Computational Fluid Dynamics Model for Liquid Poison Injection in the ACR-1000 Design

F. Song, R. Noghrehkar, L. Morris and K.F. Hau
Atomic Energy of Canada Limited, Mississauga, Ontario, Canada

Abstract

The Advanced CANDU Reactor (ACR-1000[TM1]) Shutdown System 2 is capable of quickly rendering the reactor core subcritical by injecting a neutron absorbing solution (poison) into the heavy water moderator via injection nozzles. A Computational Fluid Dynamics (CFD) model has been developed to simulate the poison injection into the moderator. This paper presents the model development and preliminary results to demonstrate its feasibility to the ACR-1000 design. The CFD model has been validated against the test data from the CANDU 6 LISS test. Validation tests based on the ACR-1000 design are underway, in which the poison concentration distribution will be measured.

1. Introduction

The CANDU[TM2]-type reactor design incorporates two fast-acting, fully capable, diverse, and separate shutdown systems, which are physically and functionally independent of each other. Shutdown System 1 (SDS1) uses vertical mechanical shutoff rods, while Shutdown System 2 (SDS2) injects a neutron absorbing solution of gadolinium nitrate in heavy water (poison solution), via horizontal injection nozzles spanning the calandria vessel, into the heavy water moderator contained in the calandria.

The liquid injection shutdown system (LISS), shown in Figure 1, is the liquid poison injection portion of SDS2. Each poison tank feeds one injection line, which passes through the reactor vault to an injection nozzle in the calandria. Rows of small holes drilled along the nozzle tube length direct jets of the poison solution to achieve a rapid dispersion of the solution in the moderator. On trip signals, quick opening valves allow stored high-pressure helium to pressurize the poison tanks and thereby cause transfer of the poison solution through the piping and nozzle tubes into the moderator. The poison that is dispersed throughout the moderator is effective in rapidly shutting down the reactor.

During liquid poison injection, the hydraulic transients in the poison solution flow path and the temporal and spatial distribution of the poison in the moderator play a significant role in quickly shutting down the reactor. The flow transients in the LISS piping up to the injection nozzle have been measured by AECL for the CANDU 6 LISS design. Additionally, the poison jet growth patterns exiting the injection holes along the nozzle tube were visualized and the time-dependent jet length was recorded. Based on the measurements, a computer code ALITRIG was developed by AECL to predict the flow transients in the LISS. The ALITRIG code also predicts the

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[1] ACR-1000[TM] (Advanced CANDU Reactor) is a registered trademark of Atomic Energy of Canada Limited (AECL).

[2] CANDU[TM] (CANada Deuterium Uranium) is a registered trademark of Atomic Energy of Canada Limited.

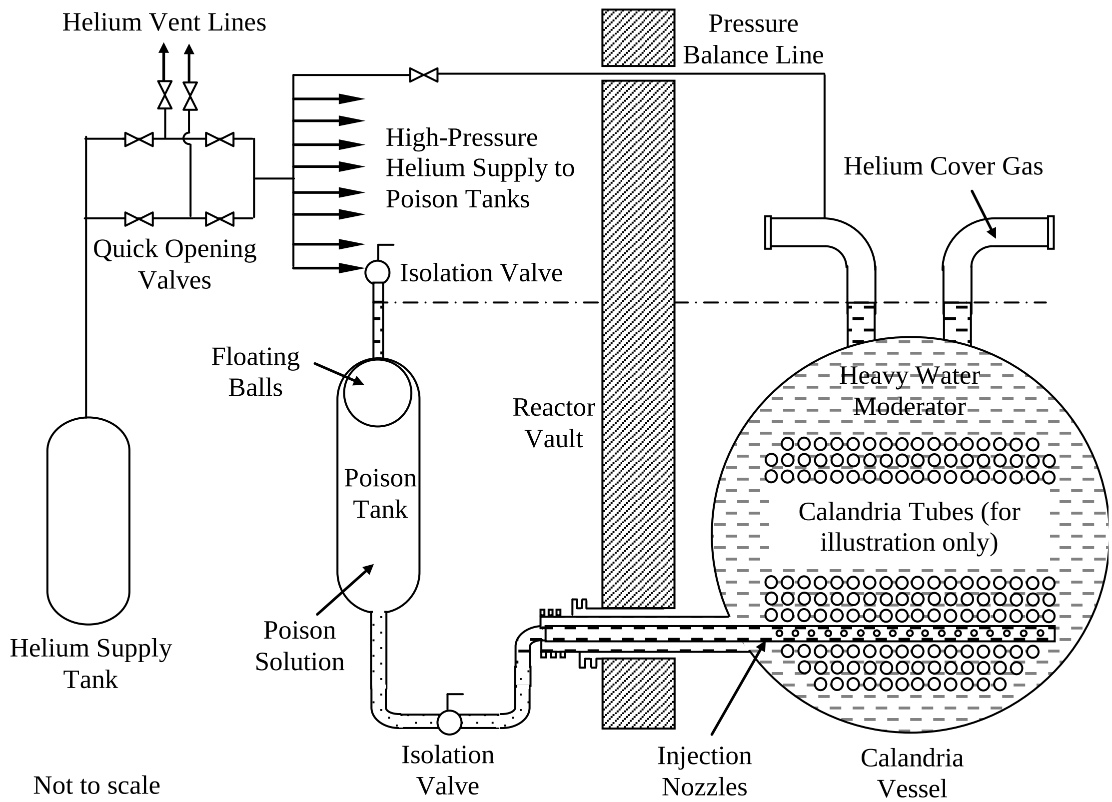

Figure 1 Schematic of Liquid Injection Shutdown System of Shutdown System 2

transient one-dimensional poison jet length in the moderator by using a semi-empirical jet model. The ALITRIG code has been used to provide input to the reactor physics analysis for the calculation of dynamic reactivity and time-dependent power during reactor shutdown by SDS2. The results of the hydraulic-neutronic analysis have been found to agree well with the flux measurements in two CANDU 6 reactors [1].

The basic design concept of the CANDU 6 LISS is adopted for ACR-1000 (Figure 1), except that eight injection nozzles are used in ACR-1000 (Figure 2) rather than six in CANDU 6. The injection nozzle design has also been modified, in particular from four rows of injection holes along the nozzle tube length to six, as shown in Figure 3, to suit the ACR-1000 reactor core configuration. Thus, the ALITRIG code is still applicable in predicting the flow transients of poison solution in the injection path of the LISS due to the similarity of out-of-core component design. Different poison jet growth patterns in the moderator, however, will result following an injection from the modified injection nozzle.

A Computational Fluid Dynamics (CFD) model has been developed using the commercial CFD software ANSYS-CFX 11.0 [2] to simulate the transient, three-dimensional poison jet growth behaviour through an injection nozzle into the moderator. The application of this CFD model to the ACR-1000 LISS design has been found to be feasible in providing to physics analysis the

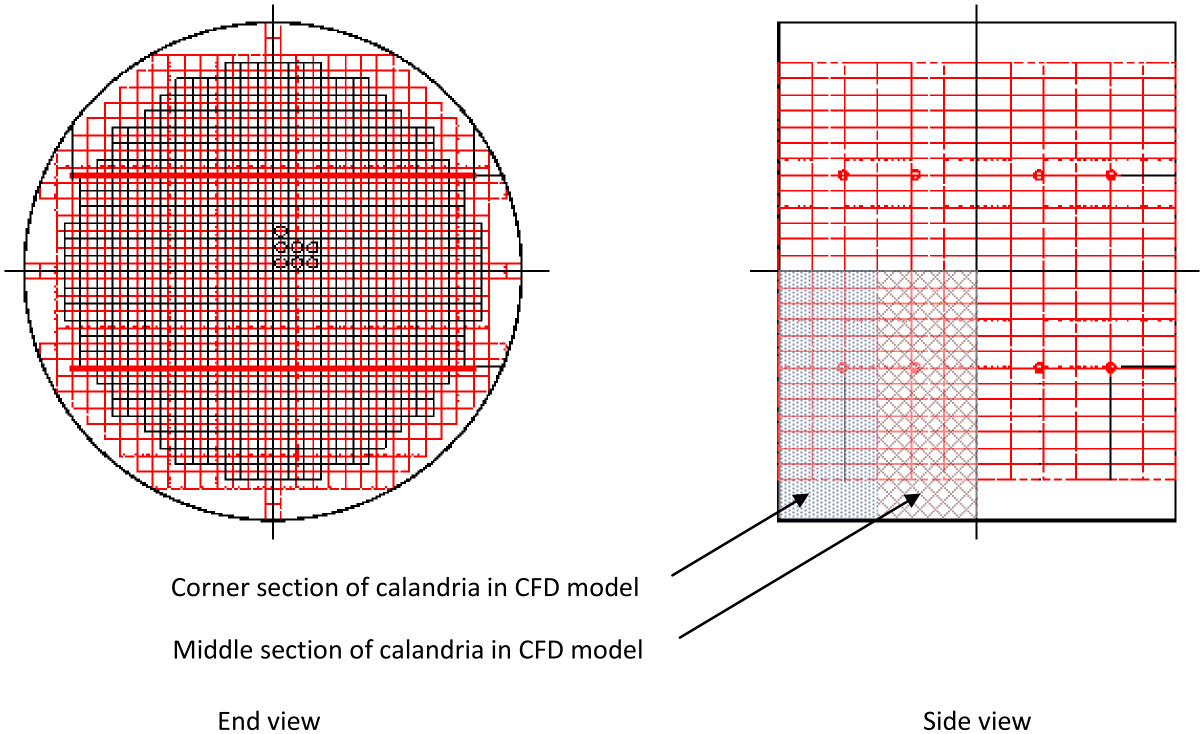

Figure 2 Placement of Injection Nozzles in ACR-1000

results of detailed poison distribution in the moderator and thus obtaining enhanced accuracy of the SDS2 design margin analysis. The CFD model has been validated against the test data of jet length for the CANDU 6 LISS design with good agreement. Tests for the ACR-1000 LISS and injection nozzle design are currently underway to provide poison concentration measurement in the moderator for a full validation of the CFD model.

2. Development of CFD Model for Poison Injection in ACR-1000

2.1 Modelling approach

Two modelling approaches are available for describing the poison injection phenomenon. The first one is a two-phase flow approach, with the assumption of a continuous moderator fluid in the calandria and a dispersed poison fluid from the LISS [3]. The second one, considers a single-phase heavy water flow from the LISS into the heavy water moderator in the calandria, with a scalar component of poison being transported through the flow assuming the presence of poison has negligible effect on the flow stream. Both approaches were examined for the problem of interest and found to predict the jet growth characteristics with the same accuracy. Therefore, the second approach has been chosen for developing the CFD jet growth model due to the simplicity nature of a single-phase model.

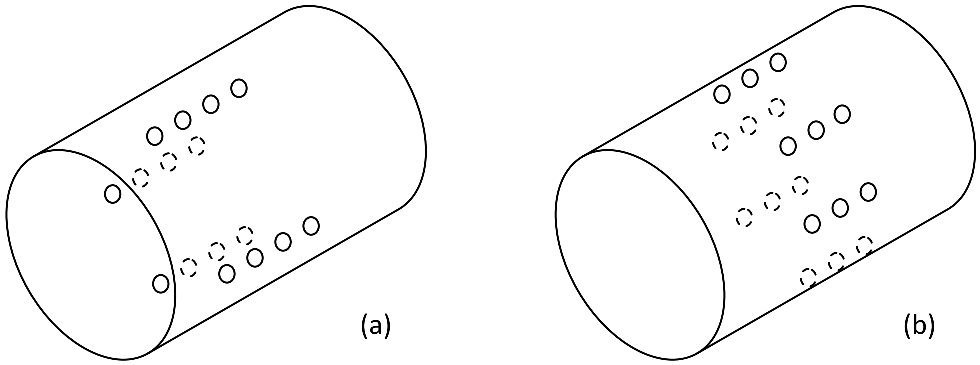

Figure 3 Schematic of One Group of Injection Holes (Injection Node) on Inner Wall Surface of (a) CANDU 6 Injection Nozzle; (b) ACR-1000 Injection Nozzle

The governing equations to be solved are the three-dimensional Navier-Stokes and the mass conservation equations for the incompressible heavy water flow. An additional variable is introduced in terms of volumetric mass of pure poison (or poison density), which is a function of the poison concentration with a unit of ppm (parts per million) and density of poison solution. The kinematic diffusivity of the additional variable is 10^{-7} m^2/s, which is typical for the diffusion of most ions in dilute aqueous solutions. The standard k-ε turbulence model and conventional wall functions are used. No heat transfer is included in the CFD model due to the short-term injection and small temperature difference between the poison and moderator fluids. Before injection, the heavy water moderator in the calandria is assumed stagnant, which should not have significant effect on jet growth because the nominal moderator flow velocity is relatively small, typically on the order of 10^{-1} m/s.

2.2 Flow domain and mesh

Poison injection from one individual injection nozzle is modelled to reduce the computational cost. The calandria is divided into four quarters, each containing two sections, the corner and the middle sections, as shown in Figure 2. The flow in each quarter of the calandria is considered symmetrical to that in any other one. Each section including the enclosed injection nozzle is used as the flow domain of the CFD model.

Taking the corner section as an example, the flow domain is about 1.5 m along the calandria tubes and about 7.4 m in diameter (Figures 2 and 4). The injection holes are distributed in the circumferential direction of the nozzle tube, and are arranged along the nozzle tube length in separate groups, so called the injection nodes (Figure 3). One side of the flow domain represents the calandria side wall, while the other side represents the symmetric middle surface between the corner and the middle sections. The outlet boundary condition was specified at the top of the domain with a pressure given by the sum of the moderator cover gas pressure and the hydrostatic head of the moderator. The inlet boundary condition was specified at the inlet of injection nozzle with the transient one-dimensional poison flow velocity given by the ALITRIG predictions.

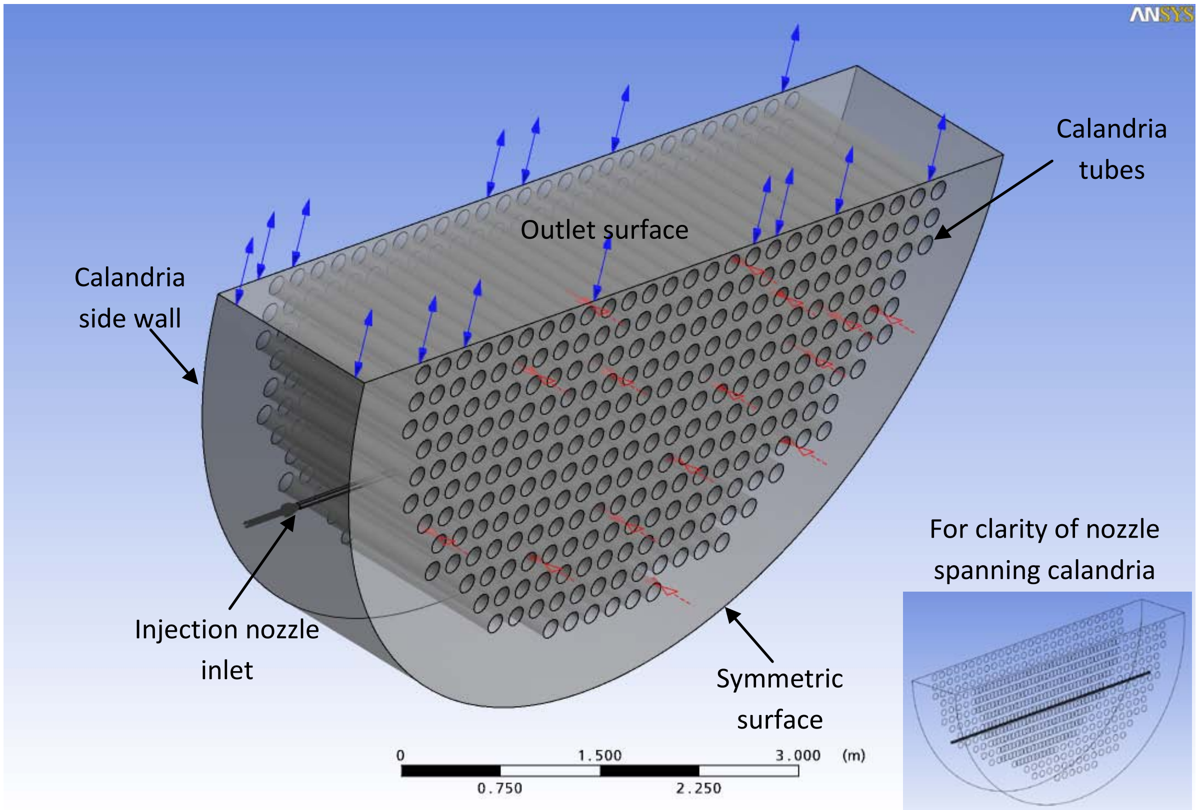

Figure 4 Flow Domain for Poison Injection in the Corner Section of ACR-1000 Calandria

One of the major challenges of this CFD model is the mesh strategy for the relatively large flow domain with hundreds of small injection holes of a diameter in millimetres. Dedicated mesh refinement in the jet growth region particularly near the injection holes is implemented to obtain sufficient mesh resolution with controlled number of mesh elements (Figure 5). The total number of mesh elements is approximately 16 million, which requires about 10 gigabyte computer memory to run the CFD simulation.

2.3 Application to ACR-1000 Design

The applicability of the CFD model to the ACR-1000 design has been examined by simulating the poison injection in the individual corner and middle sections of the ACR-1000 calandria (Figure 2). The simulation period is from the initiation of quick opening valves at time zero upon trip signals until the completion of injection indicated by the depletion of poison in the poison tank. The results of poison concentration distribution can be projected onto the other three quarters of the calandria to produce the poison distribution map over the full reactor core.

A typical plot of instantaneous poison flow velocity vector on a cut-out plane through two rows of injection holes of the nozzle is shown in Figure 6. The jet velocity at the injection node is driven by the local pressure difference across the node. The moderator pressure outside the injection nozzle is essentially constant. The poison flow pressure in the nozzle varies along the

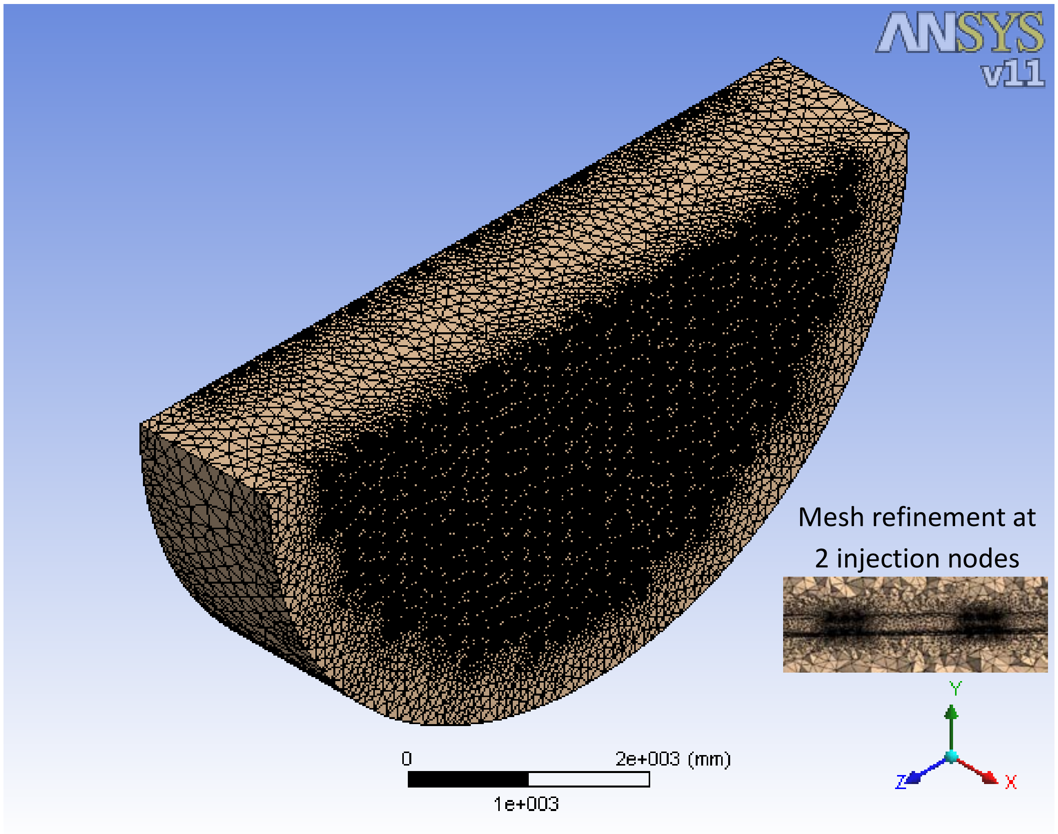

Figure 5 Surface Meshes of Flow Domain and Mesh Refinement Near Injection Nodes in the CFD Model for the ACR-1000 Design

nozzle tube axis under the combined effect of: (a) the wall friction acting on the flow, which tends to decrease the pressure in the flow direction; and (b) the momentum change due to deceleration of the main flow stream near the injection nodes, which tends to increase the fluid pressure. In the entrance region of the nozzle, the pressure difference across the injection node is relatively small, thus the jet velocity exiting the injection node and the momentum change of the main flow are small. The wall friction effect is dominant and the pressure drops along the nozzle, leading to decreasing jet velocities at injection nodes along the nozzle length. As the poison flow marches downstream towards the nozzle dead end, the pressure level in the nozzle and the jet velocity at injection nodes increase. The momentum change effect becomes more significant and eventually exceeds the friction loss effect for the current injection nozzle design, leading to higher local pressures and jet velocities along the poison flow in the nozzle.

A typical instantaneous poison density contour of six individual jets exiting an injection node is shown in Figure 7. The magnitude of poison density is the highest at the injection hole surfaces, and then decreases as the jets develop in both axial and radial directions in the moderator.

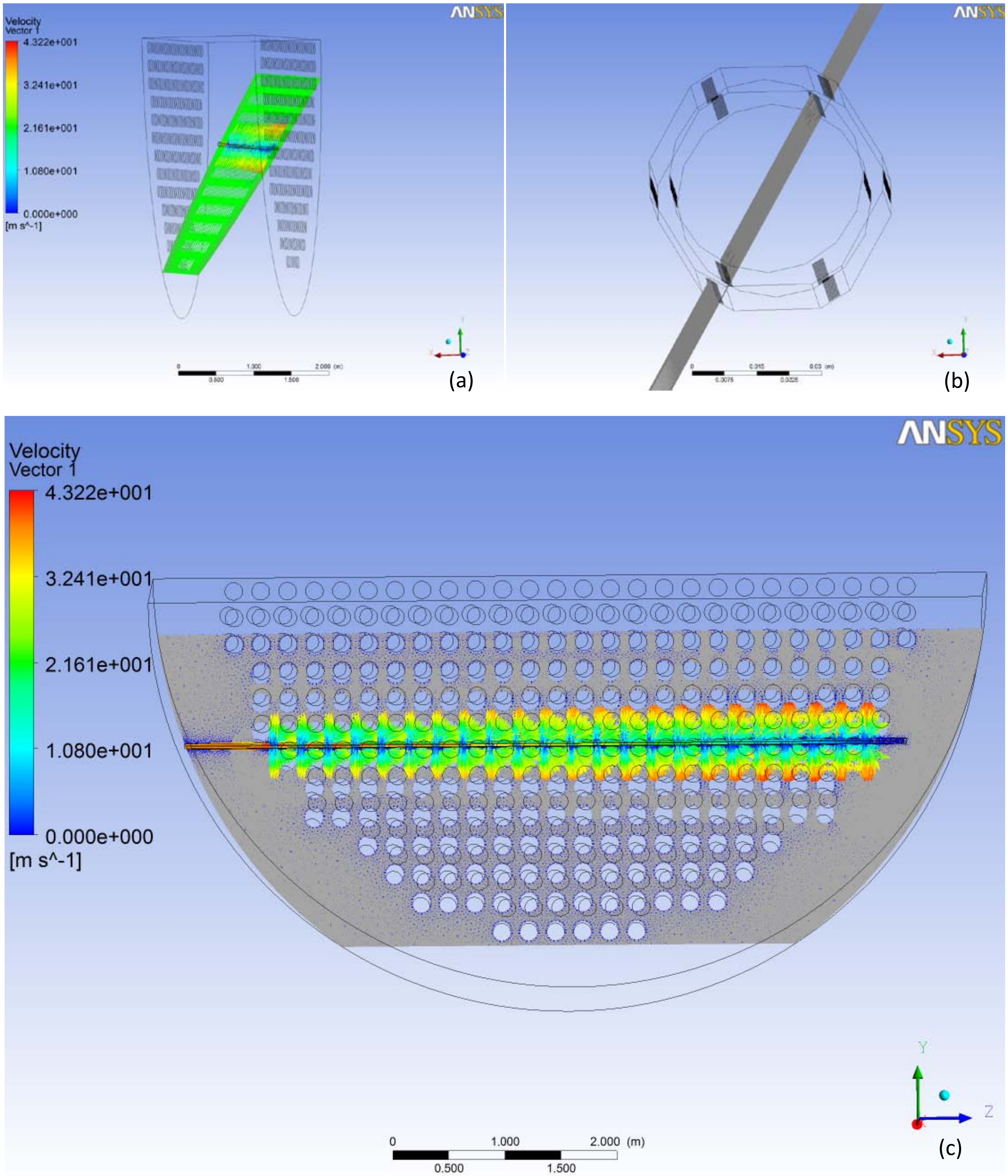

Figure 6 (a) Cut-Out Plane of Injection Nozzle Through the Calandria; (b) Zoom In of Cut-Out Plane Through Two Rows of Injection Holes; (c) Typical Plot of Instantaneous Poison Flow Velocity Vector at Cut-Out Plane

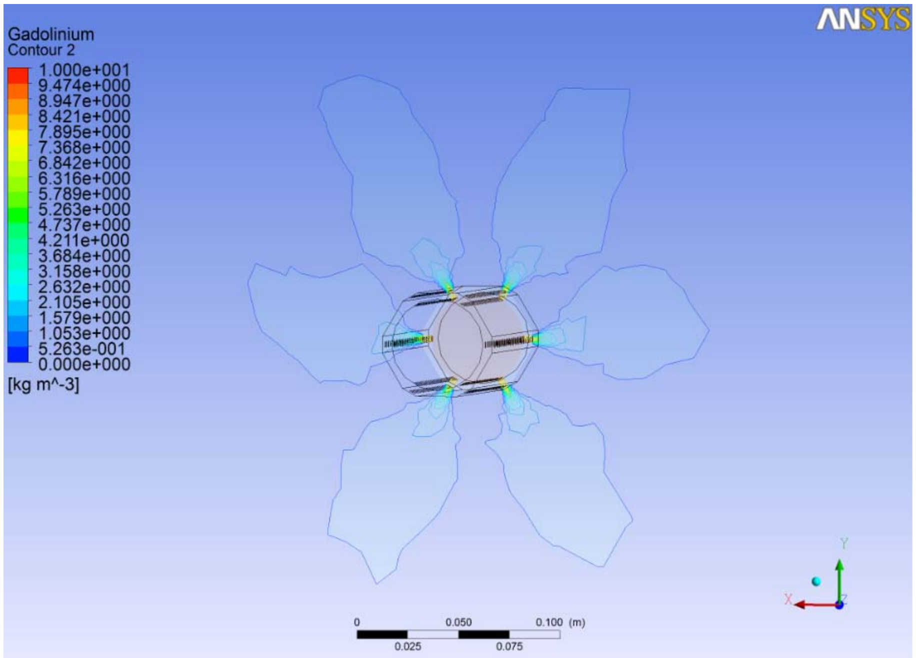

Figure 7 Typical Instantaneous Density Contour of Poison Jets From an Injection Node

3. Validation of CFD Model

The CFD model described in Section 2 has been validated by comparing the CFD results of jet length against the test data obtained in the CANDU 6 LISS test. The test rig included one helium tank, one quick opening valve, one poison tank, associated piping, and one injection nozzle in a water tank with up to three rows of horizontal tubes mounted in the water tank to represent the calandria assembly. Quiescent light water in the water tank and a phenolthalein dye solution in light water in the poison tank were used to represent the moderator and poison fluids.

The CFD model was used to simulate the jet growth from the injection node measured in the CANDU 6 LISS test. The flow domain and mesh were modified with respect to the calandria and nozzle configurations in the test, as shown in Figure 8. For simplicity, the inlet boundary condition was given by the transient poison velocity at the particular injection node obtained from the ALITRIG predictions. The predicted time-dependent jet length compared to the test measurements is shown in Figure 9. Time zero corresponds to the beginning of poison injection at the injection node. The CFD prediction of the local jet length agrees well with the measurements. The rate of increase in jet length becomes smaller as the jet axial momentum decreases with time.

Tests for the ACR-1000 LISS and injection nozzle design are currently underway, in which the temporal and spatial distribution of poison concentration will be measured for fully validating the CFD model.

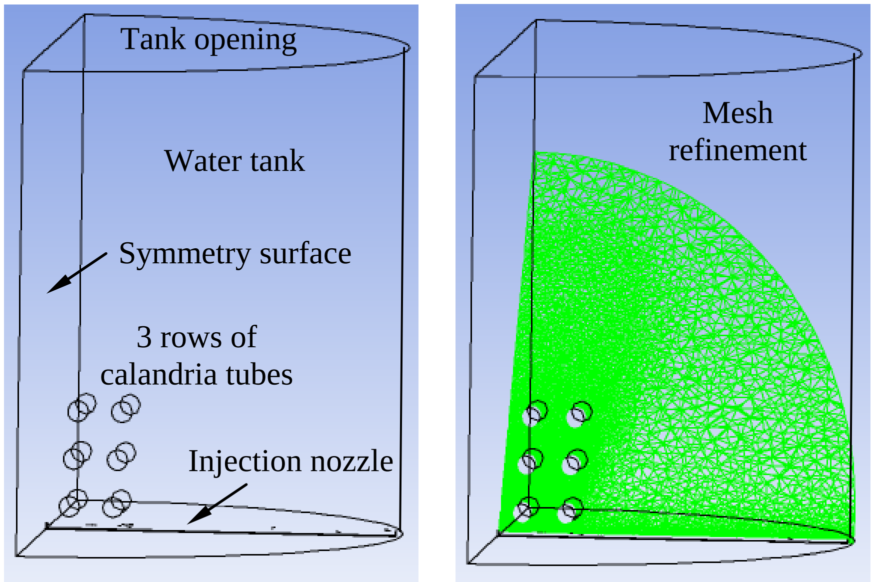

Figure 8 Simplified Flow Domain and Mesh Refinement in the Jet Growth Region of CFD Model for the CANDU 6 LISS Test

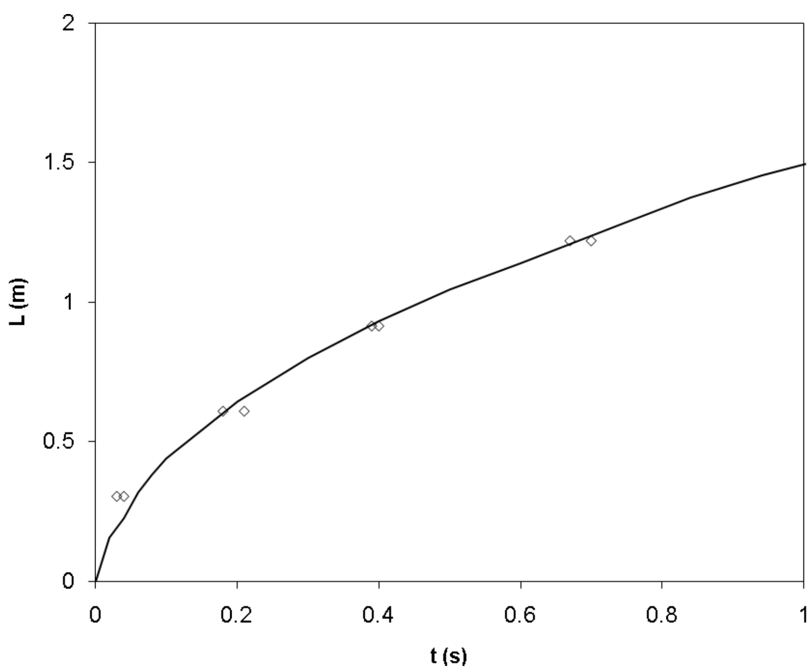

Figure 9 Comparison of Transient Poison Jet Length Between CFD Predictions (Represented by line ——) and CANDU 6 LISS Test Measurements (Represented by Symbol ◊)

4. Conclusions

A CFD model for the LISS poison injection in the ACR-1000 design has been developed and compared against the test data of jet length in the CANDU 6 LISS design. The CFD results of poison distribution in the moderator can be used to provide input in great details to physics analysis of SDS2 performance. The application of the CFD model to the ACR-1000 design, in conjunction with the ALITRIG code, has demonstrated its feasibility as a LISS/SDS2 design tool for obtaining enhanced accuracy in analysing the SDS2 design margin. Tests based on the ACR-1000 design are being prepared for validation of the CFD model against the measurement of poison concentration distribution in the heavy water in the calandria.

5. References

[1] R.D. McArthur, B. Rouben, R. Robinson, L. Boruvka, P.D. Thompson, A. Baudouin, and J. Koclas, "Simulation of CANDU 6 LISS Tests", Proceedings of the CNS 16th Annual Nuclear Simulation Symposium, Saint John, New Brunswick, Canada, 1991.

[2] ANSYS-CFX Manual, release 11.0, 2006.

[3] F. Song, R. Noghrehkar, and K.F. Hau, "CFD Modelling of Liquid Poison Injection in ACR-1000 Shutdown System", Proceedings of the 16th International Conference on Nuclear Engineering, Orlando, Florida, USA, 2008.