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《Technical Note》

Review on Gas-Voiding Models for HCDA(Hypothetical Core Disruptive Accident) Initiating Phase in LMR Analysis (I)

W.P. Chang, Y.M. Kwon, D.H. Hahn, S.D. Suk
Korea Atomic Energy Research Institute
150 Dukjin-dong, Yusong-gu, Taejon 305-353, Korea
wpchang@nanum.kaeri.re.kr

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Abstract

The present review report introduces the existing analysis codes and physical modeling of two-phase flow associated with initiating event of HCDA in Liquid Metal Reactors for the effective study in the future, because the related research has not been systematically carried out in Korea compared with other areas. The description in this report is specifically addressed to the results yielded from careful review of the technical concepts on the two-phase flow modeling in the SAS2A code which was developed in ANL. The report is prepared in 2 parts based on the definite physical phenomena. The liquid slug and gas behavior models are main representations in the part (I) and (II), respectively. In this regard, it is expected that this report provide a fundamental knowledge on the two-phase flow model in LMR and, thus, contribute to establishment of the necessary HCDA analysis technology concerned with the LMR development in Korea.

Key Words : Gas-viding model, HCDA, LMR

1. Introduction

1.1. Background

Generally, boiling of the core coolant is not allowed for the inherent safety under DBE (Design Basis Event) in LMR (Liquid Metal Reactor) designs. Two-phase flow analysis in the coolant channel, however, should be considered for the initiating event of HCDA, which is classified as BDBE(Beyond Design Basis Event). The representatives of such accidents are UTOP (Unprotected Transient Over-Power), ULOF (Unprotected Loss Of Flow), ULOHS (Unprotected Loss Of Heat Sink), and Flow Blockage due to Malfunctions.

Nevertheless, information on both the analysis methodologies and relevant experimental data have not been available in Korea enough to set up an internal research strategy effectively for the LMR development, since no particular investigation on the physical phenomena or analysis models for HCDA in LMR has been carried out. The only technical review was found

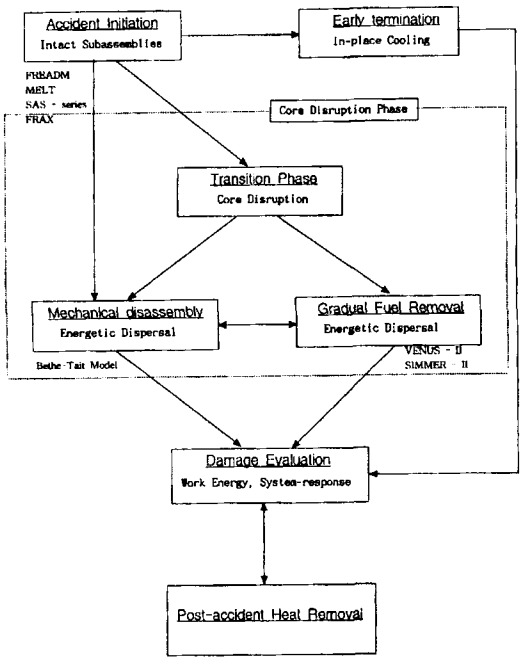

Fig. 1. Classification of HCDA Analysis for LMR

in the report [1] which overviews the HCDA analysis methodologies, licensing requirements, analysis results of CRBRP (Clinch River Breeder Reactor Plant) and ALMR(Advanced Liquid Metal Reactor), and future HCDA analysis trends, etc. The report, however, described only overall methodologies associated with HCDA and so it was not detailed technically enough to understand the anticipated phenomena or analytical models necessary for HCDA analyses.

To this end, the present review paper extends a part of the previous report to the specific topic by representing a detailed modeling on the two-phase flow in LMR. Thus, it must contribute to gaining physical insight of a basic idea behind modeling of the HCDA initiating events.

1.2. Scope of Analysis

HCDA is broken into four phases because quite different analysis techniques are required to solve different aspects of the overall problem[2,3]. Fig. 1 represents a schematic for the sequential analyses for HCDA in LMR. The initiation phase of this accident involves coolant flow rate decay, heat up and voiding of the hottest channels up to clad dryout, clad melting and relocation, and early fuel melting. The analyses in this phase have been identified with two other possibilities for the accident progression. Early termination may be possible if enough negative reactivity is introduced during an early stage when very little damage has been done to the core. On the other hand if a large amount of positive reactivity is initially inserted by sodium voiding and clad relocation, the accident may progress directly to hydrodynamic disassembly. Such a possibility can be ruled out for a small core size as for FFTF (Fast Flux Test Facility), but could be appeared in a larger core like that of CRBR[2]. The initiating phase analysis involves a calculation of the core neutronics and thermal behavior up to the point of loss-of-subassembly geometry. Early multichannel codes which were developed in the USA for initiating phase analysis were FREADM[3], MELT[3], and SAS series codes. On the other hand, the FRAX code developed in AEA, UK, is a well known code for this purpose in Europe. These codes were designed to provide a reasonable and conservative accounting of the reactivity effects during the initiating phase, in order to provide initial conditions for the core disassembly codes.

Beyond this point, it has become practice to identify this sequence of events with the "transition phase". The transition phase involves the stage of the accident between the time when substantial deviation of reactor core geometry begins to the time when a large amount of the fuel is finally removed from the core(or equivalently, the core become subcritical

permanently). The disassembly phase of the calculation is entered when a prompt critical excursion is included. The rapid heating and subsequent vaporization of the fuel produce high pressures that disassemble the core and terminate the power burst. However, a "transition phase" has also been identified as an entry point into this general core disruption phase. This transition phase is characterized by a gradual meltdown of the core. A number of variations and improvements have subsequently been made to this basic approach[4]. The improvements in Doppler feedback, equation-of-state used to estimate the pressure, implementation of more accurate neutronics, and the capability for calculations in two-dimensional (r, z) geometry were made. A number of disassembly codes have been developed in USA as successive improvements were made. One of the most representative codes in this phase are VENUS-II developed at ANL and SIMMER-II developed at LASL.

If a core disruptive accident is predicted to terminate via an energentic disassembly, it is essential to evaluate the response of the reactor primary system structure to any pressure pulses to which it might be subjected as a result of fuel vapor generated in the core. This phase is classified as 'Damage Evaluation Phase'. Thereafter, the final phase called "Post-accident Heat Removal Phase", is followed.

The present review report focuses on the two-phase flow phenomena and related models during the HCDA initiating phase, since the main concerns during the LMR accidents include the possibility to induce a recriticality event because of positive reactivity insertion, led by two-phase flow or core melting. Available information on the applicable extent of those codes for the initiating event, namely, SAS series and FRAX-5 codes, are first introduced briefly in the following section with some key phenomena to be modeled. Then, the main effort is made in introduction of the two-phase flow modelling represented in SAS2A. Detailed description of the governing equations, however, are precluded due to their complexity. Instead, physical meaning of each term comprising the equations are addressed. The report is finally ended with the description of discussions and conclusion which are led from the present review, after short information on the FRAX modelling.

The whole review report is divided into 2 parts, i.e. (I) and (II), based on definite physical phenomena. The present report is limited to description of the liquid slug, because content of the entire model is too large to be included in this compact report. The rest part may be continued in the next time and it will describe the review result of the gas behavior from the gas plenum or fission gases released through a ruptured point on the cladding to coolant channel together with calculation of the gas pressure distribution, etc. This is the reason why "(I)" must be put at end of the title and the next review report will be titled with putting "(II)" for consecutive description.

2. Summaries of the Codes for Initiating Event Analysis

2.1. SAS2A

SAS2A code[5] calculates the HCDA progresses from steady state pre-accident conditions up to the start of a disassembly that might result from initiating events in LMFBR(Liquid Metal Fast Breeder Reactor). Accidents related with power excursion due to reactivity insertion and abnormal flow coast-down in the core coolant channel are the representatives for HCDA analyses. The basic calculational model used in SAS2A was designed to treat the

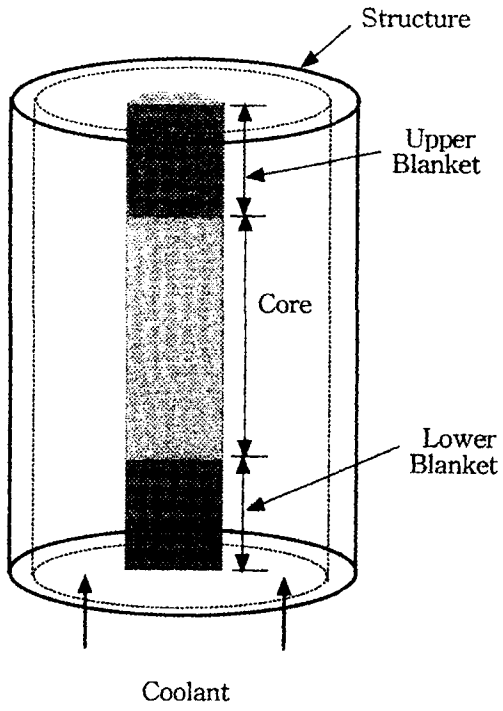

Fig. 2. A Fuel Rod, Coolant Channel, Structure

configurations most commonly found in the current large LMFBR reactors. This includes reactor cores ranging from extreme pancake designs to those having ratios of length to diameter closer to one and having axial and radial breeding blankets. The accident is predicted under the assumption that the behavior of the entire core can be represented by up to 10 fuel pins and their associated coolant as shown Fig. 2. In addition to the core and blanket regions, the code also treats thermal-hydraulic aspects of gas plenum above the upper blanket, and of reflectors above the gas plenum and below the lower blanket. The calculational model is based on the assumption that the core fuel elements and coolant channels are essentially intact until the disassembly calculation is started. Reactivity effects due to fuel slumping, however, can be modelled using point-kinetics model. When the fuel melts down after the disassembly and power burst resulting from the prompt critical occurs, the phenomena should be calculated using completely different codes. This period is called transition phase and SIMMER-II, updated version of SIMMER-I[3] or VENUS code[3] are usually used to calculate total energy release during this phase. Since these codes are proprietary codes by the code developing countries, sufficient information is not available in Korea.

2.2. SAS3A

Since SAS2A version had some limitations, for example, behaviors of the gas in the gas plenum and vapor and it addresses the core related models, the updated SAS3A version[4] had been developed to provide more general models up to the disassembly including fuel pin damage for the initiating phase. In addition, the calculations have been improved in initial conditions such as radius of the irradiated fuel in the restructured region, fuel expansion, cladding expansion, and fission gas release and retention from SAS2A. Fuel-coolant interaction model has been added and for cases which proceed to an energetic core disassembly, the new models provided and improved definition of core conditions and reactivity insertion rate at the time of a transition to VENUS-II[3].

The new capabilities provided by SAS3A include a primary loop hydraulics model, a fuel-coolant-interaction model for transient overpower conditions, a new moving-film treatment in the multi-bubble sodium boiling model, and cladding and fuel motion models for voided assemblies in a loss-of-flow accident. To verify further the boiling model, a pretest analysis was made of the TREAT R5 seven-pin LOF experiment[6]. The coupling between the primary system and the core are

numerically explicit at the inlet and exit to each channel rather than immplicit or iterative. The first major application of this code was to the study of the ULOF of the FFTF reactors. Since this study, it has been applied extensively to the analysis of the ULOF and UTOP for the CRBR(Clinch River Breeder Reactor)[7.8] and in a preliminary fashion to the analysis of these same accidents for 1000 MW(e) and larger LMFBRs[9,10]. The SAS3A has then been updated into the SAS3D in two points. Implementation of a generalized data management technique permits it to treat an unlimited number of channels, while a substantial rearranging effort has resulted in a doubling of its running speed over SAS3A. These codes, however, do not show a reasonable prediction in the sodium void reactivity model and thus SAS4A has been developed to improve the model.

Cladding Relocation in Voided Subassemblies

In analysis of the loss-of-flow (LOF) accident for FFTF[11] it was recognized that, under the expected relatively constant power conditions, cladding would melt some 2~3 sec prior to fuel melting in the first subassemblies to void. Thus, it was reasonable to assume that the molten cladding would relocate, possibly moving out of the heated region, freezing, and plugging. The cladding relocation model uses explicit calculation of the motion of molten clad consistent with the sodium-vapor-pressure-gradient model. Physically one of discrete clad segments which can combine by moving over other clad segments. Each segment moves under the influence of gravity, the channel pressure gradient, the frictional drag due to streaming sodium vapor, and friction between moving clad and the fuel pin, as shown in Fig. 3.

Fuel Motion in Voided Subassemblies

In an ULOF accident, only fuel removal from the core region can terminate the accident. Thus,

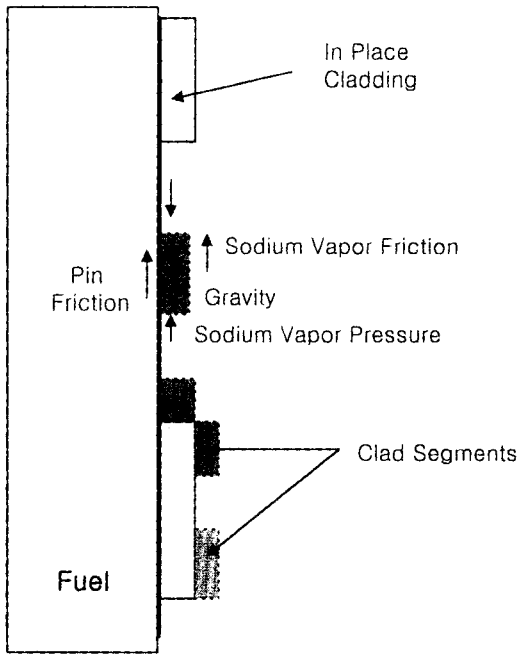

Fig. 3. SAS3A Cladding Relocation Model

fuel motion is a very important phenomenon and must be modeled explicitly in a CDA (Core Disruptive Accident) analysis code. For this reason, the fuel motion model was developed for SAS3A. A conceptual representation of the assumed motion geometry is shown in Fig. 4. The model provides a compressible-hydrodynamics calculation of fuel motion under the influence of gravity, sodium vapor, fission gas, friction, steel vapor and fuel vapor driving forces. It can be used either to supply detailed initial conditions to a VENUS-II two-dimensional disassembly calculation, or it can be used directly as a disassembly code within the limitation of one-dimensional motion. As the fuel melts, individual axial fuel segments join the "slumped" region treated in the model calculation. The unmelted fuel above the slumped region can fall into for be pushed out of this slumped region. The unmelted pin below the slumped region is assumed to be stationary. The boundary conditions may be

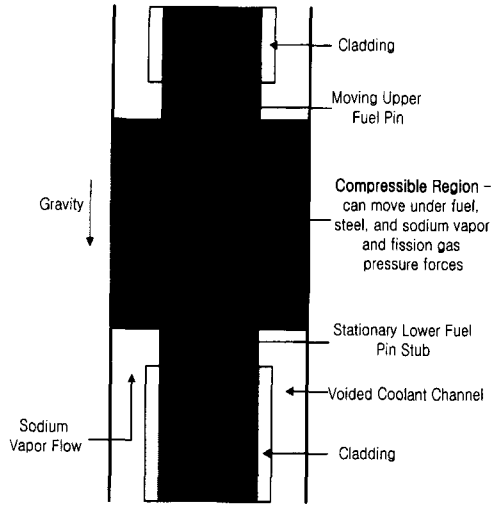

Fig. 4. SAS3A Fuel Motion Model

determined by the time-dependent positions of calculated clad blockages.

Fuel-Coolant Interactions

This model was originally developed to treat pin failures into flowing sodium in UTOP accidents. The model is based on the concept of a pressurized cavity in the fuel pin expelling a molten fuel-fission gas mixture through a cladding rip and into an interaction zone in the coolant channel, where the fuel fragments and rapidly transfers heat to the flowing sodium. The sodium vapor that is formed plus any fission gas that has escaped the fuel pin pressurize this interaction zone and thus cause rapid voiding of the channel, particularly in the upwards direction.

The fuel pin cavity model treats the cavity as having an axially-uniform composition and pressure. Any fuel melting into the cavity is homogenized over the entire cavity length. The mixture of molten and solid fuel particles and fission gas is ejected into the coolant stream through a cladding rip whose fixed length is user-specified. The ejection model uses the time-dependent Bernoulli equation to compute the ejection rate. Once in the coolant stream, the fuel is assumed to interact with the coolant according to a modified Cho-Wright enthalpy equation.[12] The pressure in the interaction zone is assumed to be uniform axially. The interaction zone is constrained by the incompressible liquid sodium slugs above and below it.

2.3. SAS3D

The SAS3D code represents a substantial modifications of the SAS3A code. These include the ability to couple the steady-state fuels characterization and thermal-hydraulic models in SAS3D to a consistent three-dimensional steady-state neutronics model, as well as improvements in the steady-state fuels categorization algorithm and the transient fission gas release models. In purely computational improvements, a flexible data management strategy which permits treatment of an essentially unlimited number of channels has been implemented, along with improvements in coding style which have speeded up the execution of SAS3D. In the previous versions of SAS, the user had the responsibility to provide, all neutronics-related input such as power distributions, reactivity coefficients, and point kinetics parameters. The most significant conceptual improvement in SAS3D relative to SAS3A is the addition of a capability to consistently couple the SAS3D steady state fuels characterization and thermal-hydraulic models to a three-dimensional neutronics treatment.

SAS3D code permits two geometric modeling options, both of which consider the entire reactor. In the first, subassemblies are assigned to radial locations in a two-dimensional, azimuthally-symmetric (r-z) neutronics model which preserves the subassembly volume. In the second type of

geometric model available in the code, every subassembly is represented explicitly in a three-dimensional hexagonal-z representation. It is known that other model improvements have been implemented in SAS3D. These includes a reformulated axial expansion reactivity feedback algorithm, implementation of a two-stage steady-state fuel swelling algorithm which permits early closure of the fuel-cladding gap, etc.[3].

2.4. SAS4A

From the examination of the scenarios generated in LMFBRs of the size of CRBR and larger, It has become obvious that the SAS3A does not adequately model three key phenomenological sequences, thus indicating that additional model and code development must be done. These model deficiencies are : (a) disruption of fuel and cladding in voided subassemblies under LOF conditions and their subsequent interaction with streaming sodium vapor and fission gas, (b) pin failures into flowing sodium in unvoided or partially-voided subassemblies under overpower conditions and (c) time-and space-dependent changes in the neutron flux distribution brought about by gross material relocation.

Studies of the LOF accident in CRBR[9] have indicated that fuel motion in such an accident would, in general, begin before molten cladding has been relocated sufficiently to freeze and block the channel. In larger LMFBRs with even larger overall sodium voiding reactivities, fuel and cladding would melt and begin to relocate practically simultaneously due to the rapid pressure rise brought on by the initial sodium voiding. In this complex scenario, which is evolving under conditions of rising power, it is necessary to treat in an integrated fashion the sodium vapor dynamics and any fission gas present and their interaction with the molten fuel and cladding. Another important point would be the axially-dependent mixing of fuel with any remaining cladding and the subsequent axial energy equilibration through mass transport of steel and fuel vapor relative to the solid and liquid mixture components.

A phenomenological sequence where model development effort is needed occurs in the low power subassemblies in LOF scenarios where a voiding-induced burst causes overpower-type pin failures to be predicted to occur in many partially-voided or unvoided subassemblies in rapid succession. This is the so-called LOF-driven TOP. The energetics for these scenarios tends to be dominated by the fuel motion and sodium accelerations resulting from fuel-to-sodium energy transfer. Important phenomena to be treated here include the initial cladding failure characteristics and any time-dependent melting of fuel and fission gas evolution, the subsequent accelerations of this mixture both within the pin and into either flowing sodium or a voided region, and the momentum and energy transfer mechanism which determines cooling rates and fuel motion in the coolant channels.

In order to terminate a HCDA, it would generally be necessary to relocate fuel. Concern has been expressed that a neutronics model based on first-order perturbation theory might be inadequate for predicting the reactivity state of a larger LMFBR in which the HCDA sequence involves substantial fuel relocation. In such cases, a neutronics model capable of accounting for significant space-time effects would be desirable to alleviate concern, thus suggesting a third model development area for SAS4A. The channel concept of the earlier SAS codes is retained in SAS4A. However, following the lead of the SAS3D code, up to 35 channels are available. The steady-state fuels characterization module is being upgraded so that it can account for the time-

dependent power history of each axial fuel node in determining the restructuring, gas retention and other nodal characteristics.

Primary Loop Thermal-Hydraulics

The 4-loop primary thermal-hydraulics system can be modelled from a single loop, so as to model the pipe rupture.

Space-Time Neutronics

The SAS4A neutronics model contains as options the neutronic capabilities of both SAS3A and SAS3D, but also includes a multidimensional quasi-static space-time diffusion theory model. This multi-dimensional capability implemented in SAS4A permits to obtain the two- or three-dimensional flux shape calculations for both the steady-state eigenvalue and transient inhomogeneous solutions.

Integrated Voiding, Plenum Fission Gas Release and Cladding Relocation

One significant change is in the treatment of the re-entry of cold sodium over hot clad in the lower core region during the sodium chugging phenomenon which follows complete voiding. Here, an attempt is being made both to stabilize the numerical treatment so that the voiding dynamics time steps will not have to be cut so drastically, and to better simulate the lower amplitude chugging behavior observed in TREAT LOF simulations. The previous SAS version to treat the release of plenum fission gas through a breech in the clad into the coolant channel. However, this release is permitted to occur only into flowing sodium or into an existing fission gas bubble in the channel, since a bubble in these codes must be either a sodium vapor bubble or a fission gas bubble. Recent calculations indicate that any fission gas released would mix with the sodium vapor in the voided region so that the compressible treatment of vapor flows in such a bubble in SAS4A includes a fission gas continuity equation as well as total momentum and continuity equations.

Cladding relocation model also has improved to permit reactivity calculation to moving cladding.

Fuel Motion in Voided Subassemblies

In reactors with positive sodium voiding reactivity, fuel motion could be significantly influenced by the mixing of axially-varying quantities of molten steel and the influence of the high-velocity flowing sodium vapor. A more sophisticated fuel motion model is thus required in order to treat these phenomena adequately. SAS4A treat hydrodynamics of the fuel, steel and fission-gas motion in the remaining coolant channels and in the axial region in which the pins are disintegrated. This dynamics calculation treats three moving numerical fields, each defined by its own unique velocity at a given axial location. These fields are a moving liquid fuel-steel mixture or a liquid steel film field, a vapor-gas consisting of fuel vapor, steel vapor, sodium vapor, and fission gas field, and the non-melted fuel chunks which result from fuel pin disruption at high power.

Others

The improvement has been made in the areas of fuel pin dynamics and failure, the fuel pin failures in unvoided or partially-voided subassemblies, etc. As results of these improvements, most of molten fuel behaviors limited in the previous SAS version have been resolved significantly. However, SAS4A is still limited in several ways in its ability to describe event sequences in postulated HCDA. For example, the data base on transient fuel behavior at high power, significant subassembly-to-subassembly thermal and mechanical interactions, and treatment of intra-subassembly

incoherence. The mode verifications based on experimental data are also included.

2.5. FRAX-5

FRAX-5 code had been developed in AEA, UK in order to analyze accident scenarios of UK or European developing Liquid Metal Reactors during the initiating events similarly as SAS4A, since 1984, starting with FRAX-3 and approximately 30~40 man-years had been invested for completion of the recent version, FRAX-5D in 1993[13]. Initiation phases codes, such as FRAX, model the progression of an WCA(Whole Core Accident) from an initiating event up to the formation of molten pools where 1-D motion dominates[14]. Two-phase flow modelling is also similar as SAS and module Homsep-2 can calculate fully heterogeneous two-phase flow with stand along version or it can be coupled with FRAX as well. Similar assumptions used in the SAS such as a maximum of ten vapour bubbles in the sodium channel at any one time, a vapor bubble cannot form within half an axial segment lenghth of an existing vapour bubble, and two adjacent vapour bubbles are assumed to coalesce if the length of sodium slug between them falls below a user specified minimum. etc. are applied. The model validation was carried out in two stages (a) against Cabri TUCOP(transient under cooled over powered), (b) benchmarking validation against other individually experimentally validated codes in a whole-core accident, loss of flow(LOF), comparative studies exercise[15].

The inlet and outlet pressure conditions and an incompressible sodium slug approximation are used in the calculation. The governing equations are two mass equations, two momentum equations, and one energy conservation equation. As a result of analysis of CABRI B15 experiment, despite continual vapour buble formation, bubble collapse ensures that the number of vapour bubbles in the sodium channel oscillates between only tow and three. It could be well predicted by the FRAX. Homsep-2 assumes sodium film is simply stationally and approximates the differential equations with finite difference equations and semi-implicit is used. It resulted in numerically stable and effective method to obtain the fast solutions.

3. Basic Hydraulic Equations for Two-Phase Flow in the SAS2A

Voiding model for two-phase flow simulation assumes to consist of multiple-bubble and bubble slug and liquid slug as shown in Fig 5. Each coolant channel is represented by a fuel pin with the related coolant and structure, as seen in Fig. 2.

Voiding is assumed to result from the formation of bubbles that fill the whole cross section of the coolant channel that is left on the cladding and structure. Up to nine bubbles, separated by liquid sugs, are allowed in a channel at any time. Each bubble can contain any one of sodium vapor, fission-product gas released by a failure of the fuel-pin cladding, or sodium vapor plus enough fission-product gas to inhibit condensation of sodium vapor.

The liquid film left on the cladding and structure is assumed to be a static film whose thickness varies only due to vaporization and condensation. Fig.5 represents the modelling.

Mass Flow Rate for Liquid Slug and Motion of Bubble-Slug Interface

Continuity and momentum conservation equations for a liquid slug to represent the flow rate and bubble interface motion are given as;

Continuity

$$\frac{\partial \rho_l}{\partial t} + \frac{\partial G}{\partial z} = 0 , \quad (1)$$

where

ρ_l = liquid density

G = mass flow rate (Kg/m^2 · s)

Momentum

$$\frac{\partial G}{\partial t} + \frac{\partial}{\partial z}\left[\frac{G^2}{\rho}\right] + \frac{\partial P}{\partial z} + g\rho + \left(\frac{\partial P}{\partial z}\right)_{fr} = 0 \quad (2)$$

where

g = accelerational gravity,

P = pressue,

and

$\left(\frac{\partial P}{\partial z}\right)_{fr}$ = friction pressure gradient

The friction gradient is

$$\left(\frac{\partial P}{\partial z}\right)_{fr} = \frac{f_l(Re)G|G|}{2\rho_l D_h} , \quad (3)$$

and the friction factor is defined as $f_l\,(Re) = A\,(Re)^b$, where A and b are input quantities. D_h = effective diameter of the channel, Re = Reynolds number = $(D_h G)/\mu$, and μ = viscosity of the liquid.

The momentum equation is treated in integral form. If a liquid sulg extends from $z = z_b$ to $z = z_t$, then Eq. (2) is integrated over this range and gives

$$L\overline{\frac{\partial G}{\partial t}} + \frac{G_t^2}{\rho_t} - \frac{G_b^2}{\rho_b} + P_t - P_b + g\int_{z_b}^{z_t}\rho(z)dz + \int_{z_b}^{z_t}\left(\frac{\partial P}{\partial z}\right)_{fr}dz + \Delta P_{end} = 0 \quad (4)$$

where

$$L\overline{\frac{\partial G}{\partial t}} = \frac{\int_{z_b}^{z_t}\frac{\partial G(z,t)}{\partial t}dz}{z_t - z_b} \quad (5)$$

and it corresponds to averaged momentum change within liquid slug, and $L = z_t - z_b$ defined as the length of liquid slug. The Pressure P_b and P_t are determined either by the lower and upper coolant-plenum pressure or by the interface pressures in the bubbles below and above the liquid slug. ΔP_{end} in Eq. (2) accounts for pressure drop due to flow-area expansion or contraction at the end of the subassembly and due to an orifice at the subassembly inlet.

Incompressible flow is assumed in calculating the motion of a liquid slug, and variations in mass flow rate within a liquid slug are ignored. To obtain a discretized form of Eq. (4) for a finite time step Δt, define the average value, $\overline{F}$ of any time-dependent term $F(t)$ as $\overline{F} = 1/2\,[F(t+\Delta t) + F(t)]$ and by use of the definition $F(t + \Delta t) = F + \Delta F$ for most of the time-dependent functions F(t), the resultant mass flow rate within a liquid slug finally reduces to the following algebraic equation throughout complex derivations:

$$\Delta G = \frac{-[A_0 + (\Delta P_t - \Delta P_b)/2]\Delta t}{L + \frac{\Delta L}{2} + B_0\Delta t} \quad (6)$$

Where, A_0 and B_0 are equations defined during the derivation of Eq. (16), and detailed description will be found in the reference [4]. ΔL corresponds to $v\Delta t$ for the upper slug and does $-v\Delta t$ for the lower slug. Otherwise, it is 0(zero).

The values of $\overline{P}'$s are obtained from a coupling of the slug calculations with the bubble calculations to be described later and the interface velocity v_i is not defined yet. Thus, complete $G(t + \Delta t)$ is finally obtained after calculations of the interfacial velocity and the pressure distribution.

Interface Motion

When a region is voided, a liquid film of initial thickness, w_{f0} is left on the cladding and structure in the voided region. The film thickness can be changed due to vaporization or condensation, and film dryout can occur in hotter regions of the core. When a liquid slug reenters a voided region, the film thickness is assumed to be restored to its intial value. Thus a short liquid slug reentering a voided

region where film dryout has occurred should shrink and may disappear as it rewets the cladding. This shrinking is an appreciable effect only for a shor liquid slug intermediate between two bubbles. This shrinkage effect is ignored for the upper (outlet) and lower (inlet) liquid slugs. For intermediate liquid slugs, the shrinkage effect is accounted for by adjusting the interface velocities. Thus, the interface velocities, v_i for bubble K are given by

$$v_i(K, L = 1) = \frac{G(K)}{\rho_K} F_{rwt}(K) \quad (7)$$

$$v_i(K, L = 2) = \frac{G(K+1)}{\rho_{K+1}} F_{rwt}(K+1) \quad (8)$$

where L = 1 for the bubble-liquid interface at lower end of bubble, L = 2 for the interface at upper end of bubble, and $G(K)$ is mass flow rate for liquid slug K as shown in Fig. 5. In addition, $\overline{\rho_K}'$ s are densities for inlet and outlet liquid slugs and $F_{rwt}(K)$ has 1.0 for inlet and outlet slug. However, for intermediate slug, $F_{rwt}(K)$ and $F_{rwb}(K)$ are defined as

$$F_{rwt}(K) = 1 \text{ if } G(K) < 0 \quad (9)$$

$$F_{rwt}(K) = 1 - \frac{2\pi r_e}{A_c}[w_{f0} - w_{fei} + \gamma_2(w_{f0} - w_{fsi})] \text{ if } G(K) \geq 0 \quad (10)$$

and

$$F_{rwb}(K) = 1 \text{ if } G(K) \geq 0 \quad (11)$$

$$F_{rwb}(K) = 1 - \frac{2\pi r_e}{A_c}[w_{f0} - w_{fei} + \gamma_2(w_{f0} - w_{fsi})] \text{ if } G(K) < 0, \quad (12)$$

defined depending on the flow direction, where w_{fei} and w_{fsi} are the thicknesses of the liquid film on the cladding and structure, respectively, at the appropriate bubble-liquid interfaces. The term $2\pi r_e [(w_{f0} - w_{fei}) + \gamma_2 (w_{f0} - w_{fsi})]$ corresponds to total film thickness variation in the channel. Thus, variation of this value leads to change of liquid

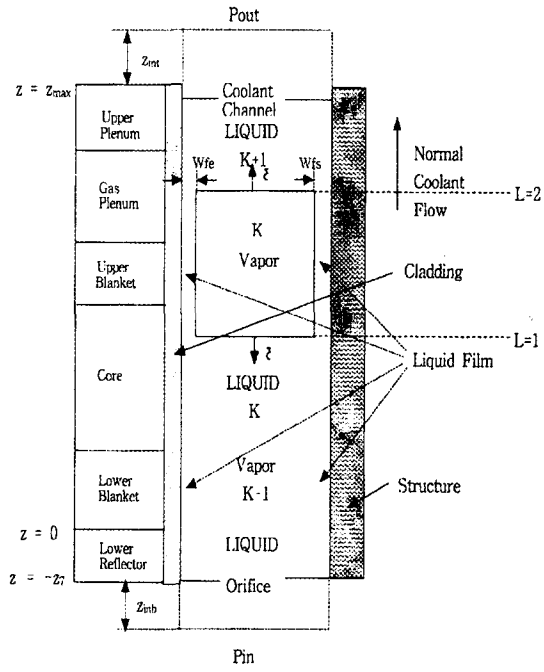

Fig. 5. Two-phase Flow Model in SAS2A

mass passing the interface and then the interface velocity is modelled such that it increases or decreases due to flow area change rate. Note that bubble K is above liquid slug K and below liquid slug K+1 as seen in Fig. 5.

In this manner, after ΔP_b and ΔP_l which are related with a bubble pressure are determined, the mass flow rate can be calculated, but the pressure distribution within a liquid slug has not been calculated yet.

Pressure Profile in Liquid Slugs

At the end of a time step (time=t + Δt), after the mass flow rates and bubble pressures of a liquid slug have been claculated, the pressures and corresponding saturation temperatures at axial nodes within liquid slugs are calculated.

For each liquid slug, the instantaneous rate of change of the mass flow rate $dG(t+\Delta t)/dt$. Then, if the liquid slug is the upper slug, the effects at the

subassembly exit are accounted for. The pressure at the upper end of the liquid slug, P_u, after removing the pressure loss at the end of the subassembly, is calculated as

$$P_u = P_t(t+\Delta t) + \frac{G|G|k_t}{2\rho_t} + \Delta z_{tot}\frac{dG(t+\Delta t)}{dt} \quad (13)$$

for the upper slug, or

$$P_u = P_t(t+\Delta t) \quad (14)$$

for other liquid slugs. The pressures in the slug are then calculated, starting at the top and working down using $dG(t + \Delta t)/dt$.

Temperature of Liquid Coolant

The basic equation used for conservation of energy in a liquid slug is

$$\rho_t c\frac{\partial T_c}{\partial t} + Gc\frac{\partial T_c}{\partial z} = \gamma\phi(z,t) + Q_c(z,t) \quad (15)$$

and it is non-conservative form. Where, H = enthalpy, γ = surface area of cladding/volume of coolant, ϕ = heat flux from cladding and structure, Q_c = volume source due to direct heating by neutrons and gamma rays (W/cm^3), C = heat capacity, T_c = coolant temperature, and $dH = cdT_c$. Note that almost all the coolant variables are channel-dependent, but the channel dependence is not explicitly indicated in most of these equations. In the gas plenum and reflector regions, $Q_c = 0$. In any voided region of the core or blankets, the fraction γ_c of total power is added to the heat source in the fuel.

Two computational schemes are available in SAS2A for computing transient temperatures in the liquid coolant: (1) an Eulerian scheme and (2) Lagrangian scheme. Normally, the Eulerian calculation is used before voiding starts. Also, this method is used after voiding starts for the inlet liquid slug until flow reversal occurs. After boiling starts, the Lagrangian calculation is used for all liquid slugs other than the inlet slug, and for the inlet slug after the initial flow reversal has occurred. Optionally, the Lagrangian calculation usually more accurate for high coolant flow rates and large time steps. If the coolant flow rate is very small, as in a flow-blockage case, then the Lagrangian calculation is more accurate.

For the Eulerian calculation, approximating the derivatives in Eq. (15) is given by:

$$\frac{dT_c}{dt} = \frac{1}{2}\left\{\frac{[T_c(z+\Delta z,\ t+\Delta t) - T_c(z+\Delta z,\ t)}{\Delta t} + \frac{[T_c(z,\ t+\Delta t) - T_c(z,\ t)}{\Delta t}\right\} \quad (16)$$

On the other hand, the Lagrangian calculation rewrite the basic equation for the liquid temperature as:

$$\rho c\frac{dT_c}{dt} = \gamma\varphi(z,\ t) + Q_c(z,\ t) \quad (17)$$

Where the Lagrangian total time derivative dT_c/dt, as seen by an observer moving with the coolant velocity, is used. This derivative is approximated by:

$$\frac{dT_c}{dt} = \frac{T_c(z,\ t+\Delta t) - T_c(z-\Delta z,\ t)}{\Delta t} \quad (18)$$

The Lagrangian calculation is used to calculate liquid coolant temperatures both at the fixed axial mesh points and at moving points near the liquid-bubble interfaces. Axial heat conduction through the interface is ignored in the calculation of the interface liquid temperatures.

Since these temperature equations form complex algebraic equations and physical meaning has been already described, the detailed derivations of these equations are ignored in this report and readers may refer the details in reference[4].

4. Basic Thermal-Hydraulic Equations in the FRAX-5

Thermal-hydraulic governing equations in FRAX

are described using 5 equations, namely, 2 mass, 2 momentum, and 1 energy conservation equations. The assumptions and modelling in a channel basically similar to SAS.

Mass

for liquid phase :

$$\frac{\partial}{\partial t}(1-\alpha)\rho_l + \frac{1}{A}\frac{\partial W_l}{\partial Z} = -\Psi \qquad (19)$$

for gas phase :

$$\frac{\partial}{\partial t}(1-\alpha)\rho_v + \frac{1}{A}\frac{\partial W_v}{\partial Z} = \Psi \qquad (20)$$

Momentum

for liquid phase :

$$\frac{1}{A_l}\frac{\partial W_l}{\partial t} + \frac{1}{A_l}\frac{\partial}{\partial Z}\left(\frac{W_l^2}{\rho_l A_l}\right) = \qquad (21)$$

$$-\frac{\partial P}{\partial Z} - \rho_l g - \frac{W_l^2}{2\rho_l A^2}\left(\frac{f_l}{D}(Re) + \sum_i \lambda_i(Re)\delta(Z-Z_i)\right)$$

for gas phase :

$$\frac{1}{A_v}\frac{\partial W_v}{\partial t} + \frac{1}{A_v}\frac{\partial}{\partial Z}\left(\frac{W_v^2}{\rho_v A_v}\right) = -\frac{\partial P}{\partial Z} - \frac{W_v^2 \gamma_v^2}{2\rho_v A^2}$$

$$\left(\frac{f_v}{D}(Re) + \sum_i \lambda_i(Re)\delta(Z-Z_i)\right) + \frac{W_v}{\rho_v A_v}\Psi \qquad (22)$$

Where $A_l = (1-\alpha)A$, $A_v = \alpha A$, and these are flow areas for liquid phase and vapor phase, respectively. $f_l\,(Re)$ is friction factor for each phase and lambda $\lambda_i\,(Re)$ corresponds to singularity pressure drop at singularity point, expressed as:

$$\int_x^y f(Z)\delta(Z-Z_i)\,dZ = f(Z_i) \quad \text{if} \quad x \le Z_i \le y \qquad (23)$$
$$= 0$$

For the liquid phase, momentum lost/gained due to vaporization/condensation is ignored and for the vapour phase gravity is ignored. In the vapour phase it is assumed that any vapour gained due to vaporization has an initial velocity equal to the bulk vapour velocity. The sodium liquid film is assumed to be static. Hence, there is no momentum equation required for the liquid film.

Energy Conservation

As thermal equilibrium between the sodium vapour and liquid is assumed, only one energy equation is required and is obtained by adding together the two separate energy equations. No mechanical energy terms are included.

$$\frac{\partial}{\partial t}(\rho_l(1-\alpha)h_l + \rho_v\alpha h_v) + \frac{1}{A}\frac{\partial}{\partial Z}(W_v h_v + W_l h_l)$$
$$= Q + \Phi S/A \qquad (24)$$

Where, Φ = wall heat flux, S = cladding outer perimeter.

The liquid film on the cladding is initially set to a user specified thickness. Subsequent vaporization/condensation can then decrease or increase the thickness of the film. Thermal equilibrium between the sodium film and vapour is assumed at all times. Entrainment of the liquid film by the sodium vapour is not explicitly modelled. However, it has been shown in other studies[16] that triggering dry-out when the film reaches two thirds of its original thickness. When a liquid slug passes through an axial segment, whether or not it is dried out, rewetting is allowed and the film is restored to its original thickness.

5. Discussion and Conclusions

The present review has been performed to provide basic concepts such as a brief idea on existing codes or some physical models on the HCDA initiating phase analysis for establishment of an effective HCDA analysis strategy in LMR development in Korea.

It has been identified that the models in SAS2A are not adequate for the HCDA analysis with the present status, because it was developed in 1970 so that it used rather simplified thermal-hydraulic models and, thus, they could not be applied for general purpose. The typical examples are bubble generation and motion, flow regimes, governing

equation formulations, and solution methods. As enough validation for the models is not carried out in Korea, the reliability of the code prediction is still unknown. In addition, this code cannot be applied to the entire initiating events because proper progress models for HCDA analysis during the initiating events, such as motions of molten fuel and cladding failure processes with post-failure behavior, are not incorporated. Hence, a code capable of modelling the propagation of disassembly with experimental data for the validation should be introduced in order to analyze complete HCDA initiating event..

On the other hand, SAS4A and FRAX are considered as much advanced codes in this area and may be an option for the analysis, but both codes model oxide fuel and, therefore, their various modules should be modified and verified for application to matallic loaded LMRs such as KALIMER (Korea Advanced Liquid Metal Reactor) [17].

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