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System Transient Analysis Code for Advanced Liquid Metal Reactor

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Abstract

The SSC-K code has been used as the principal tool for analyzing a variety of off-normal conditions or accidents in the preliminary KALIMER design. The SSC-K code features a multiple-channel core representation coupled with a point kinetics model with reactivity feedback. It provides a detailed, one-dimensional thermal-hydraulic simulation of the primary and secondary sodium coolant circuits, as well as a balance-of-plant steam/water circuit. The SSC-K contains detailed models for a passive decay heat removal system and a generalized plant control system. Particularly, a two-dimensional hot pool model is incorporated into SSC-K for analysis of thermal stratification phenomena in the hot pool. A long-term cooling method is developed as a stand-alone model and it will be included in the SSC-K. This paper presents an overview of recent activities concerned with the SSC-K code model development, and focuses on descriptions of the newly adopted thermal hydraulic and neutronic models.

1. Introduction

The Korea Atomic Energy Research Institute (KAERI) is developing a conceptual design of KALIMER (Korea Advanced LIquid MEtal Reactor) [1], which is a sodium cooled, 150 Mwe, pool-type reactor. The primary heat transport system (PHTS) of KALIMER is submerged in a big sodium pool, which provides a large thermal inertia of the system. KALIMER, with a metallic fueled core, is designed in such a way that an intrinsic negative reactivity feedback effect is expected during the anticipated transients without scram (ATWS) conditions. KALIMER features such safety systems as a self-actuated ultimate shutdown system (USS), and gas expansion module (GEM) in the core. In the rare event that the intermediate heat transport systems (IHTS) become unavailable during power operation, the passive decay heat removal system (PSDRS) is designed to remove the core heat by natural circulation of air around the containment vessel.

The SSC-K [2] code is being developed for assessment of inherent safety features in the KALIMER conceptual design. The role of SSC-K is aimed at not only extensive analysis capability and flexibility, but also efficiently fast running enough to simulate long transients in a reasonable amount of computer time. The code thus becomes capable of handling a wide range of transients, including normal operational transients, shutdown heat removal transients, and hypothetical ATWS events. The SSC-K code is currently being used as the main tool for system transient analysis in the KALIMR development project.

2. System Analysis Code SSC-K

2.1 General Description

The SSC-K is based on the methods and models of SSC-L [3], as its parent code, that was originally developed at Brookhaven National Laboratory to analyze loop-type liquid metal reactor (LMR) transients. Because of the inherent difference between the pool and loop designs, major modifications to the SSC-L have been made in order to analyze thermal hydraulic behavior within the pool-type reactor. Now, the SSC-K code has the capability to analyze both LMR designs, loop and pool type reactors. Additional developments in the SSC-K code include models for reactivity feedback effects for the metallic fuel, and the PSDRS. Recently, a two dimensional hot pool model has also been employed into SSC-K for analyzing the thermal stratification phenomenon in the hot pool. The control system model in SSC-K is flexible enough to handle any control system. For code maintenance and readability, SSC-K was converted to FORTRAN 90 free form and the use of standard FORTRAN 90 has enhanced code portability. Now, SSC-K version 2 is available and maintained in a PC/Windows environment. The SSC-K code also has been applied to the computational engine for interactive simulation of the KALIMER plant.

2.2 Pool Thermal Hydraulic Model

The SSC-K code simulates multiple heat transport system modules and associated controllers. A full plant model for SSC-K is used to represent KALIMER as shown in Fig.1 in which several major components are represented. Each PHTS is represented by reactor vessel flow passages, the primary pump, and the shell side of the IHX. Each IHTS is represented by the tube side of the IHX, piping, the shell side of the steam generator (SG), and the intermediate pump.

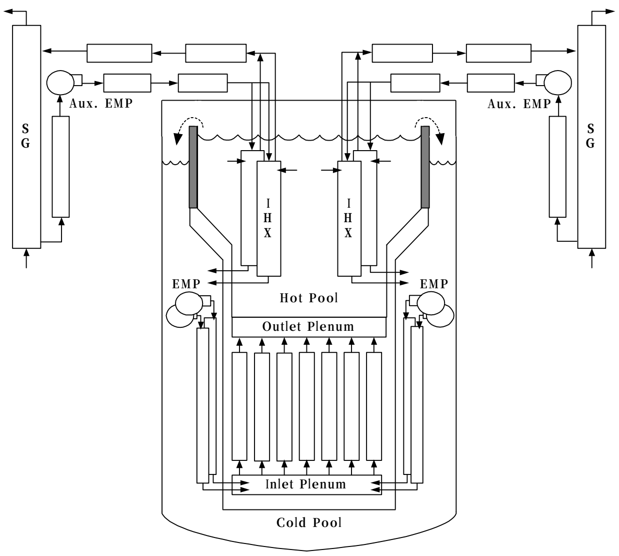

Fig.1 SSC-K modeling for KALIMER plant

Major modifications of SSC-K have been made in order to analyze the thermal hydraulic behavior within the pool. In KALIMER, both the hot and cold pools have free surfaces and there is direct mixing of the coolant with these open pools prior to entering the next component. Therefore, at least two different flows would have to be modeled to characterize the coolant dynamics of the primary system. The flow from the pump to core inlet plenum would respond to the pump head and losses in that circuit. The pump inlet pressure can be obtained by calculating the elevation head for the cold pool sodium level. It is obtained by solving coupled differential equations derived by mass and momentum conservation at the core inlet plenum.

Pipe rupture can only happen in the pump discharge line to the reactor. When a pipe break occurs, an additional equation is needed to describe the break flow. The external pressure for the break corresponds to the static head of the cold pool. This pressure acts as the back pressure opposing the flow out of the break. The IHX flow is determined from the level difference between the two pools, losses and gravity gains in the IHX.

The SSC-K core region is divided into parallel channels, and each one represents a subassembly or a group of similar subassemblies. The whole length of a subassembly, from coolant inlet to coolant outlet, is represented by a channel. Usually an average rod within a subassembly is modeled, but it is possible to represent a hot subassembly instead. Figure 2 shows the radial and axial slice of a fuel channel used for temperature calculation. Each axial segment is divided radially into several sections

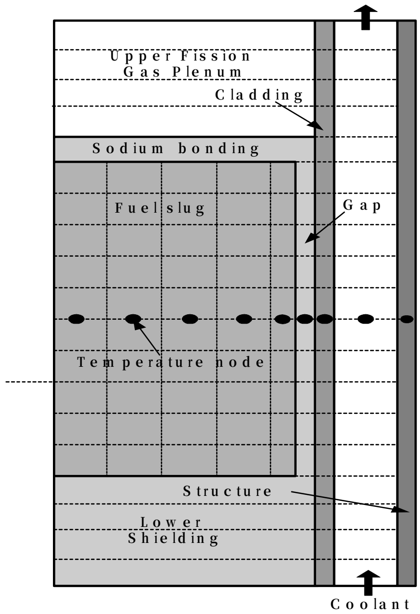

Fig.2 Core channel Model

that represent fuel, gap, clad, sodium coolant, and structure sections. Thermal expansions are accounted for in the fuel and clad, but those of the coolant channel flow area or the structure are not considered for the steady-state and transient calculations. Thermal power generation is represented by point neutron kinetics and decay heat equations. A specified fraction of the total reactor power is generated in fuel, cladding, blanket and sodium. The axial variation of power generation is determined with an input axial power profile.

The flow splits among the channels are adjusted at each time step to account for the friction factor and pressure drop changes. Friction factors in the hydraulic equations are continuously updated. They account for the transition from laminar to turbulent flow in all parts of the sodium system. Reverse flow in the channels can be handled. Natural circulation also takes into account thermally driven density changes in all parts of the primary, intermediate and water/steam loops with elevation changes.

When reactor scram occurs, the heat generation is reduced almost instantaneously while the coolant flow rate follows the pump coastdown. This can result in a situation where the core flow is colder than the bulk hot pool sodium. This temperature difference leads to stratification when the flow momentum is not large enough to overcome the negative buoyancy force. The two-zone model employed in the original SSC-L code has been modified. The hot pool is divided into two perfectly mixing zones determined by the maximum penetration distance of the core flow. The time rate change of energy in the pool is added to energy balance equations in the SSC-K code to make conservation. Currently, perfect mixing of the IHX flow with the cold pool sodium is assumed.

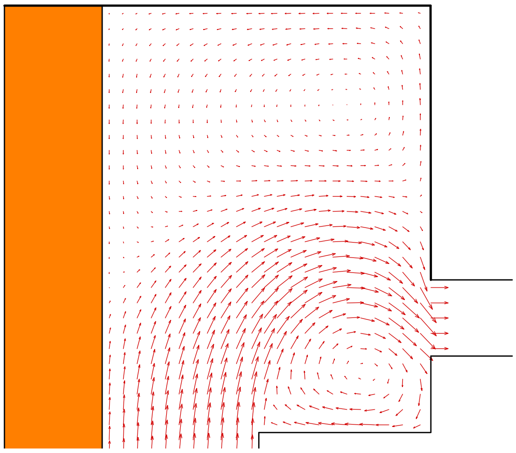

Fig.3 Sodium velocity distribution in hot pool during normal operation

In the SSC-K code, the two-dimensional hot pool model [4] has also been developed to calculate the coolant temperature and velocity profiles in the hot pool. The governing equations for conservation of mass, momentum, energy, and both turbulent kinetic energy and the rate of turbulent kinetic energy dissipation for the ê-å turbulence model are made in a generalized coordinate system. The SIMPLEC [5] algorithm is used for pressure-velocity coupling. After validation of the stand-alone version of the two-dimensional pool model against the sample problem, it is coupled into the SSC-K code. Figure 3 shows the sodium velocity distribution in the KALIMER hot pool during normal operation. Figure 4

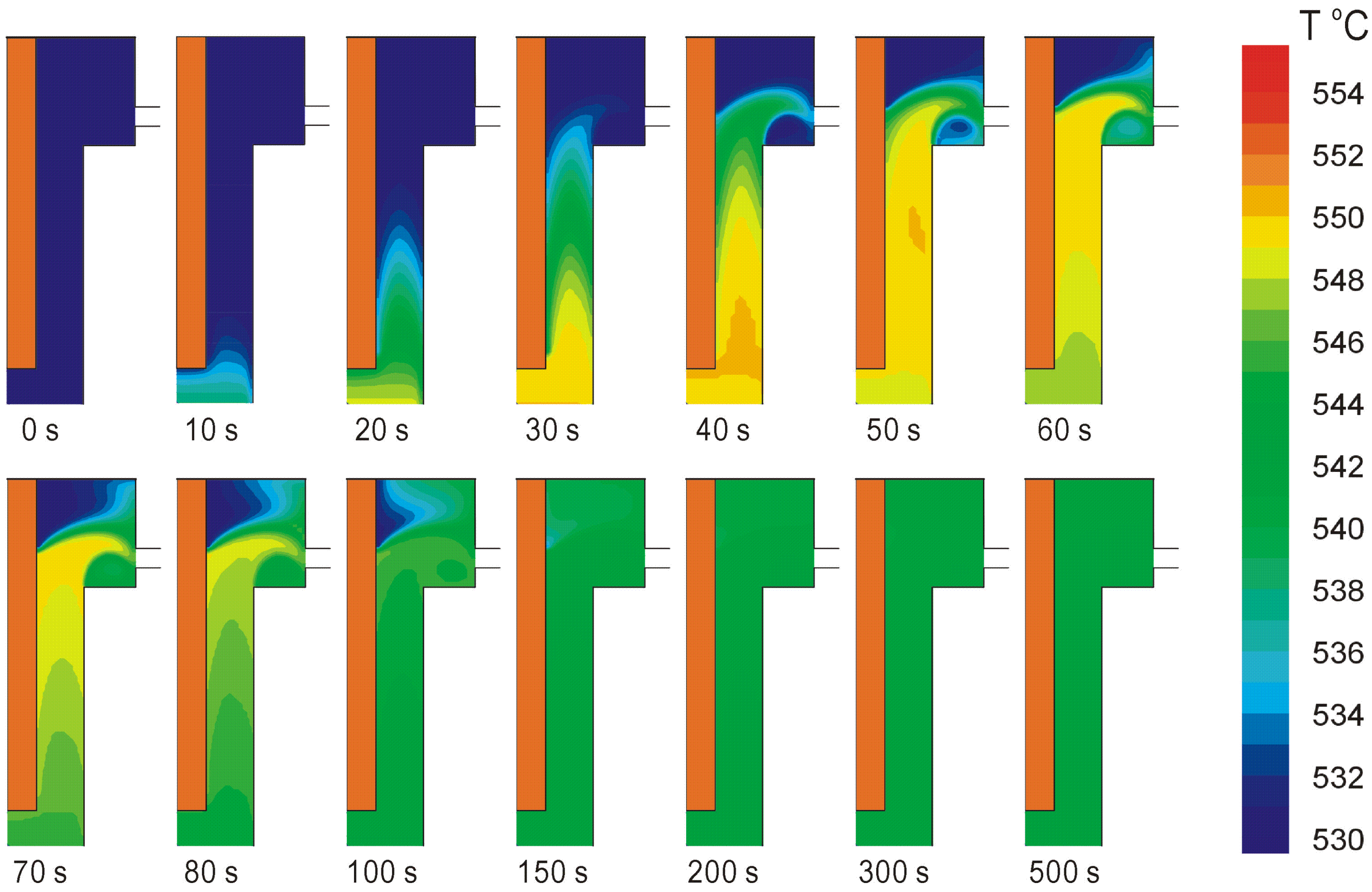

Fig.4 Sodium temperature distribution in hot pool during UTOP event

shows the temperature distribution in the hot pool during typical UTOP event. In the early stage of transient, the upper portion of hot pool remains cold temperature condition.

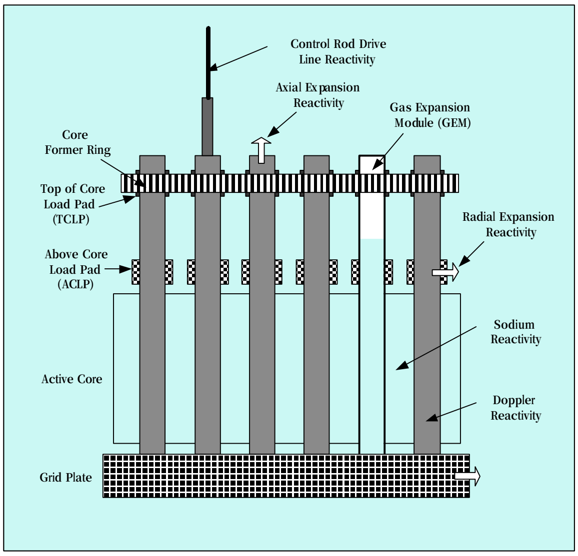

Fig.5 Reactivity components in a metallic fueled core

2.3 Reactivity Models for a Metallic Fueled Core

The SSC-L code was originally developed to analyze oxide fuel LMRs. To facilitate modeling of the metal fuel used in KALIMER, several modifications have been made [6]. For neutronic calculations, SSC-K uses a point kinetic equation with detailed reactivity feedback from each channel. Reactivity effects are required both for transient safety analysis and for control requirements during normal operation. Reactivity changes are calculated for control rod scram, the Doppler effect in the fuel, sodium voiding or density changes, fuel thermal expansion, core radial expansion, thermal expansion of control rod drives, and vessel wall thermal expansion. Figure 5 shows the components of reactivity feedback considered in the KALIMER core.

In addition to the reactivity model, a GEM model has been developed for SSC-K. The GEM assemblies are added to the KALIMER core in order to supplement the negative reactivity feedback once the pump is tripped. When the pumps trip and the pressure drops, the sodium within the GEMs at the active core elevation is displaced by expanding helium gas, thus increasing the leakage of neutrons from the core. Currently, the sodium density inside the GEM is assumed to be the axial average of the neighboring channels. A sensitivity study is needed to investigate the effect of sodium density on the sodium level. If needed, the GEM model will be modified so that the axial sodium density can be calculated considering inter-assembly heat transfer. The temperature of the GEM gas is assumed to be the average of the structural temperature of neighboring channels. It is noted that improvement of the current GEM model can also be made by calculating the GEM gas temperature while taking account of the inter-assembly heat transfer.

SSC-K uses a decay heat treatment similar to that normally used for delayed neutron precursors. Up to six decay heat precursor groups are used, each with its own yield and decay constant.

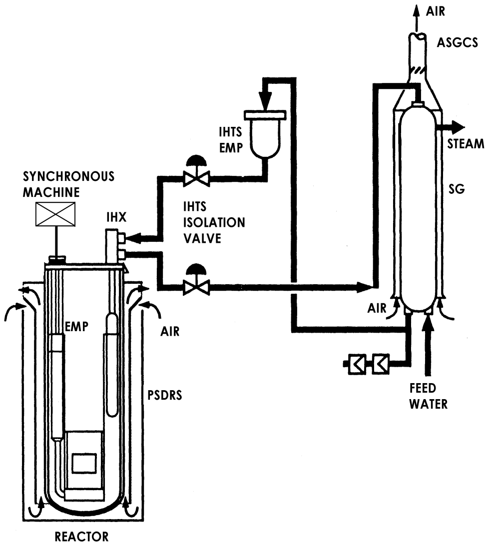

Fig.6 Schematic diagram of the PSDRS

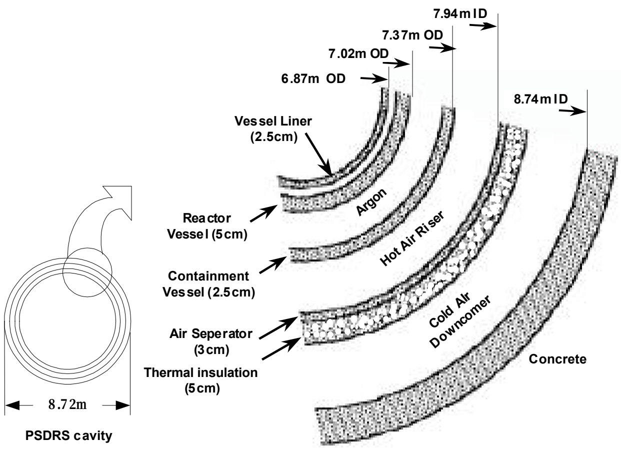

Fig.7 Cross-sectional flow areas of the PSDRS

2.4 Passive Decay Heat Removal System Model

PSDRS is a heat removal feature in the KALIMER design which is characterized to cool the containment outer vessel with atmospheric air in a passive manner. Figures 6 and 7 exhibit the schematic of PSDRS and its cross-sectional flow areas. The gap between the reactor vessel and the containment vessel is filled with argon gas and thus radiation heat transfer prevails due to the high temperature of these walls. Atmospheric air comes in from the inlets located at the top of the containment, and flows down through the annulus gap between the air separator and the concrete silo. It then turns back upward passing through the other annulus gap between the containment outer surface and the air separator, and finally flows out through the stack with a raised temperature due to the energy gained from cooling the containment vessel. The air flow rate is determined from various

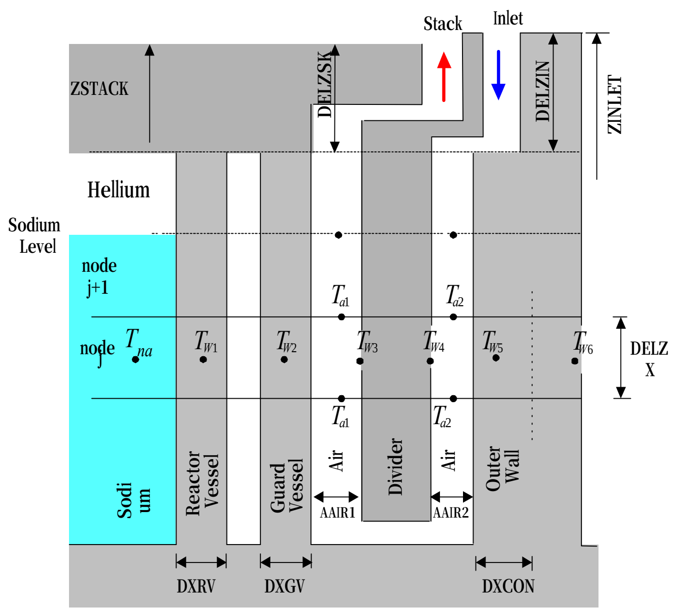

Fig.8 PSDRS model

parameters. The air temperature difference between the two annulus channels, flow path or pressure drop of an orifice placed for flow control, and friction exerted on the surfaces are the main parameters affecting the flow rate.

The significance of PSDRS in the KALIMER design is that it plays the role of the only heat removal system in a total loss of heat sink accident. For this reason, its function is crucial to prevent core damage, so that performance an analysis as well as realistic modeling of the system might be a key issue to provide essential knowledge for a safety evaluation of the KALIMER design. The PSDRS model [7], as shown in Fig. 8, was developed to predict the heat removal rate by this system. The model calculates not only energy balances by the heat transfers between the walls, but also the air flow rate driven by gravitational force between the air flow channels to estimate the heat removal rate. Non-linear differential equations are solved using the Runge-Kutta method while the air temperature profile is obtained from theoretical manipulation. The PSDRS model is connected to the SSC-K code, and the present model will be continuously improved through more rigorous theoretical bases.

2.5 IHTS and Steam Generation System Models

The representation of the IHTS and steam generation system in the SSC-K code is handled within the MINET [8] package, which was coupled and interfaced to SSC-L. The MINET package is a computer code developed for the transient analysis of intricate fluid flow and heat transfer networks, such as those found in the balance-of-plant in power generation facilities. It can be utilized as a stand-alone code, or interfaced with another computer code. The SSC-K code coupled with MINET can fully represent the thermal hydraulic system such as pipes, pumps, heat exchangers, valves, etc., thereby reducing the need for estimating essential transient boundary conditions. SSC-L/MINET has been applied to the analyses of the Clinch River Breeder Reactor (CRBR) and the Japanese MONJU plants. Most of the MINET portion except some heat transfer correlations for the helical coil steam generator remains in the SSC-K code development without further modification.

2.6 Long Term Cooling Model

The KALIMER design adopts PSDRS, which uses a passive way to remove the decay heat, as an ultimate heat sink for the loss of heat sink accident. The system removes the heat generated in the reactor core by cooling the containment vessel wall through natural circulation as discussed in section 2.4. The top-tier requirement of the KALIMER conceptual design excludes an operator action for 72 hours when an accident occurs. So, it is necessary to estimate the time and coolant temperature when the ultimate balance between the core heat generation and heat removal is made, for assessment of the design safety. However, since SSC-K takes long time for such long transient calculation, it is not adequate to apply SSC-K code to the long-term cooling event. A long-term cooling model was developed to overcome the difficulty by extrapolating the calculation results from the system analysis code SSC-K. The model simplifies the KALIMER system based on reasonable assumptions for such long time simulation. The system conditions predicted by the SSC-K at the switchover time for the long-term phase are manually transferred to the long-term model. A stand-alone version of the long-term cooling model is available at the present time and it will be included in the SSC-K code that the long-term calculation can be automatically performed if it is required.

2.7 Further Study for SSC-K Improvement

The SSC-L code has a fairly generalized and detailed modeling of the plant protection system, and the plant instrument and control systems. However, these models need to be modified to be eligible for the KALIMER specific design. The SSC-K control system model is being developed for design and analysis of the KALIMER control systems. The model is flexible, allowing the user to select any number of plant variables for input to the control system as measured quantities.

A sodium boiling model [9] for the analysis of the coolant boiling sequence from the inception of boiling up to the time when the loss of fuel pin integrity is anticipated is being developed. If the coolant bulk temperature exceeds the saturation temperature by a user-specified amount of superheat, coolant boiling is assumed to be initiated, a vapor bubble is then generated at the place where the superheat criterion is met as shown in Fig. 9. The two-phase flow of transient liquid metal boiling in a narrow channel is characterized by use of the multiple-bubble slug flow approximation. Prediction of typical phenomena is now possible, but sufficient validation of the calculation algorithm, as well as validation of the assumptions used in the model has not been done.

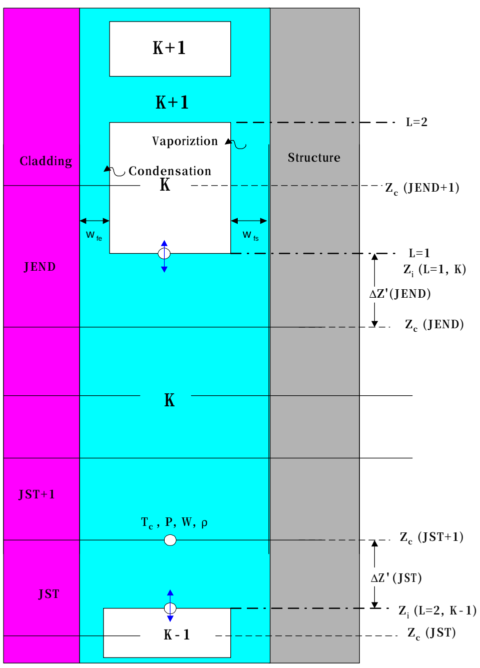

Fig.9 Sodium boiling model

The SSC-K code has the following advantages compared to other system codes. SSC-K can be applied to both loop and pool-type LMR designs, whereas most systems codes are written for only one reactor type. SSC-K treats the hot pool in more detail than most of the system codes. The SSC-K code combines the PSDRS module so that it does not require a sequence of other codes to calculate decay heat removal. SSC-K is considerably faster than multi-dimensional system analysis codes.

The SSC-K code is being used for analyzing operational transients and safety analyses in the current KALIMER design. The SSC-K thermal hydraulic models for the pool plants need to be validated. EBR-II tests have been used for SSC-L validation that has loop type thermal hydraulics models. In a similar manner the PSDRS model in SSC-K needs validation against data from a large scale experiment.

3 SUMMARY

In summary, the SSC-K code is extensively used as the main tool for system transient analysis in the KALIMR development project. The code contains the models and features required for a pool-type reactor vessel and metallic fueled core. The preliminary analysis results [10], which are not included in this paper, showed that the models implemented in SSC-K work properly in a qualitative sense. Thermo-hydraulic and reactivity feedback models of SSC-K produced physically consistent results, which show that the code is capable of modeling the phenomena properly. However, code validation has to be done in order to use in KALIMER design application.

Acknowledgement

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