Effect of Internal Heat Generation on Solidification of Molten Fuel Droplet during its Interaction with Coolant in a Nuclear Reactor

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Abstract. One of the important issues in safety analysis of severe accidents in fast reactors is Molten Fuel Coolant Interaction (MFCI). MFCI is the phenomenon in which fragmentation of the molten fuel takes place when it comes in direct contact with liquid sodium coolant. For complete understanding of MFCI, we need to study the solidification of the molten fuel happening along with fragmentation. Solidification / melting of any material initially held at its melting temperature is the classic Stefan’s problem. In the case of a severe reactor accident the molten fuel might have a significant amount of decay heat, even though nuclear fission reactions have been stopped by reactor shut down systems. The presence of decay heat in this case, makes the transient Stefan problem more difficult to solve analytically. Here, an investigation of this special case of Stefan’s problem with internal heat generation in nuclear materials has been carried out considering a typical droplet size of 4 mm diameter. The numerical heat transfer analysis has been carried out using the commercial software Fluent. The validation of the problem is done with the steady state analytical solution available for the position of phase change front. Parametric studies have been carried out by varying internal heat generation rates and convective heat transfer coefficient at the surface of the droplet. Temperature profiles and liquid fraction are obtained at different instants. Solidification time and final equilibrium temperature are estimated from the results. It is observed that there is significant increase in drop solidification time for heat generation rates (HG) greater than 100 MW/m³ for the drop size of 4 mm. The maximum HG which is tolerated by the droplet without reaching its boiling point is about 6 GW/m³ when the heat transfer coefficient from its surface is fixed at $h=56000\text{W/m}^2\text{K}$.

1. Introduction

A nuclear core meltdown is the worst case of accident that can happen in a nuclear power plant. Such an accident is categorised under design extension condition in reactor safety analysis, where its consequences have to be minimised and in-vessel retention of the core debris has to be ensured [1]. Two diverse, fast acting and independent Shutdown Systems (SDS) and several engineered safeguards...
such as core catcher serve to accomplish this purpose. Severe core meltdown accident may happen either in a case of transient over power or in a loss of coolant flow when SDS in the nuclear reactor fail to operate when there is a SCRAM signal. The molten corium melts through the grid plate and then it interacts with the coolant sodium. This interaction of the molten fuel with the colder coolant results in quenching, fragmentation of the fuel and sudden expansion of the coolant and may cause mechanical work on the mechanical structures. Therefore the study of the MFCI (Molten Fuel Coolant Interaction) plays a vital role in the post accident heat removal process. The study of fragmentation of the molten fuel is known to be a complex phenomenon because of the presence of thermal as well as hydrodynamic effects taking place at the same time. The solidification of decay power heated molten fuel, cooled by liquid sodium is analyzed in this present paper. Here a spherical molten UO$_2$ droplet is considered and heat transfer to surrounding sodium is accounted by defining heat transfer coefficient. The classic solidification or melting problem of the sphere at its melting temperature is known as Stefan’s problem. But the nuclear fuel in our case is a self heat generating material and it has a significant amount of decay heat in it. So, the present problem deals with the Stefan’s solidification problem including heat generation.

A large amount of literature can be found regarding the solution to the Stefan’s problem but a very few literature were found which deals with the Stefan’s problem with heat generation. Dhir et al. [2] were the first to present the solution for the Stefan’s problem with heat generation. They considered dimensionless form of 1D transient heat conduction equation. Depending on the volumetric heat generation and surface heat removal rate, the initially molten material might solidify, remain liquid, or re-melt after solidifying or may reach the partially molten steady state. Chan and Hsu [3] also presented a detailed investigation of melting and solidification with the heat generation. They studied the characteristics of the mushy zone in which liquid and solid phases co-exist. Generally this mushy zone is present in the case of simple melting and solidification also but with the introduction of the internal heat generation this zone is enhanced. They developed generalized phase change models for studying the characteristics and role of this mushy zone in the phase change. Crepeau and Siahpush [4] used the quasi-static approach to find the solution to the Stefan’s problem with heat generation for Stefan number less than one. A quasi-analytical solution was developed for cylinder, sphere and semi infinite plane wall for constant surface temperature and the constant heat flux. The results showed that the solidification thickness for the plane wall is proportional to the inverse square root of the internal heat generation. In another work, Crepeau and Siahpush [5] compared the results of the numerical solution of solidification of the cylindrical body with that of the quasi analytical solution. They were found to be in good agreement for the Stefan number less than one. Chen et al. [6] provided a conduction model that can provide average temperature histories of the fuel and cladding. The fuel pin and the cladding are assumed to be undergoing phase change with the internal heat generation. The time required for the melting of the fuel pin can also be obtained from the model.

This area of research involving Stefan’s problem with heat generation is particularly important not only in the nuclear industry but also in study of heat transfer in the biological systems, material processing and geophysical modelling. Here Stefan’s problem with heat generation is analyzed in context of MFCI happening in the fast reactor. Further a parametric study is done by varying the heat generation and heat transfer coefficient to see its effect on the solidification time.

2. Problem Formulation

The transient heat conduction equation for the spherical co-ordinates with heat generation is given by

$$\frac{1}{r} \frac{\partial}{\partial r} \left( kr \frac{\partial T}{\partial r} \right) + \frac{1}{r^2} \frac{\partial}{\partial \theta} \left( k \frac{\partial T}{\partial \theta} \right) + \frac{\partial}{\partial z} \left( k \frac{\partial T}{\partial z} \right) + \dot{q} = \rho C_p \frac{\partial T}{\partial t}$$  \hspace{1cm} (1)

Considering changes in temperature along the radial direction only, the equation can be rewritten as

$$\frac{1}{r} \frac{\partial}{\partial r} \left( kr \frac{\partial T}{\partial r} \right) + \dot{q} = \rho C_p \frac{\partial T}{\partial t}$$  \hspace{1cm} (2)
Here the numerical simulation is carried out in the commercial CFD software Ansys Fluent with axisymmetric geometry. Convective heat transfer boundary condition is applied at the spherical surface and constant heat generation source term is applied to the interior of the molten fluid.

Following are the conditions applied for the case study

Initial Condition

\[ T_i = 3100 \text{ K for } 0 < r < a \text{ at } t = 0 \]

\[ \dot{Q} = 1 \text{ MW/m}^3 - 5 \text{ GW/m}^3 \text{ (Constant Heat Generation)} \]

Boundary Conditions

\[
\frac{k}{r} \frac{\partial T}{\partial r} = h(T - T_c)
\]

\[ T_c = 673 \text{ K} \]

Following assumptions are made in the simulation

- The molten fuel is assumed to be the pure and the phase is clearly defined for the material.
- Internal heat generation rate remains constant with time. This assumption yields conservative results since the decay heat is a function of initial reactor power and time and decreases drastically with time.
- Thermo-physical properties of the molten fuel are assumed to be the same in solid and liquid phase neglecting the variation of about 10%.
- The geometrical integrity of the molten fuel remains same while freezing and after freezing.

Since the initial temperature of the molten droplet is very high and the heat is continuously generated internally, convection in the surrounding liquid coolant can take place in film boiling regime, nucleate boiling or natural convective regime depending on the surface temperature of the droplet. Defining time and temperature dependent heat transfer coefficient will make computation more complex, hence \( h \) has been varied as a parameter encompassing all the convective regimes of the coolant. The heat transfer coefficient of the above mentioned regimes for sodium is obtained from the work of Deane et al. [7]. The present computational model has been validated from the analytical model proposed by the Dhir et al. [2] and is explained in the next section.

2.1 Validation

Dhir et al. [2] addressed the issue of solidification of a sphere with internal heat generation and convective cooling at the surface. In this paper they provided the analytical solution for non-dimensional radius of solid liquid interface by solving the energy equation for solid and liquid sections separately. The accuracy of the numerical simulation is compared with the literature values [2] when the solidification has reached a steady state. The analytical solution for position of the phase front at the steady state for the spherical droplet during phase change with heat generation is given by

\[
\frac{r_1^2}{r} = 1 \pm \frac{2}{Bi} \frac{6 k_s}{Q_k L}
\]

\[
\dot{Q} = \frac{\dot{q} r^2}{k_d T}
\]

Where

- \( r_1 \) = Non dimensionalized radius at the solid liquid interface
- \( Bi \) = Biot Number
- \( k_s \) = Thermal conductivity of the solid of the metal
- \( k_l \) = Thermal conductivity of the liquid phase of the metal
- \( \dot{Q} \) = Non Dimensional form of heat generation
- \( r \) = radius of the molten spherical droplet
For the validation purpose, the Stefan number is kept as 4.39. Here heat generation is kept constant at $Q=10$.

The accuracy of the numerical model in the present work is compared with the literature values [3] and the agreement between the two is very good as can be seen from Table 1.

| Biot Number | Final steady state liquid fraction | Error % |
|-------------|-----------------------------------|---------|
|             | Analytical                        | Numerical |
| 3           | 1                                 | 1        | 0        |
| 4           | 0.9145                            | 0.9361   | 2.36     |
| 5           | 0.9025                            | 0.8803   | 2.46     |

3. Results and Discussion

After validation of the present computational model, parametric studies were carried out for the spherical droplet of 4mm diameter by varying heat transfer coefficient and heat generation rate and observing the changes in the solidification time. In MFCI, though the debris size may vary from a few microns to a few millimetres, a typical size of 4mm is adopted for the present study. The heat generation rate is varied from 1 MW/m$^3$ to an upper bound value where the droplet centre temperature doesn’t exceed the boiling point (3600 K). In a medium sized fast reactor, decay power levels can initially be in the order of GW/m$^3$ for about a few milliseconds in the disassembly phase of the accident but comes down to about 100 MW/m$^3$ soon after disassembly of the core.

Figure 1 shows the contours plots of the spherical droplet solidifying in the liquid sodium pool. The internal heat generation rate and the convective heat transfer coefficient are 5000 MW/m$^3$ and 5000 W/m$^2$k respectively.

Figure 1. Temperature contours of spherical droplet for HG = 5000 MW/m$^3$ and h=5000 W/m$^2$k.
The melting temperature of UO$_2$ is 3100 K which is the initial temperature of the molten droplet. Since there is internal heat generation occurring in the droplet we can see from the contour that the temperature at the centre of the droplet rises past the initial temperature but in the later stages the temperature in the centre of the droplet starts falling because of the convective heat transfer taking place on the surface of the spherical droplet and solidification of the droplet takes place. And finally the liquid droplet reaches a steady state temperature with the surrounding which is seen from the temperature contours with time stamps $t=5$ s and $t=10$ s.

The contour plots of the liquid fraction for the molten droplet for the same case are shown in the Figure 2. In the figure it is seen that solidification progresses from the surface to the centre. The red colour region in the contour signifies the liquid while the blue region signifies the solidified portion of the droplet. Therefore from the figure it is observed that the droplet is entirely solidified by 2.5 s.

![Liquid fraction contour of droplet for HG=5000 MW/m$^3$ and h=5000 W/m$^2$k.](image)

**Figure 2.** Liquid fraction contour of droplet for HG=5000 MW/m$^3$ and h=5000 W/m$^2$k.

Time history plot for the solidification of the molten droplet for different heat generation rate and convective heat transfer coefficient of 5000 W/m$^2$k corresponding to natural convection is shown in Figure 3. From the graph the general trend that can be inferred is, by increasing the heat generation rate, the time required to solidify the droplet will also increase. Further it is found that there is no significant change in the solidification time for the heat generation rates upto 100 MW/m$^3$ and the solidification fronts overlap on one another upto this value.

The temperature history at the centre of the spherical droplet is given in Figure 4. From the graph it can be seen that the droplet central temperature first rises above the initial temperature, it can be reasoned that the hump created in the plot is due to the internal heat generation rate. Higher the heat generation rate higher will be the maximum droplet centre temperature. As it is seen from the previous graph, it can also be inferred from this graph that there is no significant temperature rise above the melting point for heat generation upto 100 MW/m$^3$.

In Figure 5 the solidification time is plotted against heat generation rate for the different cases of varying heat transfer coefficient ($h$). It is seen that beyond 100 MW/m$^3$, the solidification time increases gradually first, then shows a sharp rise. Therefore it can be inferred that convective heat transfer from the surface of the droplet controls the solidification up to 100 MW/m$^2$, beyond that internal heat generation rate influence the solidification time greatly.
Figure 3. Time history plot of liquid fraction for h=5000 W/m²k for various heat generation rate.

Figure 4. Temperature history at the centre of droplet for various heat generation rates.

Table 2 gives the solidification time and temperatures observed in the centre and surface of molten spherical droplet with 1 GW/m³ internal heat generation rate for various heat transfer coefficient (h). The minimum value of h chosen corresponds to film boiling regime while the maximum value corresponds to nucleate boiling regime of the coolant sodium.

It is observed that droplet centre temperature and surface temperature go on decreasing with the increase in the heat transfer coefficient. It is interesting to note that the temperature difference between the final steady state centre temperature and surface temperature remains same independent of the heat transfer rate.
4. Conclusion
In the present work, the changes in solidification characteristics of molten uranium oxide droplet, when subjected to varying heat transfer coefficient and internal heat generation rate are analyzed. From the numerical heat transfer study, it is concluded that there is very small or insignificant change in the solidification time, internal temperature and surface temperature when heat generation rate is raised up to 100 MW/m$^3$ for a typical droplet diameter of 4 mm. It is observed that the solidification is governed by the external cooling condition at the surface defined by heat transfer coefficient rather than the internal heat generation up to this point. The maximum heat generation rate that can be sustained by liquid droplet without onset of boiling within the drop is found to be 6 GW/m$^3$ when heat transfer from its surface is 56000 W/m$^2$K. Normally, in a medium sized fast reactor, decay heat levels
envisaged are much less than 100 MW/m$^3$. Decay heat decreases with time whereas constant levels are assumed in the present study, making the results conservative. Hence there is no chance of fuel vaporising within the fuel droplet due to decay heat. Moreover, complete solidification of the droplet is possible, irrespective of the boiling regime of coolant. Even with film boiling happening in the coolant, the droplet freezes fully within a few seconds bringing the fuel coolant thermal interaction and further secondary fragmentation to a halt. Depending on the cooling rate from the droplet surface, the time for complete solidification ranges from 1 s to 10 s.

5. References
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