



An experimental investigation of supercritical heat transfer in a three-rod bundle equipped with wire-wrap and grid spacers and cooled by carbon dioxide



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HIGHLIGHTS

- Heat transfer at supercritical pressures was studied experimentally in a three-rod bundle equipped with wire-wrap spacers or grid spacers.
- Heat transfer deterioration occurred near the heated inlet under certain conditions.
- Normal heat transfer was generally comparable to that in a tube and the predictions of a correlation.

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ABSTRACT

Heat transfer measurements in a three-rod bundle equipped with wire-wrap and grid spacers were obtained at supercritical pressures in the Supercritical University of Ottawa Loop (SCUOL). The tests were performed using carbon dioxide, as a surrogate fluid for water, flowing upwards for wide ranges of conditions, including conditions equivalent to the nominal and near-normal operating conditions of the proposed Canadian Super-Critical Water-Cooled Reactor. The test section contained three heated rods and three unheated rod segments with an outer diameter of 10 mm and a pitch-to-diameter ratio of 1.14; the heated length was 1500 mm. Detailed surface temperature measurements along and around the three heated rods were collected using internally traversed thermocouples. The following ranges of test conditions were covered, with equivalent water conditions given inside parentheses: pressure from 6.6 to 8.36 MPa (19.7–25 MPa); inlet temperature from 11 to 30 °C (330–371 °C); mass flux from 200 to 1175 kg m⁻² s⁻¹ (340–1822 kg m⁻² s⁻¹); and wall heat flux from 1 to 175 kW m⁻² (11–1847 kW m⁻²). For one set of tests, the heated rods were fitted with a 1.3 mm OD wire wrap, having an axial pitch of 200 mm along the entire heated length; for a second set, the heated rods were fitted with grid spacers having a 5.3% flow blockage and located at 500 mm axial intervals. The effects of spacer configuration on heat transfer at supercritical pressures were documented and analyzed. The observed experimental trends were compared to those obtained in a heated tube at similar conditions and with predictions of a supercritical heat transfer correlation. Heat transfer was observed to deteriorate near the start of the heated section of the rod bundle equipped with either type of spacers as well as in a circular tube for mass fluxes between 200 and 700 kg m⁻² s⁻¹. The onset of deterioration occurred at a higher heat flux for the wire-wrapped bundle than for the one with grid spacers, and at the lowest heat flux for the tube. Normal heat transfer in either of the rod bundles behaved similarly to the one in the tube and was also compatible with the predictions of the correlation of Jackson. The grid spacers introduced a strong local enhancement, but their effects disappeared only about 10 rod diameters downstream.

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1. Introduction

The Super-Critical Water-Cooled Reactor (SCWR) is one of the candidate designs considered by the Generation IV International

Forum as an innovative nuclear energy system; it is expected to have increased safety, more compact size, lower cost of energy production and reduced volume of nuclear waste, compared to existing systems. The present research is in support of the Canadian National Program for the development of the SCWR.

The supercritical heat transfer (SHT) mode has distinct characteristics not present at subcritical pressures. When the fluid pressure and temperature are near their critical values, or when

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Nomenclature

D	rod diameter, mm
D_h	hydraulic diameter of the rod bundle, mm
G	mass flux, $\text{kg m}^{-2} \text{s}^{-1}$
H	heat transfer coefficient, $\text{kW m}^{-2} \text{K}$
H_{av}	circumferentially averaged heat transfer coefficient, $\text{kW m}^{-2} \text{K}$
H_{min}	minimum heat transfer coefficient at an axial location, $\text{kW m}^{-2} \text{K}$
h	specific enthalpy, kJ kg^{-1}
h_b	bulk specific enthalpy, kJ kg^{-1}
h_{in}	specific enthalpy at inlet, kJ kg^{-1}
h_{out}	specific enthalpy at outlet, kJ kg^{-1}
h_{pc}	pseudo-critical specific enthalpy, kJ kg^{-1}
k	thermal conductivity, $\text{kW m}^{-1} \text{K}$
L_h	heated length, mm
$\dot{m}$	mass flow rate, kg s^{-1}
P	pressure, MPa
P_c	critical pressure, MPa
Q	volumetric heat generation, kW m^{-3}
Q_e	electric power to the test section, kW
q	heat flux, kW m^{-2}
q^{3D}	heat flux, kW m^{-2}
r_i	rod outer diameter, mm
r_o	rod inner diameter, mm
T_b	bulk temperature, $^{\circ}\text{C}$
T	temperature, $^{\circ}\text{C}$
T_{in}	test section inlet temperature, $^{\circ}\text{C}$
T_{max}	maximum wall temperature across an axial location, $^{\circ}\text{C}$
$T_{w,o}$	outer wall temperature, $^{\circ}\text{C}$
$T_{w,o}^{1D}$	outer wall temperature, estimated by 1D analysis, $^{\circ}\text{C}$
$T_{w,o}^{3D}$	outer wall temperature, estimated by 3D analysis, $^{\circ}\text{C}$
$T_{w,o}^{1Dav}$	circumferentially averaged outer wall temperature, estimated by 1D analysis, $^{\circ}\text{C}$
$T_{w,i}$	measured rod inner wall temperature, $^{\circ}\text{C}$
z	axial distance, mm
z_h	axial distance from the start of the heated section, mm
φ	angular coordinate, $^{\circ}$

the pressure is supercritical (SC) and the temperature is near its pseudo-critical value, small changes in temperature can cause large changes in the thermo-physical properties and the heat transfer may undergo enhancement or deterioration. Of particular importance for the safety of SCWR is the phenomenon of heat transfer deterioration (HTD). HTD occurs when the heat transfer coefficient drops below the value that would occur during normal forced convective heat transfer; in such cases, the wall temperature rise would be higher than normal. Heat transfer deterioration is thought to be associated with the suppression of turbulence near the wall and is more likely to be encountered at low mass flows, high heat fluxes and in the vicinity of the pseudo-critical enthalpy.

Heat transfer in channels may be significantly affected by the presence of flow obstructions, including rod spacers in rod bundles. Eter et al. (2013) reviewed the literature of the spacer effect on SCHAT. It has been observed that flow obstructions generally enhance heat transfer and that the highest heat transfer enhancement occurred when the flow temperature was near the pseudo-critical value; in such cases, the enhanced heat transfer coefficient was more than twice its value in channels without flow

obstructions. Significant heat transfer enhancement was found to occur downstream of grid spacers in upflow; in downflow, however, the effect of grid spacers on heat transfer was less pronounced and it was sometimes absent altogether. Predictions of spacer effects on super-critical heat transfer using CFD codes were found to be in fair agreement with experimental observations for normal heat transfer conditions, but were deemed to be of questionable accuracy for HTD conditions.

Eter et al. (2013) reported that the vast majority of previous SCHAT experiments were performed in tubes and, to a lesser degree, in annular channels. Very few experimental studies are available for SC flows in rod bundles. Dyadyakin and Popov (1977) conducted experiments in tight-lattice seven-rod bundles having different flow areas (102, 112, 113, 121, and 134 mm^2). A movable thermocouple was installed in the central rod and used to measure the wall temperature. Significant pressure oscillations (± 5 MPa) with frequencies in the range between 0.033 and 0.040 Hz were observed at a mass flux of 2000 $\text{kg m}^{-2} \text{s}^{-1}$ and high heat fluxes; these pressure oscillations resulted in burnout of the test section. Silin et al. (1993) obtained a database for water at supercritical pressures flowing in rod bundles in the Russian Scientific Centre (RSC); they reported that no HTD occurred in multi-rod bundles at the same operating conditions as those for which HTD occurred in tubes. Wang et al. (2014) investigated SCHAT of water flowing vertically upward through a 2×2 rod bundle. The test section contained four heated rods, having an 8 mm OD and a heated length of 600 mm, installed inside a square channel with rounded corners. The results revealed that (i) the maximum temperature occurred at the corner; (ii) the effect of inlet temperature was small, especially at the corners, where the axial location at which the temperature reached the pseudo-critical value did not vary much; (iii) the circumferential temperature gradient increased as the mass flux was decreased and as the heat flux was increased; and (iv) the heat transfer coefficient was sensitive to mass flux and heat flux variations but less sensitive to pressure variation. Gu et al. (2015) investigated the heat transfer characteristics of water flowing in a 2×2 bare rod bundle having a heated length of 800 mm. They found the circumferential wall temperature distribution to be non-uniform around the heated rod. In general, the effects of operating conditions on the SCHAT in the rod bundle were similar to those observed in tubes and annuli. Fewer experimental studies have addressed directly the spacer effect on SCHAT. Mori et al. (2012) used HCFC-22 as a coolant. Upward and downward flows were investigated in a tube having a 4.4 mm ID and in sub-channels of a 3-rod bundle and a 7-rod bundle, having a sub-channel hydraulic diameters of 4.4 and 3.2 mm, respectively. The tube had a heated length of 2000 mm and the rods in the three and seven-rod bundles had heated lengths of 1450 and 1950 mm, respectively. Grid spacers were used to maintain the design conditions for the pitch-to-diameter ratio in the bundle. The trends in heat transfer in the three test sections were found to be similar at low heat fluxes, for which the heat transfer enhancement in the bundles was small; in contrast, at a high heat flux, the heat transfer characteristics were different, as HTD occurred in the tube but not in the bundle near grid spacers. These authors found that the heat transfer enhancement diminished gradually over a downstream distance of 60–70 diameters. With down-flow, no HTD was observed in either the tube or the bundle and no significant spacer effect on the normalized heat transfer coefficients was observed. Richards et al. (2013) examined SCHAT of Refrigerant R-12 in a seven-rod bundle with a pitch-to-diameter ratio of 1.19, having rods with 1.00 m heated lengths and 9.5 mm OD; the assembly had three grid spacers with a spacing of 500 mm. Their results show that HTD was encountered in all tests, despite the presence of spacers; in some cases HTD occurred once, while in others twice. The effect of grid spacer was significant only at the low mass flux of 515 $\text{kg m}^{-2} \text{s}^{-1}$.

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