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Discharge Simulation of an MTR Pool Type RR due to a Break in the Reactor Tank

Neama M. El-Sahlamy#, Ahmed S. Khedr
Department of Nuclear Safety Engineering, Nuclear and Radiological Safety Research Center, Egyptian Atomic Energy Authority, Cairo, Egypt.

A POOL type reactor is a kind of MTR research reactors (RRs). The reactor core is immersed in a tank containing a huge amount of coolant which is normally used for cooling, moderation, and shielding purposes. If a break occurs at the bottom of this tank or at a large piping connected to it, pool discharge takes place and core uncover will be predicted. Loss of Coolant Accident (LOCA) is one of the most important postulated accidents considered in the design basis of nuclear reactors. From the lessons learned after Fukushima accident, the assessment of low probability severe accidents such as the RR tank break with using best estimate codes must be considered. During the simulation of LBLOCA in an MTR reactor using RELAP5/Mod3.3, some confusion in the results is observed. Therefore, a simple system consisting of a tank filled with water and a discharge valve is assumed to investigate the best nodalization for LBLOCA simulation using RELAP5 Code. Multiple nodalizations for the system are presented. It is noticed that the nodalization used in the analysis and some other user's options in the input file affects the simulation results. Additionally, a simple mathematical system of equations expressing the case is modeled using FORTRAN program to verify the best nodalization.

Keywords: LBLOCA, RELAP5, Research Reactor, Tank Discharge

Introduction

Research reactors play an important role in the development of nuclear science and technology. They comprise a wide range of different reactor types that are not used for power generation. The primary use of research reactors is to provide a neutron source for various applications namely, material testing, isotope production, neutron activation, and scientific education and training (IAEA, 2014, 2016). For nuclear research and technology development, to continue to prosper, research reactors must be safely and reliably operated. To ensure this, a set of postulated, severe accidents must be assessed and analyzed. One of the most common research reactor designs is a pool-type reactor, (Rachamin et al., 2017).

Most of the pool type reactors have design features such as high level penetrations for the reactor tank, and siphon breakers on the suction and discharge pipes of the primary cooling system, to prevent/or mitigate the LOCA consequences. Some breaks, such as pool tank break, a break in irradiation tube or experimental beams (even have a very low probability), are large enough and difficult to mitigate their consequences by the reactor features or Mack up system. These breaks are Large Break LOCA (LBLOCA) and are usually classified as design basis accident (DBA) or beyond design basis accident (BDBA) based on their cross section area. After Fukushima accident, all the BDBAs are renamed Design extension conditions (DECs) and can be assessed and analyzed using the Best Estimate Codes (BECs) (IAEA SS, 2016). The drainage through these breaks will result in complete dry out of the reactor pool leaving the core fully exposed to air. The exposure of core to air reduces considerably its cooling capability and therefore a substantial temperature increase due to fuel residual heat occurs, the extent of which depends on operating

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#Corresponding author e-mail: eng.neama@yahoo.com
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history of the core and power of the reactor. If the core temperature exceeds the clad melting point, the radioactivity will be released to the reactor confinement building and eventually to the atmosphere causing high radiation doses to the surrounding population.

In the current work, a LOCA accident is considered in an MTR pool type reactor as a result of rupture at a lower point of the reactor pool, i.e. due to rupture of any experimental beam, tangential tube, or reactor tank. This accident is classified as a LBLOCA due to its large break area. Pool discharge through the ruptured part is modeled using RELAP5/Mode3.3 code. RELAP5 is an advanced Thermal Hydraulic System Code used for the simulation of a wide range of postulated accidents in power reactors such as loss of coolant, anticipated transients without scram (ATWS), loss of flow, loss of feed water, and loss of offsite power. The capabilities of its new versions, such as Mode3.2 and Mode3.3, are extended to cover the low pressure and temperature facilities such as Research Reactors (RRs). Due to the wide spectrum of RR configurations, these versions require a large number of applications for the purpose of their validation (Pakistan Reactor Operation Group, 1993; Di Maro et al., 2003; Hamidouche et al., 2004; Khedr et al., 2005a, b; Adorni et al., 2006; El-Sahlamy et al., 2015).

Multiple nodalizations are proposed for the system considered. To verify and select the best nodalization, a simple mathematical system of equations expressing the system hydraulics was modeled and a computer program was built using the FORTRAN Language. The study is focused on the hydraulic characteristics to investigate the time for core uncover. The thermal behavior is ignored.

System configuration

A simplified reactor configuration is considered in the current analysis, as shown in Fig. 1. The system consists of a top's open tank containing a huge amount of water for the purpose of cooling and radiation shielding. A core contains a group of fuel elements at the lower end of the tank. At the core level, there are a group of experimental beams and a tangential tube located for the purpose of irradiation. The core analysis is not considered in the current analysis. Drainage of the reactor pool occurs due to a break on the tank wall or the tangential tube leaving the core partially or fully exposed to air. This accident leads to overheating and/or melting of the nuclear fuel in addition to radiation and releasing of fission products to the environment.

System nodalization

Several nodalizations are used to simulate drainage of the pool water. The nodalization is only used for pool discharge simulation, i.e. core simulation is not considered in the analysis. The main nodalization used in the present study is shown in Fig. 2. The assumed reactor data used in the current analysis is shown in Table 1. The components of the nodalization are given in Table 2.

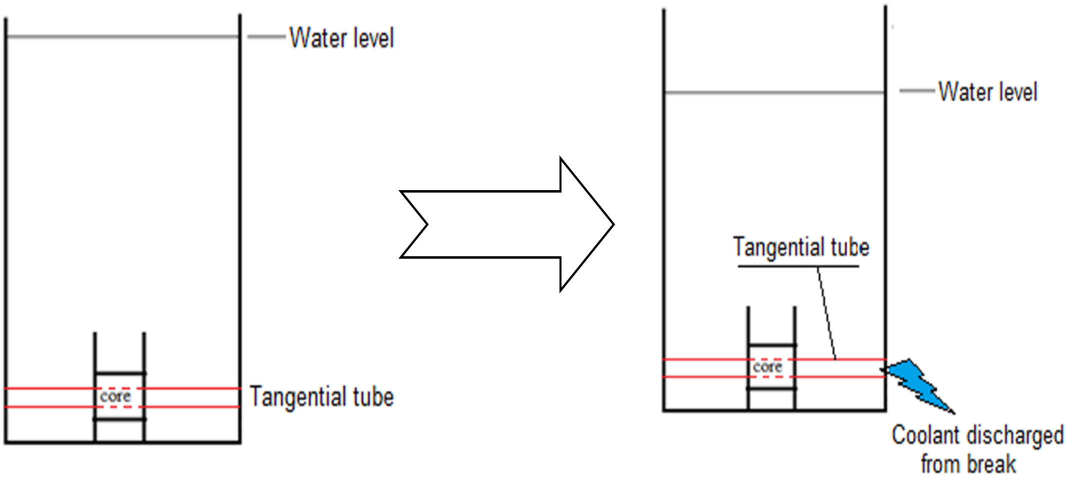


Fig. 1. System configuration

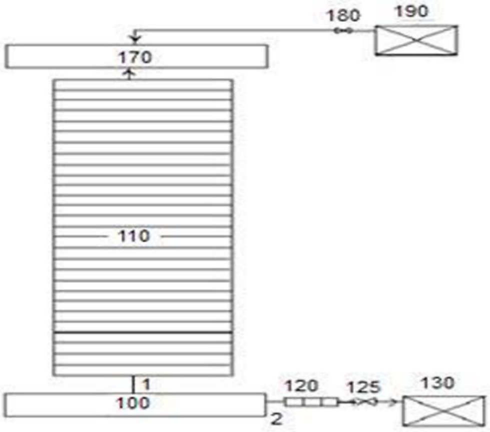


Fig. 2. Main system nodalization

TABLE 1. Hypothetical reactor data

Parameter	Value
Pool Water level (m)	8.15 m
Break cross section (m^2)	0.07
Valve type	Gate valve, with smooth area change model
Tank diameter (m)	4.5
Tangential tube diameter (m)	0.3048
Tangential tube roughness (m)	$5x10^{-5}$
Tangential tube length (m)	1.5
Water temperature	40 ^oC

TABLE 2. Components of the main nodalization

Component	Nodalization number
Reactor pool	Pipe 110+Branches 100, 170
Boundary conditions	TDV 190, 130 (at atmospheric pressure)
Tangential tube (discharge pipe)	Pipe 120
Tangential tube break	Gate valve 125

Mathematical Model

From Bernoulli's equation for frictionless, incompressible flow between points 1 and 2 as Shown in Fig. 3:

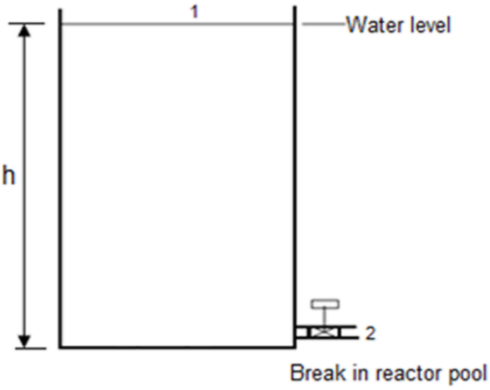


Fig. 3. Water pool

$$\frac{P_1}{\rho}+\frac{v_1^2}{2g}+Z_1=\frac{P_2}{\rho}+\frac{v_2^2}{2g}+Z_2$$

where point 1 is at the pool water surface and point 2 is at the exit of the discharge pipe. In addition, $P_1 = P_2$, $h = Z_1 - Z_2$, v is the velocity, and the valve is fully opened.

$$\frac{v_1^2}{2g}+h=\frac{v_2^2}{2g}$$

If A = the tank cross sectional area, and a= the pipe cross sectional area, from continuity equation:

$$v_1=\frac{a}{A}v_2 \qquad (2)$$

From (1) and (2)

$$v_2 = \sqrt{\frac{2gh}{\left(1-\left(\frac{a}{A}\right)^2\right)}} \qquad (3)$$

From Eq. (2) the velocity

v_1 is: $$v_1 = \sqrt{\frac{2gh}{\left(\frac{A}{a}\right)^2 - 1}} \qquad (4)$$

To calculate the tank water head change:

$$v_1 = -\frac{dh}{dt} \qquad (5)$$

From (4) in (5) and integrate:

$$h^{1/2} = h_o^{1/2} - 0.5Ct \qquad (6)$$

where $C = \sqrt{\frac{2g}{\left(\frac{A}{a}\right)^2 - 1}}$, and h_o is the value of *h* at $t=t_o$

For frictional incompressible flow, the Bernoulli's equation takes the form:

$$\frac{P_1}{\rho} + \frac{v_1^2}{2g} + Z_1 = \frac{P_2}{\rho} + \frac{v_2^2}{2g} + Z_2 + h_l$$

where, h_l is the head losses be tween the two points. With the assumption that $h_l = F\frac{v_2^2}{2g}$ and with some manipulations:

$$v_1 = \sqrt{\frac{2gh}{\left(\frac{A}{a}\right)^2 + F\left(\frac{A}{a}\right)^2 - 1}} \qquad (7)$$

And from Eq. (5),

$$h^{1/2} = h_o^{1/2} - 0.5Ct \qquad (8)$$

where $$C = \sqrt{\frac{2g}{\left(\frac{A}{a}\right)^2 + F\left(\frac{A}{a}\right)^2 - 1}}$$

F = minor loss factor + friction loss factor
= pipe entrance losses + valve losses + pipe exit losses + pipe friction losses
= $f_i + f_v + f_e + f_f$

Usually, $f_i = 0.5$ and $f_e = 1.0$. The valve losses is represented by a contraction loss factor and an expansion loss factor, i.e.; $f_v = f_{con} + f_{exp}$

The friction loss factor (f_f), it is calculated according to Reynold's number (Re_n)

- For $Re_n < 2000$ (laminar zone):

$$f_f = f_{fl} = \frac{64}{Re_n}$$

- For $4000 > Re_n > 2000$ (transition zone);

  - ○ For smooth pipe;

$$f_f = f_{fs} = f_{fl} + \left(f_{ft} - f_{fl}\right)\frac{Re_n - Re_{nl}}{Re_{nt} - Re_{nl}}$$

where $Re_{nl}=2000$ & $Re_{nt}=4000$, & $f_{ft} = \frac{0.316}{Re_{nt}^{0.25}}$

  - ○ For rough pipe;

$$f_f = \left[\frac{1.0}{1.14 - 2.0 * \log_{10}\left(R_r + \frac{9.35}{Re_n 2\sqrt{f_f}}\right)}\right]^{2.0}$$

where R_r is the relative surface roughness = (K/D)

- For $Re_n > 4000$;

  - ○ For smooth pipe;

$$f_f = 0.316/Re_n^{0.25} \qquad Re_n \leq 1\times10^5$$

For $Re_n > 1 \times 10^5$, iterate on f_i as follows:

$$f_i = 0.316/Re_n^{0.25}$$

$$f_{f1} = 1/f_i^{0.5}$$

$$f_{f2} = 2.0\log_{10}\left(Re_n * f_i^{0.5}\right) - 0.8$$

Stop the iteration at f_{f1} equals f_{f2}; then $f_f = f_i$

  - ○ For rough pipe:

$$f_f = \left[\frac{1.0}{1.14 - 2.0 * \log_{10}\left(R_r\right)}\right]^{2.0}$$

And $$Re_{nl} = \frac{200}{R_r\sqrt{f_f}}$$

If $Re_n > Re_{nl}$

$$f_f = \frac{0.25}{\left[\log_{10}\left(\frac{R_r}{3.7} + \frac{5.74}{{Re_n}^{0.9}}\right)\right]^{2.0}}$$

After that, a FORTRAN program was built containing all of these correlations. The program can predict the hydraulic behavior of a system consisting of a pool of water connected at its bottom to a gate valve through a discharge pipe. The used data is given in Table 1. Three types of flow boundaries; frictionless, smooth, rough, and completely rough are considered in the mathematical model.

Main nodalization qualification

In this section, results of the RELAP5/Mod 3.3 and the Mathematical Model (MM) for frictionless flow are compared and discussed for a break area of 0.07297 m^2 equal to the tangential tube cross section area. The discharged velocity of RELAP5 and MM is shown in Fig. 4. As shown, up to nearly 100 sec after opening of the gate valve, the RELAP5 discharged velocity is higher than the velocity of frictionless flow and consequently the discharged time is much less than the MM. This result remains as is whatever the pipe roughness and the forward/backward valve losses used in RELAP5 input. From the principles of fluid mechanics, RELAP5 main nodalization based results are non-logic and some modifications must be implemented on the nodalization. Therefore three modifications are suggested and implemented on the main nodalization which results in three new nodalizations referred to Nod 1, 2, 3. Table 3 demonstrates the modifications corresponding to each one. In the three nodalizations, the gate valve characteristic is modified from smooth area change model to full abrupt area change model. In the following part, the results for RELAP5/Mod 3.3 are given, discussed, and compared with corresponding results of the MM for the three nodalizations considered.

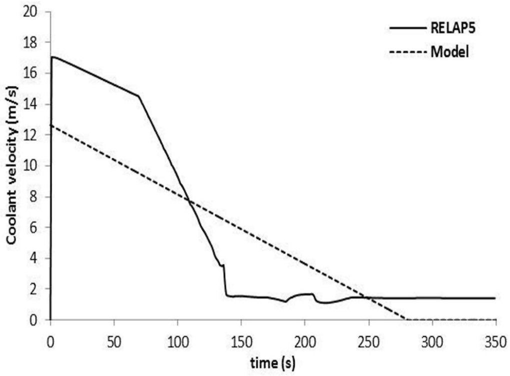


Fig. 4. Discharge velocity (m/s)

TABLE 3. The modifications implemented on the main nodalization

Nodalization number	**Referred name**	**Implemented modification**
Nodalization (1)	Nod1	Gate valve, with full abrupt area change model
Nodalization (2)	Nod2	Modification 1 + Pipe 120 is removed
Nodalization (3)	Nod3	Modification 1 + branch 100 and pipe 120 are removed

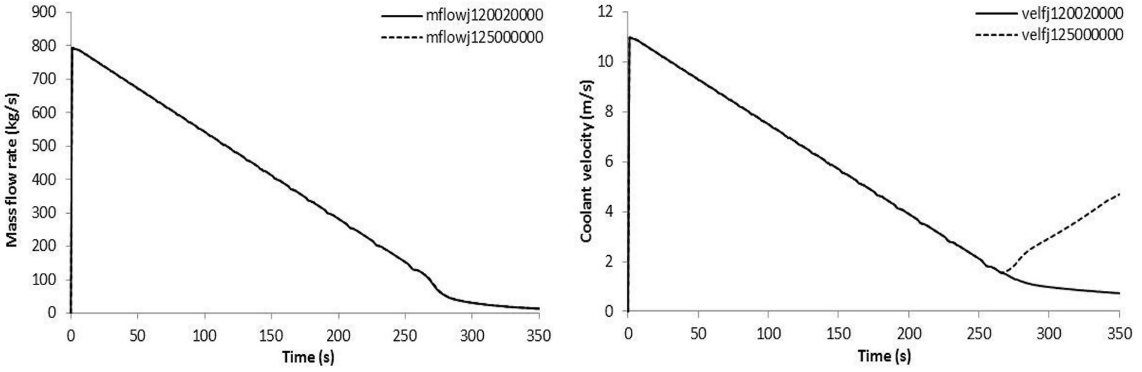
Results and Discussion

First nodalization (Nod1)

This nodalization contains the same components as the main nodalization. The only modification implemented is the valve characteristic to be fully abrupt area change instead of smooth area change. Figures 5(a-e) show the results of Nod1 for a large break in the tangential tube with break cross section equal to the total area of the discharge pipe; i.e., 0.07297 m^2. Figures 5(a and b), show the mass flow rates and discharged velocity at two points; the discharge pipe (Pipe 120) and the gate valve (valve 125). As shown, the discharged mass flow rate is more logical compared to the frictionless flow shown in Fig. 4. In addition, near the end of the transient, the discharged velocity at the gate valve is non-logical, i.e. increases; in contradict to that at the pipe. Figures 5(c and d), give the total pool liquid mass and the pressure at the discharge pipe, respectively. The pool water mass is of logical trend , but the pressure in the pipe behaves in a non-logical way; it drops sharply at time zero to nearly atmospheric pressure then drops slowly. Figure 5(e) presents the pool liquid level. If a core height of 0.8 m from the tank bottom is assumed, then the core uncover is expected to start at time t= 220 s from the beginning of the transient.

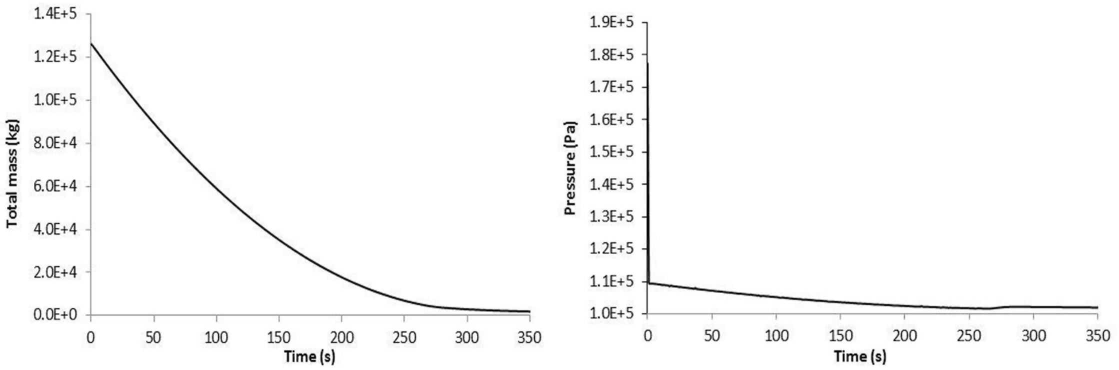
Second nodalization (Nod2)

Figures 6(a-e) are obtained using the second nodalization, where the discharge pipe (Pipe 120) is removed and the lower plenum (branch 100) is connected directly to the TDV 130 through the broken valve 125. The valve cross sectional area is 0.07297 m^2 with fully abrupt area change. The used valve's forward/backward energy loss coefficient is 0.1. Figures 6(a and b) show the mass flow rate and the coolant velocity through the break valve 125. Although pipe 120 was removed, the break velocity and mass flow rate at time zero become greatly lower than the corresponding values in Figures 6(a and b). Therefore, the tank discharge time becomes longer. Figures 6(c and d), give the total pool liquid mass and the pressure at the pool's lower volume, respectively. As shown, the pool content and consequently the pool water head decreases gradually with time and reaches nearly zero at the end of the transient time. Therefore, the pressure at the break point decreases in a similar way to water head until reaches the atmospheric pressure. Also, the core uncover starts to occur lately at t= 315 s, as shown in Fig. 6(e). As noticed in these Figures, the trends of all the variables for Nod2 seem logical but the values, especially the discharged flow and velocity, are greatly less than those from Nod1.



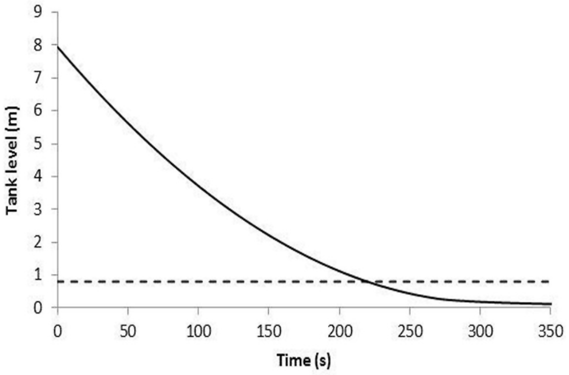
(a) Mass flow rate (kg/s)

(b) Coolant velocity (m/s)



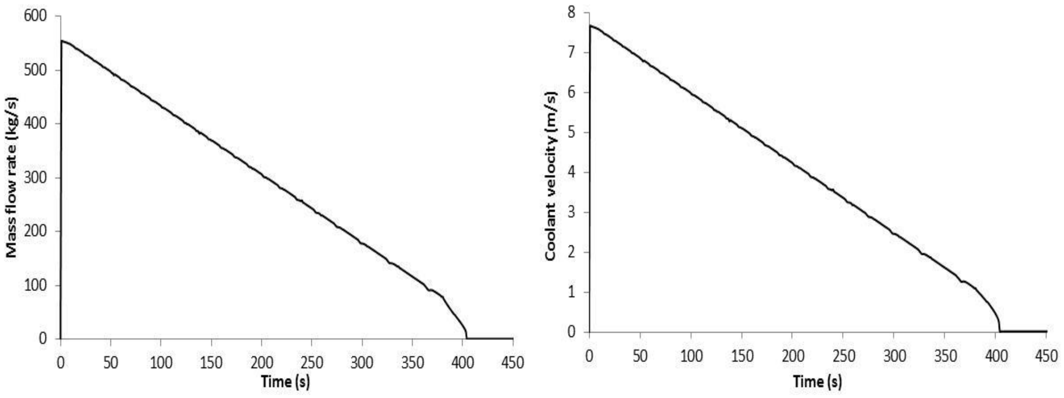
(c) Total pool liquid mass (kg)

(d) Pressure at the discharge pipe (Pa)

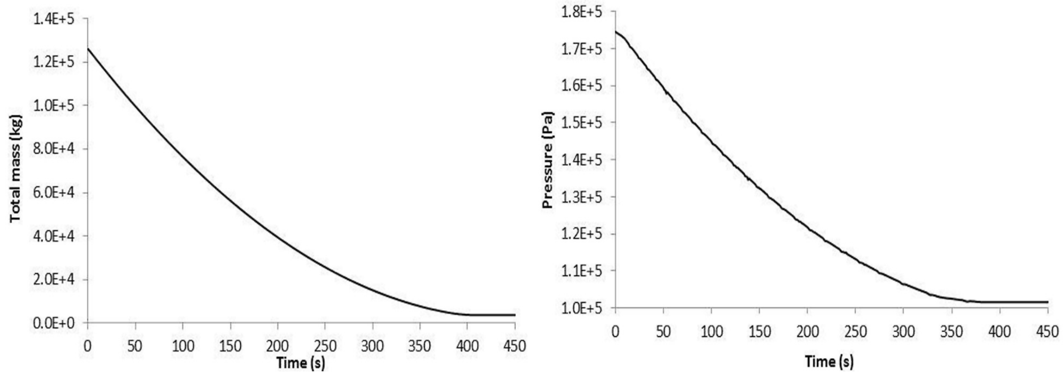


(e) Pool liquid level (m)

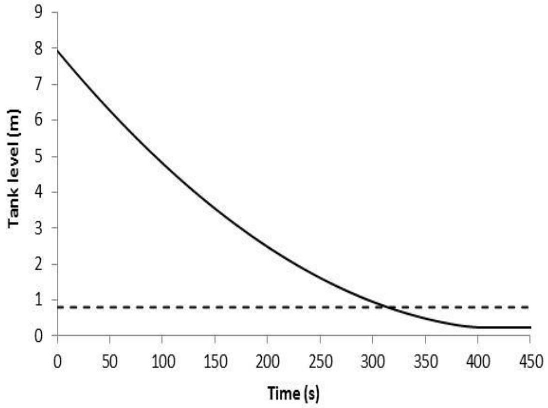
Fig. 5. System parameters using Nod1 with break area equal to the total area of the discharge pipe



(a) Mass flow rate (kg/s) (b) Coolant velocity (m/s)



(c) Total pool liquid mass (kg) (d) Pressure at the pool lower volume (Pa)



(e) Pool liquid level (m)

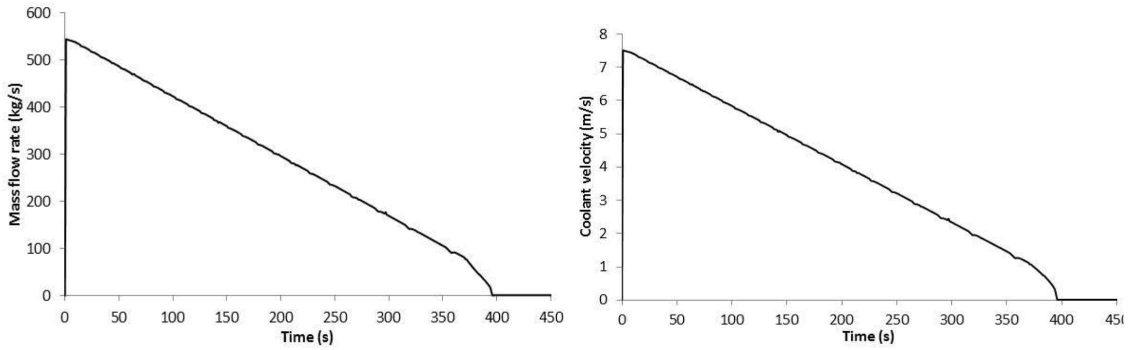
Fig. 6. System parameters using Nod2 with break area equal to the total area of the discharge pipe

Third nodalization (Nod3)

Figures 7(a-e) are obtained using the third nodalization, where the discharge pipe (Pipe 120) and the lower branch (Branch 100) are removed from the main nodalization. Only the break valve (valve 125) is considered to simulate the break in the third nodalization. The number of volumes in Pipe 110 is unchanged but the length of each volume is changed to give the same total head. The valve cross sectional area equal to the tangential tube cross section is considered for this group of curves. The full abrupt area change model is activated. Moreover, the valve's forward/backward energy loss coefficient equal to 0.1 is considered. Figures 7(a, b) show the mass flow rate and the coolant velocity in the discharge valve (Valve 125). Figures 7(c and d), give the total pool liquid mass and the pressure at the pool lower volume, respectively. Figure 7(e) presents the pool liquid level, where core uncover starts to occur at about 305 s; i.e., too close to that of the previous case of Nod2. As shown, the trends of all the curves are the same as in Nod2. This means that removing the lower branch, 100, has no effect on the results. Therefore, the performance of Nod3 is similar to that of Nod2.

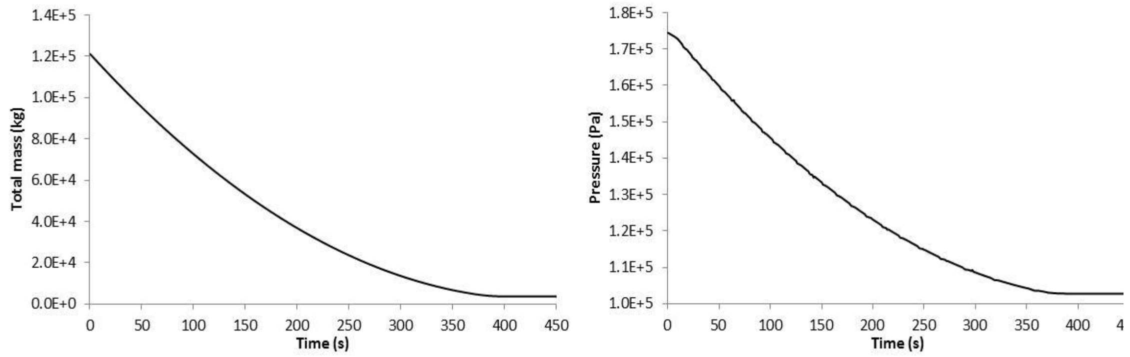
Comparison with the mathematical model

In this section, the results obtained from the FORTRAN program are compared with RELAP5 results for the second nodalization (Nod2). The break area is 0.07297 m^2. Figures 8(a-c) show comparisons between Relap5 and the FORTRAN program for parameters of break velocity, mass flow rate and total pool liquid mass, respectively. The mathematical model calculates the previous parameters assuming frictional flow, with rough boundaries. The mathematical model results are referred on the next Figures as Model- FR results.



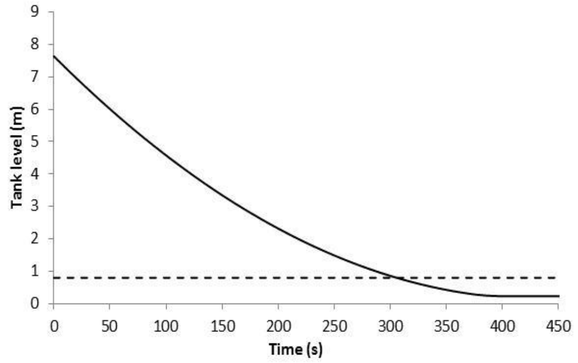
(a) Mass flow rate (kg/s)

(b) Coolant velocity (m/s)



(c) Total pool liquid mass (kg)

(d) Pressure at the pool lower volume (Pa)



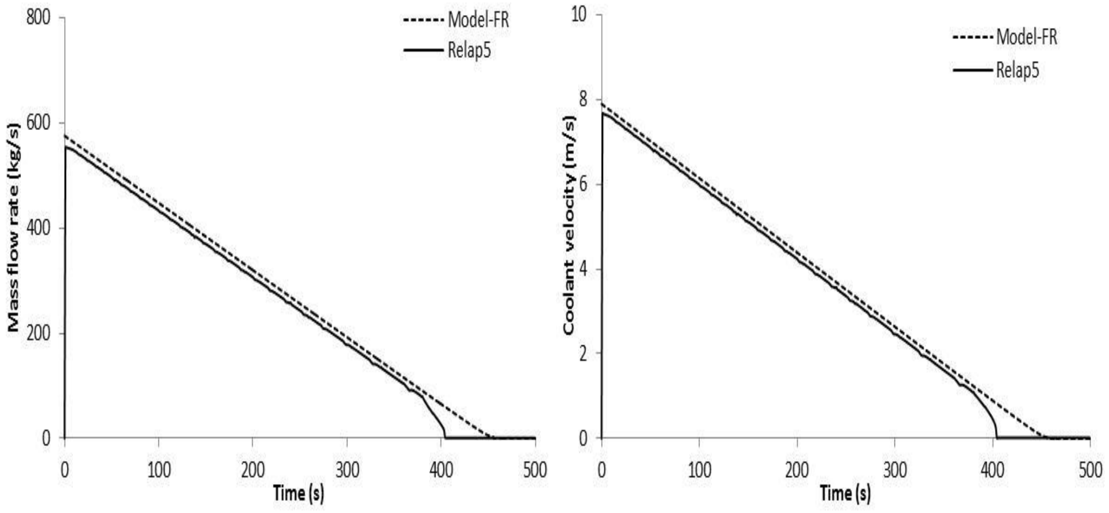
(e) Pool liquid level (m)

Fig. 7. System parameters using nodalization (3) with break area equal to the total area of the discharge pipe

As shown form Fig. 8, the mathematical model results show a tank empting time of about 450 sec.

Where, at nearly 400 sec, the RELAP5 results go faster to zero because the pool water level becomes less than the break diameter and the flow becomes open channel flow. Due to the small value of the used surface roughness in the discharge pipe ($5*10^{-5}$ m), Table 1, the result for smooth and rough boundaries are similar and in a good agreement with RELAP5 results. Therefore, only the results for rough boundary are used in the following comparisons.

For more evaluation, a small break area equal to half the previous one (0.03648 m^2) is considered. All the other data are not changed. Figures 9(a-c) show the comparison between Relap5 and the mathematical model for the parameters; discharge velocity, mass flow rate and total pool liquid mass, respectively. Only the mathematical model results for rough boundary are considered. The results show that even for a break area equal to half the pre-considered one, good agreements between Relap5 results and FORTRAN model results are achieved for the three system parameters; mass flow rate, discharged velocity, and pool water mass.



(a) Mass flow rate (kg/s) (b) Coolant velocity (m/s)

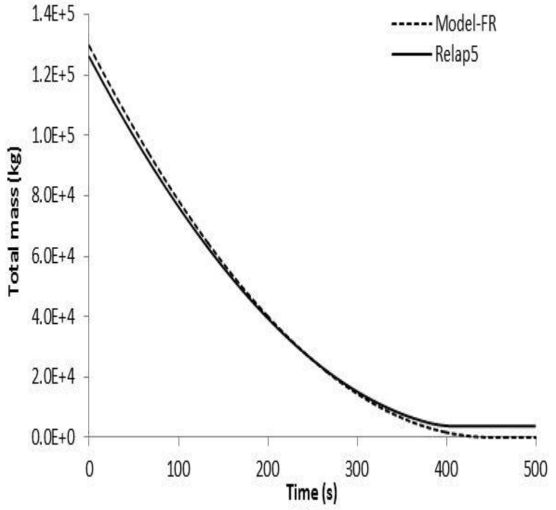
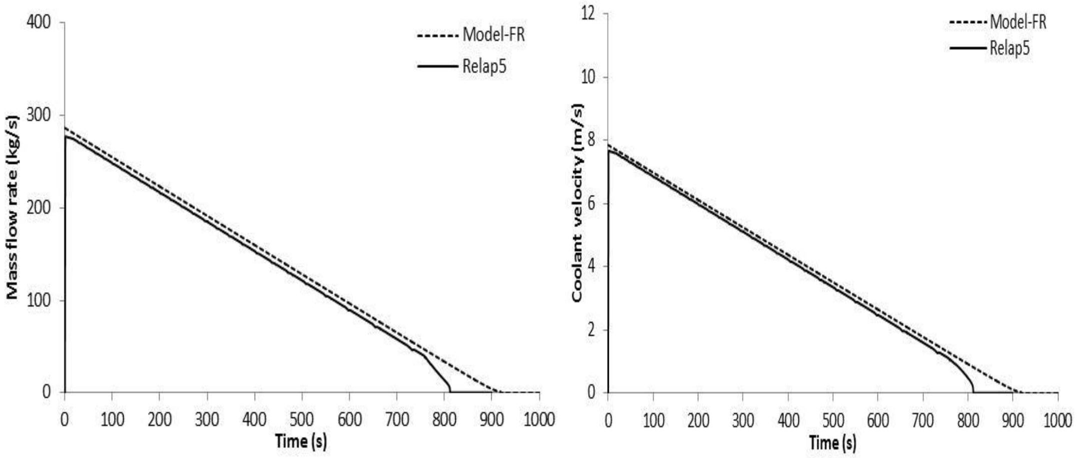
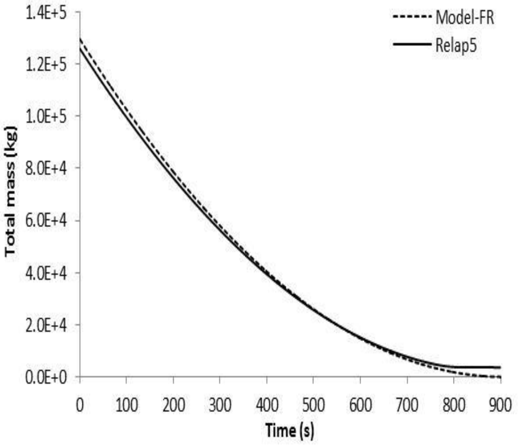


Fig. 8. Comparison between Relap5 and Theoretical Model with break area equal to the total area of the discharge pipe



(a) Mass flow rate (kg/s)

(b) Coolant velocity (m/s)



(c) Total pool liquid mass (kg)

Fig. 9. Comparison between Relap5 and Theoretical Model for break area equal to half the area of the discharge pipe

Conclusion

In the present paper, one of the LBLOCA in a pool type research reactor was analyzed. This accident is due to a complete break in a tangential tube with diameter equal to 30.48 cm. The hydrodynamic sequence of the accident was only considered. The RELAP5 Mod 3.3 system code was used. A simple system was investigated consisting of a pool of water and a tangential tube located near the pool bottom. Three suggested nodalizations for the system were used. In the first nodalization, a pool with lower plenum was connected to the break through a tube. In the second one, a pool with lower plenum was connected directly to the break. In the third one, a pool without lower plenum was connected directly to the break. In the three nodalizations the driving head was kept constant. To verify the most relevant nodalization, a FORTRAN model and program were built for three types of flow; frictionless, smooth and frictional flow. In the beginning, the RELAP5 results show that the break flow rate was higher than the frictionless flow. Upon that, it was very important to choose the characteristics of the valve, simulating the break, as fully abrupt area change in steed of smooth area change. In the following analysis, this choice was valid for all the nodalizations. The results of the first nodalization show that, the static pressure and the coolant velocity in the tangential tube are non-logical. The pressure suddenly drops at the beginning of the transient and the coolant velocity at the later transient time increases again in spite of the very low driving head. On the other hand, the results from the second and third nodalizations were logical and in agreement with the FORTRAN program results. This conclusion is directed to the code users during simulation of LBLOCA in pool type research reactors.

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