SIMULATION OF A CS28-2 HIGH TEMPERATURE EXPERIMENT BY USING THE CFX CODE

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Abstract

A computational fluid dynamics (CFD) simulation tool for the CS28-2 high temperature experiment is developed with CFX-10 software and the results obtained from the simulations are compared with the experimental data. The CS28-2 test is one of the experiments to understand the high-temperature fuel channel behavior and to establish the effectiveness of the moderator as a heat sink to demonstrate the safety of CANDU reactors. The main heat transfer characteristics of the CS28-2 are a super-heated steam convection and a radiation heat transfer from the hot rods to the surrounding cold wall. The CFX-10 predictions of the temperatures of the heater rods and the pressure tube are in good agreement with the measurement data.

1. Introduction

An experimental program, the CHAN thermal Chemical Experimental Program [1], has been performed by AECL in Canada for a validation of computer codes such as CHAN-II [2] and CATHENA [3]. These codes are capable of predicting the thermal-chemical response of CANDU fuel channels during a postulated Loss-of-Coolant Accident (LOCA) without an Emergency Core Cooling System (ECCS). This program consists of several series of experiments: a single fuel element simulator (FES) [1], 7-element [4, 5], and 28-element tests [6].

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Table 1 shows the classification of these experiments according to 3 parameters such as the number of FES, the channel orientation, and the degree of the FES temperature rise during a transient. Each experiment is named as the index specified in Table 1.

Table 1 Classification of thermal-chemical experiments

No. of FES	Single-element		7-element						28-element		
Channel Orientation	Vertical		Vertical				Horizontal		Horizontal		
FES Max. Temp. (℃)	1706	1300	1213	1343	1700	1650	1760	1720	1730	1860	>1860
External cooling	Water jacket		Water jacket						Pool		Water jacket

The results of the single-element tests were used to verify the individual codes (such as the CHAN-II and CATHENA models) for a convection, radiation heat transfer (low temperature experiment; ~1300℃) and Zircaloy/steam reaction (high temperature experiment; just below the Zircaly melting temperature, ~1700℃) in a simple geometry. In the 7-element test, seven FESs were used to represent a multi-rod geometry. A vertical configuration was adopted to assess the CHAN code under the axi-symmetric conditions, while a horizontal configuration was used to simulate the actual fuel channel orientation. The final series of the CHAN experimental program used a full scale horizontal fuel channel with 28-element fuel bundles to simulate the actual geometry of a Pickering type CANDU reactor.

CS28-2, one of the 28-element tests, has 3-dimensional effects due to an eccentric configuration of the test section. The Computational Fluid Dynamic (CFD) code, CFX-10 [7] is used to simulate the CS28-2 test for this study.

2. Overview of the CS28-2 Experiment

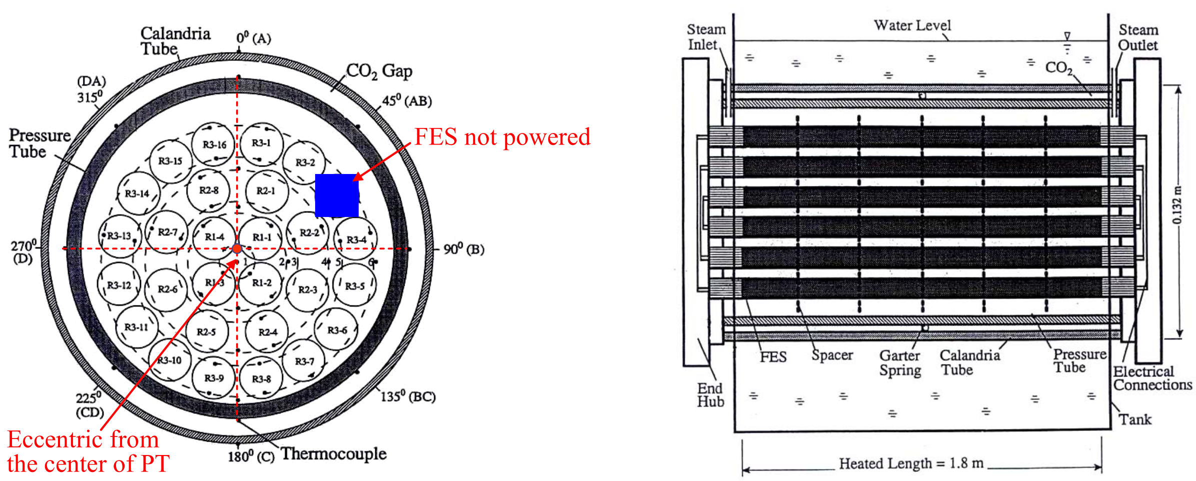
2.1 Test Apparatus

The test apparatus is shown in Fig. 1. The test section consists of the electrically heated FES bundle, pressure tube, gap annulus, and Calandria tube. The Calandria tube is surrounded by an open tank of 40℃ water. The FES bundle consists of three rings of FESs and they are eccentrically located inside the pressure tube. This eccentric configuration is prepared to understand the fuel channel behavior when the pressure tube is ballooned and most of the steam flow is bypassed through the upper part of the channel.

The superheated steam at 670℃ is injected to the inlet of the test section with a mass flow of 15 g/sec. The CO_2 gas flow in the annulus gap is 1.6 SLPM.

One of the sixteen outer ring FESs (pin R3-3, Fig. 1-a) was not powered in this test section.

During the experiment, the electrically heated FESs are cooled by a steam convection, conduction, and a thermal radiation radially from the FESs to the pressure tube and from the pressure tube to the Calandria tube.



(a) Cross-sectional view (b) Longitudinal view

Figure 1 Schematic diagram of the test section

2.2 Main Test Results

The power history curve of the FES bundle is shown in Fig. 2. The individual power supplied to the outer, middle and inner rings are shown in addition to the total bundle power which was the sum of all the rings powers. The temperatures measured at FES and the pressure tube are plotted in Fig. 3. The reference test data for a steady-state condition are obtained from the values at 500 sec.

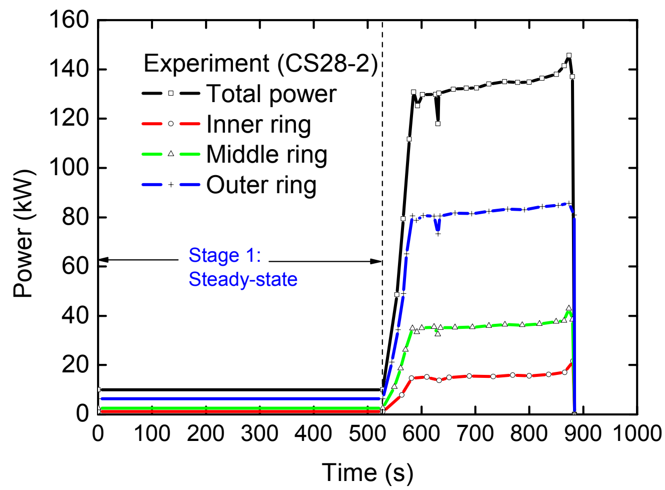


Figure 2 FES power transient

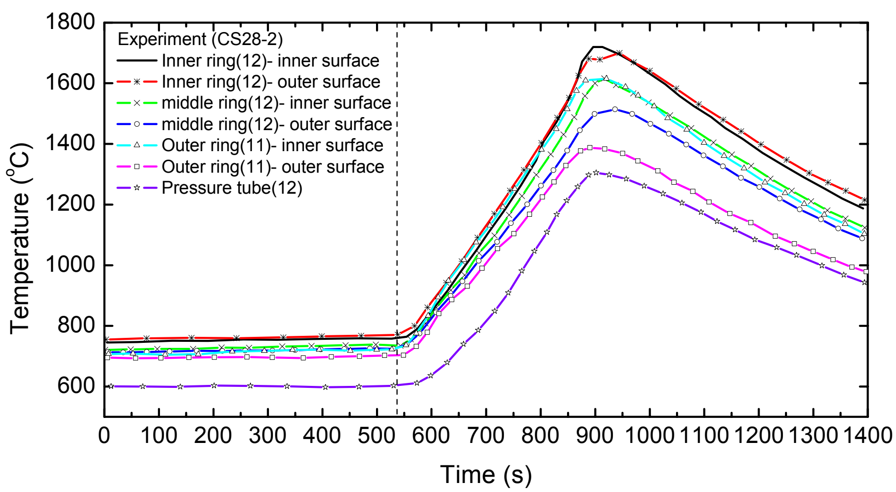


Figure 3 FES and pressure tube temperatures

3. CFX Modeling of CS28-2

3.1 Mesh Generation

The grid of the CS28-2 test section is generated by using the ICEM CFD [8] software. Figure 4 shows the results of the grid generation and the mesh layers near the solid walls.

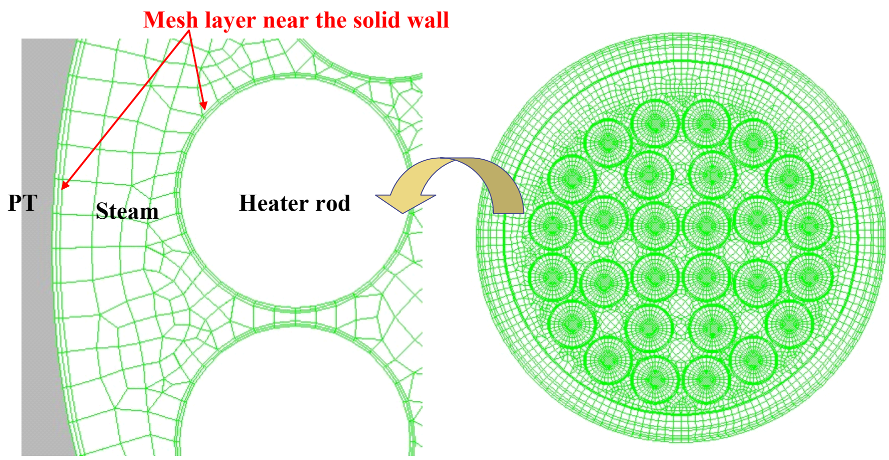


Figure 4 Mesh generation of the CS28-2 test section

3.2 Material Properties

The materials used in the domain setting are graphite, Al_2O_3, Zircaloy, steam, and CO_2. Zircaloy is used for the FES sheath, pressure tube, and Calandria tube. These properties are the same as those used in the CATHENA code [3].

3.3 Boundary Conditions

The modeling of a pool surrounding the Calandria tube is simplified by using the temperature boundary condition (40℃) on the outer surface of the Calandria tube. The steam injection flow is modeled by the mass flow rate boundary condition at the inlet on the interface between the steam and pressure tube domains. The FES power is modeled by an energy source within a solid sub-domain. The total thermal power for a steady-state condition is 10 kW and the normalized ring radial powers are 1.111, 0.894 and 0.775 for the outer, middle, and inner FES rings, respectively.

4. Thermal radiation model of CFX-10

In problems where a thermal radiation is significant, a proper choice of the thermal radiation will affect the quality of the solution. Therefore, a proper selection of the radiation model is made from physical considerations [7].

For the case of the CANDU fuel channel where superheated steam becomes the only coolant available to the fuel channel under a postulated LOCA without an emergency cooling in CANDU reactors, a radiation heat transfer analysis with assumptions of a non-participating medium completely enclosed with the diffuse, gray and opaque surfaces are practically used by most fuel channel codes. Therefore, the Discrete Transfer Model (DTM) developed by Lockwood and Shah [9] is applied to model a surface radiation heat transfer in the present study. The DTM of calculating radiative heat transfer involves the tracing of representative rays from one surface to another through the domain of interest. The intensity distribution along each ray is calculated by solving a discretization of the equation of radiative heat transfer. The fundamental equations for the transfer of thermal radiation may be expressed as:

$$\frac{dI}{ds} = -(k_a + k_s)I + k_a \frac{E_g}{\pi} + \frac{k_s}{4\pi} \int_{4\pi} P(\underline{\Omega}, \underline{\Omega}')\, I(\underline{\Omega}')\, d\Omega' , \tag{1}$$

where I is the radiant intensity in the direction of $\underline{\Omega}$, s is distance in the $\underline{\Omega}$ direction, $E_g \equiv \sigma T_g^4$ is the black body emissivity power of the gas at temperature T_g, k_a and k_s are the gas absorption and scattering coefficients, and $P(\underline{\Omega}, \underline{\Omega}')$ is the probability that incident radiation in the direction Ω' will be scattered into the increment of solid angle $d\Omega$ about Ω. This method is numerically exact, geometrically flexible and easily coupled to a CFD solver.

Once the DTM has been selected for the CFX-10 calculations, it is applied in the fluid domain enclosed by the opaque diffuse surfaces with specified emissivities. The emissivities of the fuel sheath and inner and outer surfaces of the pressure tube are assumed constant and equal to 0.8. The emissivity of the inner surface of the calandria tube is set to 0.34.

5. Simulation results

Table 2 shows the heat transfer rates in the steady-state calculation by the CFX-10. The total power from the FES rods is 10 kW, which is transferred to the steam by a convection (8,688.1 W) and to the inner surface of the pressure tube by a thermal radiation (1,311.6 W).

Table 2 Heat transfer rates between the FES and steam in the steady-state calculation

Heat transfer mechanism		**Domain**		
		FES	⇒	Steam
Thermal radiation	(W)		*8,688.1*	
Convection	(W)		*1,311.6*	
Total	(W)		*9,999.7*	

After the CFX calculation result has been converged, the following parameters are chosen to show the comparison between the CFX-10 predictions and the experimental results: the temperature of the sheath surfaces of the inner, middle and outer rings, the pressure tube temperature, and the steam temperature.

Figure 5 shows a front view of these temperature predictions by CFX-10. We can see that the FES temperatures are increased towards the center of the ring because the thermal energy generated in the 28-element is radially transferred to the surrounding pressure tube. Figure 6 shows the axial temperature predictions of the FES bundle. Since the R3-3 in the outer ring is not powered its temperature is lowest among those of the other FES's.

Figures 7, 8 and 9 show the measured and predicted FES temperatures of the inner, middle and outer rings, respectively, at different axial locations. We can see that the FES temperatures are increasing inwards from the fuel bundle because the thermal energy generated in the 28-element is radially transferred to the surrounding pressure tube. Since the heat generation rate in the FES is essentially uniform along the length of the test section, the steam flow along the test section leads to higher FES temperatures near the exit of the test section. The predictions of the FES temperatures are in good agreement with the measured data to within ±2% of the error, which is defined as the ratio of the temperature difference to the measured temperature. The uncertainties in the thermocouple readings are roughly ±1% plus there is some additional uncertainties arising from the radial temperature variations from the inner edge of the fuel ring to the outer edge. On this basis, the FES thermocouple readings have a maximum uncertainty of ±20~±30℃ during the steady-state condition. The maximum difference between the predictions and the measured data is less than 20 ℃, which is less than the uncertainty of the temperature measurements.

Figure 10 shows the comparison between the measured data and the CFX-10 predictions for the pressure tube temperatures at different axial locations. The CFX-10 predicted the measured data excellently at the locations of 0.525 m and 0.825 m, but it under-estimated at locations of 1.125 m and 1.725 m. The difference between the code prediction and the measured data is about 50 ℃ at the location of 1.725 m. The difference exceeds the uncertainty of the temperature measurements which remains unexplained.

The measured and predicted steam temperatures at the exit to the test section are shown in Fig. 11. The agreement is reasonably good between the measurements and the code predictions for the steam temperatures, especially inside the inner sub-channel (between the inner ring and the middle ring).

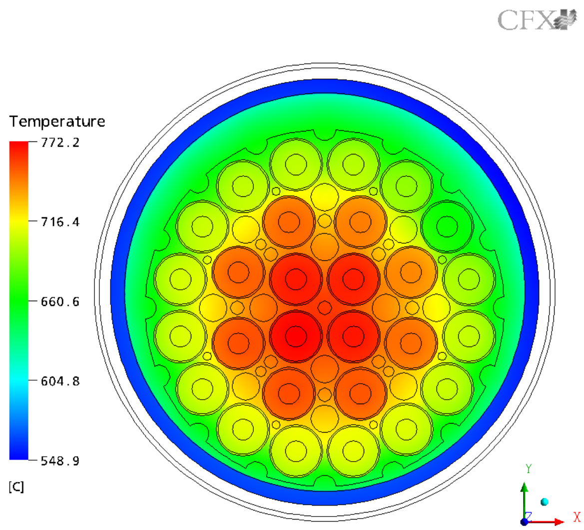


Fig 5. Two-dimensional view of the temperature calculation by CFX-10 (at axial location of 1.0 m)

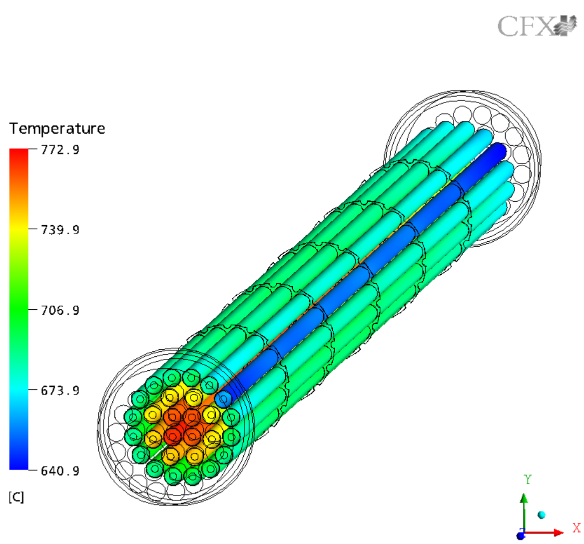


Fig 6. Axial temperatures predictions of the FES bundle by CFX-10

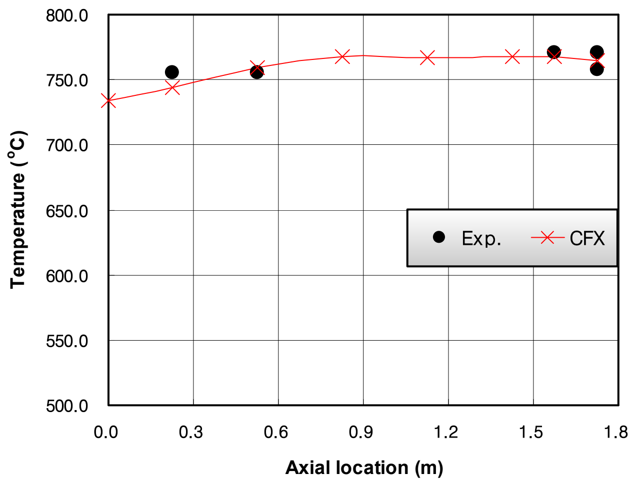


Fig 7. Comparison of the CFX-10 prediction and the experimental data for the FES temperatures in the inner ring

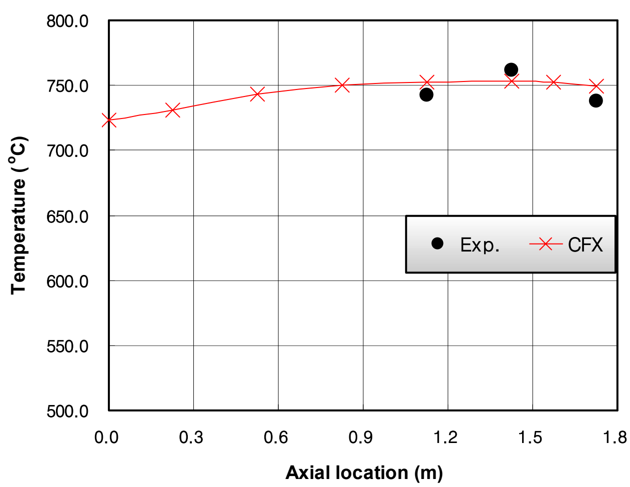


Fig 8. Comparison of the CFX-10 prediction and the experimental data for the FES temperatures in the middle ring

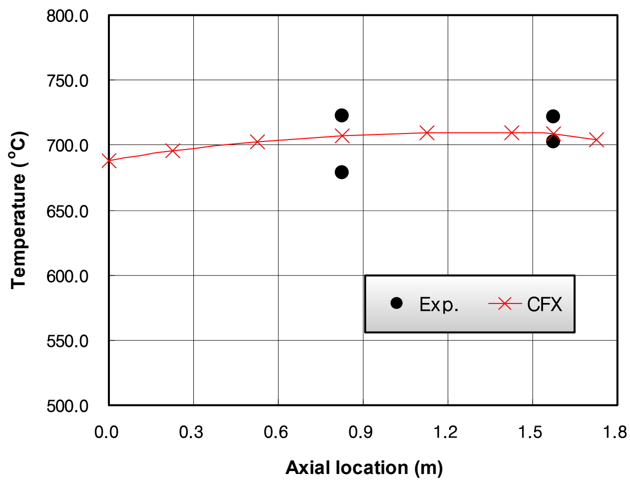


Fig 9. Comparison of the CFX-10 prediction and the experimental data for the FES temperatures in the outer ring

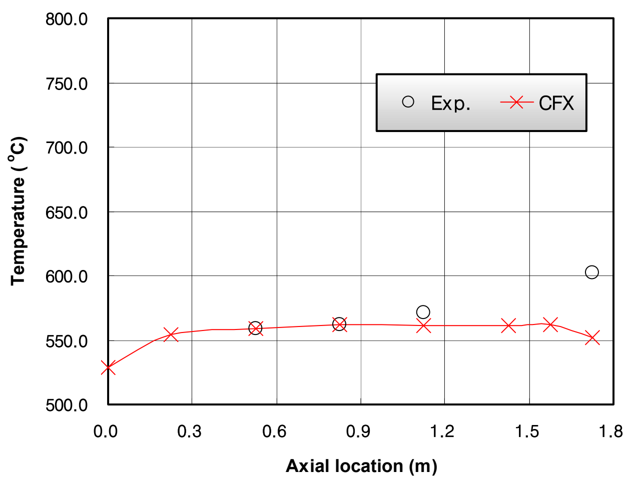


Fig 10. Comparison of the CFX-10 prediction and the experimental data for the pressure tube temperatures

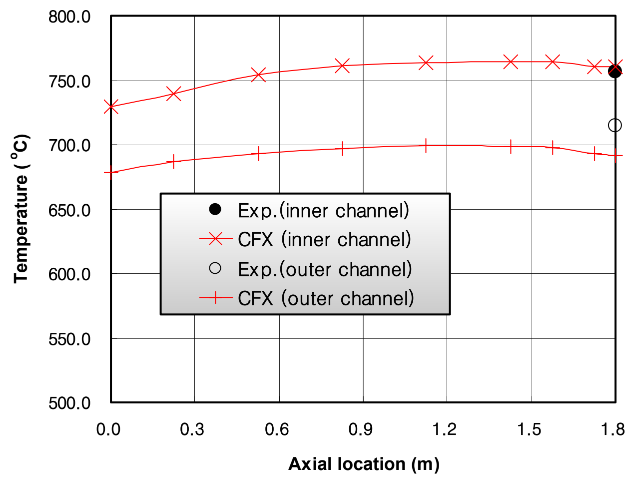


Fig 11. Comparison of the CFX-10 prediction and the experimental data for the steam temperatures

6. Conclusion

The CFX-10 code is used to simulate the CS28-2 experiment. From the present study the following conclusions can be made.

- It is confirmed that the thermal radiation heat transfer is a dominant mode in the CS28-2 experiment from the present simulation: 87% of the heat source from the FES's is transferred to the steam by a thermal radiation.
- The predictions of the FES temperatures of the inner, middle and outer rings at different axial locations agreed well with the measured data to within 20 ℃, which is less than the uncertainty of the temperature measurements.
- A reasonable agreement between the predictions and the measurements of the pressure tube temperatures is obtained, except that the pressure tube temperature is under-estimated by 50 ℃ near the exit to the test section.
- The convection heat transfer by the steam flows in the test section increases the steam temperature along the length of the test section. The CFX-10 predictions for the steam temperatures at the exit to the test

section are in good agreement with the measurement data.

This is a steady-state calculation for the CS28-2. Further works are recommended to complete the simulation for the transient phase of the CS28-2 experiment.

Acknowledgements

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