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Analytical Investigation of the Draining System for a Molten Salt Fast Reactor

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ABSTRACT

Molten Salt Fast Reactor (MSFR) is a conceptual design by European Union that contains a draining tank located underneath the reactor. In case of a planned reactor shut down or in emergency situations or in case of accidents leading to an excessive increase of the temperature in the core, the liquid fuel will be passively drained into the draining tank by gravity force. Ni-based alloy is considered to be resistant against damage at temperatures in the range of 1250°C-1350°C. According to the previous calculation in the EVOL project, this damage temperature could be reached in approximately 20 minutes in the worst case, if the liquid fuel stays in the core. Based on the core geometry of MSFR in the EVOL project, times for draining fuel from the core region are analytically evaluated through variation of draining tube diameter, draining tube length and variation of damage degree of freeze plug. A preliminary evaluation of some orders of magnitude of draining time periods is presented in this paper, supporting the precise engineering and design of the draining system for the MSFR within SAMOFAR project of European Union.

KEYWORDS

Molten Salt Reactor; Draining System; Draining Time; Freeze Plug.

1. INTRODUCTION

From the experience of Fukushima-Daiichi nuclear power plant disaster, it is preferred to remove the decay heat from reactor core passively, i.e without mechanical or electrical assistance. Molten-Salt Reactors (MSRs) offer inherent safety advantages with a kind of salt draining system. MSRs designs have a freeze plug at the bottom of the core — a plug of salt, if temperature rises beyond a threshold point, the plug melts, and the liquid fuel in the core is immediately and passively evacuated by gravitational draining into a draining tank or several draining tanks located underneath the reactor. This dedicated catchment basin geometry ensures the sub-criticality of the relocated fuel. Clearly, this formidable safety tactic is only possible if the fuel is a liquid.

R&D efforts have been continually developing on this new concept of a molten salt reactor called the Molten Salt Fast Reactor (MSFR) by European Union. Within the SAMOFAR project (A Paradigm Shift in Reactor Safety with the Molten Salt Fast Reactor), [1], one of the tasks is to perform the key safety features of the draining of the fuel salt. In essence, the SAMOFAR project is the continuation of the successful actions of the EVOL project (Evaluation and Viability of Liquid Fuel Fast Reactor System), [2]. The reference MSFR design is a 3000 MW_{th} reactor with a total fuel salt volume of

18 m^3 in the active core range, operated at fuel temperatures between 650°C and 750°C, (Fig. 1). In case of a planned reactor shut down or in emergency situations or in case of accidents leading to an excessive increase of the temperature in the core, the safety system is required to drain in due time the fuel into the draining tank located below the reactor. Based on the previous results, though the salt boiling point is 1755°C, the damage to the reactor system occurs at an earlier temperature of the containing material depending on its nature. For Ni-based alloy the temperatures could be in the 1250°C-1350°C range, slightly below alloy partial melting [3]. The damage temperature can be reached in approximately 20 minutes in the worst case [4]. Hence the fuel draining time is a key parameter for the engineering design of the MSFR draining system and the safety characteristics of the MSFRs.

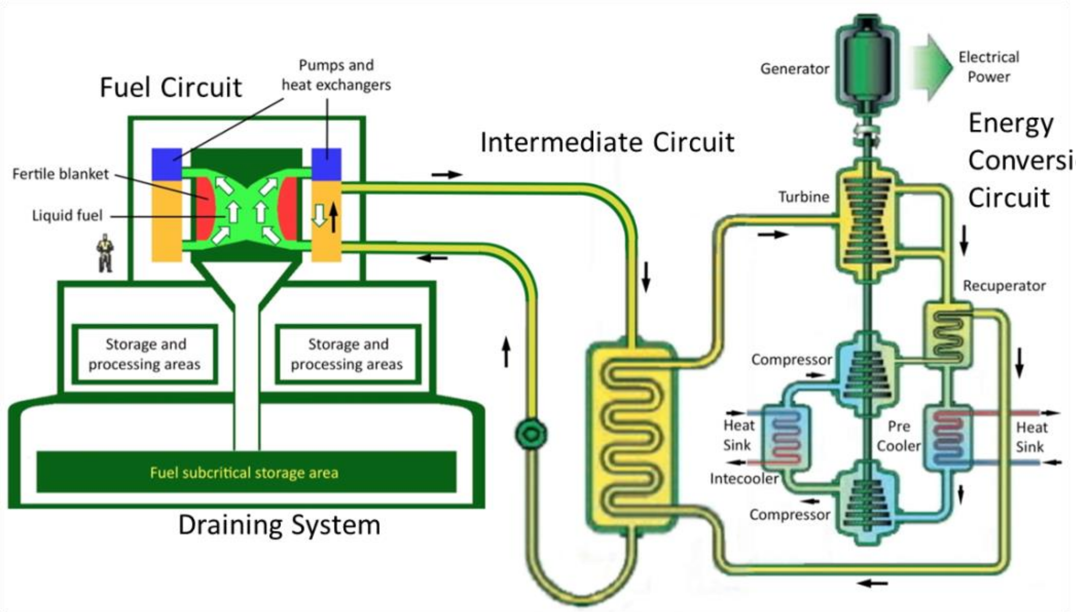


Fig. 1 MSFR power plant, [5].

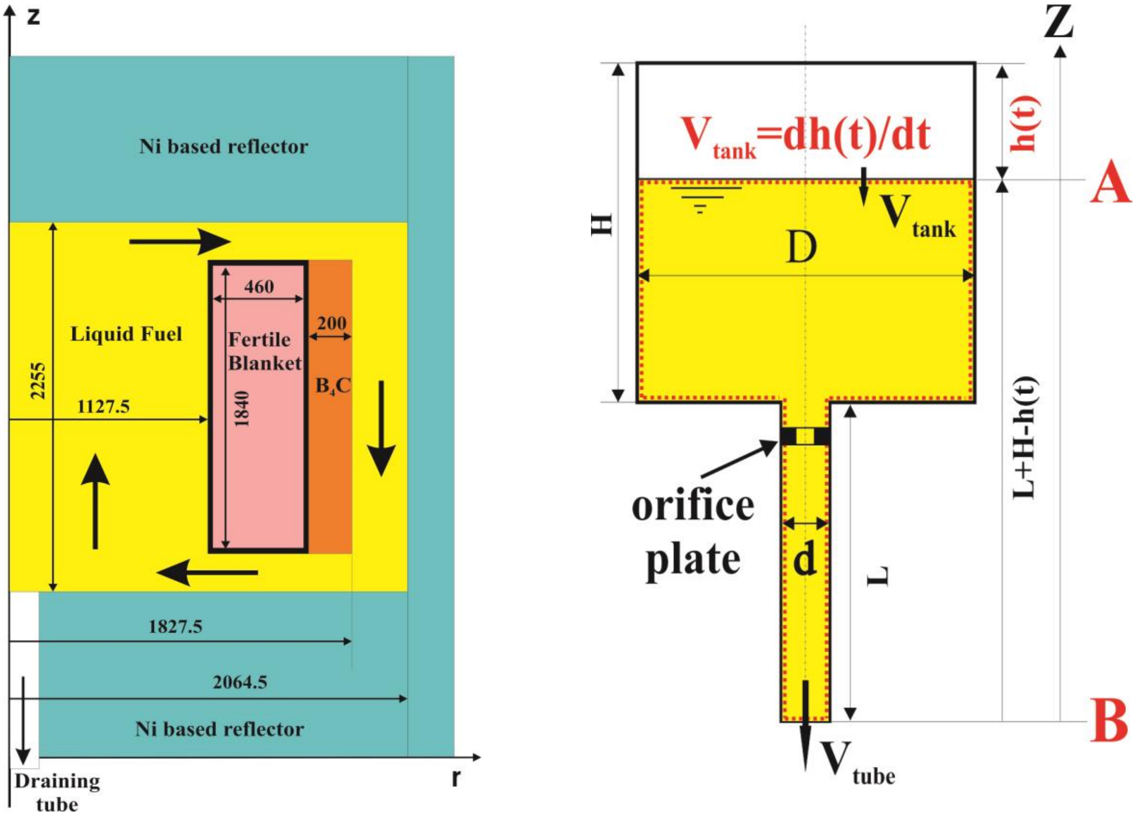
In this paper, the reactor model, behavior, and parameters are adopted from the outcome of the EVOL project. The following parameters are analytically investigated as a part of the design of the draining system:

1) Draining time taken vs. draining tube diameter;
2) Draining time taken vs. draining tube length;
3) Draining time taken vs. damage degree of freeze plug.

A preliminary evaluation of some orders of magnitude of draining time periods is given in this paper; supporting to give a first evidence for precise engineering and design studies.

2. PHYSICAL MODELING

The MSFR geometric design in the EVOL project [2] is used as the base case for these analyses. Geometric arrangement and reactor core of the MSFR and its dimensions for computation are shown in Fig. 1 and Fig. 2(a), respectively. The main parts of the reactor core include a liquid fuel cavity (yellow part), a fertile blanket (pink), a B_4C shielding (orange), and Ni based alloy reflectors around the active core. All dimensions in Fig.2 (a) are in mm.



(a) (b)

Fig. 2 (a) MSFR reactor core and (b) analytical model for draining time calculation

To simplify the analysis, the reactor system under consideration is assumed to be symmetric about its centerline, i.e., possible variations of flow fields in azimuthal direction of the cylindrical coordinates are ignored. The draining tube is assumed to be arranged symmetrically about its centerline below core cavity. For the draining time calculations, the liquid fuel height in the core is a key parameter, therefore for the geometrical modeling the height of the fuel tank (H) in Fig. 2(b) must be consistent with the original core height, that is H=2255mm, while the diameter D can be adjusted to match the fuel volume. The liquid fuel volume in active core range amounts to 18m^3, thus the equivalent diameter of the model is D=3188 mm in Fig.2 (b).

Molten salt thermophysical properties used in this paper are assumed to be representative for the fuel mean temperature at 700°C. Accordingly the density of liquid fuel is ρ=4124.9 kg/m^3, and the kinematic viscosity is 0.010147254 m^2/s, [3, 6].

3. MATHEMATICAL MODELING

3.1. Mass Conservation

Consider a cylindrical tank of Fig. 2(b), with a diameter *D*, partially filled with a liquid to a height *H-h*. The pressure in the tank on the liquid upper surface is constant at P_A. The tank is emptying through a draining tube of diameter *d* at the base of the core tank to a catchment tank of pressure P_B.

If the flow can be assumed to be *steady* (i.e. not varying with time) and the fluid is *incompressible* (i.e. its density does not vary), then the total mass of liquid fuel in the considered reactor core at any time *t* can be written as:

$$M(t) = \rho\pi\frac{D^2}{4}[H - h(t)]. \tag{1}$$

Differentiating this Eq. with respect to time *t* , we get the rate of change of mass inside the tank as:

$$\frac{dM(t)}{dt} = \rho\pi\frac{D^2}{4}\frac{d[H-h(t)]}{dt}\,. \tag{2}$$

Conservation of mass states that:

$$-\rho\pi\frac{D^2}{4}\frac{dh(t)}{dt} = -\rho\pi\frac{d^2}{4}\cdot V_B, \tag{3}$$

where

$$\frac{dh(t)}{dt} = V_A \tag{4}$$

is the magnitude of the average drain velocity of molten salt in the reactor core, (i.e. the speed of the free surface in the core).

With the assumption that the liquid fuel is incompressible, the average discharge speed in the draining tube then can be expressed as:

$$V_B = \frac{dh(t)}{dt}\cdot\left(\frac{D}{d}\right)^2. \tag{5}$$

3.2. Energy Conservation

Total energy of a fluid in motion per unit mass is

$$e_{total} = h + \frac{V^2}{2} + gZ = u + pv + \frac{V^2}{2} + gZ, \tag{6}$$

where u, p and $\boldsymbol{v}$ are internal energy, pressure and volume per unit mass, respectively. Furthermore, g, Z and V are gravitational acceleration, elevation above a reference level and the velocity of a finite element of the liquid fuel, respectively.

Beginning with the first law of thermodynamics for an open system, as the liquid fuel flows from A to B, the rate of energy accumulation per unit mass in this open system is expressed as

$$\frac{de_{total}}{dt} = q_{net.in} + \left(h + \frac{V^2}{2} + gz\right)_A - \left(h + \frac{V^2}{2} + gz\right)_B, \tag{7}$$

where $q_{net.in}$ is the net heat production in the reactor core and draining tube per unit mass and unit time.

For steady flows, the time rate of change of the energy content of the control volume is zero, and the energy equation can be expressed as

$$\left(h + \frac{V^2}{2} + gz\right)_B - \left(h + \frac{V^2}{2} + gz\right)_A = q_{net.in}. \tag{8}$$

Using the definition of enthalpy $h = u + p/\rho$ and by rearranging the terms, the steady-flow energy equation can also be expressed as

$$\frac{P_A}{\rho_A} + \frac{V_A^2}{2} + gz_A = \frac{P_B}{\rho_B} + \frac{V_B^2}{2} + gz_B + \sum\frac{\Delta p}{\rho}, \tag{9}$$

where P/ρ represents the *flow energy*, $V^2/2$ is the *kinetic energy*, and *gz* is the *potential energy* of the liquid fuel, all quantities per unit mass. The last term,

$$\sum \frac{\Delta p}{\rho} = (u_B - u_A - q_{net.in}), \tag{10}$$

represents the mechanical energy loss per unit mass because of friction.

Substituting Eq. (4) and (5) into (9)), with the hypothesis of incompressibility and rearranging terms, the average drain speed of molten salt in reactor core can be expressed

$$\frac{1}{2}\left({R_B}^2 - 1\right)\left[\frac{dh(t)}{dt}\right]^2 - g\,[L + H - h(t)] + \left(\frac{p_B - p_A}{\rho}\right) + \sum \frac{\Delta p}{\rho} = 0, \tag{11}$$

where

$$R_B = \left(\frac{D}{d}\right)^2. \tag{12}$$

Eq. (11) gives the rate of change of the liquid fuel surface level inside the active core with respect to time. Integrating this equation gives the height of the liquid in the reactor core at any time *t*.

3.3. Mechanical Energy Loss

For the flow of a liquid fuel, the total frictional head loss, $\sum \frac{\Delta \boldsymbol{p}}{\boldsymbol{\rho}}$, can be expressed as [7, 8]:

$$\sum \frac{\Delta p}{\rho} = \frac{\Delta p_{core}}{\rho} + \frac{\Delta p_{tube}}{\rho} + \frac{\Delta p_c}{\rho} + \frac{\Delta p_{orif}}{\rho}, \tag{13}$$

where $\frac{\Delta p_c}{\rho}$ and $\frac{\Delta p_{orif}}{\rho}$ are the frictional head loss due to sudden contraction and orifice plate in the draining tube, respectively. On the other hand, $\frac{\Delta p_{core}}{\rho}$ and $\frac{\Delta p_{tube}}{\rho}$ are the frictional head loss due to fluid-core wall and the fluid-tube wall loss respectively.

3.3.1. Pressure loss due to sudden contraction ($\Delta \boldsymbol{p_c}$)

For a sudden contraction at a sharp-edged entrance from core to the draining tube, the entry pressure loss can be approximated via the following equation [9, 10]:

$$\Delta p_c = K_c \cdot \frac{1}{2}\rho U^2 = 0.5 \cdot \left(1 - \frac{d^2}{D^2}\right)\frac{1}{2}\rho V_B^2. \tag{14}$$

3.3.2. Fluid-wall frictional pressure loss ($\boldsymbol{\Delta p_{core}}$ and $\boldsymbol{\Delta p_{tube}}$)

The Fanning equation gives the friction pressure loss for flow in a straight pipe:

$$\Delta p_f = (4C_f) \cdot \frac{L}{D} \cdot \frac{1}{2}\rho V^2 \tag{15}$$

where C_f is the Fanning friction factor. (The Fanning friction factor should not be confused with the Darcy friction factor which is 4 times larger).

According to Morrison [11], there is an empirical data correlation that spans the entire range of Reynolds numbers, from laminar flow, through transitional flow, and reaching the highest values of Reynolds number, till $Re=10^6$,

$$C_f = \frac{16}{Re} + \frac{0.0076\left(\frac{3170}{Re}\right)^{0.165}}{1+\left(\frac{3170}{Re}\right)^{7.0}};\ \ \mathrm{Re} < 10^6. \tag{16}$$

3.3.3. Flow through a sharp-edged orifice (Δp_{orif})

Consider an orifice plate placed in the draining tube as shown in Fig. 2(b) , because of the partial melting of freeze plug, the friction pressure loss for flow can be expressed as

$$\Delta p_{orif} = \frac{\mathbf{1}}{\boldsymbol{C_d^2}} \cdot \frac{1}{2}\rho V^2 \left[\left(\frac{d_{tube}}{d_{orif}}\right)^2 - 1\right], \tag{17}$$

where d_{orif} represents the orifice plate diameter and the typical value for the discharge coefficient is C_d=0.61, [12].

The function resulting by substituting Eq. (13) − (17) into Eq. (11) describe a first-order non-linear ordinary differential equation. The initial condition needed to specify a unique solution is (corresponding to a completely filled active core),

$$h(t = 0) = 0. \quad \wedge \tag{18}$$

There is no analytical solution for Eq. (11). Therefore, the numerical ODE solution method must be employed.

4. CALCULATION RESULTS

In the previous section the detailed physical and mathematical model to analyze the liquid fuel draining time in the core of MSFR has been established. This section will present the results of a series of parametric studies based on the application of the above model. The studies include investigating draining time variations by varying the the draining tube length, the draining tube inner diameter and by the orifice plate effect at different damage degrees of the freeze plug, in order to investigate the significance of magnitude of draining time periods, supporting to give evidence for precise engineering and design studies in the SAMOFAR project.

4.1. A Representative Geometry

As a representative geometry the draining tube length is considered 2 m long and its diameter equal to 0.2m. As already said, the initial surface level of the molten salt H in model is 2250mm, corresponding to the EVOL core height.

Fig. 3 gives the surface level evolution with time, measured from the core top. After about 95s the molten salt is completely evacuated from the core under the above mentioned geometry and conditions.

The draining velocities and Reynolds numbers in reactor core and in draining tube can be seen in Fig. 4 and Fig. 5, respectively. The molten salt surface velocity in core is about 28 mm/s in the initial phase of the drainage, decreasing as the core is emptied up to 19mm/s, when the core is almost empty. In a similar way, the fuel speed in draining tube decreases from ~7.3m/s to ~4.8m/s.

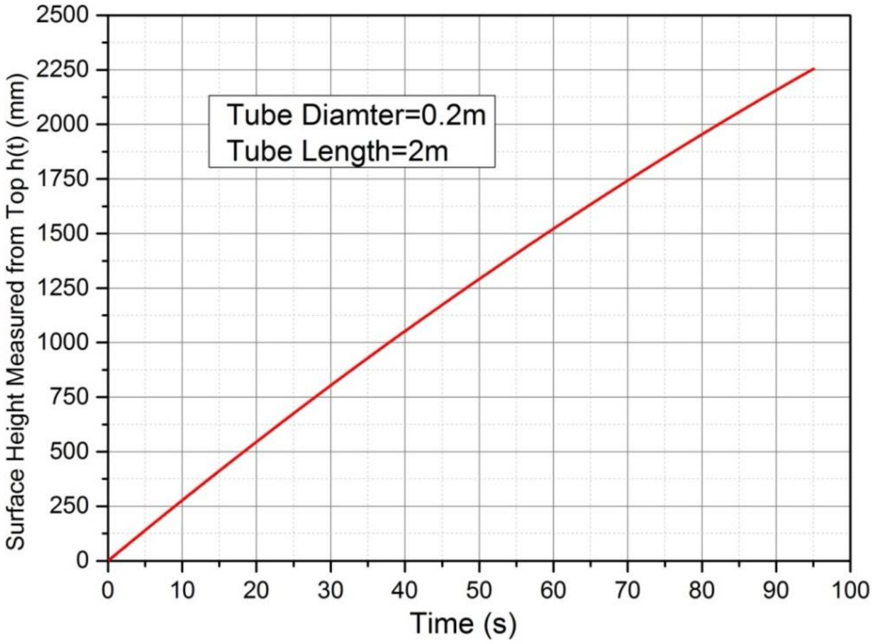
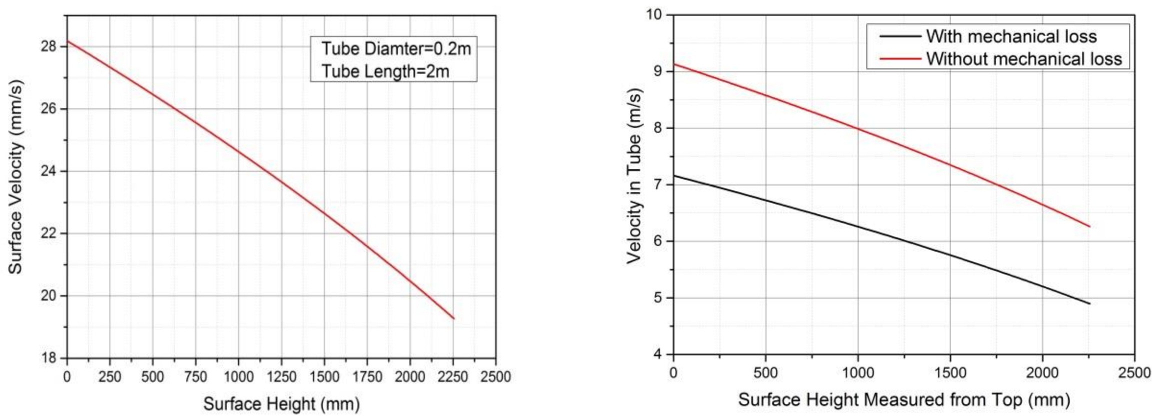


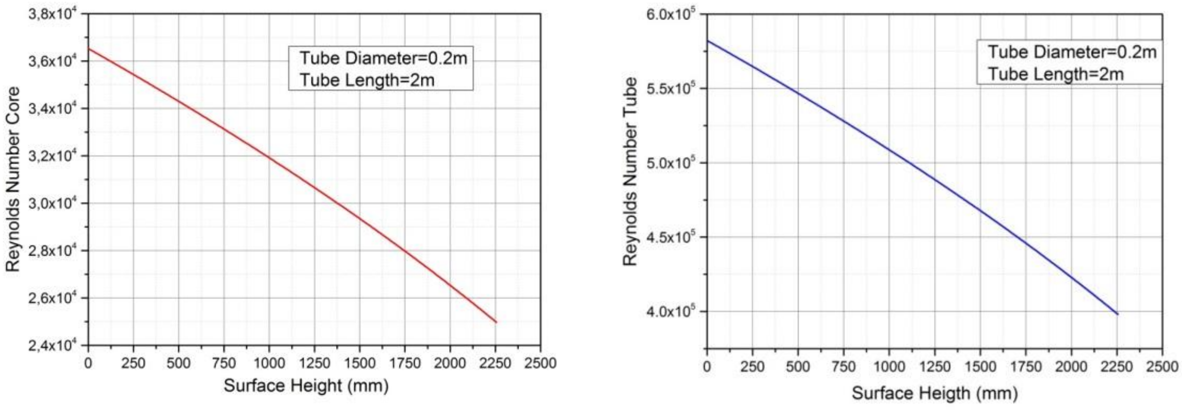
Fig. 3 Surface height change with time, draining tube length and diameter are 2m and 0.2m, respectively



(a) (b)

Fig. 4 Draining velocities in (a) core and (b) draining tube

As Morrison's general Fanning friction correlation (Eq. 16) is applicable only with Reynolds number up to $Re=10^6$, it is important checking if this condition is met in both the core and the draining tube. The Reynolds number in the core follows the same trend of the velocity, decreasing from ~$3.65x10^4$ at the start of the draining to ~$2.5x10^4$, when the salt reaches to the core bottom. Similarly, in the draining tube the Reynolds number passes from ~$5.8x10^5$ to ~$2.5x10^4$, at the start and at the end of the draining respectively. Hence, the Reynolds number always lies in the applicability range of Morrison's correlation, which is fully applicable.



(a) (b)

Fig. 5 Draining Reynolds numbers in (a) core and (b) draining tube

In order to illustrate the influence of the mechanical loss on the draining behavior, in Fig.4 (b) a comparison of the draining velocity in the tube is given for both the case with mechanical loss and the one without it. It can be recognized that the draining velocity was decreased by 25-30% because of the mechanical loss compared with the inviscid flow.

4.2. Variation of the Draining Tube Diameter

The impact of a draining tube diameter variation on the discharge time is given in Fig. 6. In this study the tube length, L, is fixed to 2.0m.

As it can be expected, as the draining tube diameter decrease, the needed draining time increases, It is interesting observing that, if the diameter is reduced to a value smaller than d=0.1m, the draining time increases dramatically, while the impact of the draining tube diameter on the discharge time becomes weaker if the diameter becomes greater than d=0.2m,. Thus the benefit of an increasing diameter for the discharge time becomes less important.

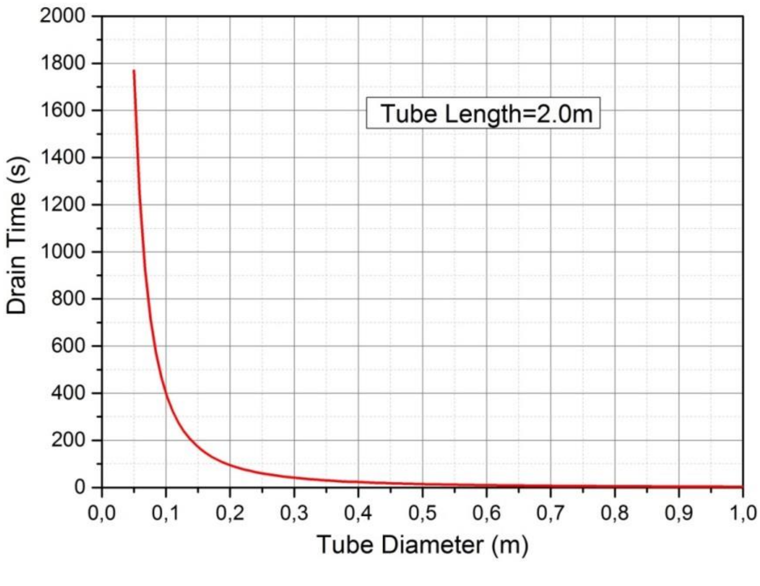


Fig. 6 Impact of the draining tube diameter variation on the discharge time

4.3. Variation of the Draining Tube Length

Fig. 7 demonstrates the effect of the draining tube length variation on the discharge time. The tube diameter, d, is held constant as 0.2m.

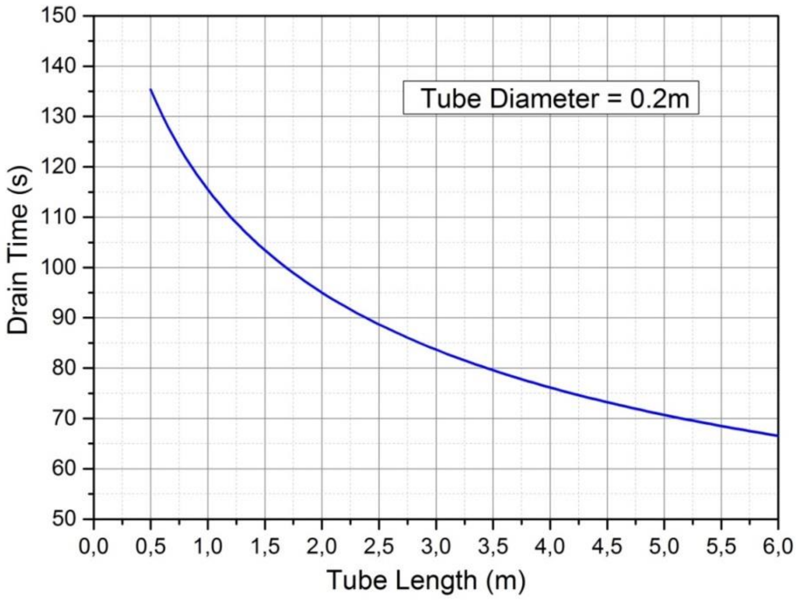


Fig. 7 Effect of the draining tube length on the discharge time

It follows from the results shown in Fig. 4 and 5, and it can be seen from Fig. 7 that, although the wall friction increases with increasing of the tube length, the draining time decreases. This is a direct consequence of Eq. 11, where the tube length appears both in the gravitational term and in the mechanical loss one (through Eq. 15). The gravitational term grows as the tube length increases, providing in this way more energy and so a higher speed to the fluid. This effect is counterbalanced by the friction, which not only is proportional to the length of the tube, but also depends in a quadratic manner on the velocity. This means that when the tube length is short the draining speed grows quickly, but the speed growth slows down as longer tubes are used.

4.4. Partially Melted Freeze Plug

As already mentioned before, the freeze plug should be actively cooled to keep it at a temperature below the freezing point of the salt. In case of a planned reactor shut down or in emergency situations or in case of accidents leading to an excessive increase of the temperature, if the fuel salt overheats and its temperature rises beyond a threshold point, the freeze plug melts and the liquid fuel in the core starts immediately to be evacuated. However, if the plug is only partially melted, the remaining plug will form an orifice plate placed in the draining tube flow which will causes an extra mechanical energy loss (see Fig. 2(b)). Fig. 8 exhibits this effect of the freeze plug diameter variation on the draining times. This effect can also be deduced from Eq. (17) showing that the mechanical energy loss is proportional to the square of the diameter ratio of d_{tube}/d_{orif}.

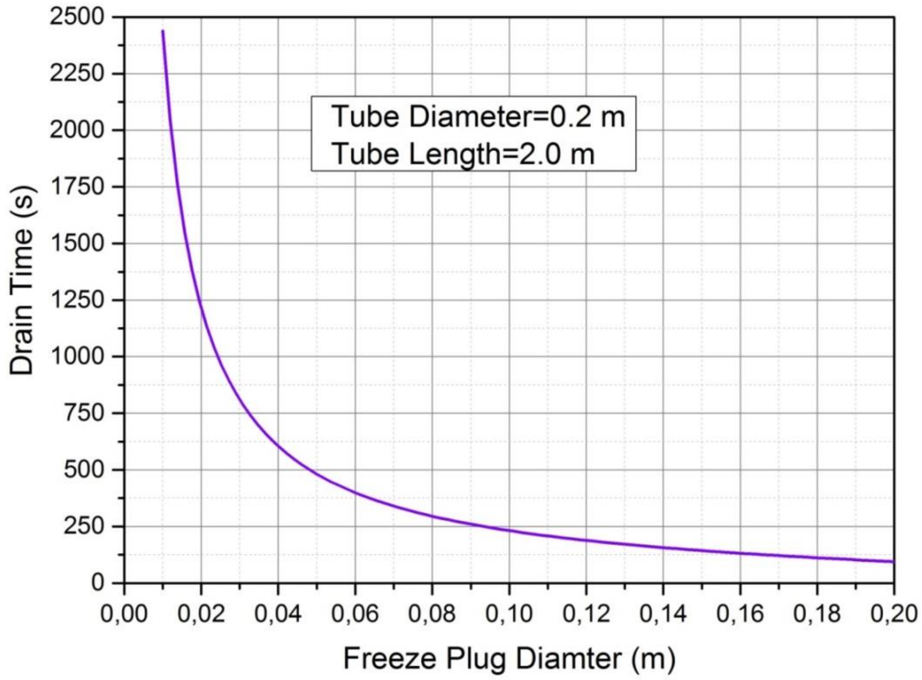


Fig. 8 Orifice plate effect of the partially melted freeze plug on draining time

5. CONCLUSIONS

In this study it has been shown that the draining time of MSFR into the draining tank located underneath the reactor is strongly affected by the draining tube diameter, the draining tube length and the melting degree of the freeze plug.

The important findings of this study can be summarized as follows:

1. In the computation it is assumed that the core and sub-critical storage facility are connected each other, and so have the same pressure $p_A = p_B$, Anyhow, a favorite & beneficial layout for drainage of the fuel salt out of the core is $p_A \geq p_B$.

2. If the draining tube length and diameter are 2m and 0.2m, respectively, a total 18m^3 liquid fuel can be drained out from the core in about 95s. It is further shown that the magnitude of the draining velocity decreases by 25-30% due to the mechanical loss compared to an inviscid flow.

3. Calculations performed with a fixed draining tube length of 2 m show that the draining time does not change appreciably if the draining tube diameter grows over 0.2 m.

4. Keeping fixed the draining tube diameter to 0.2 m, by increasing the draining tube length, though the wall friction should be proportional to the tube length, the draining time decreases due to the effect of the gravitational term of the energy conservation equation. The gravitational effect dominates the friction one for short tube lengths, while the friction term becomes more important for longer tubes**.**

5. If the freeze plug is only partially melted, the formed orifice plate impact on the draining time is strong. In fact, the friction pressure loss is quadratic proportional to the diameter ratio of d_{tube}/d_{orif}, (through Eq. 17).

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