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Review of Thermal-Chemical Experiments for a CANDU Fuel Channel

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1. Introduction

During a postulated Loss-of-Coolant Accident (LOCA) without Emergency Core Cooling System (ECCS), it is important to through understand high-temperature fuel channel behavior and to know the effectiveness of the moderator as a heat sink to demonstrate the safety of CANDU reactors. For this purpose, the CHAN thermal Chemical Experimental Program [1,2,3,4] has been performed at Whiteshell Laboratories in Canada since 1981. It consists of several series of experiments: a single fuel element simulator (FES), 7-element, and 28-element tests.

This paper reviews the experimental results from two single-element tests [1], six 7-element tests [2,3], and three 28-element tests [4]. The information on these experiments is reviewed and summarized. The test data has been collected from the published references [1,2,3,4] and will be used to validate 3-dimensional Computational Fluid Dynamic (CFD) code model of a 37-element CANDU6 fuel channel.

2. Thermal-Chemical Experiments

2.1 Classification of the Tests

The thermal-chemical experiments consist of three series of the experiments: single, 7-element, and 28-element tests. Table 1 shows the classification of these experiments according to 3 parameters such as the number of FES, the channel orientation, and degree of FES temperature rise during transient. Each experiment is named as the index specified in Table 1.

Table 1 Classification of thermal-chemical experiments

No. of FES	Single-element		Seven-element						28-elemen)		
Channel Orientation	Vertical		Horizontal				Horizontal		Horizontal		
FES Max. Temp.(℃)	1706	Low 1300	Low 1213	1343	1700	1650	1760	1720	1730	1860	>1860
External cooling	Water jacket		Water jacket						Pool		Water jacket
Index	**V1-1**	**V1-2**	**VC7-1**	**VC7-2**	**V7-1**	**V7-2**	**H7-1**	**H7-2**	**CS28-1**	**CS28-2**	**CS28-3**

The results of the single-element tests were used to verify the individual codes (such as CHAN-II and CATHENA) models for 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 CHAN code under the axi-symmetric conditions, while a horizontal configuration, 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.

2.2 Test Apparatus

Figure 1 shows the main test loop of the CHAN experiments. The steam is supplied by the steam generator and superheated to 700℃ at atmospheric pressure. It passes through the test section and picks up energy from the electrically heated FESs. It also reacts with the hot FES sheaths and the pressure tube initiating an exothermic reaction from which energy and hydrogen are produced. The steam and hydrogen gas mixture leaves the test section and flows into the condenser where steam is condensed. The hydrogen gas is separated from the condensate in a water trap, dried in water filters, measured by a mass flow meter and vented to atmosphere.

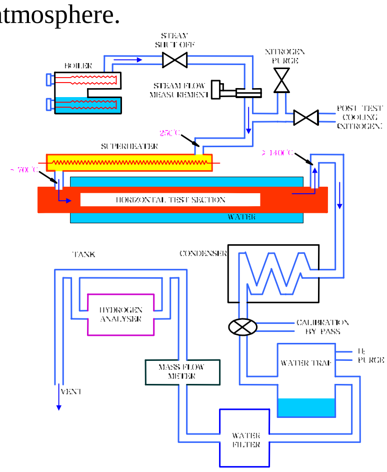

Figure 1 Configuration of the test loop

Figure 2 illustrates the cross-section of each test-section installed in three 28-element test series (CS28-1, CS28-2, and CS28-3).

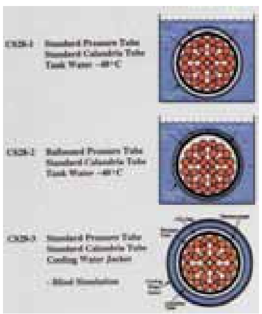

Figure 2 Comparison of 28-element test sections

The same test apparatus was used for all three 28-element experiments with some variation in the design of the test section. The Calandria tube was surrounded by an open tank of water during the first two experiments (CS28-1 and CS28-2). However, CS28-3 used a cooling water jacket in place of the open tank. The diameter of pressure tube was extended and FES bundle was displaced to the bottom of test section in CS28-2.

2.3 Measurement

The main measurement parameter in the thermal-chemical experiments is the FES and pressure tube temperatures at each axial location as shown in Fig. 3.

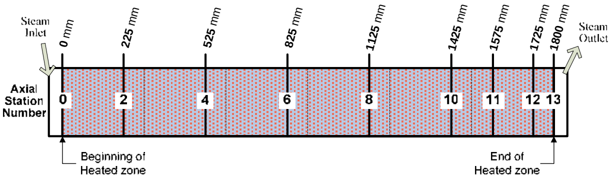

Figure 3 axial locations of the thermocouples and spacer plates in the 28-element tests.

2.4 Test Procedures

The experiments were generally conducted in three stages: a low-power, a high-power and a no-power.

A low power, stage 1 continued to reach a quasi-steady state condition. At the end of stage 1, power was raised up to full power to start stage 2. A power was maintained at maximum until FES temperature exceeded 1700℃ and the electric power was turned off before starting stage 3. Stage 3 was terminated by shutting off the steam flow when the reaction rates and test section temperatures decreased.

2.5 Experimental Conditions

The experimental conditions for steam, coolant, and FES power are summarized in Table 2. The thermal properties of the solid materials and the fluids in the test apparatus are collected in this work.

Table 2 Experimental conditions

Test parameter		Single-element		7-element						28-element		
		Vertical channel		Vertical channel				Horizontal channel		Horizontal channel		
		V1-1	V1-2	VC7-1	VC7-2	V7-1	V7-2	H7-1	H7-2	CS28-1	CS28-2	CS28-3
Steam	Inlet temp. (℃)	230	210	242	242	700	700	700	700	700	670	700
	Pressure (kPa)	125.8	125.8	428.4	202.4	140	140	150	150	115	130	100-175
	flow (g/s)	2.7	3.8	9.54	5.4	5.2	5	5.4	3	10.2	15	9
Coolant	Inlet temp. (℃)	15	2	2.5	1	16	9	0	0	40*	40*	23
	Flow (g/s)	70	80	100	90	170	170	170	170	-	-	355
Steady / Transient FES Power (kW)		1/ 12	/ 9	10 / 45	10 / 38	10 / 36	10 / 37.5	10 / 37	11 / 37	10 / 135	10 / 130	10 / 130

* pool temperature

3. Discussion and Conclusions

The test data are collected from the references and stored in the database. From the review of the test results, the following conclusions can be derived.

Some conditions among the reviewed experiments were not fully reaching the quasi-steady state in a low-power stage and followed by a high-power stage. Zircaloy/steam reaction began when FES temperature reached 800℃ and accelerated when temperature exceeded 1150℃ (Fig. 4).

Self-sustaining temperature excursion due to auto-catalytic Zircaloy/steam reaction was not observed after electrical power was shut off.

There were no significant circumferential temperature gradients in the FES bundle and pressure tube for the experiments performed in a vertical channel orientation. However, noticeable circumferential gradients were found in the horizontal pressure tube (Fig. 5). These gradients were attributed to slumping of the FES bundles (sagging).

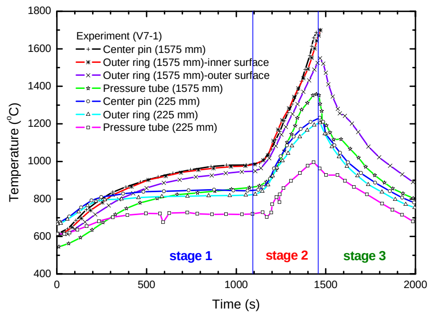

Figure 4 The FES and the pressure tube temperatures for experiment (V7-1)

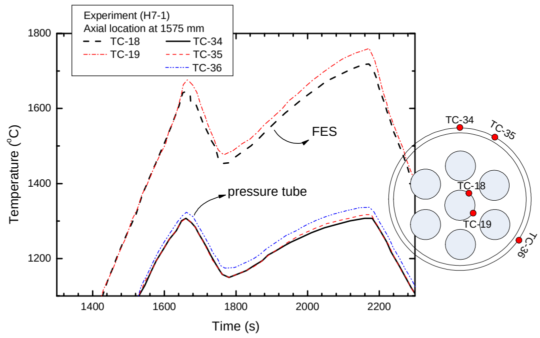

Figure 5 Circumferential The FES and the pressure tube temperatures for experiment (H7-1)

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