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Extended Validation of 3-D CFD Model for Liquid Poison Injection of CANDU Reactors

Bo Wook Rhee, Jae-Ho Choi, Byung-Joo Min

Korea Atomic Energy Research Institute

150 Dukjin-Dong Yusong-Gu Daejeon, Korea
bwrhee@kaeri.re.kr, ex-cjh@kaeri.re.kr, bjmin@kaeri.re.kr

3-D CFD Model, Liquid Poison Injection, Shutdown System, CANDU-6, Model Validation,

ABSTRACT

An extension of the validation of an existing CFD model for liquid poison injection phenomena of CANDU Shutdown System No.2 is made so that the model developed in the previous researches can be applied to the case where calandria tube banks are present in the CANDU moderator tank. While the previous validation[1] of the pertinent CFD model were limited to those experiments where no calandria tube banks are present as the existing 3-D CFD model for liquid poison injection assumes by postulating the wall effect on the poison growth negligible, current work shows that this assumption is really the case even for those experiments where calandria tubes are present in the CANDU moderator tank.

In this study, a set of model equations developed previously for analyzing the transient poison concentration induced by this high pressure poison injection jet initiated by the reactor trip has been summarized. The poison injection rate through the jet holes drilled on the nozzle pipes is obtained by a 1-D transient hydrodynamic code called, ALITRIG, and the injection rate is used to provide the inlet boundary condition to a 3-D model of the moderator tank based on a CFD code, CFX4.3[2], to simulate the formation of the poison jet curtain inside the moderator tank. As for validation, a new validation work is carried out for the liquid poison injection experiments for 850MWe CANDUs with and without the calandria tube banks present[3]. Along with the previous validation of the current model against the poison injection experiment performed at BARC[4] and the poison jet growth experiments[5] for a generic CANDU-6, the current work would extend the applicability of the current CFD models developed at KAERI for liquid poison injection for SDS 2 design analysis for the past a few years to the case where pressure tube banks exist in the moderator tank. The analyses results well agree with the experimental data for the case with and without the calandria tube bank present[5]. Therefore, the 3-D CFD model developed at KAERI is judged to be

appropriate for verifying the effectiveness of SDS 2 liquid poison injection for intended functional design requirement of the system.

1. 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 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[6]. Then these local neutron fluxes are compared with those measured by the neutron detectors during the shutdown test. 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 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 experiment setup necessary, this part of the work needs to heavily depend on numerical analyses partially validated against few available experimental data.

Current work is an extension of a series of development work carried out at KAERI for the past few years for developing design and analysis tool for CANDU-6 SDS 2 to another experiment for large size 850MWe CANDUs. The previous works involves developing a 3-D CFD model for analyzing the liquid poison injection and dispersion process in the CANDU moderator tank, and two validation analyses for an Indian researchers’ experiment at BARC and a Poison Jet Experiment of Generic CANDU-6 performed at AECL. Details of these validations can be found in the previous works.

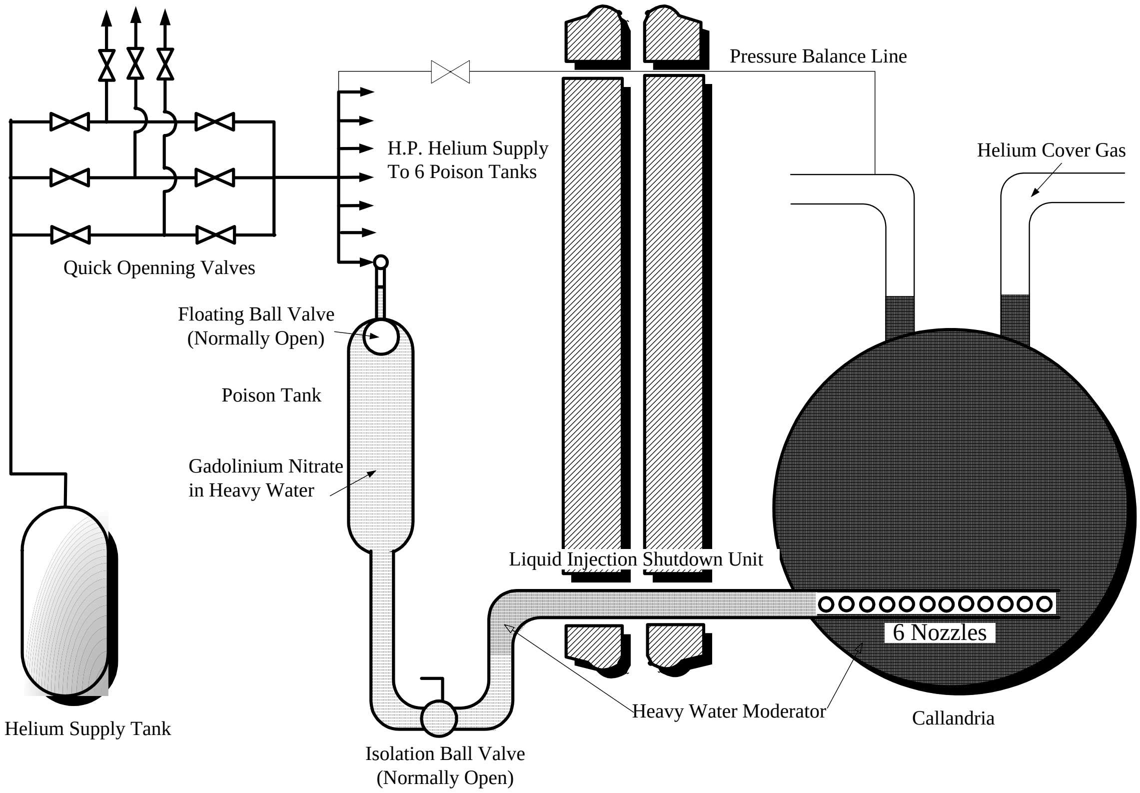


Figure 1. Schematic of Liquid Injection Shutdown System

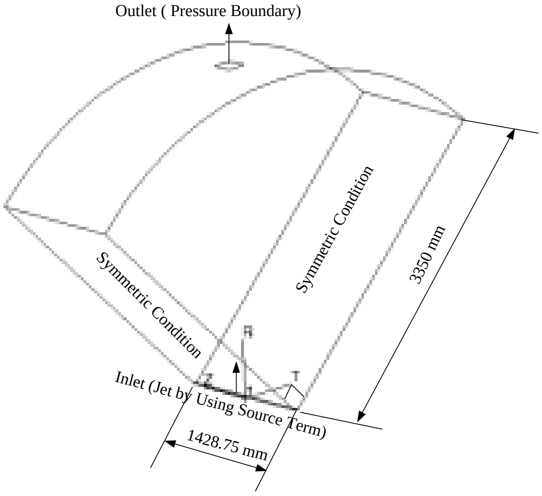


Figure 2. Segment of Calandria Tank used for 3-D Jet Simulation

2. THEORETICAL MODELS

2.1 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.

2.2 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:

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

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

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:

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

$$\frac{\partial r\, u_i}{\partial t} + \frac{\partial r\, u_i u_j}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial t_{ij}}{\partial x_j} + s_i$$

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

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

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

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,[7] and m_t is the turbulent viscosity. For the analysis of a turbulent flow, the standard $k-e$ model based on an eddy-viscosity hypothesis is used in this study. where s_i is the source term and t_{ij} is the stress tensor.

As for the boundary conditions, 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.

The general formulation of the source term can be mathematically written as

$$\sum_m a_m (f_P - f_m) = S_P f_P + S_c$$

where the summation is over a neighbouring cells of the control volume. The velocity f 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	$-r V_{inlet}$	0.0	$-r V_{inlet}$
S_c	$r V_{inlet} V_{inlet}$	$r V_{inlet} A_{inlet}$	$r V_{inlet} Y_{A,inlet}$

3. VALIDATION SIMULATION

3.1 Indian BARC SDS-2 Phase 1 Experiment[4]

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. 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. 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. The comparison of the analysis results denoted by black circles and triangles with the jet height estimated based on the experiment data denoted as solid line are shown in Figures 3 and 4, and shows good agreement assuming that the poison concentration at the jet front is 100 ppm.

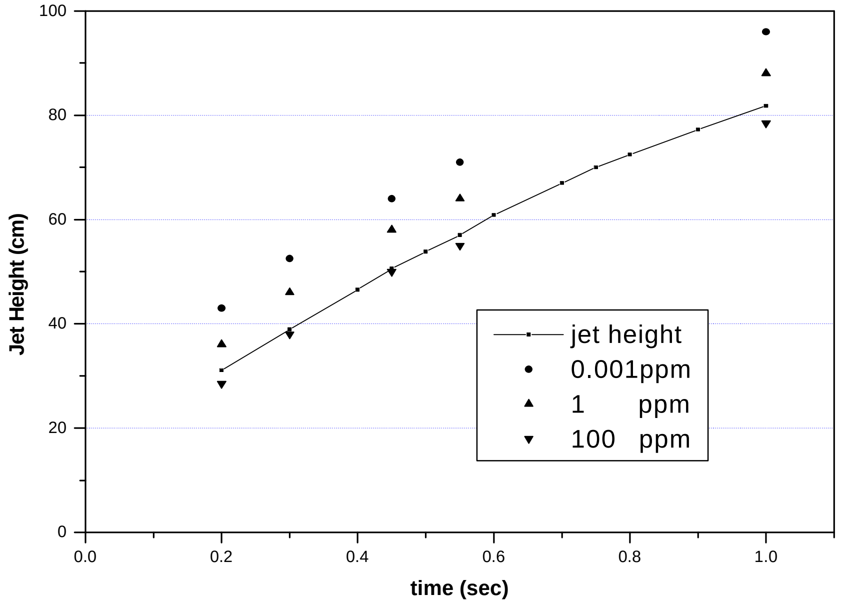


Figure 3. Poison Jet Front Height Growth for Poison Tank pressure of 10kg/cm2

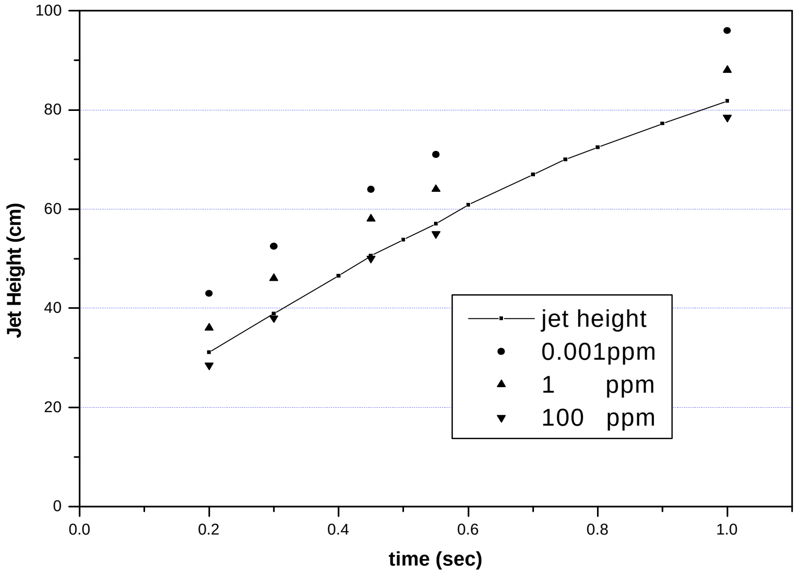
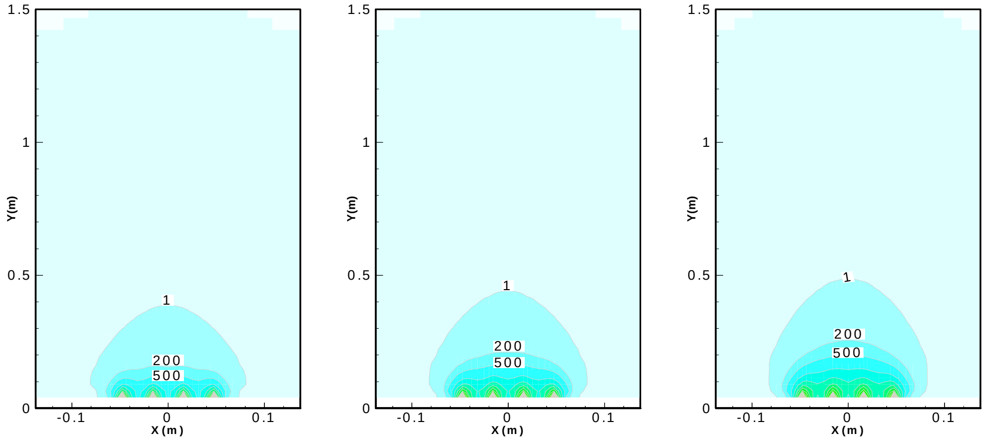


Figure 4. Poison Jet Front Height Growth for Poison Tank pressure of 15kg/cm2

3.2 Generic CANDU-6 Poison Injection SPEL Test[5]

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 Fig.5 the height of poison jet front grows rapidly right after the poison begins to be injected following the D_2O 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.



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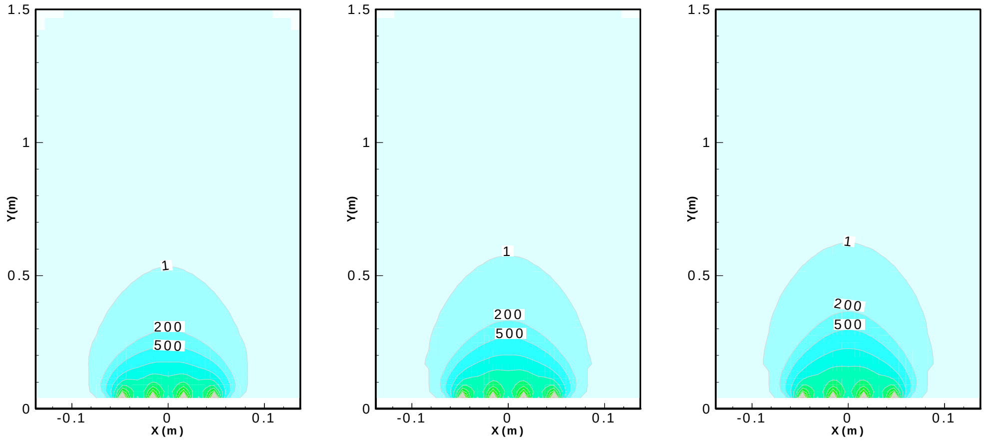

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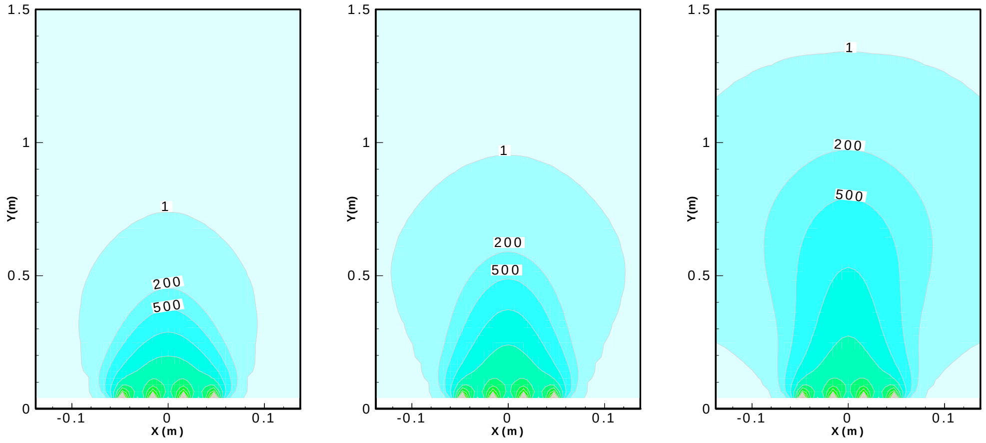

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Figure 5. Concentration profile at a specified pitch of nozzle#1 for Generic CANDU-6 (delay time : 0.758sec)

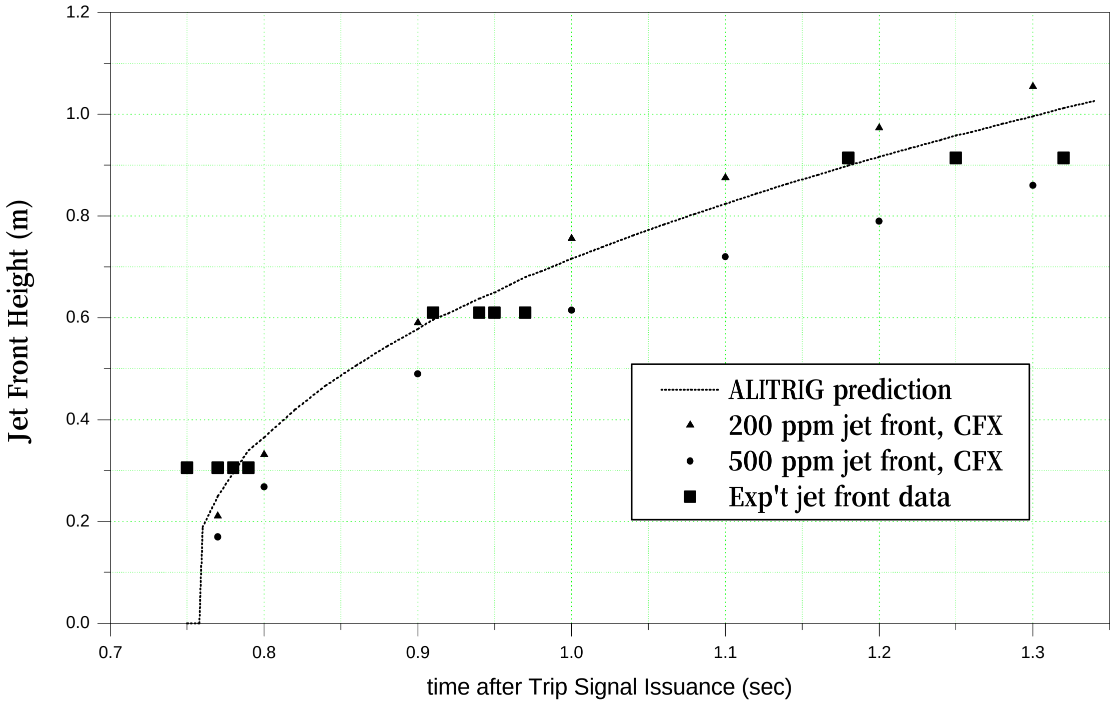

Figure 6. Jet Growth Exp't Data for CANDU-6 Generic Case with Calandria Tubes

3.3 850MWe CANDU Poison Injection SPEL Test[3]

Another simulation for a very different nozzle hole configuration for 850 MWe CANDU reactor is performed to validate the current model against the available experimental data with and without the presence of these tube banks. Though the current model assumes that the effect of the calandria tubes on the poison jet injection phenomena is negligible by not accounting for the tube wall boundary as the physical boundary in the CFD model, the analyses result in Figure 7 shows that this assumption is legitimate as the current model with the poison concentration of the jet front at 200 ppm can predict the poison jet growth trend quite well with reasonable accuracy for both cases with and without the presence of the calandria tube bank.

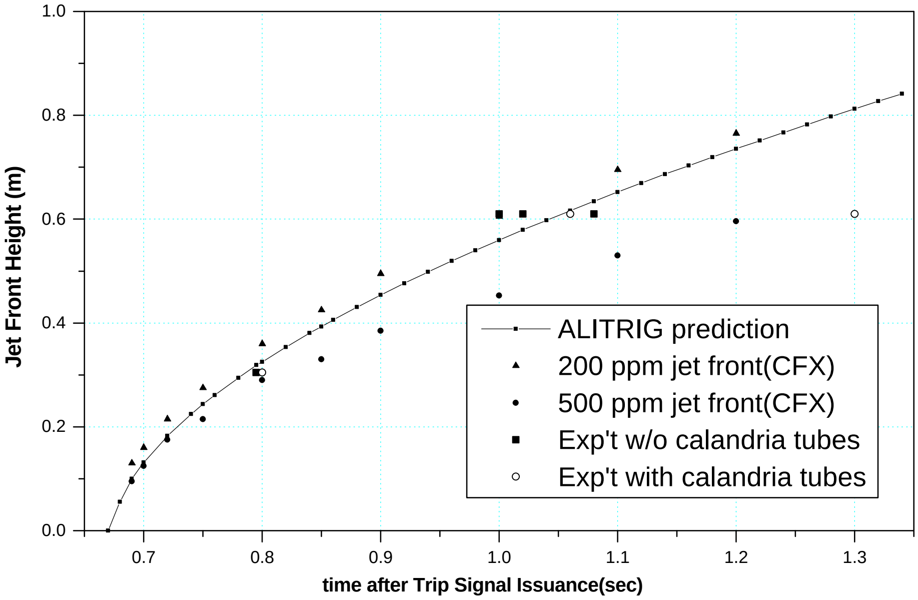

Fig 7. Comparison of CFX Jet Growth with Exp't Data for 850MWe CANDU with & w/o Cal-Tubes

4. CONCLUSIONS

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 three independent poison injection experiment data, one performed at BARC, India and the others at AECL, Canada. One experiment for 850 MWe CANDU includes the case with and without the presence of the calandria tube bank. All comparisons showed that the model is able to predict the poison jet front height growth consistently with reasonable accuracy. Therefore, the current 3-D model combined with the 1-D ALITRIG hydraulics code is judged be appropriate to generate the poison concentration distribution during injection for neutron cross section generation for verifying effectiveness of SDS 2 liquid poison injection for intended functional design requirement of the system.

ACKNOWLEDGEMENT

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