Status of Molten Fuel Coolant Interaction Studies and Theoretical Modelling Work at IGCAR

P. Bhaskar Rao, Om Pal Singh and R. Shankar Singh
Reactor Physics Division
Indira Gandhi Centre for Atomic Research

Kalpakkam 603102
India

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STATUS OF MOLTEN FUEL COOLANT INTERACTION STUDIES AND THEORETICAL MODELLING WORK AT IGCAR

P. Bhaskar Rao, Om Pal Singh and R. Shankar Singh
Reactor Physics Division, Indira Gandhi Centre for Atomic Research,
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Abstract

Status of Molten Fuel Coolant Interaction (MFCI) studies is reviewed and some of the important observations made are presented. A new model for MFCI that is developed at IGCAR by considering the various mechanisms in detail is described. The model is validated and compared with the available experimental data and theoretical work at different stages of its development. Several parametric studies that are carried using this model are described. The predictions from this model have been found to be satisfactory, considering the complexity of the MFCI. A need for more comprehensive and MFCI-specific experimental tests is brought out.

1 Introduction

The interest in this area started as early as 1957 [1] when in a foundry accident, molten aluminium came in contact with water and resulted in steam explosion with an efficiency which almost touched the thermodynamic limit. Subsequently also there were several incidents[2-9] involving the molten-fuel- coolant-interaction (MFCI) in thermal reactors, where efficiency in the order of 2% was noticed. The efficiency more than 1% is usually termed as violent. The interest in this topic increased further with the advent of liquid metal cooled fast breeder reactors(LMFBRs) where a potential for MFCI exists. Basically, because of the good expansion properties of the sodium as compared to the fuel, and also as the fuel temperature is considerably higher than that of sodium, it is feared that MFCI may lead to large and even explosive pressure build-ups. Some of the likely consequences of an MFCI could be as mentioned below. If a single pin or a few pins are involved in MFCI, then the coolant expulsion may trigger reactivity transients and the pressure pulses may damage the neighbouring pins leading to pin- to-pin failure propagation. If all the pins in a Subassembly(SA) are involved in the MFCI, the reactivity transient is more severe and the pressures produced are larger. This, combined with the possible reactivity changes caused by the movement/deformation of subassembly and rapid expulsion of sodium, could lead to further escalation of the problem through reactivity transient and may cause SA-to-SA failure propagation. In a whole-core meltdown accident, an MFCI may produce large amount of mechanical work to cause severe damage to the reactor vessel system.

Consideraable amount of theoretical and experimental work is reported on this topic and excellent reviews are available in the literature[10-13]. The main aim of the work was to investigate and study physical mechanisms and processes that are responsible for energetic interaction, and the physical conditions that are necessary to trigger energetic interaction in LMFBR fuel coolant systems.

In section 2 we describe MFCI phenomenon, and in section 3 we give a brief review of the status of work done in this area. In section 4, theoretical model development and analysis work carried out at IGCAR is presented. In Section 5 we give conclusions.

2 MFCI Phenomenon

The MFCI studies warrant the knowledge of initial temperatures and amounts of fuel and coolant, the mode of mixing, and the interaction processes such as mechanism of heat transfer and interdispersion of molten fuel and coolant.

With the experience gained from a large number of MFCI tests conducted all over the world in the last 25 years , this interaction may be defined to occur as follows. Molten fuel in bulk comes into contact with the coolant.Three modes of contact are possible,

(i)- molten fuel dropped into a pool of coolant

(ii)- coolant enetering a pool of molten fuel and

(iii)- molten fuel and coolant mix forming stratified layers.

In the fuel-to-coolant mode (Mode i) of contact extensive fragmentation is caused with relatively less rapid heat flux,

where as in the coolant-to-fuel mode (Mode ii) of contact the fragmentation is less, but coolant is superheated almost to the homogeneous nucleation temperature.

On the whole the interaction in general proceeds in the folowing manner. Initially a coarse mixing of the fuel and the coolant occurs with a stable vapour blanketing. A local disturbance or an external trigger then results in vapour film collapse. It then leads to differential acceleration between the fuel and the coolant masses due to one of the three processes, viz, Rayleigh-Taylor Instability, Kelvin- Helmholtz Instability, and Boundary-Layer stripping. The Rayleigh-Taylor instability is found to be the dominant mechanism, which causes widespread fuel fragmentation and a fine fuel-coolant mixing. Further a liquid-liquid intimate contact is also established , resulting in rapid coolant over-heating. A rapid heat transfer then results particularly when the interface temperature between the fuel particle and the coolant is close to coolant homogeneous nucleation temperature. The heat transfer rate that results varies by several orders based on the interface temperature and other physical conditions. The extent of mixing which gives a measure of the amount of coolant being overheated is important, and depends on the interaction propagation velocity and the size of the system. The fragmentation[14] process occurs due to several physical processes some of the importnt ones are (i) Thermal, (ii) Hydrodynamic, (iii) Entrapment and (iv) Entrainment. The most dominant for the reactor cases are the thermal and hydrodynamic mechanisms.

One of the worries in an MFCI is whether a vapour explosion occurs in a reactor situation. Two theories are available which give the criteria for vapour explosion. First is the spontaneous nucleation theory propounded by Fauske[12] and the criteria are (i) coarse premixing followed by film boiling, (ii) liquid-liquid contact , (iii) initial contact temperature exceeding spontaneous nucleation temperature of the coolant and (iv) adequate physical constraint. Second is detonation theory, propounded by Board and Hall [16] and the criteria are (i) fuel and coolant get coarsely intermixed, (ii) film boiling results, (iii) an unidentified trigger results in liquid-liquid intimate contact and a rapid heat transfer and (iv) shock travelling through the mixture causes wide-spread fragmentation of the fuel, and further mixing.

3 Status of MFCI Work

3.1 Experimental Work

A large experimental effort [17-41] was put to understand the basic MFCI phenomenon. Most of the experiments were carried out with a number of fuels and coolants and were directed towards identifying basic processes involved and the fuel/coolant types and the physical conditions that lead to energetic interaction. Some experiments were also carried out to support theoretical model development . A very few experiments however were carried out with the reactor materials in the in-pile conditions. A limited amount of experimental work on the UO_2-Na and Tin-H_2O systems has been done.In our centre also experimental facility is set up to carry out work on MFCI.

The main findings of the experimental work reported in the literature are :

(i) Extremely rapid boiling heat transfer leading to over- pressurization is always observed in MFCI where the fuel-coolant interface temperature reached the coolant spontaneous necleation temperature [12].

(ii) Wide spread fuel fragmentation to a size of the order of 200 μ m occurs in all fuel-coolant systems where the mode of contact is fuel-into-coolant [42].

(iii) Experiments with sodium as coolant indicate a benign interaction as compared to those with water as coolant[43].

(iv) Fuel and coolant thermal diffusivities influence the MFCI energetics considerably.

(v) Coolant superheating followed by explosive vaporization and consequent overpressurization [44] is observed in some experiments.

(vi) Wide spread fuel fragmentation and nonenergetic MFCI results in LMFBR materials if mode of contact is fuel-dropped/injected- into-coolant. Coolant overpressurization and no fragmentation results for coolant-into-fuel mode of contact.

(vii) In-reactor MFCIs [45,46] for LMFBR accident conditions, for UO_2-Na and UC-Na, are always found to be non-energetic with efficiency less than 0.2%.

3.2 Theoretical work

The theoritical work was initiated starting with the conservative model of Hicks and Menzies which gave the upper limit to the efficiency. Subsequentily, several mechanistic models were developed. A brief review is given below.

3.2.1 Thermodynamic Models

These models ignore the details of interaction proceses by assuming instantaneous heat transfer from the fuel to the coolant and give the thermodynamic upper limit of the mechanical work energy generated in the MFCI. A fixed fuel to coolant mass ratio is assumed. Various thermodynamic models are discussed in this sub-section.

(i)Hicks and Menzies Model

In this model [47] it is assumed that the mixing of the fuel and sodium takes place at constant volume, the thermal equilibrium is attained before any expansion takes place, the equation for expansion of sodium-fuel mixture is derived by assuming that thermal equilibrium exists at all

times between the two materials and the expansion of the mixture is adiabatic, and the properties of fuel and coolant do not change during expansion. They found that the expansion work varied with sodium to fuel mass ratio and that a peaking behaviour was observed and that the maximum corresponded to complete vaporization of the liquid with insignificant superheating of the vapour. The efficiency of thermal-to-mechanical energy conversion of as much as 30% is observed.

(ii)Modified Hicks and Menzies Model

In this model, the heat transfer between the fuel and sodium is stopped during the expansion process. One finds that this modification is more realistic than the original model as vapour blanket of the fuel reduces the heat transfer. Adiabatic model gives about one fourth of mechanical work energy release as compared to the original model at optimum sodium-to-fuel mass ratio. Also, the original model, this model does not exhibit a sharp peaking behaviour in the mechanical work potential as a function of fuel-to-coolant mass ratio.

(iii) Klickman's Modification

Klickman[48] modified the Hicks and Menzies model by taking into account the temperature dependant sodium heat of vaporization which allows the sodium to be heated above its critical point.

(iv) Padilla's Model(SOCOOL Model)

Padilla[49] improved the Hicks and Menzies model by dropping all the limitations of the Hicks and Menzies model. He specified completely all the thermodynamic properties of sodium and fuel required for the calculation of energy release. The assumed processes are illustrated on an idealised temperature - entropy diagram for sodium. Sodium is heated along the vapour pressure curve. If the rate of heat transfer is assumed to be infinite, the sodium can expand to the terminal pressure in three distinct phases. The sodium first expands to the melting point of the fuel in thermal equilibrium with the liquid fuel, then undergoes an isothermal expansion as the fuel solidifies and finally expands in thermal equilibrium with the solid fuel. (b) If it is assumed that no heat transfer occurs during the expansion phase, the sodium expands to the terminal pressure along a path corresponding to an isentropic expansion.

This model, accounts for the heat of fusion of the fuel and allowed for variable specific heats of liquid and solid fuel. The work energy for the thermal equilibrium expansion process was found to be approximately three times that for the isentropic- expansion process.

(v) Judd's Model

Judd[50] applied the Himpan equation to sodium above the temperature range of the data recommeded by Golden and Tokar[51]. His predictions for the mechanical work energy are about 30% higher than those reported by Hicks and Menzies and he obtained a much broader peak as a function of sodium/fuel mass ratio. He found that the sodium/fuel mass ratio is not so important in determining the optimum mechanical work energy. This is because the present method does not ignore the work done by the liquid.

A comparison of the work potential as a function of fuel-to- coolant mass ratio is made for different thermodynamic models in Fig 1.

3.2.2 Finite Heat Transfer Rate Models

Thermodynamic models are too conservative and the upper limit predicted by these models for the mechanical work energy is too high to provide a reasonable basis for design. Moreover, thermodynamic approach does not give pressure time histories that are needed for the assessment of the reactivity and structural damage. Therefore, there have been attempts to develop models which are less conservative and give pressure time histories. Various models developed so far are as follows:

(i) Pfefflerlen Model

Pfefflerlen[52] assumed a one-dimensional geometry where the sodium and molten fuel were both semi-infinite in extent and separated by an interface with negligible contact resistance. The rate of heat transfer is calculated from the solution of the semi-infinite heat conduction problem. When the sodium adjacent to the interface is heated rapidly, a shock wave is assumed to be generated. As the shock wave moves away from the interface, boiling is assumed to occur. The amount of sodium that is superheated is then expanded to the terminal pressure assuming that the fuel surface is vapour blanketed. The acoustic work and the inertial work were determined by evaluating changes in the entrophy and inertial energy of the sodium. This model gives work energies about an order of magnitude lower than both the Hicks and Menzies model and the model of Padilla.

(ii) Padilla's Model(SOCOOL -II)

In this model[53], it is assumed that fuel particles are instantaneously and uniformly dispersed in a mixing region surrounded by unheated liquid and there is no heat transfer between these two regions. Heat transfer from fuel to coolant is calculated by considering a single spherical fuel particle concentrically surrounded by sodium. Conduction heat transfer between the fuel and sodium is assumed and the parabolic heat conduction equation in spherical coodinate system with internal heat source is solved using implicit numerical technique. The rate of pressure increase for a liquid heated in a confined region, is given by the general thermodynamic relationship. The temperature increase is calculated from heat conduction equation and the rate of volume increase is calculated from one dimensional acoustic or inertial equation.

Some of the findings of this model are:

(a) For a given set of conditions, 90% of thermal equilibrium is reached within a time less than acoustic period for typical reactor MFCI conditions.

(b) For all particle sizes of less than or of the order of 1000 μ m and sodium/fuel ratio less than 0.5, the boiling occurs at 98% of thermal equilibrium.

(c) Acoustic energy is typically about 70% of the blast (inertial) energy or about 40% of the total energy.

(iii) Model of Cho,Ivins and Wright

A more comprehensive model has been developed by Cho, Ivins and Wright[54,55] at ANL. The significant feature of this model which differs from that of Padilla's model are

(a) This model allows the fragmentation of the fuel and mixing with the sodium over a specified time period instead of instantaneous mixing and fragmentation.

(b) Quasi-steady state heat transfer and transient conduction model have been used for sodium heating.

(c) Geometrical constraints used in this model are:

- Acoustic constraint of infinite extent
- Inertial constraint
- Acoustic constraint upto the time of acoustic unloading, followed by inertial constraint.

(d) The cushioning effect of non-condensible gases and sodium vapour initially present in the mixing region are taken into account.

(e) Heat transfer can be continued into the two-phase sodium region or a heat transfer cut off can be arbitrarily specified. The findings of this model are the folllowing

(a) The peak pressures occur during the liquid phase heating and expansion.

(b) The transient conduction model gives an order of magnitude higher peak pressure and larger amount of acoustic work than quasi-steady state heating rate.

(c) The peak pressure for transient conduction approximation was reduced by 6% when the presence of 1% (vol.) inert gas in the heated sodium was taken into account.

(d) There is no appreciable shock pressure for mixing time of 1 ms. In this case, pressure increases slowly while the heated sodium remains a subcooled liquid.

(e) Generally the work done decreases with decreasing heating rate as might be caused by increasing the fragmentation and mixing time constant.

(iv) Caldarola's Model

In his model[56], Caldarola assumes that the reaction takes place in two phases,i.e.,in phase A and phase B. In phase A (a) fragmentation is assumed to be instantaneous with intimate contact of the fuel with the coolant, (b) transient heat conduction model is assumed for heat transfer,(c) the heat transfer coefficient decreases with time due to the formation of a temperature profile inside the fuel particles and (d) the heated volume of the sodium is constrained by the surrounding unheated coolant and by the other materials present in the core. The sudden expansion of the heated volume first produces acoustic waves, later the sodium column behaves as a piston which is pushed inertially upwards. The pressure rises and reaches a maximum, and then falls as soon as the expansion of the liquid sodium becomes important. At a time coolant attains its saturation temperature sodium boiling starts and phase B begins. In phase B, the heat transfer process is characterised by a very large contact area, and by a thermal contact between the fuel and the coolant which becomes inceasingly worse with time, due to the formation of a sodium vapour layer at the external surface of the fuel fragments. A detailed model determines the film thickness in this phase. The sodium boils in a large quantity and hence produces large volume changes. The sodium piston is then further accelerated which allowsthe pressure in the mixing zone to decrease. The exact solution of the heat conduction inside a sphere has been obtained. The experiments of the heat transfer from a sphere to a boiling liquid are discussed to evaluate the thickness of the vapour layer around the sphere.

The main conclusions of this model are the following:

(a) The total work strongly decreases with the fragmentation and/or mixing time constants.

(b) Vapour blanketing in Phase B is effective only if it is accompanied by a relatively slow process of fragmentation and mixing.

(c) The higher value of vapour film time constant reduces the total work considerably.

(d) The effects of fuel particle size distribution and gas content are important only for rapid fragmentation and mixing.

(c) The total work rises with the initial length of the piston.

(v) Jacobs Model

In almost all the models, the commonly employed approximation is that in the mixing zone,the temperature and pressure are independent of space. Jacobs and Thurnay[57] and Jacobs[58,59] investigated the consequences of this approximation by developing the code BRENDY-I where the effect of temperature and pressure gradients within the heated sodium is taken into account. With this, the estimates of pressure, energy transfer and kinetic energy production are significantly reduced.

(vi) CORFOU Model

CORFOU computer code has been developed by Amlard et al[60]. The main phenomena, i.e. fragmentation, heating, vapourisation and condensation of sodium mass and heat exchange between the surroundings and interaction zone are taken into account to study the influence of several parameters. Fragmentation is represented in CORFOU by the successive generation at defined times of 'families' of small particles from an initial assemblage. The exchange of mass and heat is considered between vapour and liquid that are not in thermal equilibrium. Additional coolant can enter the interaction zone. Non- interacting liquid is taken as incompressible, giving inertial loading.

(vii) Hoskin and Morgan Model (TOPAL)

Hoskin and Morgan developed[61] the code TOPAL to explain the results of shock tube experiments. TOPAL-I calculates pressure history corresponding to a given energy input whereas TOPAL-II calculates an energy input which could produce a given pressure history.

Mixing ratio is specified at each mesh point along the mixing volume, and a detailed and thermodynamically consistent equation of state is used together with exact, compressible flow dynamics. The authors conclude that the code TOPAL can be used to analyse the current series of shock tube experiments.

Recently in the last 5 years some good modelling work and experimental results are reported[62-81]. All except one of the above developed models and the supporting experiments were directed towards UO_2-water interaction of direct interest only to Light Water Reactors. Typical parameters of interest in MFCI have been reported for UO_2-water as follows

- fuel particle size lies between 24 and 85 μ m.

- mixing and fragmentation time constant is around 200 ms.
- mixing and interaction propagation velocity is about 120 meter/s
- efficiency is in the order of 1 to 2%

The findings of the recent work are that (a) the models for UO_2-water are well validated and can reasonably predict the LWR MFCI and the models can be used in LWR accident analyses codes (b) the models for UO_2-Na are not well developed (c) the experimental tests reported in the last twenty five years were on small-scale-type giving very low efficiency of 0.2% ,which can not be extrapolated to full scale as is supported by a recent experimental test[81] where a large scale test on UO_2-Na gave an efficiency of about 4%.

4 Theoretical Modelling Work at IGCAR

A new theoretical model has been developed at IGCAR by incorporating some of the physical processes that were not accounted for in previous models. The model is applied to the MFCI in UO_2-Na, UO_2-H_2O, UC-Na, UC-H_2O and Al-H_2O systems.

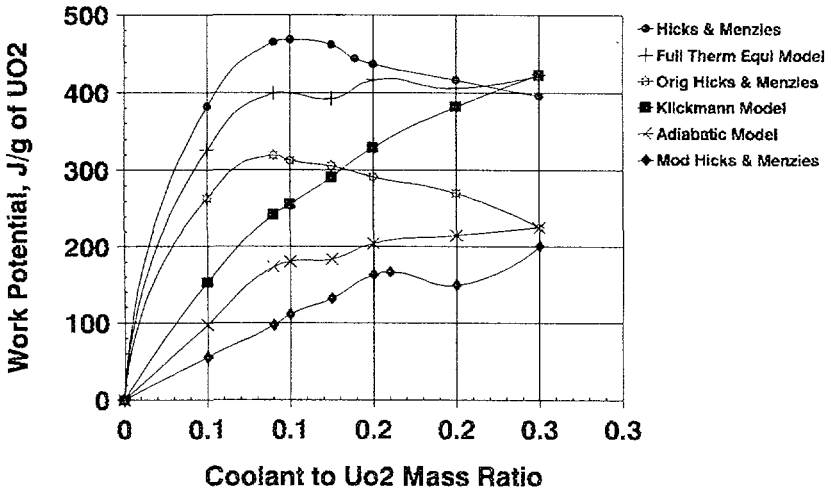


Fig 1: Comparison of Thermodynamic Models

4.1 Theoretical Model and Code FCI

The theoretical modelling work at this centre was initiated in the year 1978. The initial efforts were concentrated in the understanding of some of the basic features of MFCI. Therefore computer codes were developed based on the available theoretical models in the literature. Efforts started with the development of code 'THERM'[82] for calculating the thermodynamic upper limit of efficiency. The code was validated by comparing with other available thermodynamic codes. Results were in good agrrement with other results as shown in Fig 1. It was followed bythe development of a code 'FCI' [83] based on the mechanistic parametric model of Cho et al [54]. This code was validated against the theoretical results of Caldarola. Results compared are the time profiles of (a)liquid coolant pressure (See Fig 2), (b) two- phase pressure (See Fig 3), (c) liquid coolant temperature (See Fig 4), (d) two phase coolant temperature (See Fig 5) and (e) specific work (See Fig 6).Subsequently, we carried out several investigations for MFCI energetics using this code in order to have an understanding of broad areas of the interaction.

A new and more accurate geometrical constraint typical of reactor vessel system is modelled [84]. This model accurately considers the stress retaining ability and three dimensional motion. The new geometrical constraint is more accurate representative of the whole-core MFCI. The new model is shown in Fig 7 and the influence of the new model is shown in Fig 8.

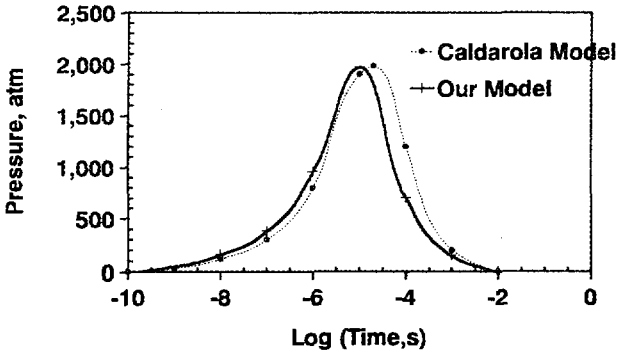


Fig 2: Liquid Phase Sodium Pressure

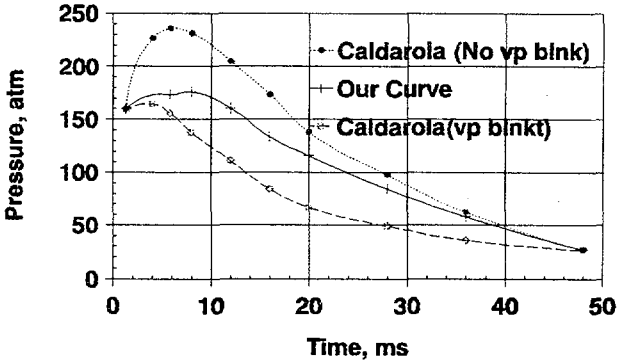


Fig 3 : Two Phase Sodium Pressure

Cho et al assumed a linear temperature profile in the fuel particle where as the shape should be realistically parabolic. A new and more accurate heat conduction equation was developed [85] and used in the model. The influence of the new model is presented in Table 1. It may be

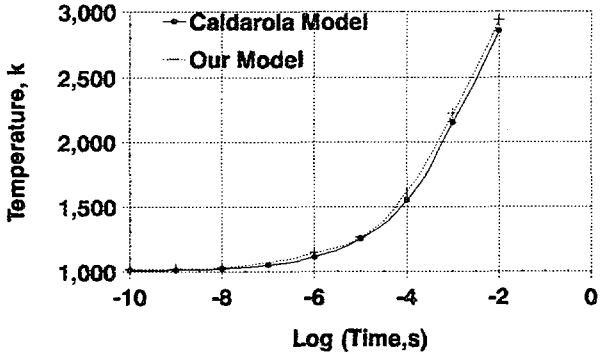


Fig 4: Liquid Phase Sodium Temperature

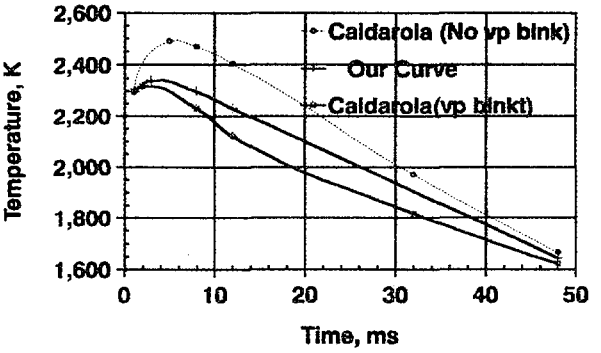


Fig 5: Two Phase Sodium Temperature

seen that for small particle size, the Cho's approximation is valid but several percent error occurs for larger particle sizes.

A parameteric study of the influence of several physical parameters on the efficiency are conducted [86]. The parameters chosen are (a) fuel particle size,(b) mixing time constant, (c) coolant slug height (d) fuel-to-coolant mass ratio,(e) vapour blanketing ,(f) mixing zone height. The results of the analysis are reported in Table 2. The influences of the parameters are discussed in detail elsewhere.

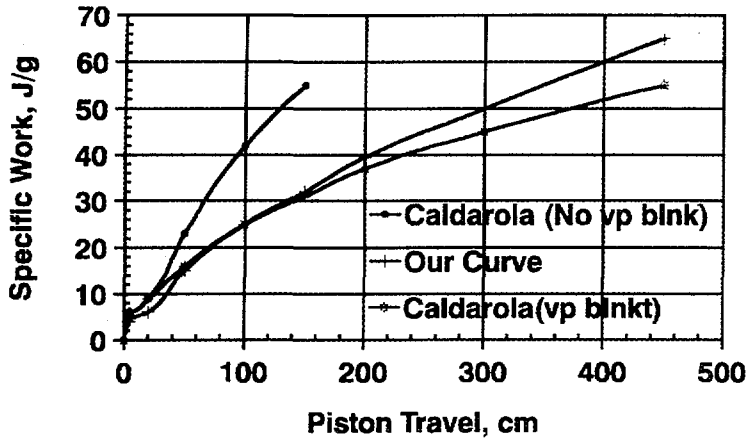
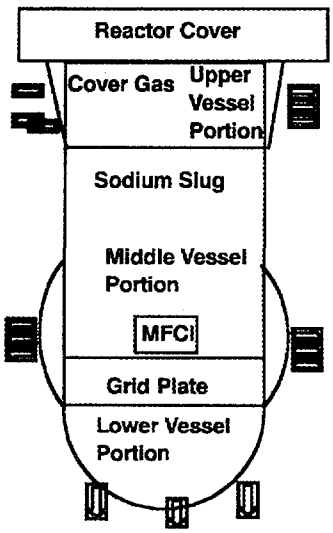


Fig 6: Specific Work

Fig 7: Reactor Vessel and Loading Pattern



In a whole-core MFCI involving vessel motion, its response is strictly biaxial. The use of this accurate Primary System type geometrical constraint on the MFCI energetics is analysed by developing and using more accurate biaxial deformation model for reactor vessel [87]. The results indicate that up to 5% error can occur in the vessel strain if less accurate uniaxial stress-strain curve is used.

In the previous parametric study a geometrical constraint is simply assumed as slug of a specified height, for analysing the damage potential in a core disruptive accident, in reality the geometrical constraint has to be represented by several parameters of the reactor vessel system. Another detailed parametric study was carried out [88] using the realistic geometric constraint using the parameters of the reactor vessel system, viz, (i) masses of the upper-, lower-, and middle vessel portions, (ii) strengths of the holddown bolts and of the reactor vessel material, (iii) other MFCI parameters mentioned in the previous paragraphs (iv) cover gas volume . The details are presented in the Table 3.

As another improvement in the code a more accurate boiling heat transfer model which depends on the interface temperature and vapour blanketing conditions is modelled and used in place of conduction heat transfer model. The results show significant differences[89]

A spherical geometrical constraint is also modelled and incorporated in the FCI code as a separate option [90].

This code like all other similar codes, could not predict the MFCI energetics correctly. It has been observed that this is mainly because some of the important mechanisms of MFCI like heat transfer, boiling heat flux, fragmentation and mixing time, coolant superheating and geometrical constraint are not treated accurately. Therefore, we developed a new model, FCI-2 [91] derived from the code FCI with additional features to take into account the above mentioned defficiencies

4.2 FCI-2 Model

(i) The heat diffusion equation is solved exactly in the entire fuel and the coolant. This results in the exact transient temperature profile in the fuel and the coolant and therefore predicts accurate

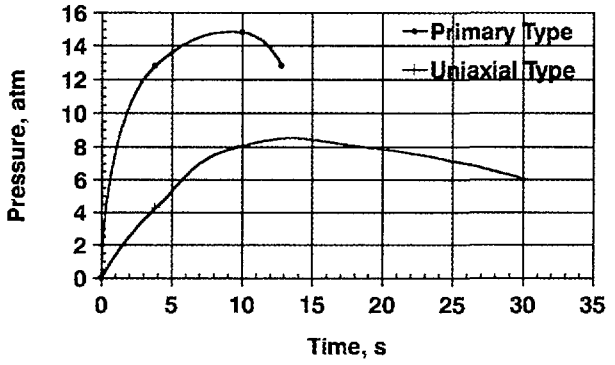


Fig 8:Influence of the Type of Geometrical Constraint

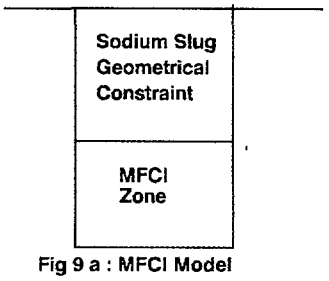


Fig 9 a : MFCI Model

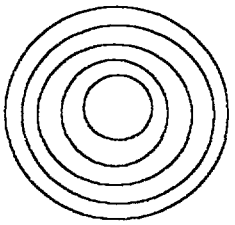


Fig 9b :Fuel-Coolant Unit for Heat Transfer Calculations

heat transfer. It also gives the actual amount of coolant which is above the saturation temperature and which does the expansion work.

(ii) Additional heat transfer mechanism through boiling is incorporated as a function of interface conditions. This mechanism is vital and dominant for some specific interface conditions.

(iii) The amount of interacting coolant in the MFCI is chosen to be that which is physically and thermally connected with the ejected molten fuel. The earlier 'mixing zone' concept cannot be applied for high thermal conductivity coolant.

Molten fuel in the form of fine spherical particles is assumed to mix and uniformily disperse in the entire availble coolant. The system is then represented by a unit of one fuel particle surrounded by corresponding amount of coolant. A continuous heat transfer takes place from the fuel to the coolant developing a transient temperature profile in both fuel and the coolant.

The unit is subdivided into a number of spherical shells (see Fig 8) in the fuel and coolant and the heat diffusion equation is solved for each shell. The heating rate,dq/dt, of any shell i is given in finite difference form as ,

$$dqdt = \frac{8 * \pi}{(\Delta r_i + \Delta r_{i+1})} \left[\frac{K_i \bar{r}^2_i (T_{i-1} - T_i)}{\Delta r_i} - \frac{K_{i+1} \bar{r}^2_{i+1} (T_i - T_{i+1})}{\Delta r_{i+1}} \right]$$

where

$$\bar{r}_i = (r_i + r_{i+1})/2 \quad \text{and} \quad \Delta r_i = r_i - r_{i-1}$$

Here, K, $\bar{r}$, T are thermal conductivity, mean radius, and temperature of shell i. The change in thermal conductivity due to vapour blanketing is also considered[89]. For fuel shells the new temperature is obtained by

$$dT_i/dt = dq_i dt/(m_i c_{pf}) \qquad (1)$$

where m_i is mass of ith shell and c_{pf} is fuel heat capacity.

For coolant shells, the new temperatures are obtained by solving the equations of state, mass, momentum and energy along with eqn.(1).These are

Energy

$$(C_l - x.R_g).dT/dt = dq_i/dt/m_i - P.dV/dt + (1-x).T.V_l.\alpha_l.dP/dt + P.dV_l/dt) \qquad (2)$$

State

$$\beta_T .dP/dt = \beta_T.dT/dt - \alpha_l.dV/dt/V \qquad \text{for liquid phase}$$

$$P = P_1.\exp(-P_2/T) \qquad \text{for two phase} \qquad (3)$$

$$P.V = Z_c.R_g.T \qquad \text{for vapour phase}$$

Mass

$$(V_v - V_l).dx/dt = dV/dt - x.dV_v/dt - (1-x).dV_l / dt \qquad (4)$$

Momentum

The momentum equations and the equations of motion of different components of the geometrical constraint are modelled and used. Options are available for different types of geometrical constraints, viz, uniaxial type of Cho et al[54], Spherical type of Bhaskar Rao et al[90], Primary System type of Bhaskar Rao[84], and more realistic Primary System type[87] which have been described above.

For a uniaxial constraint used by Cho et al the equatiions are

$$dZ/dt = (P-P_0)/R/c_0 \qquad \text{for acoustic period}$$
$$d^2Z/dt^2 = (P-P_0)/(Z_{ex}+Z-Z_0)/R \qquad \text{for inertial period} \qquad (5)$$

Time Step Optimization

Because of the peculiar and rapid variations in temperatures ,pressure, heat transfer rate, vapourization rate and such other variables of MFCI, an otimization of the time step is necessary . The optimum set of upper limits thus arrived at by a numerical experimentation and the corresponding time step values are as follows. In each time step,

(i) heat transfer is not allowed to change by more than 10% ,

(ii) the time step in the acoustic period is not allowed to be higher than one hundredth of the acoustic period,

(iii) pressure is not allowed to change by a factor of more than 2 during the acoustic period,

(iv) temperature is not allowed to change by more than 2%,

(v) coolant expansion is not allowed more than 10% of its volume,

(vi) work done is not allowed to be more than 0.1% of the fuel heat content,

(vii) stability of space-time analysis require, that time step is always lesser than thermal diffusion time,

(viii) fall in pressure is not allowed by more than 10% and

(ix) fall in temperature in the coolant shells is not allowed by an amount more than 10^0

Initially, a guess for the time step is made using the rates of changes in the above variables in the previous time step, and the new values are calculated in the current time step. The present chages in the variables are then checked against the upper limits using current rates of change in the variables. If the constraints are not satisfied the cycle is repeated with reduced time step size till the conditions of constraints are satisfied.

4.3 Results and Discussions

Five different fuel-coolant types, viz. UO_2 - Na, UC - Na, UO_2 - H_2O, UC - H_2O and Al - H_2O are studied which represent all the possible combinations of fuel/coolant systems. The fuel-to-coolant mass ratio, w, selected are 14.3, 10.0, 2.0 and 0.4. This includes a range of fuel-rich and fuel-deficient MFCI of interest. The value of 0.4 corresponds to the value which could be expected in a small fast reactor when whole fuel is involved in the MFCI. For large fast reactors, value of w is still lower and so is the case if only a fraction of fuel is involved in the MFCI. Fuel initial temperature is assumed to be the melting point. The coolant below the saturation temperature does not take part in the expansion but goes as geometrical constraint. This amount decreases with time as more and more coolant goes above saturation temperature. In the present study a constant amount of geometrical constraint presented by a column of 160 cm of the coolant is assumed. This value corresponds to the amount of coolant available in small fast reactors.

In Fig. 10, the efficiency as a function of fuel-to-coolant mass ratio, w, is presented for all the fuel-coolant types. The solid curves represent lumped models developed earlier and the dashed curve correspond to the new model. The observations are as follows :

(i) All the fuel-coolant types show peaking behaviour for efficiency as a function of fuel-to-coolant mass ratio. For high thermal conductivity coolant the efficiency decreases rapidly as w is decreased. For low thermal conductivity coolant (e.g. H_2O) the efficiency falls slowly after attaining the peak and remains almost constant as w is further decreased.

(ii) Fuels with higher fuel thermal conductivity and higher heat content, have higher efficiency for all types of coolants.

(iii) Fuel-coolant types with lower coolant thermal conductivity give higher efficiency than those with higher coolant thermal conductivity for fuel-deficient systems and lower efficiency for fuel-enriched systems.

(iv) For fuel-deficient system and higher thermal conductivity coolant, the efficiency is very very small

(v) Carbide fuel gives nearly same efficiency as the oxide fuel.

(vi) The UO_2 - Na MFCI is mild and quite different from that of the UO_2 - H_2O system which is energetic.

(vii) Earlier lumped models with 'mixing zone' concept overestimates the amount of working coolant for low thermal conductivity cooolant and underestimates the amount of interacting

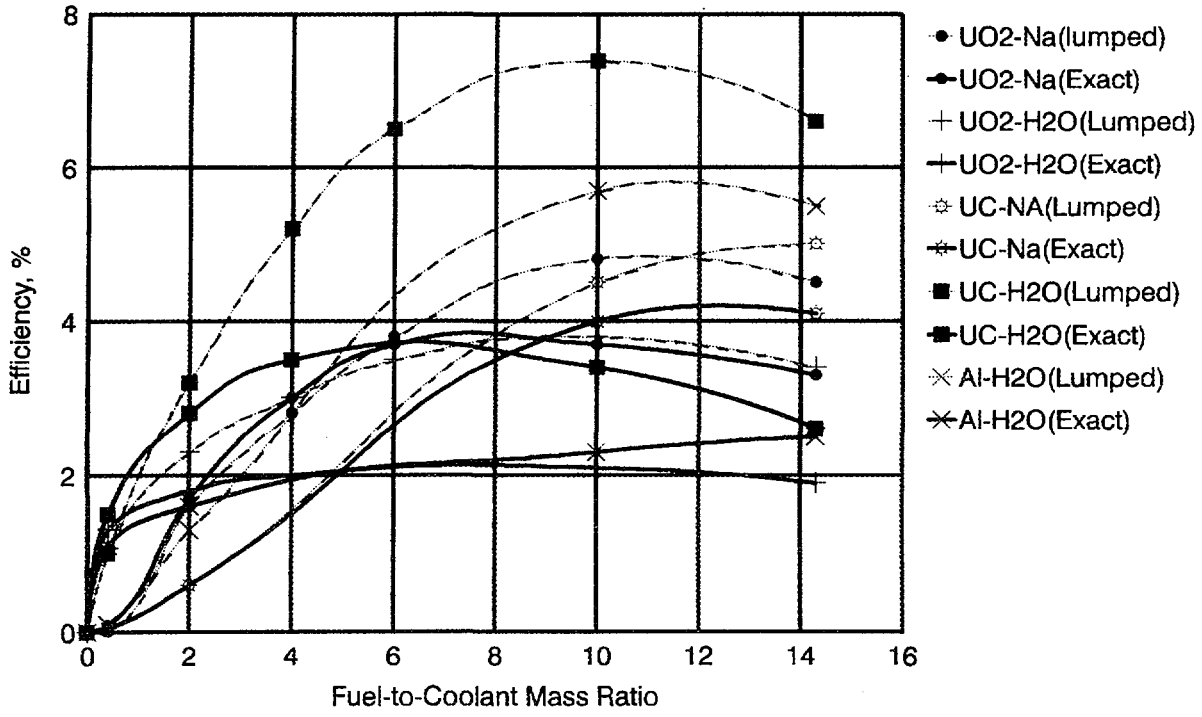


Fig 10: MFCI Efficiency (Different Fuel/Coolant Systems)

coolant for high thermal conductivity coolant. It grossly underestimates the efficiency for low thermal conductivity coolant for fuel-deficient systems.

(viii) This improved model gives results for UO_2 - H_2O and UO_2 - Na in line with the experimental observations whereas lumped model overpredicts results for UO_2 - Na system and underpredicted those for UO_2 - H_2O. Therefore the improved model is much more reliable.

(ix) Lumped model gives lower efficiency than exact model for w less than roughly 3, and higher efficiency for w greater than 3. As w increases both the models tend to give same results.

5 Conclusions

From the review the following emerge

1. The MFCI parameters are

(a)Fuel particle size is around 100 μ m.

(b)Fuel fragmentation and mixing time constant could be conservatively considered to be 200 ms.

(c)Fuel particle size distribution may be assumed Log-Normal.

(d)Efficiency though predicted around 0.2% in numerous small sized tests will have to be carefully estimated for the large sized MFCI that occurs in LMFBRs.

(e)Mixing and propagation velocity will have to be experimentally obtained. For UO_2-H_2O it is estimated to be around 120 m/s.

2. A new and more realistic model is developed which gives MFCI predictions closer to the experimental observations for a large spectrum of physical situations and fuel-coolant systems.

3. For LMFBR accidents involving MFCI in UO_2-Na and UC-Na boiling heat flux does not play important role.

4. Only one large sized test is reported in last 5 years and the efficiency is reported to be about 4%. Several experimental tests in reactor conditions may have to be conducted to estimate it. A strong need exists for experimental tests on UO_2-Na system.

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Table 1 : Mecchanical Work Energy Release, j/g

Fuel Particle Size, m m	Cho Model	Our Model
1000	86	101
200	625	650
100	755	888
10	2300	2412

Table 2: Results for Different Sets of Parameters

Parameters	Results	Efficiency, %	Peak Pressure, atm	Peak Temperature, K	Final Pressure, atm	Final Temperature, K
Base Case	First Set	5.3	3373	2610	232	2189
Fuel Size, u	10	13	11632	-	204	-
Fuel Size, u	500	1.8	621	2081	52	1872
Fuel Size, u	1000	.1	291	1163	4	1648
Time Constant, ms	1	3.2	176	2327	87	2048
Time Constant, ms	10	1.9	105	2246	61	2038
Column Height, cm	100	4	3372	2613	153	2265
Column Height, cm	300	6.7	3374	2610	53	1878
Fuel-to-Coolant Mass Ratio	3	2.3	1219	1885	41	1808
Fuel-to-Coolant Mass Ratio	8	3	2424	2402	109	2103
Fuel-to-Coolant Mass Ratio	30	3.96	4663	2812	94	2394
Vapour Blanketing	No	6.3	3915	2631	155	2483
MFCI Zone height, cm	23	3.5	4691	2623	217	2386

First Set : Fuel Radius = 100 u, Fragmentation & Mixing Time Constant = 0 ms, Slug Column Height = 160 cm, Fuel-to-Coolant Mass Ratio = 14.3, MFCI Zone Height = 10 cm, Vap Blanket = yes

Table 3: Results of the Parametric Study

Results	WP	n	E_{th}	E_{lo}	E_{mi}	E_{up}	E_{rc}	e_{lo}	e_{mi}	e_{up}	e_{hb}	RC_{li}	C_k	P_i	t_d	t_i	W	η
Ref Set	7.2	.77	922	1.1	.19	.44	.06	2.3	.53	1.4	3.6	1.7	7.2	1818	.03	.12	1.7	.19
t_m=0	9.9	1.1	922	2.5	.15	.61	.08	4.6	.45	1.9	4.9	2.3	9.9	2143	.03	.12	3.3	.36
rf 50	18.	2.0	922	9.3	.5	1.1	.16	12.	1.2	3.3	8.7	4.0	18.	2923	.03	.12	11.	1.2
w=8	5.1	.98	516	.05	.06	.31	.04	.32	10.	1.0	2.6	1.2	5.1	1530	.03	.12	.46	.09
v_0 30	5.4	-	532	.01	.04	.32	.04	.23	.14	1.1	2.8	1.3	5.4	1576	.03	.12	.54	.1
T_f 3500	8.4	.81	1041	1.9	.21	.51	.07	3.6	.58	1.6	4.2	2.	8.4	1969	.03	.12	2.7	.26
T_s 1000	6.9	-	922	1.0	.21	.42	.06	2.3	.55	1.4	3.5	1.6	6.9	1785	.03	.12	1.7	.18
hs 19	6.6	-	922	0	.02	.13	.02	.16	.07	1.6	1.4	.64	6.6	4248	.03	.00	.17	.02
hs 39	15	-	922	.11	.47	.13	.09	.41	1.1	.18	5.5	2.5	15	4413	.06	.00	.8	.09
tw=1	6.6	-	922	.41	1.3	1.11	.06	1.1	4.9	7.5	1.0	1.6	6.6	1716	.03	.12	2.9	.31
k=150 n=.2	7.21	-	922	1.1	0	.44	.06	2.3	0	1.4	3.6	1.7	7.2	1860	.03	.12	1.3	.17
σ_u 70	7.16	.77	922	1.1	.19	.44	.06	2.3	.53	1.4	3.5	1.7	7.2	1818	.03	.12	1.7	.18 9
M_m 23	7.17	.78	922	1.1	.22	.438	.06	2.3	.59	1.4	3.6	1.7	7.2	1819	.03	.12	1.8	1.9
M_u 7	7.16	.77	922	1.1	.19	.167	.06	2.3	.53	.56	3.6	1.7	7.2	1818	.03	.12	1.5	.16

t_m=fragmentation & mixing constant, ms ; rf=fuel size, u ; w=fuel-to-coolant mass ratio ; v_0= mixing zone volume; T_f=fuel temperature, K ; T_s=coolant temperature, K ; hs=slug height ; tw=vessel thickness

k,n = strain hardening parameters ; σ_u=holddown bolts yield strength ; M_m=mass of middle vessel portion ; M_u=mass of upper vessel portion ; WP=work potential,MJ ; η =efficiency, % ; E_{th}=Heat in fuel, MJ ; E_{lo}, E_{mi}, E_{up}, E_{rc} = energy dissipated , MJ, in lower, middle, upper vessel portions and reactor cover ; elo, emi, eup, ehb = strains , %, in lower, middle and upper vessel portions and holddown bolts ; RC_{li}=Cover lift, cm ; C_k=slug kinetic energy, MJ ; P_i=Impact Pressure, atm; t_d=period of impact, ms ; W=damage work , MJ ; η =efficiency of damage work, % ,t_i =Impact time, ms