Reactivity Effects of In-Pin Fuel Motion in Modern Fast Breeder Reactors

Anuj Dubey, T. Sathiyasheela and Anil Kumar Sharma

Abstract The dynamic behaviour of a fast breeder reactor core during an unprotected transient-overpower accident (hereafter UTOPA) is a function of various thermomechanical mechanisms. These impact the neutron flux in the core which in turn may affect the reactivity of the reactor. These phenomena are often quantified in the form of reactivity feedbacks. In-pin fuel motion, also known as fuel squirting, is a hydrodynamic phenomenon which can potentially create a negative reactivity feedback during the accident. The estimation of this negative reactivity feedback is essential for predicting the reactor behaviour and power excursion during UTOPA. In this work, a multiphase thermal hydraulic model for in-pin fuel motion is dynamically coupled with an in-house reactor dynamics code 'PREDIS' to predict in-pin fuel motion based reactivity feedback and estimate the outcome of UTOPA. Simulations of the reactor core are carried out with parallel processing to determine the melt propagation in different core subassemblies. It is found that in-pin fuel motion positively assists in the mitigation of a UTOPA event during severe accidents.

Keywords In-pin fuel motion · Multiphase flow · Nuclear fuel melting

1 Introduction

Fast breeder reactor safety studies involve experimental and numerical simulation of various thermomechanical and neutronic phenomena that take place inside the reactor vessel during accident conditions. Integration of these phenomena gives an overall picture of the evolution and possible outcome of the accident. The primary

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objective of such analyses is to ensure confinement of radioactivity to the greatest possible extent for a given design. Within the various severe accident scenarios, UTOPA involves a situation where an accidental control rod withdrawal leads to positive reactivity insertion inside the reactor core. This may lead to fuel heat-up and melting.

In-pin fuel motion is a peculiar phenomenon observed in transient overpower accident experiments [1, 2]. Upon melting, molten fuel travels axially along the length of the pin to regions of lower neutron density, where it solidifies, thereby effectively altering the reactivity configuration of the reactor core. This alteration is expected to give a decreasing influence on the reactivity, given the relocation occurs from where melting occurs (high flux region) to lower flux regions. This influence is quantified in the form of a reactivity feedback for the purpose of reactor dynamics calculations.

It is in this regard that a multiphase thermal hydraulic model has been developed by the authors for simulating this phenomenon [3]. The model employs enthalpy formulation to track the melting and solidification of fuel. A two-phase flow model with separate conservation equations for both liquid fuel and fission gases is employed to track the flow. The mathematical model deterministically predicts in-pin fuel motion and resultant relocation. In this work, the model is further validated against the CABRI-E9 (bis) experiment for the purpose of fluid flow comparison [4]. The model is implemented over the fuel region of a typical 500 MWe fast reactor core. The relocation feedbacks are evaluated based on the first order perturbation fuel removal worth. A dynamic coupling with PREDIS, an in-house fast reactor dynamics code is used to gauge the influence of these feedbacks on reactivity during slow transients [5]. Other feedbacks considered in power calculations are the Doppler feedback and fuel axial expansion feedback.

2 Mathematical Modelling

2.1 Reactor Core Configuration

Fuel, blanket, safety and other utility-based subassemblies in a typical 500 MWe fast breeder reactor core are arranged in a hexagonal geometry. These subassemblies can be grouped in zones or hexagonal rings, depending upon the neutron density experienced collectively by each subassembly. The subassemblies closest to the centre of the reactor core have the highest neutron density and therefore the highest power generation. This also implies that relocation in these subassemblies results in greater reactivity changes. Table 1 displays the number of fuel subassemblies, radial power factor and the fuel removal worth percentage for each zone in the reactor core. The second zone, with thirty subassemblies and closest to the centre of the core, has the largest fuel removal worth.

Table 1 Configuration of a typical 500 MWe reactor core

Zone	No. of fuel subassemblies	Fuel removal worth (%)	Radial power factor (%)
1	1	0.8	100
2	30	21.3	94.8
3	24	14.0	86.6
4	30	15.4	79.9
5	30	19.8	90.2
6	42	20.6	72.7
7	24	8.1	55.3

2.2 Solution Methodology

The model consists of two solvers coupled within the solution domain; the heat conduction and phase change module and the multiphase flow module. The 2-D heat conduction module employs enthalpy formulation to evaluate heat conduction, melting and solidification inside the fuel pin. The 1-D multiphase flow module works in conjunction with the heat conduction module [3]. Separate governing equations are solved for each of the constituent flow phases, i.e. liquid fuel and fission gases in space and time. The model utilizes a fully explicit finite difference scheme for numerical solution.

3 Results and Discussion

3.1 Validation Study

A validation exercise of the model has been carried out against the experimental data of the CABRI-E9 (bis) test [4]. Since a major objective of this work is the evaluation of reactivity changes in the reactor due to in-pin fuel motion, it is important to ensure that the developed mathematical model is generating accurate fuel relocation data. This experiment provides a unique opportunity in this regard. An annular type fast reactor fuel rod (OPHELIE-6) was subjected to slow overpower and flow coast down conditions. An important aspect was the presence of fractured pellets in the upper blanket column. This led to the recognition of a large spike in the hodoscope signal upon penetration of molten fuel inside these fractured blanket pellets. As a result, the time for this penetration was observed to be between 65 and 69 s in the transient. This time of penetration of liquid fuel into the upper blanket is a unique fluid flow parameter as far as slow transient experiments over modern fast reactor fuel pins are concerned. It was reported that the velocity of flow of liquid fuel towards the upper blanket was slow, which was in contrast with previous experimental data.

Table 2 Comparison of simulated versus experimental test parameters

Parameter	Model	Experiment
Power to melt (kW/m)	72.5	72.7
Final radial melt limits at peak power location (% Ro)	80.8	82 ± 2
Pin averaged mass melt fraction (%)	43	40–50
Time of penetration of upper blanket (s)	69	65–69

With this background, the mathematical model was further developed and validated against the experimental parameters available in literature. The results of the study are tabulated in Table 2. The model thermal parameters are in good conformance with the experimental data. Time of penetration in the model (69 s) is a clear indication that the predicted fluid flow is in line with the experimental results.

3.2 *Fast Reactor Conditions: Case Study*

The behaviour of fuel pins under UTOPA conditions in fast reactors differs from the behaviour observed in transient overpower tests. A major reason for this deviation is the presence of a fast neutron flux, which is not available in experimental environments, since experimental test reactors employ thermal neutron flux. The result is that while in experimental test reactors, there is an attenuation of neutron flux from the outer to the inner radius of the fuel pellets, there is virtually zero attenuation in fast reactors. This causes heat-up and melting at L.H.R values lower than in experimental reactors.

A nominal case study with transient parameters described in Table 3 (Case 1) is carried out on a Zone 1 fuel pin to illustrate the flow behaviour in fast reactor conditions. The resultant fuel column states are displayed in Fig. 1. From steady state ($t = 0$ s), the fuel pin heat-up causes initiation of melting ($t = 59.5$ s). Further heat-up increases the mass melt fraction. The molten fuel initially relocates towards the lower region and chokes the cavity ($t = 68$ s). Further heat-up causes evolution of a column of liquid fuel. This trend continues until the end of the transient ($t = 100$ s).

In order to correlate the effect of such relocation on the reactivity, mass worth modifications (pcm/mass of element) are evaluated for each time step of the transient. The net sum of these modifications gives the total negative reactivity feedback due to relocation within the fuel pin. Taking into consideration the central zone, the

Table 3 Transient parameters for various case studies (steady state L.H.R. is indicated)

Case	Time (s)	Insertion unit	Insertion rate	Max. insertion
1	100	(%) L.H.R.	1	100
2	750	pcm	1	500

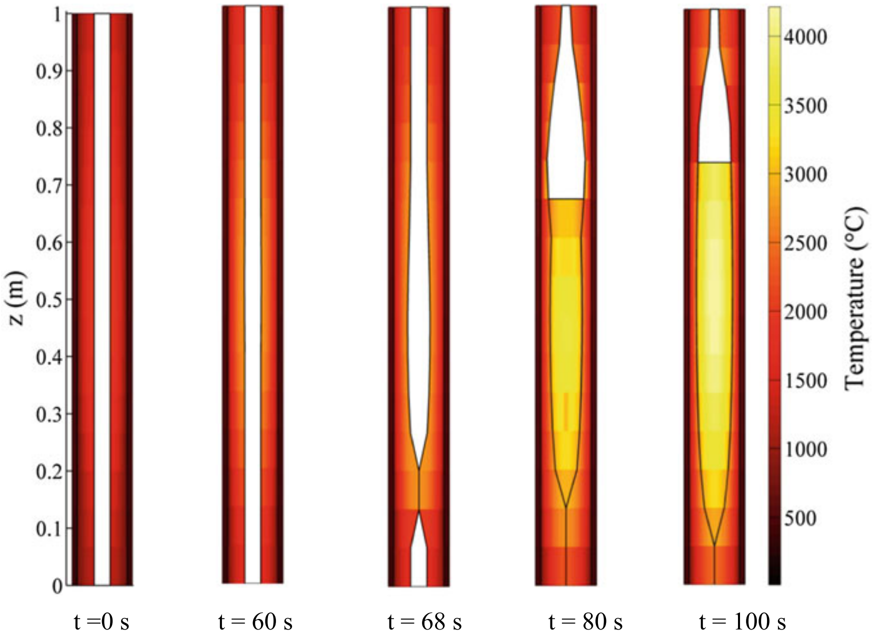

Fig. 1 Melting and fuel relocation behaviour in fast reactor conditions (Maximum temperature in all plots = 4213 °C; axial position is from the bottom of fuel column)

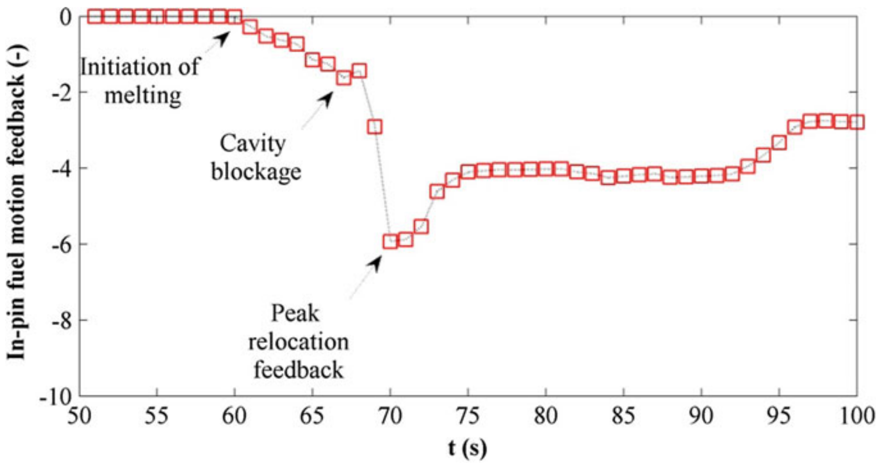

Fig. 2 Relocation reactivity feedback for ZONE 1 (CASE 1)

evolution of the relocation reactivity feedback is presented in Fig. 2. Initially, molten fuel at the centre of the fuel pin relocates downwards, thus initiating a negative feedback. Eventual cavity blockage (t = 68 s) prohibits further relocation, and the curve exhibits a slight perturbation. Opening of cavity restarts relocation and results in a peak magnitude (t = 70 s). Beyond this point, relocation to the lowest flux regions is no longer possible as the cavity fills up with molten fuel. Hereafter, the combined influence of filling of the central cavity regions and thermal expansion of liquid fuel guides the relocation feedback.

3.3 Whole Core Simulation

To evaluate the response of the entire core to a transient overpower scenario, the mathematical model has been implemented over all seven fuel zones, taking into account the respective fuel mass worth and thermal parameters of each zone, as illustrated in Table 1. Using the transient parameters described in Table 3 (Case 1), melting and fuel relocation in a single pin of each zone is simulated. The state of the fuel columns at the end of the transient (t = 100 s) is displayed in Fig. 3. The resultant relocation feedback time history is plotted in Fig. 4.

The results indicate that melting and fuel relocation in each zone initiates at a different time. The maximum magnitude occurs in Zone 2, whereas Zone 6 and

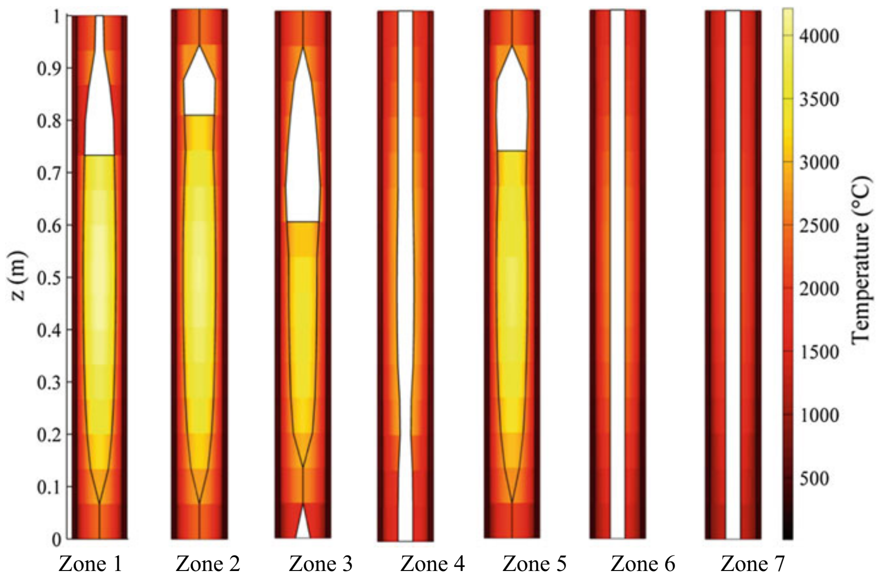

Fig. 3 Melting and fuel relocation behaviour in fast reactor conditions. (Maximum temperature in all plots = 4213 °C; Axial position is from the bottom of fuel column)

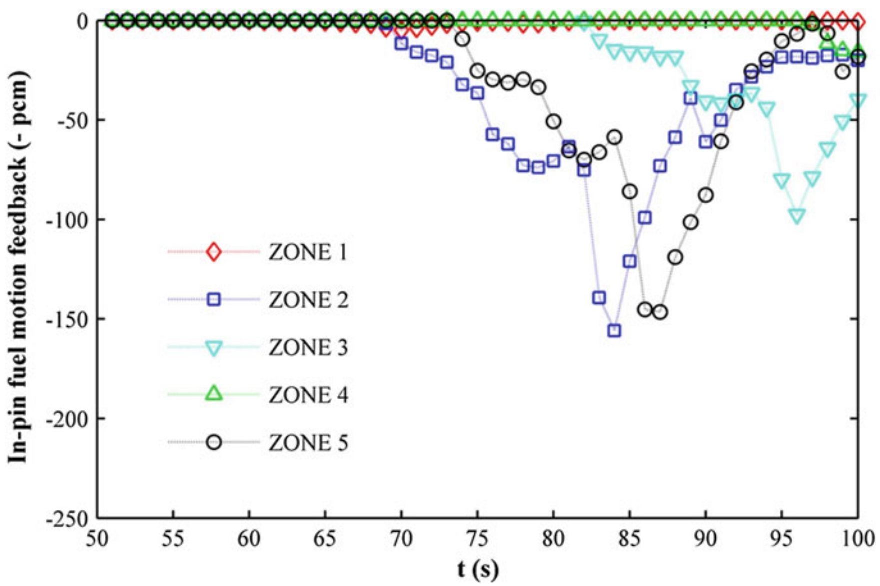

Fig. 4 Relocation reactivity feedbacks for all fuel zones (Case 1; sixth and seventh zone fuel pins did not undergo melting)

Zone 7 do not undergo melting. It is expected that during a transient overpower accident, as power rise continues in time, in-pin fuel motion in different zones will provide negative reactivity feedback at different stages.

3.4 Coupling with Reactor Neutronics

As part of this work, the developed mathematical framework has been coupled with a reactor dynamics code 'PREDIS'. Seven modules for each of the fuel zones are run in parallel with PREDIS. Upon melting, the reactor neutronics code extracts relocation feedback from each zone dynamically and returns the resultant reactor power for the next time step. The melting and fuel relocation modules for each zone receive power data and evaluate fuel relocation for the next time step. The relocation feedbacks for this time step are again extracted by PREDIS. This coupling integrates in-pin fuel motion and reactor neutronics into the evaluation of a given UTOPA scenario.

The transient parameters used for coupled simulation are presented in Table 3 (Case 2). The external power insertion is in the form of reactivity insertion (500 pcm max), which corresponds to a conservative core removal worth of a single control safety rod from the reactor core. Beyond 500 s, the reactivity insertion rate is zero. This signifies a complete withdrawal of the control rod. Results of simulation are plotted in Fig. 5. Fuel melting first starts in Zone 1 ($t = 269$ s). Further into

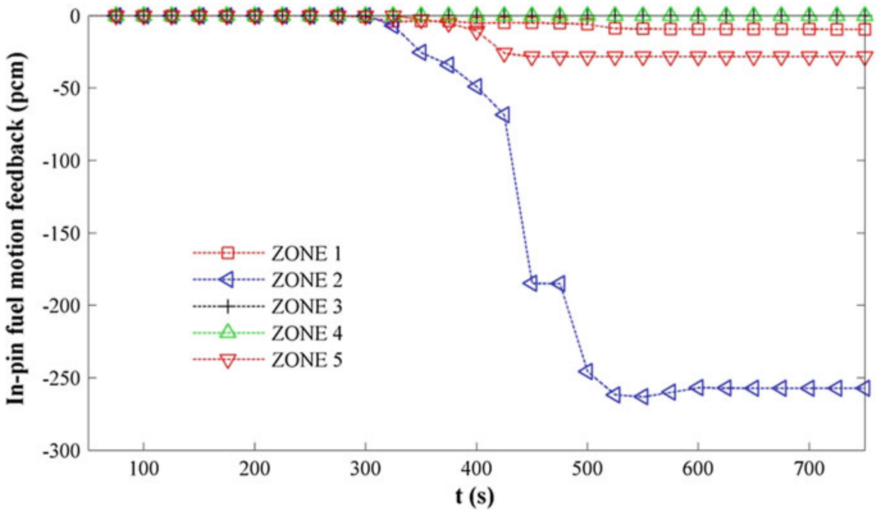

Fig. 5 Relocation reactivity feedbacks for all zones (Case 2; fourth, sixth and seventh zone fuel pins did not undergo melting)

the transient, melting initiates in the second and fifth zones. Relocation in Zone 2 causes a large negative feedback. This results in reduced reactivity in the core. The power level peaks up to 1.89 times steady power at peak reactivity insertion (t = 500 pcm). Beyond this point, the reactivity feedbacks stabilize, indicating arrest of further power increase and melting. Reactor power stabilizes at 1.52 times steady-state power towards the end of the transient. Melting remains limited to Zones 1, 2 and 5. The combined influence of fuel Doppler (−250 pcm), fuel axial expansion (−141 pcm) and in-pin fuel motion (−284.5 pcm) reduces the core reactivity sufficiently, thus mitigating the accident. It is evident that in-pin fuel motion acts in combination with fuel Doppler and other reactivity feedbacks and provides a significant mitigating effect. The relative magnitude of the feedbacks shows the significance of in-pin fuel motion.

4 Conclusions

The work is focused towards investigation of in-pin fuel motion in fast breeder reactor core and the resultant influence on the evolution of slow UTOPA events. A mathematical model developed for evaluating in-pin fuel motion is validated against experimental data to examine the predicted fluid flow behaviour. The model is implemented over all the fuel zones of a typical 500 MWe reactor core. The model is dynamically coupled with a reactor dynamics code 'PREDIS' to integrate relocation effects in the reactor power calculations. The results of the study indicate that melting and fuel relocation initiates at different stages in the transient in individual zones of the core. Relocation in Zone 2 generates maximum negative reactivity feedback. Further, melting initiates fuel relocation and related feedback in outer zones. Simulation of a typical localized control rod withdrawal accident indicates that relocation related feedback sufficiently retards fuel melting and contains it within the first, second and fifth zones, thereby demonstrating its potential as a mitigating mechanism for slow UTOPA events. In future, the developed computational system will be implemented for the study of medium and fast transients, which are postulated to occur during an unprotected loss of flow accident.

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