DEVELOPMENT AND VALIDATION OF A MODEL FOR HIGH PRESSURE LIQUID POISON INJECTION FOR CANDU-6 SHUTDOWN SYSTEM NO.2

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ABSTRACT

In CANDU reactor one of the two reactor shutdown systems is the liquid poison injection system which injects the highly pressurized liquid neutron poison into the moderator tank via small holes on the nozzle pipes. To ensure the safe shutdown of a reactor it is necessary for the poison curtains generated by jets provide quick, and enough negative reactivity to the reactor during the early stage of the accident. In order to produce the neutron cross section necessary to perform this work, the poison concentration distribution during the transient is necessary.

In this study, a set of models for analyzing the transient poison concentration induced by this high pressure poison injection jet activated upon the reactor trip in a CANDU-6 reactor moderator tank has been developed and used to generate the poison concentration distribution of the poison curtains induced by the high pressure jets injected into the vacant region between the calandria tube banks. The poison injection rate through the jet holes drilled on the nozzle pipes is obtained by a 1-D transient hydrodynamic code called, ALITRIG[1], and this injection rate is used to provide the inlet boundary condition to a 3-D CFD model of the moderator tank based on CFX4.3[2], an AEA Technology CFD code, to simulate the formation and growth of the poison jet curtain inside the moderator tank.

For validation, the current model is validated against a poison injection experiment performed at BARC, India[3] and another poison jet experiment for Generic CANDU-6[4] performed at AECL, Canada. In conclusion this set of models is considered to predict the experimental results in a physically reasonable and consistent manner.

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INTRODUCTION

In a Canadian deuterium uranium (CANDU) reactor, there are two independent shut-down systems(SDS): SDS1 and SDS2. The SDS1 is composed of 28 vertical shutoff rods (SOR) to be dropped into the core by gravity and the SDS2 is composed of 6 injection nozzles transversally penetrating the core with many small holes through which a highly pressurized liquid poison is injected. The liquid poison is gadolinium nitrate solution $Gd(NO_3)_3{\cdot}H_2O$, which is a strong neutron absorber. It has been a concern of the designer as to how to confirm the effectiveness of this SDS2 in shutting down a reactor as it involves many stages of theoretical analyses and/or experimental verification. One of them is to generate the neutron cross section for the injected poison jets based on the poison concentration, and simulate the shutdown process to obtain the local neutron flux at the location of the neutron detectors[5]. Then these local neutron fluxes are compared with those measured by the neutron detectors during the shutdown test. Another validation of the current model is against the Poison Jet Experiment of Generic CANDU-6 performed at AECL. One of the most difficult steps involved in this work is to obtain the time dependent poison concentration in the moderator tank after the trip signal is issued. This by itself involves simulation of the poison injection system which is composed of a highly pressurized

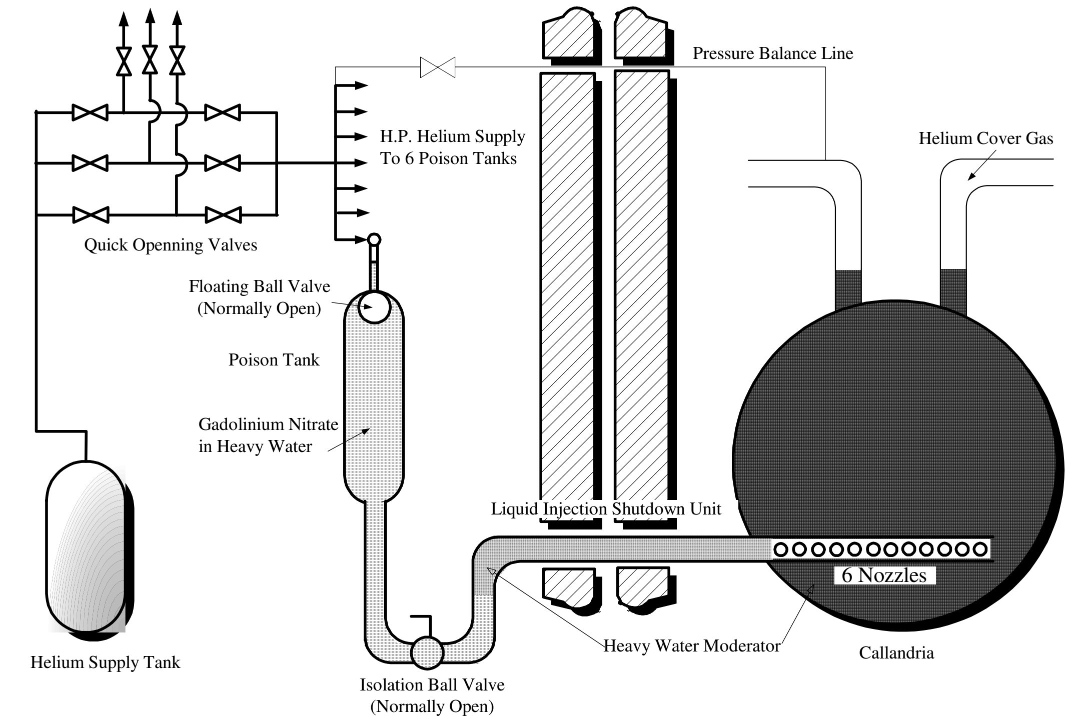

Figure 1. Schematic of Liquid Injection Shutdown System

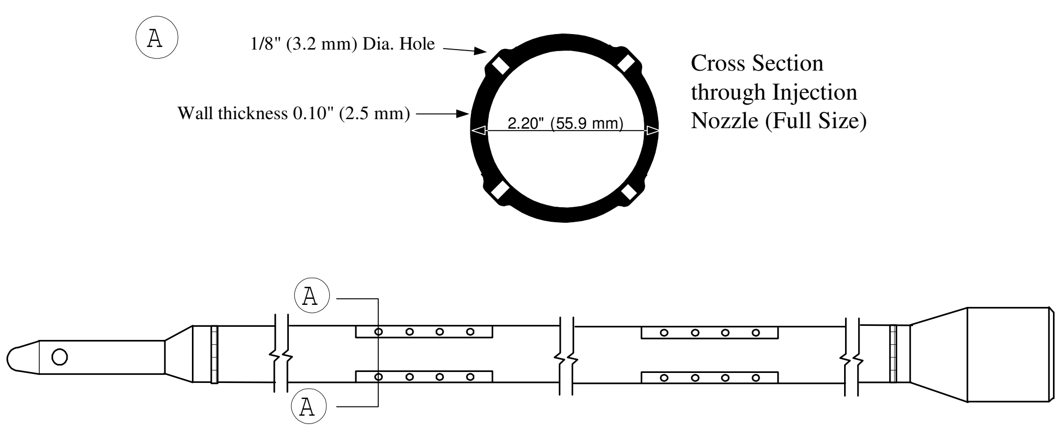

Figure 2. Configuration of a Poison Injector

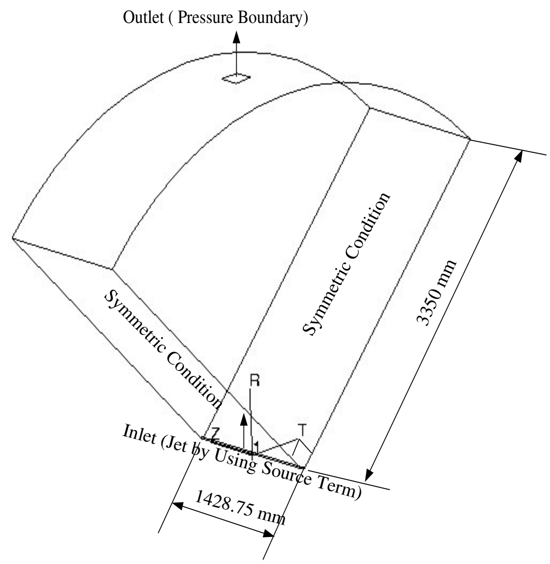

Figure 3. Segment of Calandria Tank used for 3-D Jet Simulation

poison tank, ball valve in it, discharge line piping, and injection nozzle pipe with many small size holes on it as shown in Fig.1. As It is generally known that directly measuring the velocity and concentration of the poison jet during injection is difficult because of the complex nature of the process and system, this part of the work needs to heavily depend on numerical analyses partially validated against few available experimental data.

An example is an Indian researchers' experiment aimed at assessing the proper hole size and layout of these holes on the injection nozzles by observing only the visualized phenomena of mass transfer as a function of time.[3] Once the poison injection begins in the moderator region of a reactor (see Fig. 1), the poison jet growth and transport by convection and diffusion is completed in a very short time (~1.5 second).[6] to meet the SDS2 design requirement.

In a CANDU-6 reactor, the poison injection nozzle is 21 pressure tube lattice pitch long with each span 28.575 cm. There are axially four nozzle hole positions per lattice pitch and four holes evenly spaced circumferentially at each nozzle hole position as shown in Fig. 2. For the purpose of safety analysis related to the performance of SDS2, it is required to analyze the liquid poison jet permeating into the circular D_2O filled calandria tank in a high speed to find transient poison concentration distribution. Therefore, a numerical model has been developed in previous[7] and this study to systematically and consistently estimate the concentration and diffusion of the poison injected from SDS2. An attempt was made to validate the analyses results against the Indian researchers' experiment. **Another validation of the current model is carried out against the Poison Jet Experiment of Generic CANDU-6 performed using the CANDU-6 prototype test rig at SPEL of AECL. The purpose of this experiment was to validate the 1-D Hydraulic code, ALITRIG.**

THEORETICAL MODELS

Analysis Tools

For the analysis of liquid poison injection rate, a 1-D hydraulic code ALITRIG is used. From the result of this simulation, the injection rate of liquid poison through each hole at different hole positions was available, from which the liquid velocity at the nozzle hole aperture as well as the poison concentration can be deduced as a function of time.

For the analysis of poison jet injected into the calandria tank, a commercial code CFX 4.3, developed by AEA Technology, is used.

Governing Equations

In ALITRIG code, the thermal-hydraulics of the poison/moderator flow is simplified based on the assumption that the incompressible and isothermal 1-D flow of a uniform velocity profile is retained throughout the transient. The mass, continuity, momentum and energy equation in a lumped form are used. The set of governing equations for all of the poison injection lines in the system are:

Mass equation: $$\frac{dM_j}{dt} = W_j$$

Continuity equation: $$\frac{dV_j}{dt} = Q_j$$

Energy equation: $$\frac{dE_j}{dt} = h_H W_j - P_j Q_j$$

Lumped momentum: $$\frac{dQ_j}{dt} = B_j(P_j - P_{nj}) - C_j Q_j^2$$

where Qj is the volumetric flow, Pj is the pressure at the surface of a certain control volume. And Bj and Cj are defined as:

$$B_j = 1/\left[\sum_{i=1}^{n} \frac{\rho_i L_i}{A_i}\right]_j$$

$$C_j = \frac{1}{2} B_j \left[\sum_{i=1}^{n} \frac{\rho_i}{A_i^2}\left(1 - \frac{A_i^2}{A_{i-1}^2} + K_i + \frac{f_i L_i}{D_i}\right)\right]_j$$

The initial conditions and the boundary conditions are; initial He pressure, locations of the interface between He and liquid poison, the interface between liquid poison and D_2O .

The CFX-4.3 solves for general governing equations such as continuity and momentum equations, which are written as follows:

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u_j}{x_j} = 0$$

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial \rho u_i u_j}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + s_i$$

where s_i is the source term and τ_{ij} is the stress tensor.

The mass transport equation is used in the form of Reynolds-averaged mass transport equation such as

$$\frac{\partial \rho Y_A}{\partial t} + \frac{\partial \rho u_i Y_A}{\partial x_j} = -\frac{\partial}{\partial x}\left[\left(\rho D_{AB} + \frac{\mu_t}{Sc_t}\right)\frac{\partial Y_A}{\partial x_j}\right]$$

where Sc_t is the turbulent Schmidt number, D_{AB} is the binary diffusivity of *A* and *B* which can be obtained from Perry's handbook,[8] and μ_t is the turbulent viscosity. For the analysis of a turbulent flow, the standard $k-\varepsilon$ model based on an eddy-viscosity hypothesis is used in this study.

Jet Simulation Using Source Terms

In the discretization process of governing equations, a source term is in particular used to add sources or sinks in the conservation equation. In this study, source terms are used instead of using inlet boundary condition to facilitate the grid generation,. Especially for a complex problem, it is more flexible to create grid structure near the boundary if the source term is used.

A user FORTRAN file is required to model the source term by the CFX-4.3. The CFX-4.3 provides ~30 user FORTRAN files to support users when modeling geometry, boundary condition, and phase change in the flow regime. For the simulation of jet injection through nozzles, the inlet conditions such as injection velocity, mass flow rate, and mass fraction are simulated by USRSRC subroutine. The general formulation of the source term can be mathematically written as

$$\sum_m a_m(\phi_P - \phi_m) = S_P \phi_P + S_c$$

where the summation is over a neighbouring cells of the control volume. The velocity ϕ is obtained by setting S_P and S_c as negative mass and mass flux times velocity, respectively.

Examples of other source terms are given in Table 1.

Table 1. Source Terms for Boundary Condition

	Momentum	Mass Flow Rate	Mass Fraction
S_P	$-\rho V_{inlet}$	0.0	$-\rho V_{inlet}$
S_c	$\rho V_{inlet} V_{inlet}$	$\rho V_{inlet} A_{inlet}$	$\rho V_{inlet} Y_{A,inlet}$

Because CFX-4.3 code uses body-fitted grid structure, all variables are stored in the center of a control volume, which is different from the staggered grid model. Figure 4 shows the source term (P) set for an arbitrary control volume.

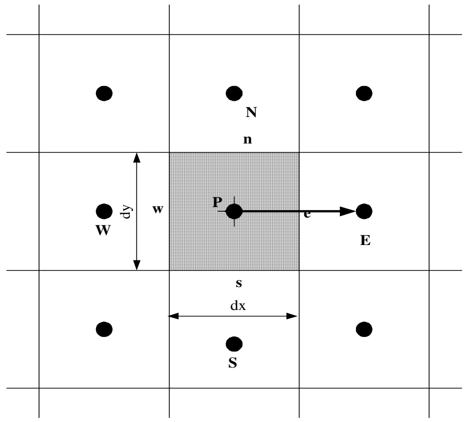

Figure 4. Source in Arbitrary Mesh Center

When the jet is injected in E-direction, the simulation of the jet flow is influenced by the magnitude of the grid spacing dx. Thus, an appropriate size of dx was determined in the previous study[7] based on the comparison of a real 2-D inlet boundary treatment case and the source term treatment of the inlet boundary condition case.

VALIDATION SIMULATION

Simulation of Indian BARC SDS-2 Phase 1 Experiment[3]

In Bhabha Atomic Research Centre(BARC) in India, an experimental facility was set up to measure the spread, penetration, growth rate of the poison jets and interaction between the multiple jets in order to find the optimal combination of the hole size, number and layout of the poison injection nozzle to meet the SDS-2 design requirement and mathematical models were developed. The system consists of a tank containing pressurized helium connected to poison tanks through quick opening solenoid valves. The tanks are connected to horizontal injection nozzles of tube form in the calandria.

Table 2. Jet Height versus Time at He Gas Pressure of 10kg/cm^2 For Single Hole Case

time(sec)	Velocity at Hole (m/s)	$v \times t \times \sqrt{A}$	Jet Height (cm)
0.2	9.214	52.262	31.084
0.3	9.519	80.982	38.934
0.4	9.802	111.191	46.519
0.5	10.065	142.710	53.835
0.6	10.276	174.845	60.841
0.7	10.292	204.345	66.986
0.8	10.303	233.740	72.448
0.9	10.310	263.149	77.274
1.0	10.318	292.612	81.760

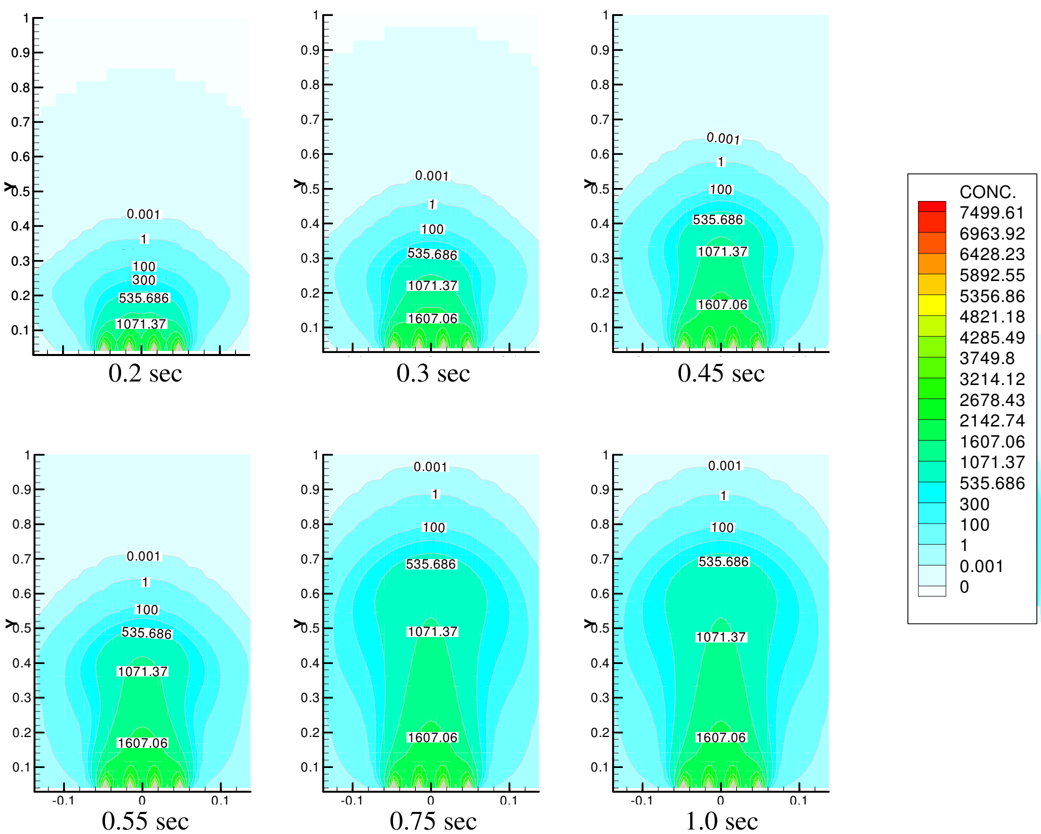

Figure 5. Poison Jet Propagation with Time for He Pressure of 10 kg/cm^2

Table 3. Jet Height versus Time at He Gas Pressure of 15kg/cm^2 For Single Hole Case

time(sec)	Velocity at Hole (m/s)	$v \times t \times \sqrt{A}$	Jet Height (cm)
0.4	12.750	144.571	53.452
0.5	12.566	178.177	61.014
0.6	12.648	215.211	67.508
0.7	12.670	2.509	73.123
0.8	12.669	287.419	78.077
0.9	12.670	323.362	82.617

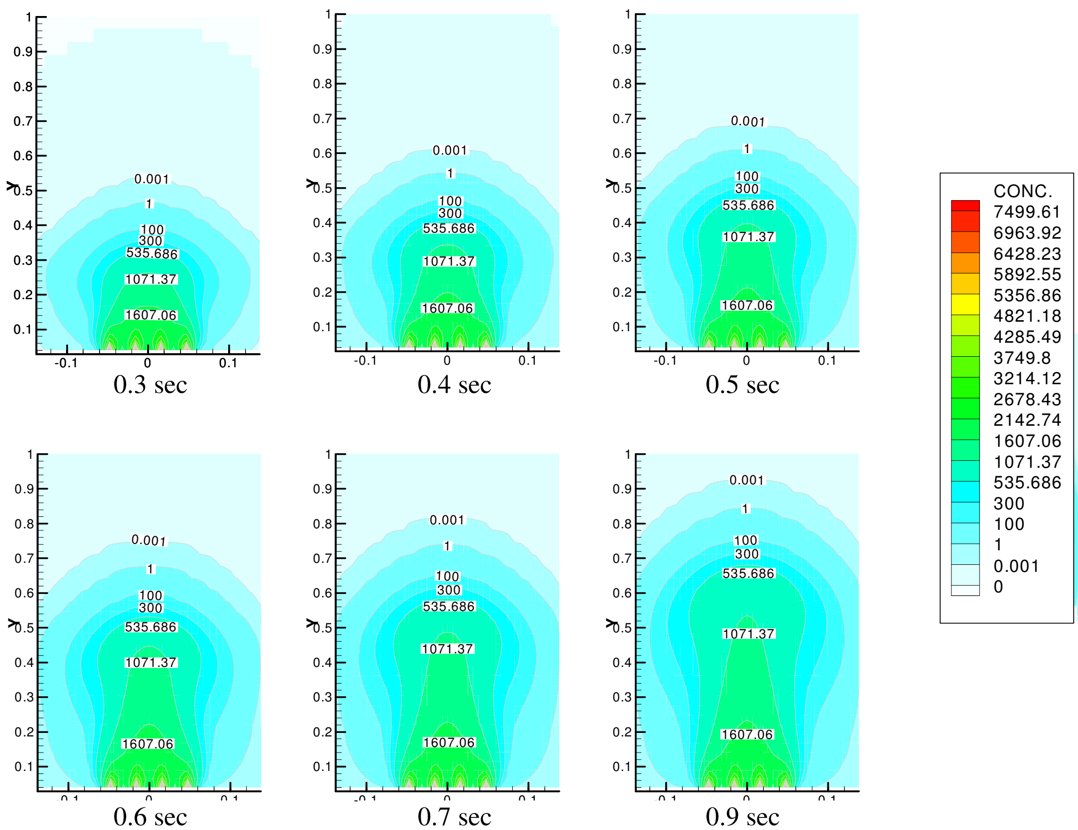

Figure 6. Poison Jet Propagation with Time for He Pressure of 15 kg/cm^2

Table 4. Jet Height versus Time at He Gas Pressure of $20 kg/cm^2$ for Single Hole Case

time(sec)	Velocity at Hole (m/s)	$v \times t \times \sqrt{A}$	Jet Height (cm)
0.2	13.8432	78.5143	40.046
0.3	14.034	119.397	51.102
0.4	14.456	160.580	60.866
0.5	13.715	194.469	68.122
0.6	13.714	233.337	74.889
0.7	13.889	275.713	81.277
0.8	14.065	319.085	86.905
0.9	14.115	360.263	91.762
1.0	13.992	396.786	95.762
1.1	13.869	432.631	99.401

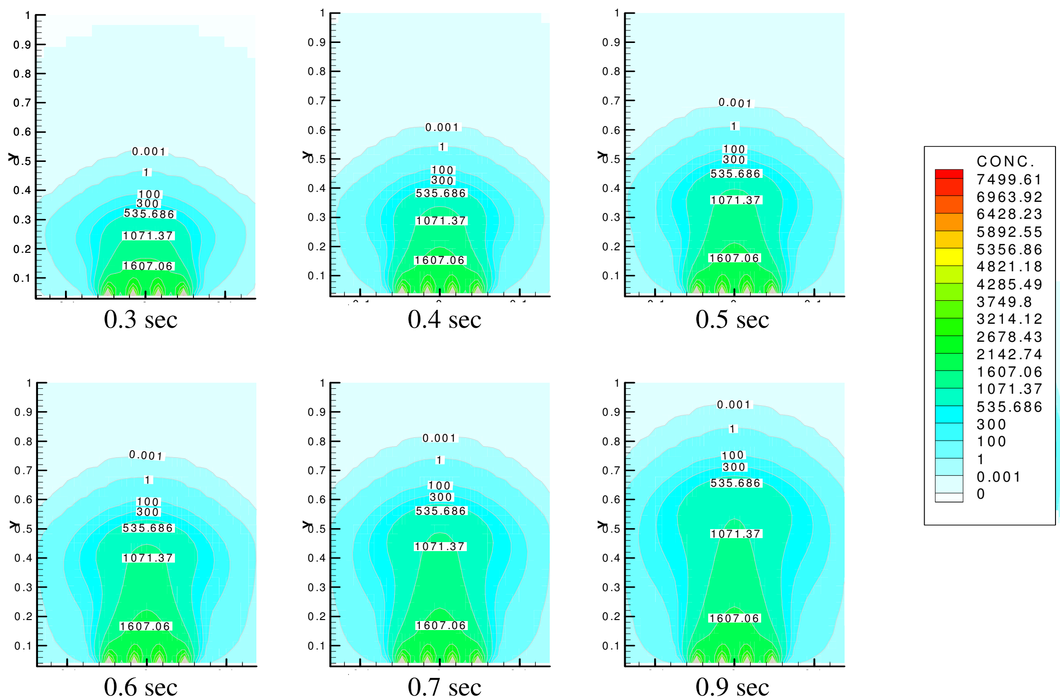

Figure 7. Poison Jet Propagation with Time for He Pressure of $20 kg/cm^2$

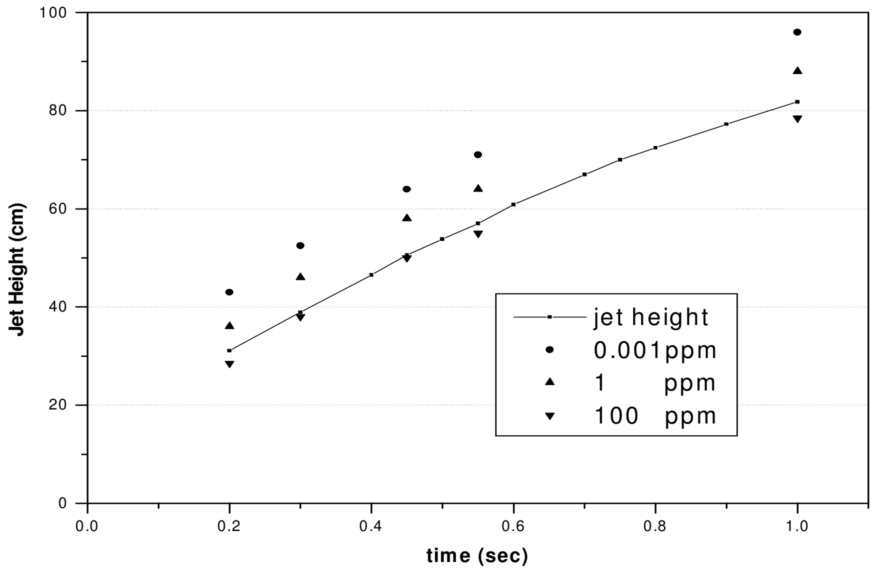

Figure 8. Poison Jet Front Height Growth for Poison Tank pressure of 10kg/cm2

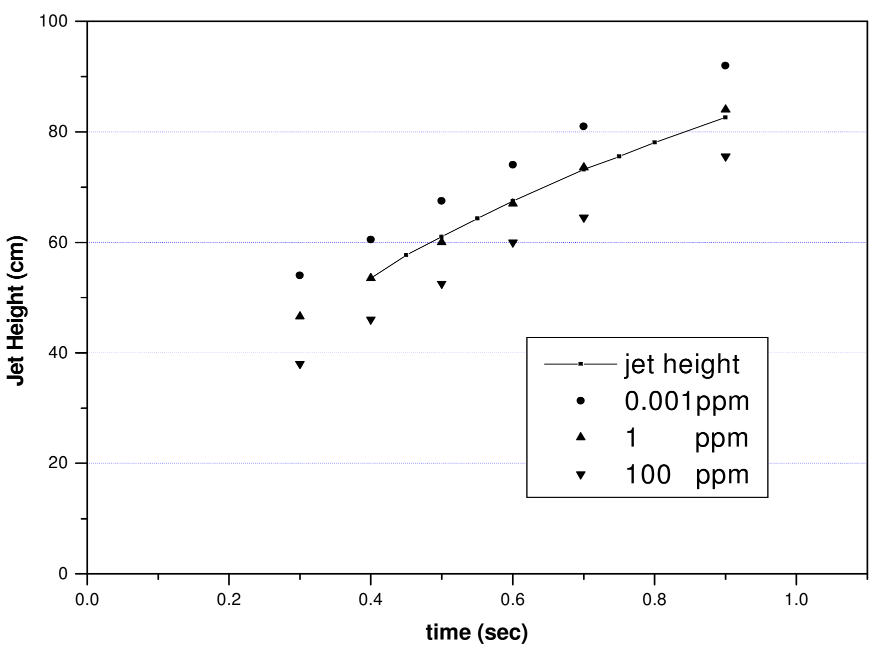

Figure 9. Poison Jet Front Height Growth for Poison Tank pressure of 15kg/cm2

On system actuation, gadolinium nitrate solution from the tanks passes to the injection nozzles which have a number of holes through which the poison enters the moderator. The following experiments have been carried out:

[1] Single hole experiments on 3.2, 4.0, 5.0, 8.0 mm diameter holes at 7 kg/cm^2 air pressure to study the spread angle and 10, 15, 20 kg/cm^2 to study the jet growth rate and discharge rate.

[2] Single slit experiments on 15x1, 12x0.75, 9x0.6, 7.5x0.5 mm slits at 7 kg/cm^2 air pressure to study the spread angle and 10, 15, 20 kg/cm^2 to study the jet growth rate and discharge rate.

To generate the data on jet growth, poison front movement and spread angle, the video photography at the rate of 1 frame in 0.04 sec and high speed camera picture were taken. The measured parameters are the pressure of Nitrogen gas tank and liquid poison tank, poison tank level, working fluid temperature.

In case of single hole experiment, test data is available, from which the average velocity of the liquid poison at the hole entrance and the corresponding jet length (or height) are deducible at various time. Thus, the poison velocity at the hole entrance is used as the inlet flow boundary condition for the 3-D jet simulation, and the resulting jet height in time is compared with the measured one for the 3 different Nitrogen pressure cases as shown in Tables 2-4, Figs. 5-9. From this comparison it is guessed that the jet front may correspond to the poison concentration of 1.0 to 100 ppm, which cannot be confirmed as no concentration measurement is made.

Simulation of Generic CANDU-6 Poison Injection SPEL Test

Another validation of the current model is against the Poison Jet Experiment of Generic CANDU-6 performed at AECL. This experiment was performed at the Generic CANDU-6 prototype test rig at SPEL to validate the 1-D Hydraulic code, ALITRIG, and the process of the poison jet growth was pictured by a high-speed camera. As the poison concentration was not measured, the poison jet front growth was identified based on the subjective visual inspection of the pictures taken. In this analysis the poison injection rate at each hole was predicted by the ALITRIG code simulation and this injection rate was used as the boundary condition for 3-D CFD simulation of the poison jet experiment. As shown in the Fig.3 the height of poison jet front grows rapidly right after the poison begins to be injected following the D2O flow preceding the poison injection as it already existed in the injection pipings before the trip signal is issued. The growth of the poison jet front height predicted by current 3D CFD model denoted by a black triangle and diamond compares well with the experimental data denoted by a black rectangle and the ALITRIG's prediction. It is considered that the jet front of 200 ppm poison concentration fits the experiment most closely. One point to mention here is that the current 3D CFD model does not explicitly account for the effect of the calandria tube banks on the jet progression. It is planned to validate the current model against the available experimental data with and without the presence of these tube banks as they are also available from the same test data.

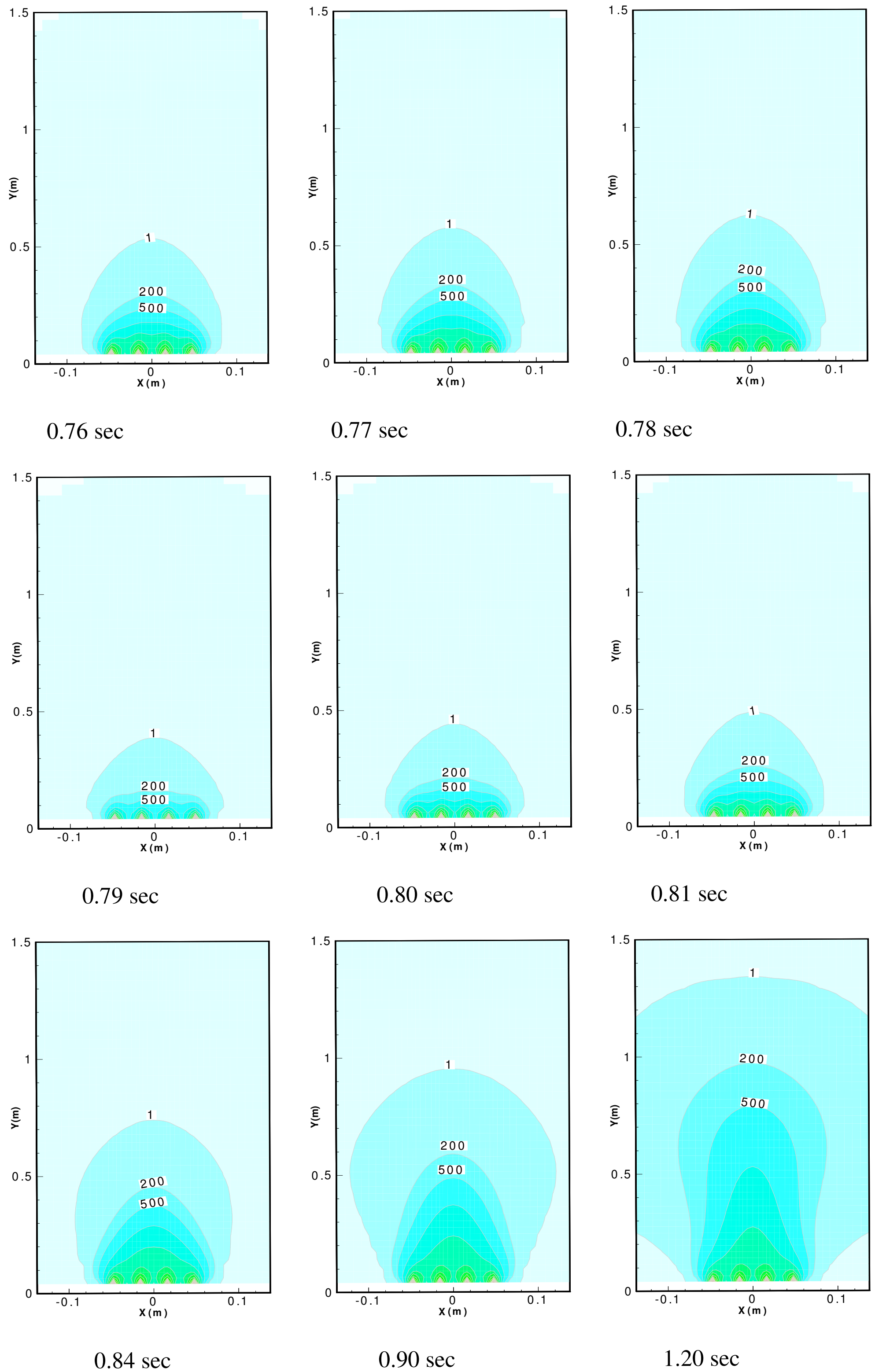

Figure 10. Concentration profile at 9-th pitch of nozzle#1 for Generic CANDU-6 (delay time : 0.758sec)

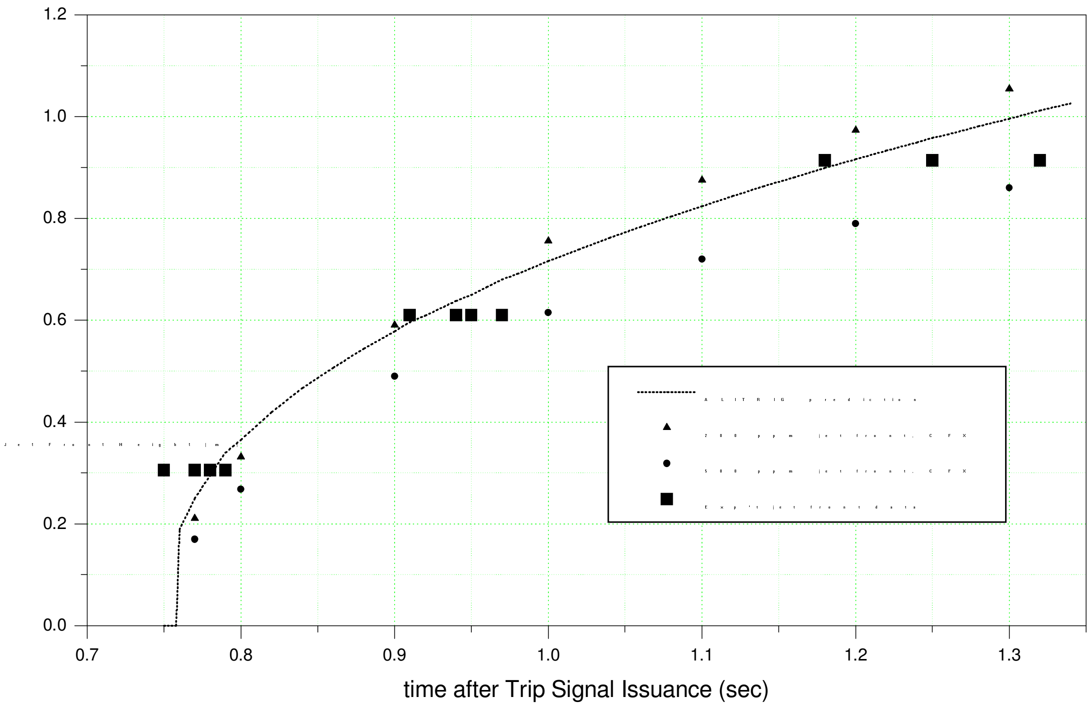

Figure 11. Jet Growth Exp't Data for CANDU-6 Generic Case with Calandria Tubes

CONCLUSION

A set of models for analyzing the transient poison concentration induced by this high pressure injected poison jet upon the reactor trip in a CANDU-6 reactor has been developed and its validity evaluated. For validation, this model's prediction was compared against two poison injection experiment data, one performed at BARC, India and the other at AECL, Canada. Both comparisons showed that the model is able to predict the poison jet front height growth consistently. In conclusion this set of models is judged to be appropriate for its intended purpose.

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