Commissioning Tests of the University of Ottawa Supercritical CO_2 Facility

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Summary

An experimental facility supporting the Canadian Super Critical Water-cooled Reactor (SCWR) research efforts has been constructed at the University of Ottawa. Loop commissioning tests have been performed, during which a number of heat transfer phenomena were observed. The measured heat transfer coefficients are compared with predictions of available correlations. The test results demonstrated that the facility operates within design specifications.

1. Introduction

The present research is in support of the Canadian National Program on Generation IV Energy Technologies for the development of a Super Critical Water-cooled Reactor (SCWR), which, compared to existing nuclear reactors, is expected to have increased safety, lower-cost electricity production, more compact size and reduced volume of nuclear wastes. The operation of such reactors requires heat transfer to the cooling fluid at pressures higher than the critical pressure. At critical and supercritical pressures, the heat transfer behaviour is quite different from that at subcritical pressures because of the drastic variations of the physical properties near the pseudo-critical temperature [1]. An accurate prediction of the heat transfer coefficient in rod bundles under near-critical and supercritical (SC) conditions is necessary for the design and preliminary analysis of SCWR, but the available information is not sufficient for these purposes. A heat transfer test facility which can be operated at subcritical and supercritical pressures using carbon dioxide as a surrogate fluid for water has been built at the University of Ottawa. CO_2 was chosen as working fluid because of its inertness and its lower critical pressure and temperature compared to those of water. Therefore, by comparison to a SC water loop, the proposed facility has lower safety requirements and lower construction and operating costs. Commissioning tests for the loop have been conducted under conditions covering subcritical, near-critical and SC pressures.

2. The experimental facility

Figure 1 is a schematic diagram of the test facility. The loop was designed for a maximum pressure of 15 MPa and a nominal operating pressure of 10 MPa. The CO_2 flow in the loop is maintained by one or more gear pumps connected in parallel. Loop pressure is stabilized by a group of bellow-type accumulators containing nitrogen. An oxygen depletion monitor has been installed to ensure that the air in the laboratory has sufficient oxygen concentration even near the floor. Three test sections can be connected in the loop: an 8 mm ID tube, a 22 mm ID tube and a three-rod bundle. The wall of each test section is heated electrically by a low-voltage/high-current DC power supply. The recirculating fluid is cooled using two helical-tube heat exchangers. Two cooling mechanisms are available: chilled water supplied by the University and a refrigeration system using Dowthem J (a type of organic refrigerant) for reaching lower cooling temperatures.

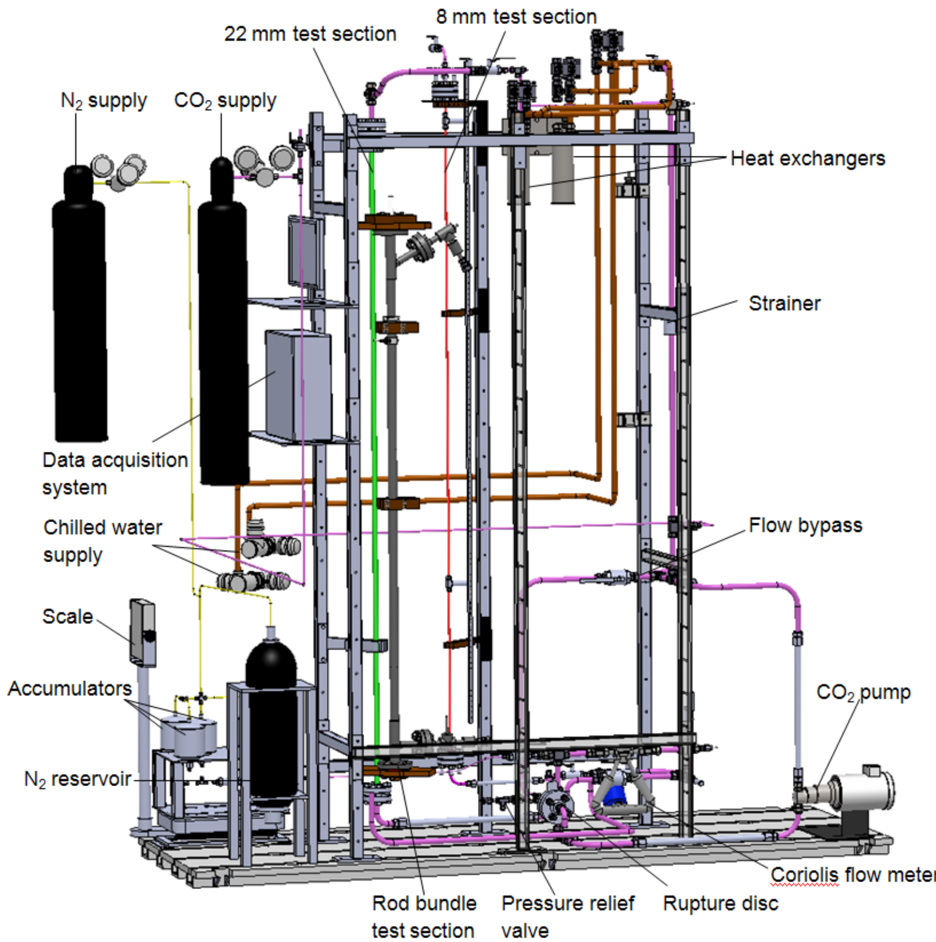

Fig. 1: Schematic diagram of the CO_2 flow loop.

Wall temperature is measured by calibrated T-type thermocouples (TC) attached to the outer walls of the tubular test sections and sliding K-type TCs traversed longitudinally and azimuthally inside the bundle rods. 41 TCs have been attached along the outer surface of the 8 mm test section (Figure 2). The CO_2 temperatures at the inlet and the outlet of each test sections are measured by in-flow RTDs. The pressure in the loop is measured using a high-precision pressure transducer. The pressure drop across each heated length is measured with a differential pressure transmitter. The mass flow rate is measured with a Coriolis-type flow meter. All instrument signals are conditioned, monitored and recorded using a dedicated data acquisition and processing system with a Labview software interface.

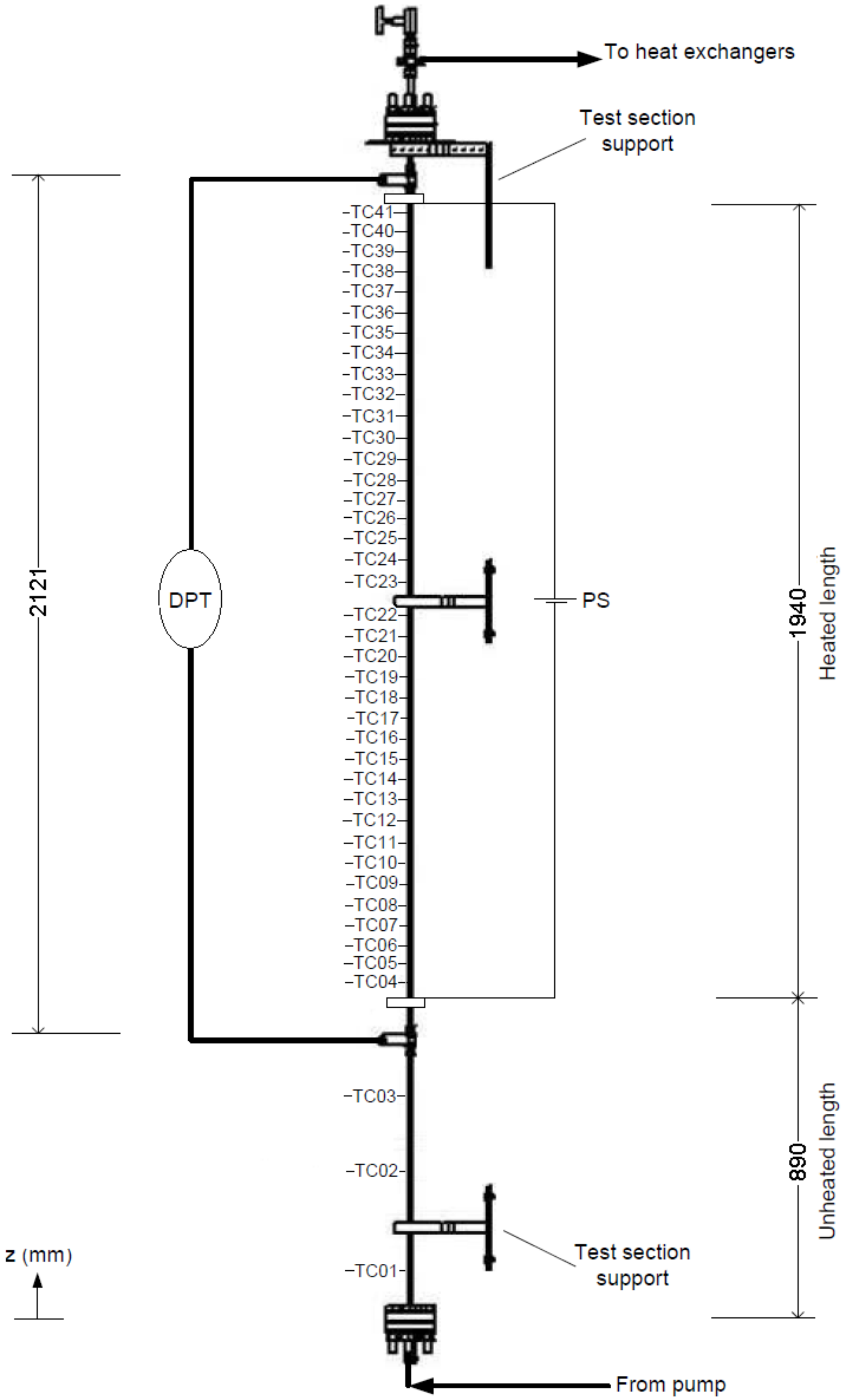

Fig. 2: Schematic diagram of the 8 mm test section showing the locations of thermocouples.

3. Loop commissioning tests

To serve as loop commissioning, measurements were conducted on the 8 mm tube test section under conditions presented in Table 1. Wall temperature variations under some of the measured subcritical, near-critical and supercritical conditions are plotted in Figure 2, 3 and 4, respectively. The results demonstrated that the facility and all instrumentation operate properly.

Table 1 Conditions for commissioning tests

Parameters	Units	Range		
		Subcritical	Near-critical	Supercritical
P	MPa	6.6	7.6	8.8
P/P_c	-	0.89	1.03	1.19
T_{in}	°C	10.5	10.5	10.5
T_{sat}	°C	26.1	–	–
T_{pc}	°C	–	32.3	39.0
G	kg/m² s	400, 800, 1500, 2000	400, 900, 1500	400, 1500
q	kW/m²	20, 50, 120, 140	25-70, 100, 240-280	40, 100, 300

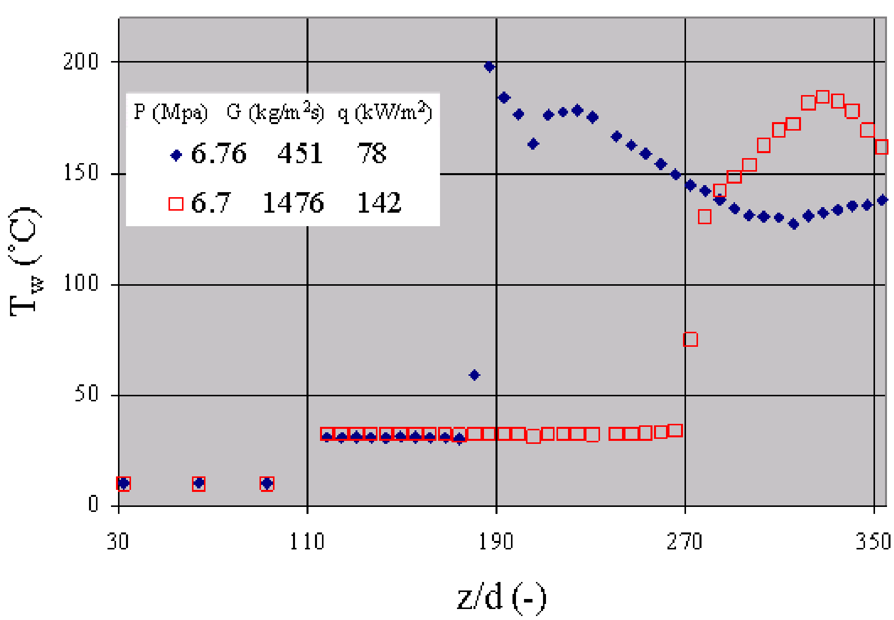

Fig. 3: Wall temperature variations for two sets of subcritical conditions, which show departures from nucleate boiling and film boiling.

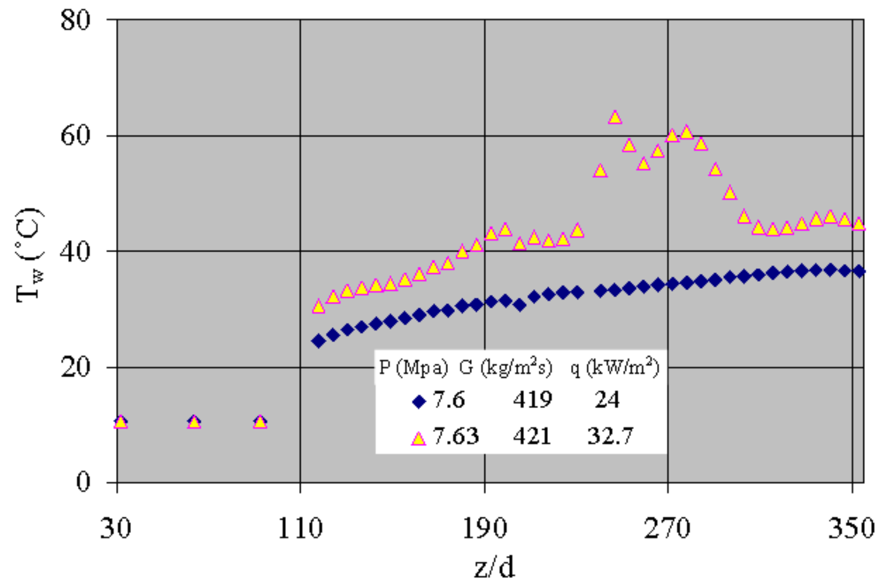

Fig. 4: Wall temperature variations for two sets of near-critical conditions, one of which shows heat transfer deterioration.

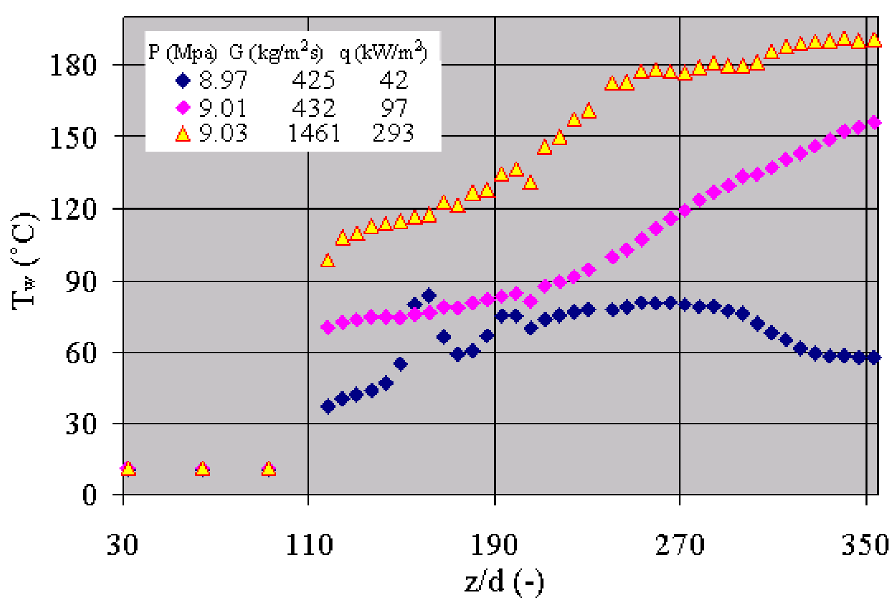

Fig. 5: Wall temperature variations for three sets of supercritical conditions, one of which shows heat transfer deterioration.

Heat balance calculations were performed and demonstrated that the rate of heat losses was very low; the effectiveness of the thermal insulation applied to the test sections was very high and within acceptable uncertainty limits. The measured heat transfer coefficients have been compared with available correlations, including the widely used Dittus-Boelter (D-B) correlation [2] for forced convection in circular tubes at subcritical pressures, the Dougall-Rohsenow form of the D-B correlation for tests during which film boiling occurred, and the Jackson and Fewster correlation [3] for tests under SC pressures.

4. Ongoing and future work

A few modifications to the loop are being made in efforts to improve loop performance and to address potential problems. A pre-cooling system is being installed to mitigate a predicted difficulty in starting the pumps in warm weather. A pre-heater will be installed to provide elevated inlet temperatures to the test sections and to permit additional control of inlet conditions.

Extensive heat transfer and pressure drop measurements covering broad ranges of conditions, including conditions never considered in previous literature, will be conducted on the 8 and 22 mm tubes. These results will be compared to past measurements in tubes and will complement and expand existing databases. They will also serve as reference for comparisons with upcoming measurements in the rod bundle test section.

Heat transfer and pressure drop measurements in the rod bundle will be conducted over the same ranges of conditions as those planned for the 8 and 22 mm tubes. The axial and circumferential wall temperature variations on the three rods will be measured and used to calculate the heat transfer coefficients. These results will be compared to available measurements in tubes and predictions of empirical correlations. Of particular interest will be the observation of different heat transfer modes occurring in the bundle under various supercritical conditions. The effects of spacers on heat transfer modes will also be examined.

The velocity and temperature fluctuations in the 22 mm ID test section will be measured with hot- and cold-wire probes, respectively. An instrument flange that will house the probes is currently being assembled. This set of measurements is expected to contribute to the understanding of turbulence phenomena in supercritical fluids and to the validation of analytical models and numerical simulations.

5. References

[1] Pioro, I.L. and Duffey, R.B., "Heat Transfer and Hydraulic Resistance at Supercritical Pressures in Power-Engineering Applications", ASME Press, New York, USA, 2007.

[2] F. W. Dittus and L. M. K. Boelter, “Heat transfer in automobile radiators of the tubular type”, University of California, Berkeley, Publications on Engineering, Vol. 2 (13), pp. 443-461, 1930.

[3] I. Pioro, H. F. Khartabil and R. B. Duffey, “Heat transfer to supercritical fluids flowing in channels – empirical correlations (survey)”, Nucl. Eng. Des., Vol. 230, pp. 69-91, 2004.