An effective conductivity model for jet ablation of a solid substrate

Tejaswi V Pawar¹, A J Sudha²*, D Ponraju², B K Nashine² and P Selvaraj²

¹ M.Tech Scholar, Dept. of Mechanical & Manufacturing Enng., Manipal Institute of Technology, MAHE, Manipal, KA 576104, India
² Safety Engineering Division, FRTG, IGCAR, Kalpakkam, Tamilnadu 603102, India

*Corresponding author: jasmin@igcar.gov.in

Abstract. Jet impingement heat transfer is a specialized area of heat transfer having numerous industrial applications involving fast and localized heating or cooling. In the very rare case of a nuclear reactor core melt-down accident scenario, the molten corium (a mixture of nuclear fuel and structural material) jet with its large heat content is capable of breaching solid structures with which they come into contact. Simulation experiments have been conducted at SED, IGCAR to study the jet ablation of solid structures, using high temperature Wood’s metal jet directed towards solid wood’s metal plate. The objective of the present work is to predict the ablation or melt through time of the plate by numerical heat transfer analysis. The computational model is also used to carry out a parametric study by varying the jet velocity and plate thickness. Comprehensive CFD analysis of impinging jet with melting entails huge computational resources. Hence in this study, an effective conductivity model has been employed to predict the solid plate melt-through time by jet impingement. Available Nusselt number empirical correlations for stagnation point heat transfer in low Prandtl number fluids are collected from literature. For the experimental conditions, Nusselt number is evaluated using the relevant correlation. Effective conductivity ($k_{eff}$) is then computed from Nusselt number. Making use of this $k_{eff}$ value, which accounts for the enhanced heat transfer due to the jet, transient heat conduction equation is solved numerically. Temperature profile across the plate is obtained as a function of time and melt-through time is estimated. The computed result is validated with the experimental result.

1. Introduction

Jet impingement is a special topic in heat transfer. As we know, jet impingement is an efficient heat transfer process due to its high heat transfer rates. In a jet impingement process, a jet of liquid or gas is directed from a nozzle (having its own configuration) towards a surface (target) which is to be cooled or heated. It has been a platform for many investigations today and will also be an area of keen interest in the future. It has many valuable industrial applications [1]. Jet impingement carries its own significance and practicality hence, the volume of contributions in this area is quite huge. Right from understanding its physics, correlations, experiments to numerical modeling, it has been explored widely [2]. But, when it
comes to jet impingement analysis of liquid metals having Prandtl number Pr < 1, not much work has been done except for a few papers related to nuclear reactor safety [3, 4]. In the past, numerical modeling of a jet impinging on a surface is done by varying important parameters such as Reynolds number, distance between the nozzle to the plate and the results obtained were compared with different turbulent flow models [5]. Nusselt number correlations have been found through numerical study and improvised flow models are suggested to study jet impingement [6, 7]. Through literature survey an overview on the subject is achieved which will help in the analysis of the present problem.

A Prototype Fast Breeder Reactor (PFBR) is a 500 MWe fast breeder nuclear reactor which is nearing completion of construction at Kalpakkam, designed by Indira Gandhi Centre for Atomic Research (IGCAR). This PFBR uses uranium 238 to breed new fissile materials in a sodium cooled fast breeder reactor design. It will burn a mixed uranium-plutonium mixed oxide fuel (MOX fuel). PFBR has been designed with two diverse, reliable and fast acting shut down systems which can bring the chain fission reaction to a halt and shut down the reactor, whenever there is a mismatch between heat generation and heat removal. Therefore, these reactors are very safe and are so reliable that the probability of a severe accident to happen is less than 10^{-6}/reactor year. During the rare occurrence of such an accident, the molten fuel breaches the clad and flows out of the subassembly as a jet and can cause local breaches on the grid plate. After getting quenched in liquid sodium, the core debris settles down permanently on the core catcher plate where it is cooled by liquid sodium pool. At SED (Safety Engineering Division) of IGCAR, simulation experiments are being carried out with wood’s metal jet directed to impinge on solid wood’s metal plate [8]. After breaching the plate, the jet is quenched and fragmented in the bulk water contained in the test vessel and gets collected on the collector plate. It is proposed to develop a computational model to predict the breaching of the plate by the hot molten jet. After validating the results with the experimental data, the model can be used to carry out parametric study by varying jet velocity and plate thickness. A schematic representation of breaching of the solid wood’s metal plate due to the molten wood’s metal jet impinging on its surface is shown in Figure 1.

Figure 1. Schematic of impinging hot jet on a solid plate

2. Problem definition and methodology

Conjugate heat transfer modeling of the convective heat transfer in the jet combined with conduction heat transfer in the plate will require quite a lot of computational time and resources. Moreover, carrying out a parametric study by varying the influencing parameters will be a time consuming task. The objective of the present study is to arrive at the plate ablation time and we are not keen to look into the flow
structure of the jet. Hence a good alternative is to use the effective conductivity method which simplifies the problem to a great extent.

In the present case, heat conduction in the solid plate is solved and the heat transferred from the jet to the plate is handled by defining a heat transfer coefficient from relevant Nusselt number correlation. This heat transfer coefficient is then converted to equivalent/effective conductivity. Two dimensional axisymmetric geometry of the plate is considered where the molten jet is impinging at the central region of the plate covering a radius of 30mm (nozzle diameter 60mm) and is prescribed a temperature of 623K which is the temperature of the molten wood’s metal jet and the other portions are considered to be adiabatic. Width of the solid plate (W) in the computation is limited to 60mm and thickness (t) is varied from 6mm to 8mm. In this study, the initial conditions and jet velocity have been taken from the experimental data [8]. The geometry of the wood’s metal plate is shown in Figure 2.

![Figure 2. Axisymmetric geometry of flat plate](image)

Transient heat conduction equation with appropriate initial and boundary conditions is solved to get the temperature evolution with time in the radial and axial directions across the plate.

\[
\rho C_p \frac{\partial T}{\partial t} = k_{eff} \left[ \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial T}{\partial r} \right) + \frac{\partial^2 T}{\partial z^2} \right]
\]

Effective conductivity \( (k_{eff}) \) is obtained from,

\[
k_{eff} = k_{fluid} [1 + Nu]
\]

Where, \( k_{fluid} \) is the actual thermal conductivity of the molten wood’s metal jet. \( k_{eff} \) is calculated from Nusselt number correlation. Generally, in jet impingement heat transfer Nusselt number is expressed as a function of Reynolds’s number (Re) and Prandtl number (Pr). Nusselt number empirical correlation obtained from Sato et al [3] for stagnation region where the jet hits the plate, has been used to determine the values of effective conductivity \( (k_{eff}) \).

\[
Nu = 0.152 Re^{0.92} Pr^{-0.8}
\]

From the effective conductivity \( (k_{eff}) \) values obtained through equation (2), problem is solved through numerical simulation. Temperature contours are obtained and melt through time is estimated.

3. Results and discussion

Thermo-physical properties of wood’s metal are assigned to the plate. The initial temperature of the jet is fixed at 623 K which is given as a constant temperature boundary on the central portion of the top surface of the plate. The rest of the plate is initially at room temperature and its surfaces are assumed to be adiabatic with no heat transfer to the surrounding air. This is justified since the simulation is a fast
transient happening in the time scale of a fraction of a second. The simulation is carried out using the commercial CFD code Fluent.

3.1 Grid sensitivity study

Grid sensitivity study has been carried out to get consistent result where the output changes only marginally with further refinement of the grid. The outcome of grid sensitivity study is given in Table 1 and Figure 3. The chosen node size is 0.5 mm based on this exercise.

| Plate thickness (mm) | Velocity (ms⁻¹) | Number of nodes | Melt through time (s) |
|----------------------|-----------------|-----------------|-----------------------|
| 7                    | 0.371           | 7               | 0.394                 |
| 7                    | 0.371           | 14              | 0.461                 |
| 7                    | 0.371           | 28              | 0.485                 |

**Figure 3.** Grid sensitivity study for 7 mm thick plate

3.2 Validation of computational model
For a 7mm thick plate, at velocity of the jet 0.371 m/s, experimentally obtained melt through time was 0.264 s. For the same initial conditions, numerical simulation of the problem was carried out. The temperature contours obtained at different instants of time is given in Table 2. The melt through or ablation time estimated at the bottom surface of the plate is 0.461 s when its temperature just touches melting point of wood’s metal. The computed melt through time is compared with this experimental value. The agreement between the results is only satisfactory, matching in order of magnitude. The discrepancy is attributed to the fact that the correlation used in the study for $k_{eff}$ is taken from literature and any empirical correlation generally has an uncertainty band of ±20%.

| Time (s) | Temperature Contours | Temperature scale (K) |
|---------|----------------------|-----------------------|
| 0.1     | ![Image](image1.png)  | 623 607 591 575 558 542 526 510 494 478 462 445 429 413 397 381 365 348 332 316 300 |
| 0.2     | ![Image](image2.png)  |                      |
| 0.3     | ![Image](image3.png)  |                      |
| 0.4     | ![Image](image4.png)  |                      |
| 0.46    | ![Image](image5.png)  |                      |

Table 2. Temperature contours for 7mm plate thickness

Therefore, it becomes necessary to fine tune the model to our experimental conditions. Guillaume et al. [9] in their work have indicated an approach to overcome this limitation by introducing a constant $\eta$ in the definition of effective conductivity. $\eta$ is a constant of order one, which is introduced to get better accuracy of results with the effective conductivity model. Therefore, the same approach has been implemented in the present study too. $\eta$ is assigned values in small increments, starting from an initial value of 1.

$$k_{eff} = k_{fluid}[1 + (\eta * Nu)]$$

Melt through time of the solid wood’s metal plate estimated with the new $k_{eff}$ values obtained through equation (4) by incrementing $\eta$ values are shown in Figure 4.

The result obtained with $\eta=1.7$ matches exactly with the experimental data thus validating the computational model. Now, the effective conductivity model can be used to predict the jet ablation of solid target plates quite accurately
3.3. Parametric study

After optimizing the grid and further validating the model with the introduction of proper $\eta$, simulations are carried out by varying the thickness of the plate and the velocity of the impinging jet.

- Thickness of plate is varied from 6mm to 8mm.
- Velocity of the jet: 0.21 m/s, 0.33 m/s and 0.371 m/s.

The important calculated parameters such as Nusselt number, effective conductivity and the main result which is the melt through time are consolidated in Table 3.

Table 3. Estimates of effective conductivity and melt through time

| Plate thickness (mm) | Reynolds number | Nusselt number $Nu = 0.0152Re^{0.92}Pr^{0.8}$ | Effective $k$ (W/mK) | Melt through time (s) |
|----------------------|-----------------|---------------------------------------------|----------------------|-----------------------|
| 6                    | 7938            | 1.84                                        | 78.59                | 0.312                 |
| 6                    | 12474           | 2.79                                        | 109.32               | 0.224                 |
| 6                    | 14023           | 3.11                                        | 119.60               | 0.205                 |
| 7                    | 9261            | 2.12                                        | 87.68                | 0.377                 |
| 7                    | 14553           | 3.22                                        | 123.09               | 0.268                 |
| 7                    | 16361           | 3.58                                        | 134.93               | 0.260                 |
| 8                    | 10584           | 2.40                                        | 96.65                | 0.449                 |
| 8                    | 16632           | 3.64                                        | 136.69               | 0.315                 |
| 8                    | 18698           | 4.05                                        | 150.08               | 0.288                 |
The melt through is said to occur when the temperature of the bottom surface of the plate reaches the melting point temperature (345K) of the solid wood’s metal substrate. Temperature contours at different time instants obtained for a plate thickness of 7 mm and jet velocity 0.371 m/s are given in Table 4.

**Table 4. Temperature contours for 7mm plate thickness (η=1.7)**

| Time (s) | Temperature Contours | Temperature scale (K) |
|----------|-----------------------|-----------------------|
| 0.05     |                       | 623 607 591 575 558 542 526 510 494 478 462 445 429 413 397 381 365 348 332 316 300 |
| 0.1      |                       |                       |
| 0.15     |                       |                       |
| 0.2      |                       |                       |
| 0.26     |                       |                       |

For a particular jet velocity and different plate thickness, temperature evolution at the bottom of the plate is shown in Figure 5.

**Figure 5. Melt through time for 6mm, 7mm and 8mm plate thickness**
From the results it is seen that:

- Higher jet velocity leads to high Re and hence higher $k_{eff}$.
- As the plate thickness increases, melt through time increases.
- For a given plate thickness, the melt through time decreases with increase in jet velocity.

4. Conclusion

An effective conductivity model has been proposed and adopted for numerical heat transfer analysis of the problem wherein a hot molten jet impinging on a solid plate breaches it by melting. The obtained results are compared with the results of reactor accident simulation experiments carried out at SED, IGCAR with molten wood’s metal jet directed to impinge on a solid wood’s metal plate. The main objective is to estimate the melt through time of the wood’s metal solid substrate due to molten wood’s metal jet impinging on it. Nusselt number was calculated from the empirical correlation of Sato et al for estimation of effective conductivity. The melt through time was estimated through numerical solution of transient heat conduction equation. Effective conductivity model saves a lot of computational time and resources and offers quick order of magnitude results. However, as suggested by Guillaumi et al, there was a need for introducing another constant $\eta$ (of order one) to fine-tune $k_{eff}$ values which would give better prediction of the result. The computational model is validated with the experimental result with $\eta = 1.7$. Parametric study has been carried out for different jet velocities and plate thickness. This study has brought out the simplicity and usefulness of the effective conductivity model which is able to predict substrate ablation by molten hot liquid jet impingement without resorting to a full-fledged CFD model.

5. References

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