] performed the temperature and stress analyses for core melting accident by using the ABAQUS code. They discussed the potential for vessel damage using the Larson-Miller curve and damage rule. They also compared the results of transient analysis with those of steady-state analysis and examined the effect of analysis conditions on the structural integrity.

2. Model Description

In this study we assume that the shear keys and the reactor vessel are assumed as the rectangular fin attached to the plate having 15 times the area as the cross-section area of the fin. We calculated the three-dimensional steady state temperature profile in the vessel and the shear key subject to boundary conditions specified in Figure 2. The size and the angular position of the shear keys were obtained from Park [4]. Boundary conditions were categorized into four cases pursuant to the conditions at the outer wall as:

(1) the bottom region of the shear key, the vessel wall below the key – film boiling
    the other region – nucleate boiling
(2) the vessel wall below the shear key – film boiling, the other region – nucleate boiling
(3) all the region- nucleate boiling
(4) partial exposure of the shear key (6.25 cm) to air, the other region – nucleate boiling

2.1 Thermal Boundary Condition

The constant heat flux boundary condition was used at the inner wall of the reactor vessel. The heat flux was determined according to the method suggested by Theofanous et al. [1]. The amount of heat source is determined from the decay heat, which is dependent on shutdown time, the amount of heat transferred downward by the natural convection, and the azimuthal variation of the downward heat flux. In this study we chose to use the decay power of 26 MW in the molten pool given by Park and Jeong [5]. To investigate the amount of heat transferred downward by natural convection we examined the correlation by Kelkar and Patankar [6]. The data were derived from the numeral study in hemisphere. Despite a great deal of studies performed so far, most of the data were taken from experiments with relatively low Rayleigh number (Ra') as compared to a postulated severe accident condition for which Ra' may well exceed 1x10^{17}. In these references Ra' is normally defined as:

$$Ra' = \frac{gbQ_V H^5}{k_p a_p n_p} \tag{1}$$

where the subscript p denotes the pool. Utilizing the natural convection correlations for the downward heat transfer (Nu_{dn}) versus the upward heat transfer (Nu_{up}) the downward heat split fraction was calculated as:

$$frac = \frac{Nu_{dn}\, 2pr^2}{Nu_{dn}\, 2pr^2 + Nu_{up} pr^2} = \frac{2\, Nu_{dn}}{2 Nu_{dn} + Nu_{up}} \tag{2}$$

The shear key is located in the molten oxide pool. Thus the heat flux of the inner wall of reactor vessel was determined from the correlation of Thefanous et al. [1] as:

$$\begin{aligned} q'(q) &= frac \times Q_{decay} \times \left\{ 0.1 + 1.08\left(q/q_p \right) - 4.5\left(q/q_p \right)^2 + 8.6\left(q/q_p \right)^3 \right\} && for\ \ 0 \le q/q_p \le 0.6 \\ &= frac \times Q_{decay} \times \left\{ 0.1 + 0.35\left(q/q_p \right) + \left(q/q_p \right)^2 \right\} && for\ \ 0.6 < q/q_p \le 1 \end{aligned} \tag{3}$$

The nucleate boiling heat transfer coefficient was taken as 20,000 W/m^2K. The average critical heat flux on the downward curved surface is 0.6 MW/m^2 and the wall superheat is generally 30K. The film boiling heat transfer coefficient was chosen to be 200 W/m^2K.

2.2 Three-Dimensional Steady-State Conduction Equation

To obtain the temperature profiles in the shear key and the reactor vessel, we solved three-dimensional steady-state heat conduction equations in the rectangular coordinates. The boundary condition for the inner surface was the local heat flux governed by the natural convection in the molten pool. The boundary condition for the outer wall was the four cases presented in the beginning of our model description. The three-dimensional conduction equation may be written out as:

$$\frac{d}{dx}\left(k\frac{dT}{dx} \right) + \frac{d}{dy}\left(k\frac{dT}{dy} \right) + \frac{d}{dz}\left(k\frac{dT}{dz} \right) = 0 \tag{4}$$

The differential equation may be discretized as:

$$
\begin{aligned}
&k\Delta y\Delta z\frac{T_{i-1,j,k}-T_{i,j,k}}{\Delta x}+k\Delta y\Delta z\frac{T_{i+1,j,k}-T_{i,j,k}}{\Delta x}+k\Delta x\Delta z\frac{T_{i,j-1,k}-T_{i,j,k}}{\Delta y}\\
&+k\Delta x\Delta z\frac{T_{i,j+1,k}-T_{i,j,k}}{\Delta y}+k\Delta x\Delta y\frac{T_{i,j,k-1}-T_{i,j,k}}{\Delta z}+k\Delta x\Delta y\frac{T_{i,j,k+1}-T_{i,j,k}}{\Delta z}=0
\end{aligned}
\tag{5}
$$

More detailed specific discretized forms of the differential equations for the respective regions follow:

<u>Vessel inner surface</u>

$$
\begin{aligned}
&k\Delta y\Delta z\frac{T_{i-1,j,k}-T_{i,j,k}}{\Delta x}+k\Delta y\Delta z\frac{T_{i+1,j,k}-T_{i,j,k}}{\Delta x}+k\Delta x\Delta z\frac{T_{i,j-1,k}-T_{i,j,k}}{\Delta y}\\
&+k\Delta x\Delta z\frac{T_{i,j+1,k}-T_{i,j,k}}{\Delta y}+k\Delta x\Delta y\frac{T_{i,j,k+1}-T_{i,j,k}}{\Delta z}+q''\Delta x\Delta y=0
\end{aligned}
\tag{6}
$$

<u>Vessel outer surface</u>

$$
\begin{aligned}
&k\Delta y\Delta z\frac{T_{i-1,j,k}-T_{i,j,k}}{\Delta x}+k\Delta y\Delta z\frac{T_{i+1,j,k}-T_{i,j,k}}{\Delta x}+k\Delta x\Delta z\frac{T_{i,j-1,k}-T_{i,j,k}}{\Delta y}\\
&+k\Delta x\Delta z\frac{T_{i,j+1,k}-T_{i,j,k}}{\Delta y}+k\Delta x\Delta y\frac{T_{i,j,k-1}-T_{i,j,k}}{\Delta z}+h\Delta x\Delta y\left(T_{sat}-T_{i,j,k}\right)=0
\end{aligned}
\tag{7}
$$

<u>Corner of the interface between the shear key and the reator vessel</u>

$$
\begin{aligned}
&k\frac{\Delta y\Delta z}{2}\frac{T_{i-1,j,k}-T_{i,j,k}}{\Delta x}+k\frac{3\Delta y\Delta z}{4}\frac{T_{i+1,j,k}-T_{i,j,k}}{\Delta x}+k\frac{\Delta x\Delta z}{2}\frac{T_{i,j-1,k}-T_{i,j,k}}{\Delta y}\\
&+k\frac{3\Delta x\Delta z}{4}\frac{T_{i,j+1,k}-T_{i,j,k}}{\Delta y}+k\Delta x\Delta y\frac{T_{i,j,k-1}-T_{i,j,k}}{\Delta z}+k\frac{\Delta x\Delta y}{4}\frac{T_{i,j,k+1}-T_{i,j,k}}{\Delta z}\\
&h\frac{3\Delta x\Delta y}{4}\left(T_{sat}-T_{i,j,k}\right)+h\frac{\Delta x\Delta z}{4}\left(T_{sat}-T_{i,j,k}\right)+h\frac{\Delta y\Delta z}{4}\left(T_{sat}-T_{i,j,k}\right)=0
\end{aligned}
\tag{8}
$$

<u>Side of the shear key</u>

$$
\begin{aligned}
&h\Delta y\Delta z\left(T_{sat}-T_{i,j,k}\right)+k\Delta y\Delta z\frac{T_{i+1,j,k}-T_{i,j,k}}{\Delta x}+k\frac{\Delta x\Delta z}{2}\frac{T_{i,j-1,k}-T_{i,j,k}}{\Delta y}\\
&+k\frac{\Delta x\Delta z}{2}\frac{T_{i,j+1,k}-T_{i,j,k}}{\Delta y}+k\frac{\Delta x\Delta y}{2}\frac{T_{i,j,k-1}-T_{i,j,k}}{\Delta z}+k\frac{\Delta x\Delta y}{2}\frac{T_{i,j,k+1}-T_{i,j,k}}{\Delta z}=0
\end{aligned}
\tag{9}
$$

The thermal conductivity of carbon steel was taken from Stickler et al. [7]. The thickness of the vessel is 15 cm. The size of the shear key is 60.48cm×25.2cm×16.25cm. We examined the temperature distribution of the region of our interest for the four cases. The error of this analysis was within ±0.001 °C. The shear key is partly exposed to the air out of the insulator in the former design. Comparison of case 3 with case 4 reveals the effect of parital exposure to air on the temperature distribtuion in the shear key and the reactor vessel.

3. Results and Discussion

Figure 3 shows the temperature distribution in the outer wall for cases 1, 2 and 3. Except for case 3, the film boiling at the bottom of the shear key raises the temperature of the region up to the melting point. Further, the temperature in the nucleate boiling region around the film boiling region is high enough for the local heat flux on the outer wall to exceed the critical heat flux (CHF) determined by Theofanous et al. [1]. It is thus considered to be necessary to maintain nucleate boiling at the bottom of the shear key.

Even though nucleate boiling may be maintained in the region, the heat flux at the outer wall is larger around the shear key. Also, the temperature in the vessel region near the shear key is much higher than that without the shear key as demonstrated in Figure 4. This is due to relatively low thermal conductivity of the steel combined with high heat transfer coefficient. The disturbance of the coolant and vapor flow by the shear key renders the local CHF smaller than that without the shear key. The higher actual heat flux and the lower CHF cause the local critical heat flux ratio (CHFR) much lower than that without the shear key. Therefore, stagnancy of the vapor underneath the key must be prevented to maintain the CHF as in the previous studies of Thefanous et al. [1], Cheung and Liu [8], and Rouge et al. [9].

The shear key is no benefit as the fin to advance heat removal capability as shown in Figure 5. The temperature around the shear key is higher than that at the effective length of fin obtained from Incropera and Dewitt [10] as 3.04cm. This is because of the high heat transfer coefficient of nucleate boiling and the relatively low conductivity of the shear key. It is

$$L_{\infty} = 2.65\left(\frac{kA_c}{hP}\right)^{1/2} \tag{10}$$

Comparison shows that the temperatures determined for case 4 are higher than those for case 3. The difference between temperatures for cases 3 and 4 is minimal as illustrated in Figure 5. That is, partial exposure of the fin to the air has little effect on the temperature field of the shear key and the reactor vessel. This is because the length of the fin in the nucleate boiling region is longer than the infinite length from equation (10). Hence, the gap size between the thermal insulator and the reactor vessel is maintained as the size of the previous design under the condition of sufficient CHFR. Figure 6 illustrates temperature distribution at the center line for cases 3 and 4 for the shear key and the reactor vessel.

4. Conclusion and Future Work

The following conclusions may be drawn from the estimation of integrity in the shear key and the reactor vessel during a severe accident.

1. The film boiling at the bottom of the shear key raises the temperature of the region near to or above the melting point.
2. The shear key has little effect of fin to advance heat removal capability, but rather negative effect on heat removal. It renders the temperature and heat flux of the region around shear key greater than those without the shear key.
3. Partial exposure of the fin to the air has little effect on the temperature field of the shear key and the reactor vessel.

Experiments on the effect of the shear key on the CHF need to be carried out. Trainsient analysis will also have to be performed to evaluate the spreading of the film boiling underneath the shear key. The time-to-failure by creep fracture must also be analyzed in the shear key and reator vessel around it.

Nomenclature

A_c	the cross section area [m^2]
$frac$	heat split fraction in the molten pool
g	gravitational acceleration [m/s^2]
H	depth of the molten pool [m]
h	heat transfer coefficient on the outer wall and the shear key [W/m^2K]
k	thermal conductivity of carbon steel [W/mK]
k_p	thermal conductivity of the molten pool [W/mK]
L_∞	infinite length [m]
Nu	Nusselt number
P	perimeter of the shear key [m]
r	inner radius of the lower head [m]
Ra'	modified Rayleigh number
Q_{decay}	decay heat [W/m^2]
Q_V	volumetric heat generation rate [W/m^3]
T	temperature [K]
x	x-coordinate
y	y-coordinate
z	z-coordinate
a_p	thermal diffusivity of the molten pool [m^2/s]
b	volumetric expansion coefficient [K^{-1}]
Δ	difference
n_p	kinematic viscosity [m^2/s]
q	azimuthal angle
q_p	azimuthal position of the pool

Subscripts

i, j, k	indices for temperature nodes

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Figure 1 Schematic diagram of the shear keys attached to reactor vessel

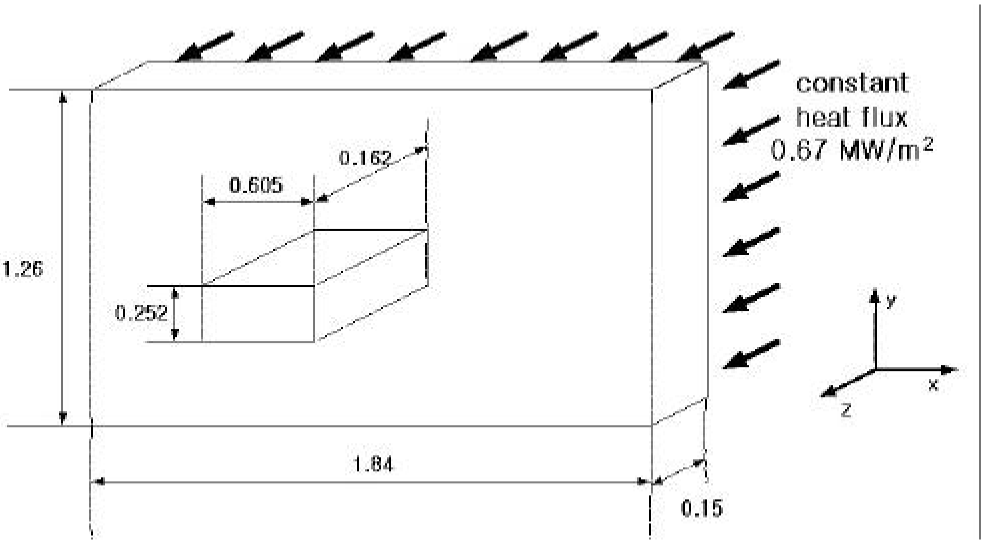
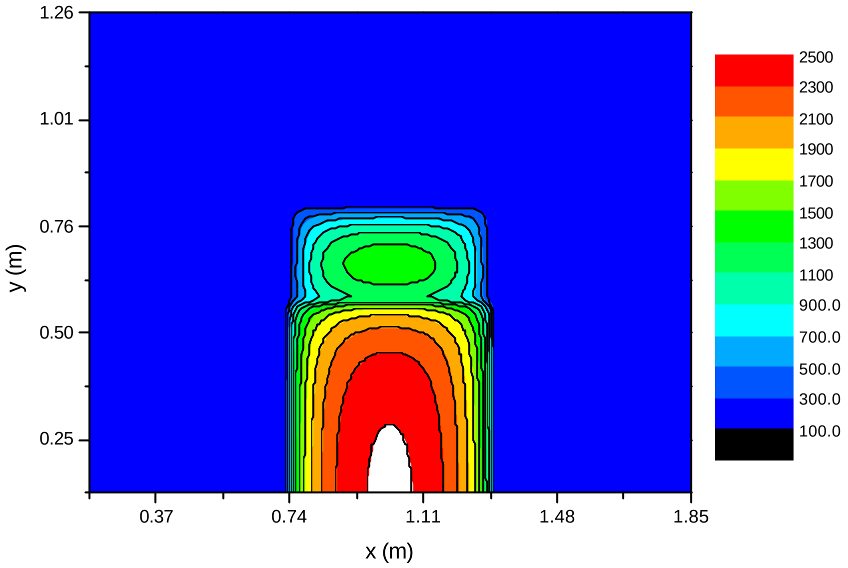
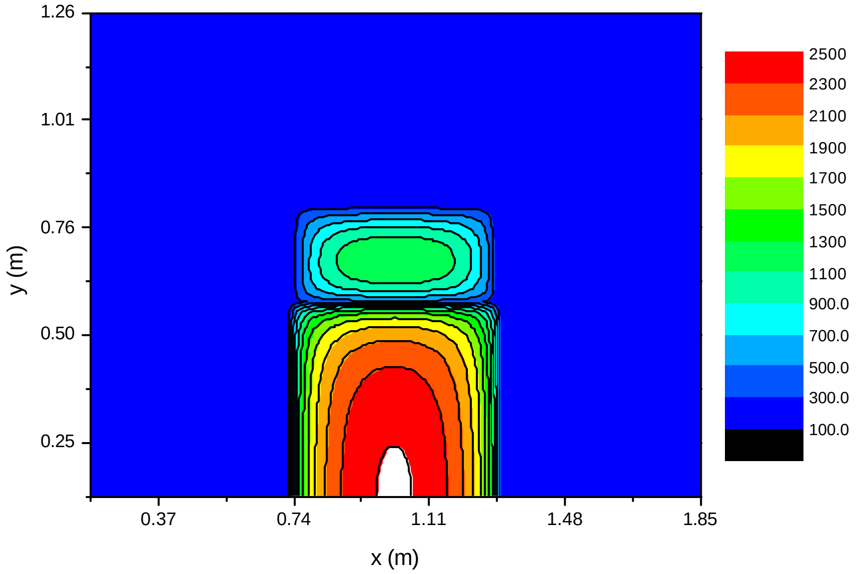


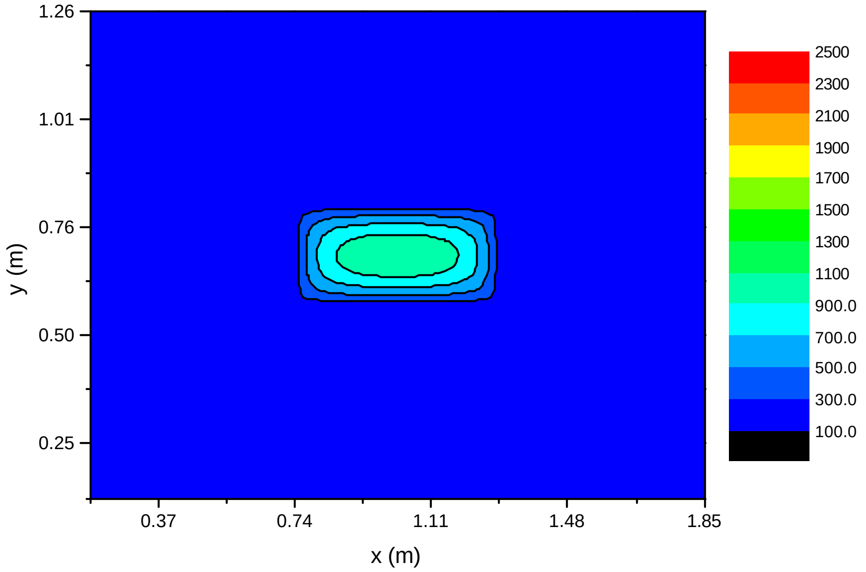
Figure 2 Thermal boundary conditions used in this study



(a) case 1



(b) case 2



(c) case 3

Figure 3 Temperature distribution on the outer wall for cases 1, 2 and 3

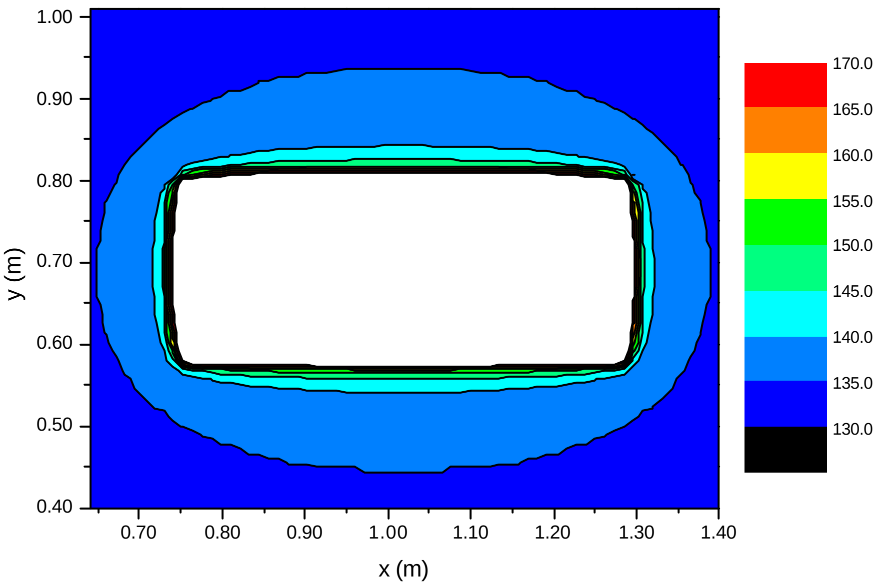
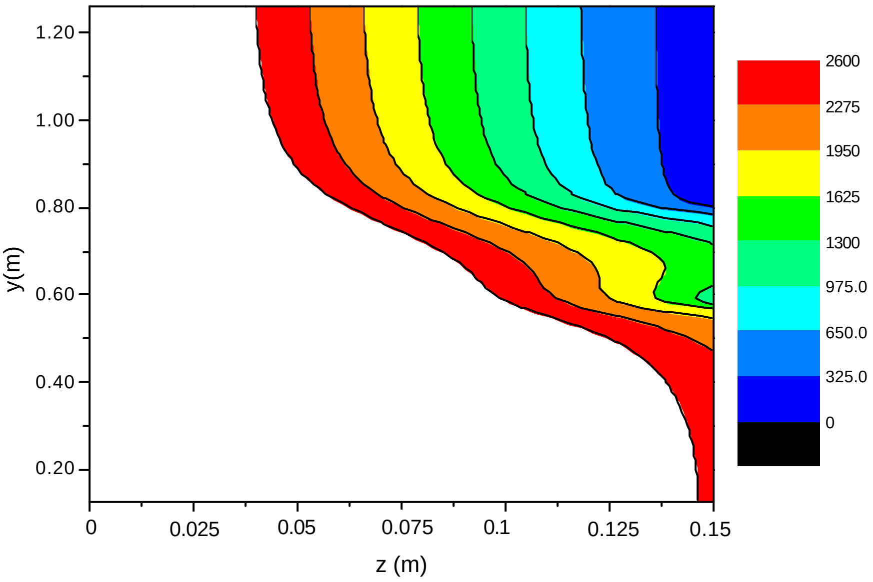
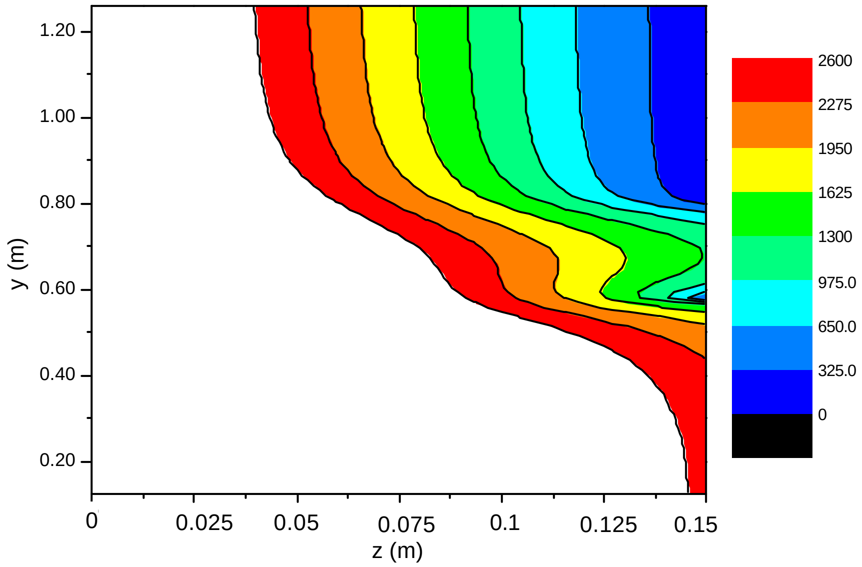


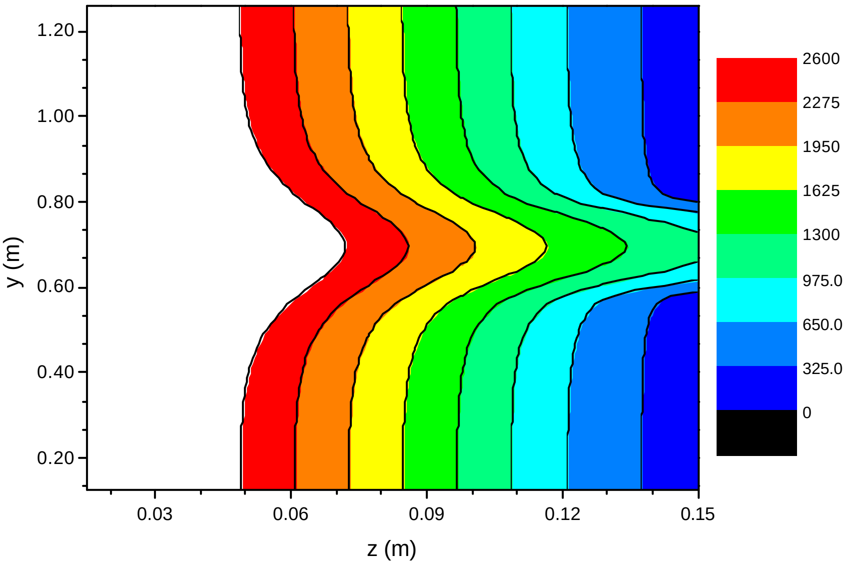
Figure 4 Temperature distribution on the outer wall around the shear key for case 3



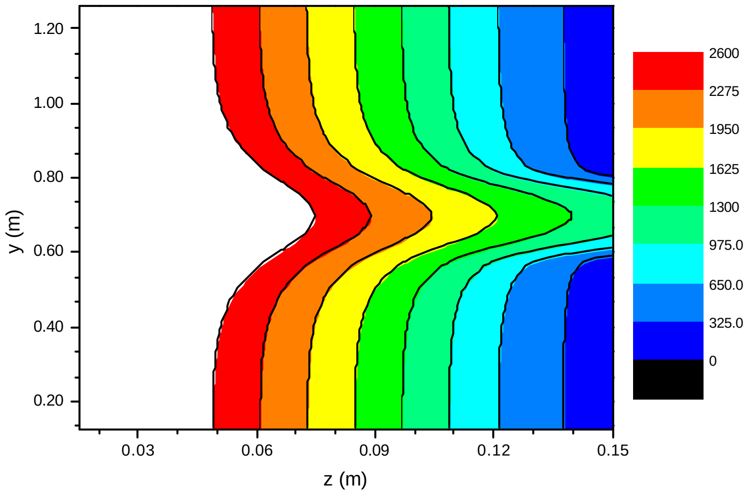
(a) case 1



(b) case 2

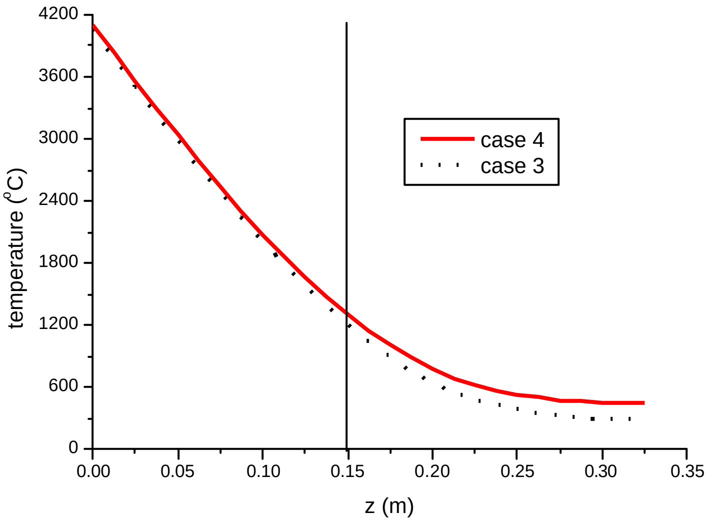


(c) case 3

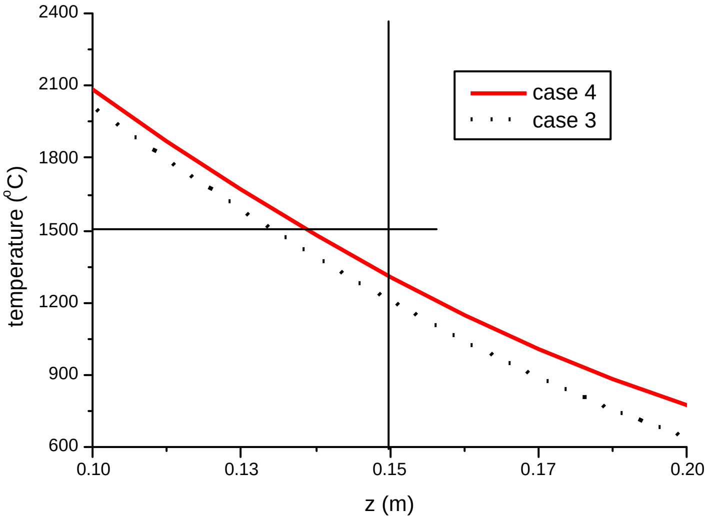


(d) case 4

Figure 5 Temperature distribution at the vertical cross section for cases 1, 2, 3 and 4



(a) Reactor vessel and shear key



(b) Around the shear key

Figure 6 Temperature distribution at the center line for cases 3 and 4