Introduction

One of the most important advantages of having a mathematical model of a process is that one can experiment with the model rather than the process. Invariably the experiments with the model are best done on a computer. The power of modern computers allows extensive simulations with even very complex models to be done quickly once the model has been programmed. Computer models can often be used to indicate what additional data would be beneficial for refining an existing model to make it more realistic and more useful.

We see the dark clouds, which we equate with imminent rain; we calculate that we can cross the road before the oncoming car reaches us; we choose the fastest moving queue in the supermarket. We don’t normally formulate equations for these models and often it wouldn’t be useful to anyway. However, there are many processes for which it is very worthwhile to develop explicit mathematical models. Such models are most often used in scientific research to understand how processes work. If there is a process involved, then it can be modeled; if there are significant benefits associated with the process then a key question for the process is how can the process be made more efficient. It may be that the best way to answer that question is to model the process and experiment with the model.

An attempt was made to arrive at mathematical solution to some of the complicated processes and phenomenon that were not fully comprehended. The paper gives highlights of the findings and how mathematical modeling helped in understanding the process more clearly.

Theory of flow pattern prediction in perforated tubes

Perforated tubes are widely used in nuclear industries for many critical process and regulatory purpose. In pressurized heavy water reactors (PHWRs), perforated tubes are used in moderator system, in shutdown system for poison injection and in reactivity mechanism for housing the safety bank inside the core. In the moderator system and in poison injection loop the flow of fluid through perforated tubes match the requirement of the system. The design of perforated tube involves arriving at the size of the holes, its spacing along the length and in the circumference. For PHWRs, the design was achieved by rigorous experimentation.

Through computational methods by solving 3-D Navier Stokes equations, outflow pattern can be predicted for given perforated tube. But, if some flow pattern is needed and perforated tube is to be designed to meet the requirement, CFD method cannot be directly used. CFD methods can predict flow when geometry is known, but cannot easily configure the geometry for a given flow.

So it becomes important to develop theories to study outflow pattern and predict perforations (hole size and pitch variations with length) needed for the desired flow pattern. The model offers an analytical method
required in arriving at the design of perforated tubes that can meet the end objective.

Flow pattern in perforated tubes is modeled by mass and momentum balance. It leads to a nonlinear differential equation whose general solution is obtained. Flow pattern is predicted by this solution. Variation of discharge velocity with length, for tube with uniform hole with equal pitch is shown in Fig. 2. It shows that more water flows out from the holes at the closed end and less flows out from holes at the entry of the tube.

These results were compared with simulated experiments and a close match was observed. Furthermore, hole size distribution along the length for desired flow profile was also estimated by proposed theory.

The Study of water ingression phenomena in melt pool cool ability

During a postulated severe accident, the nuclear reactor core can melt and the melt can lead to failure of the reactor vessel. Subsequently, the molten corium can be relocated in the containment cavity, forming a melt pool. The melt pool can be flooded with water at the top for quenching it. However, the question arises in mitigating severe accident is to what extent water can ingress to quench the melt pool. To reveal that, a model was proposed based on the physics of the process. This work is seen as first attempt to model this phenomenon from basic principles, previous modeling were mostly relying on correlations.

A computer code MELCOOL was developed based on proposed model. The code considers the heat transfer behavior in axial and radial directions from the molten pool to the overlying water, crust generation, its growth; thermal stresses built-in the crust, disintegration of crust into debris, natural convection heat transfer in debris, molten pool and water ingression into the debris bed.

Phenomena of reverse momentum pulse and fluid leak after poison injection in the shutdown system of PHWR

The secondary shut down system (SDS-2) of 540 MWe PHWR, Tarapur consists of poison tanks connected to perforated injection line in the Calandria. A high-pressure helium circuit connected to the top of the poison tanks provides the required energy for instant injection of poison into the moderator. A polyethylene ball floats on the poison in the tank. When SDS-2 is activated, the high-pressure helium gas pushes the ball and the poison gets injected in Calandria via connected pipes. The ball remains seated at the bottom of the tank after pushing the poison to prevent helium entry into the Calandria.

During the commissioning of secondary shut down system of 540 MWe PHWR in Tarapur, multiple pressure pulse were observed at the inlet pipes, after the poison was injected into the Calandria. On a closer analysis of the data captured during injection, it was observed that
after the injection of poison into the Calandria, a strong pressure wave manifests in the loop in the reverse direction moving from Calandria to poison tank. The confirmation of the reverse pulse was seen in the vibration signals from the tank as shown in Fig. 4.

Effort has been made to explain the phenomena by solving the governing equation for fluid flow in piping. The arrival time of the reverse pressure pulse and its intensity has been analytically estimated and compared with measured experimental data.

The possible interaction between the pressure pulse and the ball in the tank has been explained based on experimental data. The concept of minimum residual poison to be maintained in the tank after the injection in order to avoid leakage of gas into the Calandria, due to the action of reverse pulse on the ball, has been explained.

5.0 Conclusion

Mathematical models are not reality. The real world is often far more complex than a mathematical model used to simulate it, and so that is a limitation. However, often a mathematical model (if correct) can reasonably predict behavior for a system and can help to validate mechanisms in physical processes. Through the above examples, an attempt has been made to show how mathematical modeling helped in understanding the physics behind the complicated processes.

Fig. 4: Vibration signal showing multiple impacts after the injection