LILAC Code Development for the Nuclear Thermo-Hydraulics

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1. Introduction

The Objective of this research is development of LILAC code[1] to simulate thermo-hydraulic behaviors in a nuclear power plant. The LILAC code was initially developed for the multi-dimensional analysis of core melt relocated in a reactor lower vessel during a severe accident. The multi-dimensional thermo-hydraulic analysis code LILAC uses the Reynolds-averaged Navier-Stokes and energy equations as governing equations. LILAC is based on the unstructured mesh technology to discretise solution domain. This feature has a benefit compared to structured mesh method because it is easy to model very complex geometries of the nuclear reactor and related devices.

In this article numerical and physical models implemented in the LILAC code are described with calculated results for validation. The LILAC code has been applied to simulate natural convection of the molten corium pool in a reactor vessel and evaluate LAVA experiments. The numerical results are presented with some pictures. And finally future direction of the LILAC code development is commented.

2. Description of the LILAC code

Multi-dimensional thermo-hydraulic analysis code LILAC uses the Reynolds-averaged Navier-Stokes and energy equations as governing equations. Turbulent flows are modeled by two-equation turbulence models, and molten pool crust is modeled using enthalpy-porosity method[2]. LILAC is based on the unstructured mesh technology to discretise solution domain. The main feature of the LILAC code is depicted in the figure 1. As shown in the figure, it can solve 2-D and 3-D domain, and incompressible and compressible flows can be solved using the LILAC code. The detailed numerical and physical models are described in the following sections.

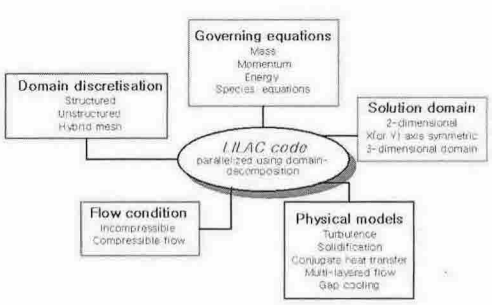


Figure 1. LILAC code structure

2.1 Numerical models

The advantage of the control volume formulation is the ability to treat complex geometry and physics in a simple and clear fashion. As described below, in all cases the basic operations of the calculation of areas, volumes, or fluxes can be accomplished with the use of vector algebra and calculus, which is a physically transparent method for the representation of processes in continuous media. To discretise the spatial domain in context with the unstructured grid finite volume method, the cell centered collocated scheme is employed here The computational domain is divided into many volume cells. The cell types may vary from triangle to quadrilateral for 2-dimensional problems and from tetrahedron, prism, pyramid, to hexahedron for 3-dimensional problems. All the transport variables are stored at cell centers. General transport equation in integral form is written as following.

$$\frac{\partial}{\partial t}\int_{\upsilon}\phi\rho\, d\Omega + \oint\phi\rho\,\vec{V}d\vec{A} = \oint\Gamma\nabla\phi d\vec{A} + \int_{\upsilon} Sd\Omega \qquad (1)$$

, where Ω is the domain of interest and $\vec{A}$ is outward vector of the surrounding surface. The discretization of each term in equation (1) is well described in the reference [1]. Pressure-correction method is used for the flow analysis using the LILAC code. The pressure correction equation is derived based on SIMPLE algorithm[3] to solve pressure field. In each time step the pressure correction equation is solved iteratively to satisfy the continuity of the flow field. To avoid checker-boarding pressure, the momentum interpolation method is used in calculating mass flux at a cell face. The matrix equation obtained from the discretized pressure correction equation is solved by preconditioned BiCGSTAB solver. In order to get accurate solutions for a large and complex flow domain, the number of the computational cells is dramatically increased, which also requires long computational time. The LILAC code is parallelized based on the domain-decomposition to reduce the computing time.

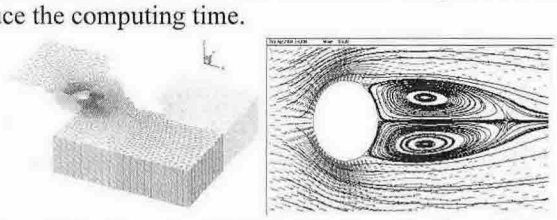


Figure 2. Partitioned solution domain for a circular cylinder.

Laminar flow around a circular cylinder at Re=40 is solved using the parallelized LILAC code. The number of cells used for this calculation is 470,400. With 16 CPUs, the speed-up obtained is almost ideal value.

2.2 Physical models

The main feature of the nuclear devices is related to heat generation and heat transfer. The coolant and structures are thermally coupled. The conductive heat transfer in the structures can not be neglected, so it is needed to solve the heat transfer in the fluid and solid like a conjugate manner. LILAC code can solve the heat transfer in the fluid and solid regions at the same time.

To analyze heat transfer with phase change like a solidification of a molten corium in a reactor lower vessel during a hypothetical severe accident, Voller [2]'s enthalpy-porosity method is implemented. In this method single fixed grid is applied for liquid and solid regions and the latent heat from phase change is added as source of energy equation.

Most of the flows occurring in the nuclear engineering are turbulent. Basically the LILAC code uses the Reynolds-averaged Navier-Stokes and energy equations as governing equations with turbulence models. Currently implemented turbulence models in the LILAC code are algebraic, one-equation, and two-equation turbulence models. Figure

2.3 Applications

LAVA4 gap-cooling experiment[4] is simulated using the LILAC code with gap-cooling model base on CCFL concept. For the experiment, molten alumina was poured into the hemispherical steel vessel filled with water. In the experiment a narrow gap was developed between the alumina crust and thermally expanded vessel wall and it was found that the water penetrated through the gap. The gap-cooling model was added to the LILAC code, and the experiment was simulated. Figure 4 shows calculated temperature distributions in the pool and vessel. It is found that the vessel is well cooled by the gap-cooling mechanism.

For our analysis, two major types of preamplifiers (charge sensitive and voltage sensitive) were modeled using MATLAB by supplying their transfer functions in

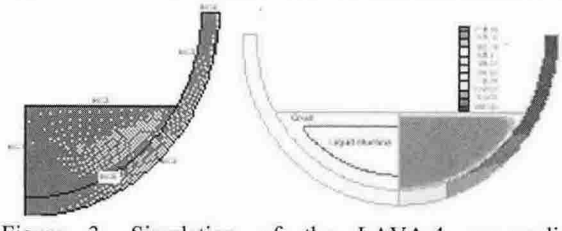
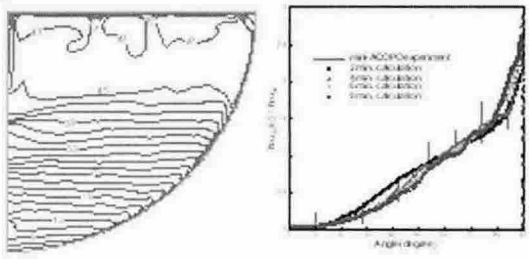


Figure 3. Simulation of the LAVA-4 gap-cooling experiment, (a) mesh, (b) calculated temperature contours and crust boundary formed.

mini-ACOPO[5] is one of the representative experiments for the high Rayleigh number natural convection. It is a transient cool-down experiment to simulate heat generation in the pool. LILAC is used to simulate the mini-ACOPO experiment and get an insight into high Ra number natural convective flow. It is seen from the figure 4 that thermal boundary layer along the curved wall and thermally stratified lower region in the pool are well resolved. And the calculated local Nu number distributions agree well with the experimental data.



(a) (b)

Figure 4. Numerical simulation of the mini-ACOPO B3 experiment, (a) Calculated temperature contours (b) local Nusselt number distributions over the lower boundary.

2.4 Future works

Currently Lilac code is under development to analyze thermo-hydraulics of the high-temperature gas-cooled reactor(GCR). Interesting thermo-hydraulic phenomena in a nuclear reactor are usually unsteady and turbulent. One way to simulate this unsteady flow is URANS which solves Reynolds-Averaged Navier-Stokes equations using time–marching method. And another way is Large Eddy Simulation in which large eddies are simulated directly and small-scale eddy below the grid-scale is modeled. The URANS methodology is available with the LILAC code, and LES model will be added in the code.

3. Conclusion

Many effort has been devoted to develop the computation fluid dynamics code LILAC, which has many state-of-the-art numerical methods such as unstructured mesh discretisation and parallelization. But it is still on the stage of enfant for the simulation of complex physics occurring in the nuclear engineering. It is necessary to add more effort than before in order to use it as a reliable and popular numerical tool.

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