Heat Transfer in a Vertical 7-Element Bundle Cooled with Supercritical Freon-12

G. Richards[1], A. Milner[1], C. Pascoe[1], H. Patel[1], W. Peiman[1], Eu. Saltanov[1], R.S. Pometko[2], A.N. Opanasenko[2], A.S. Shelegov[3], P.L. Kirillov[2] and I.L. Pioro[1]

[1]University of Ontario Institute of Technology, Oshawa, Ontario, Canada
Faculty of Energy Systems and Nuclear Science
[2] Institute of Physics and Power Engineering, Obninsk, Russia
[3] IATE, Obninsk, Russia

Abstract

Currently, SuperCritical Water-cooled nuclear Reactor (SCWR) concepts are being developed worldwide with an objective to increase thermal efficiencies of future Nuclear Power Plants (NNPs) on 10 – 15% compared to those of current water-cooled NPPs. With such an increase in the thermal efficiencies, SCW NPPs will be at the current level of the most advanced thermal power plants: coal-fired SCW NPPs and combined-cycle gas-fired NPPs. However, to be able to develop SCWRs at least several key technical problems should be resolved. One of these problems is limited amount of experimental data on heat transfer in fuel bundles and based on that SCW heat-transfer correlations.

Experiments in SCW are very complicated and expensive due to high critical parameters of water (pressure 22.064 MPa and temperature 374.95°C). Moreover, there are only few SCW test rigs, which capable to perform experiments in full-scale bundles. As a preliminary approach supercritical-pressure heat-transfer experiments in bundles can be performed in modeling fluids such as Freons or carbon dioxide.

Therefore, a set of experimental data was obtained in Freon-12-cooled bundle simulator at the Institute of Physics and Power Engineering (IPPE, Obninsk, Russia). A vertical 7-element bundle was installed in a hexagonal flow channel. The test section consisted of elements that were 9.5 mm in diameter with the total heated length of 1 m. Bulk-fluid and wall temperature profiles were recorded using thermocouples. Several heat-transfer regimes were tested. Also, this paper references thermophysical properties of supercritical Freon-12 at the critical pressure (4.1361 MPa) and test pressure of 4.65 MPa.

1. Introduction

Generation-IV nuclear-reactor technology is increasing in popularity worldwide. One of the six Generation-IV reactor options is a SuperCritical Water-cooled nuclear Reactor (SCWR). The main objective of SCWRs is increasing thermal efficiency of SCW Nuclear Power Plants (NNPs). This reactor type is being developed based on concepts of Light Water Reactors (LWRs), direct-cycle Boiling Water Reactors (BWRs) and supercritical fossil-fuel-fired thermal power plants, especially, their supercritical-pressure turbines' technology. SCWRs are similar to LWRs, but operate at a significantly higher pressure and temperature.

As an alternative to using SuperCritical Water (SCW) as a nuclear-reactor coolant, modeling fluids, for example, such as Freon-12, can be tested as a preliminary approach. The critical parameters of Freon-12 are the following: pressure of 4.1361 MPa and temperature of 111.97ºC, which are significantly lower compared to those of SCW (the critical pressure – P_{cr} = 22.064 MPa and the critical temperature – T_{cr} = 373.95ºC). Therefore, Freon-12 testing will be easier and cheaper alternative in terms of handling lower pressures, temperatures and heat fluxes compared to those of SCW.

2. LITERATURE SURVEY

Modeling Fluids

SCWRs will be cooled with a light-water coolant at a pressure about 25 MPa and within a range of temperatures from 280 – 350°C to 550 – 625°C (inlet to outlet temperatures) [1]. However, these operating conditions can be modeled with lower critical pressure and temperature fluids such as Freons as a preliminary approach. Freon-12 was widely used in industry some time ago as a refrigeration and air-conditioning agent. However, in North America using of Freon-12 has been limited, because of its damaging effects on the ozone layer. Therefore, its thermophysical properties are well known within a wide range of conditions including supercritical-pressure region.

Operating conditions of SCWR must be scaled into those of the modeling fluid in order to provide proper SCW-equivalent conditions. Therefore, the following parameters are essential for scaling: pressure, temperature, mass flux, and heat flux. Scaling parameters for fluid-to-fluid modeling at supercritical conditions are summarized in Table 1 [1]. In addition, scaling factors for the conversion of data from Freon-12 to water at supercritical conditions can be found in Table 2.

Table 1. Major scaling parameters for fluid-to-fluid modeling at supercritical conditions based on inlet-conditions approach.

Parameter	Equation
Pressure	$(P/P_{cr})_{\mathrm{W}} = (P/P_{cr})_{\mathrm{F}}$
Bulk-Fluid Temperature (K)	$(T/T_{cr})_{\mathrm{W}} = (T/T_{cr})_{\mathrm{F}}$
Heat Flux	$(q\,D/k_b \cdot T_b)_{\mathrm{W}} = (q\,D/k_b \cdot T_b)_{\mathrm{F}}$
Mass Flux	$(G \cdot D/\mu_b)_{\mathrm{W}} = (G \cdot D/\mu_b)_{\mathrm{F}}$
Heat Transfer Coefficient	$\mathbf{Nu}_{\mathrm{W}} = \mathbf{Nu}_{\mathrm{F}}$

Table 2. Scaling factors for Freon-12 to water at supercritical conditions[1]

Parameter	Equation
Pressure	$\frac{P_W}{P_F} = 5.37$
Temperature	$\frac{T_w}{T_F} = 3.3$
Heat Flux	$\frac{q_W}{q_F} = 20$
Temperature difference	$\frac{\Delta T_W}{\Delta T_F} = 15.4\left(\frac{k_W}{k_F}\right)^{0.66}$

[1] These scaling factors were proposed by R.S. Pometko, A.N. Opanasenko, A.S. Shelegov, and P.L. Kirillov.

2.1 Thermophysical Properties

The heat transfer at supercritical conditions is affected with significant variations in thermophysical properties of a fluid, specifically, within the critical or pseudocritical regions in which all thermophysical properties undergo drastic changes. The pseudocritical point is defined as a point at a pressure above the critical pressure and at a temperature corresponding to the maximum value of specific heat at this particular pressure [1]. For Freon-12, the pseudocritical temperature at a pressure of 4.65 MPa is 118.75°C.

Variations in selected Freon-12 thermophysical properties are shown in Figure 1 – Figure 8. All Freon-12 properties were calculated based on NIST (2007) software [2]. In general, all thermophysical properties experience drastic changes within the critical and pseudocritical regions. These changes are the greatest within the critical point, whereas in the vicinity of pseudocritical points they become more gradual with increasing in pressure.

Density and dynamic viscosity suffer extreme drops within the critical and pseudocritical points. However, dynamic viscosity will rise gradually right after the drop. This drop is nearly vertical within a very narrow temperature range near the critical point. Specific enthalpy and kinematic viscosity undergo abrupt increases. In all other cases, including volume expansivity, specific heat, thermal conductivity, and Prandtl number, these thermophysical properties have peaks at the critical and pseudocritical points. With pressure increase, magnitude of these peaks decreases.

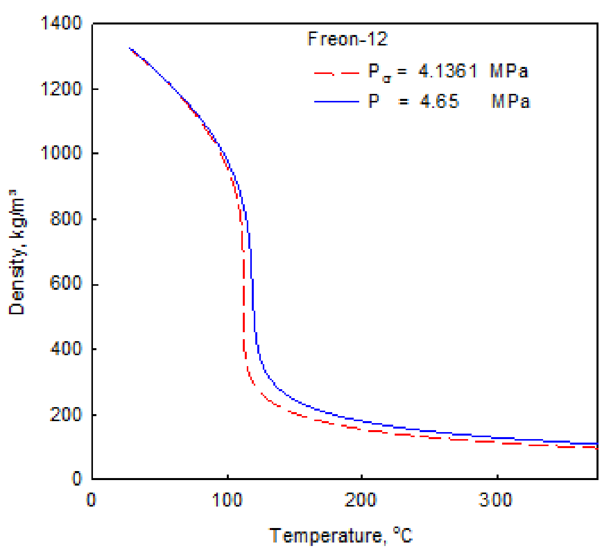


Figure 1. Density vs. Temperature.

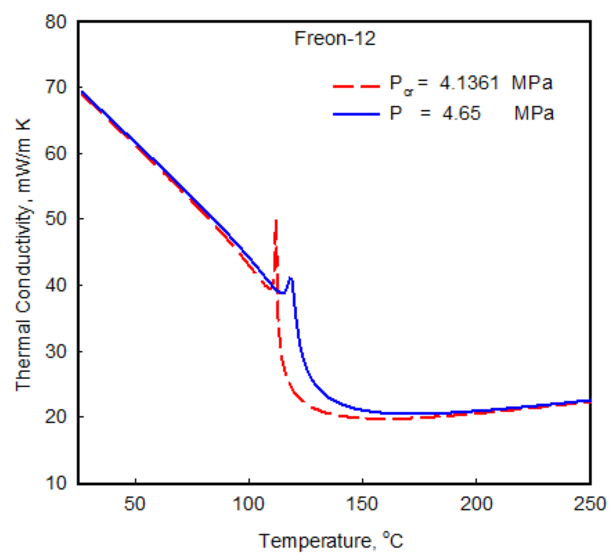


Figure 2. Thermal conductivity vs. Temperature.

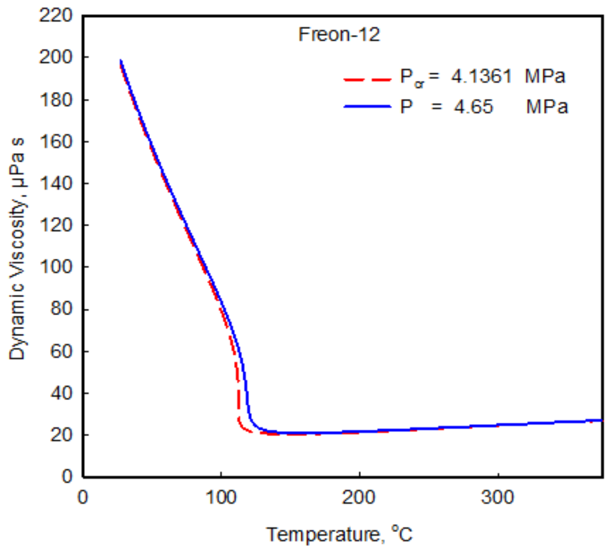


Figure 3. Dynamic viscosity vs. Temperature.

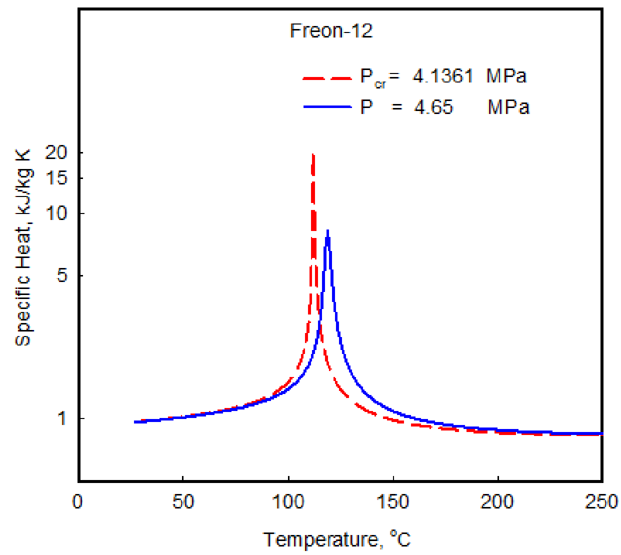


Figure 5. Specific heat vs. Temperature.

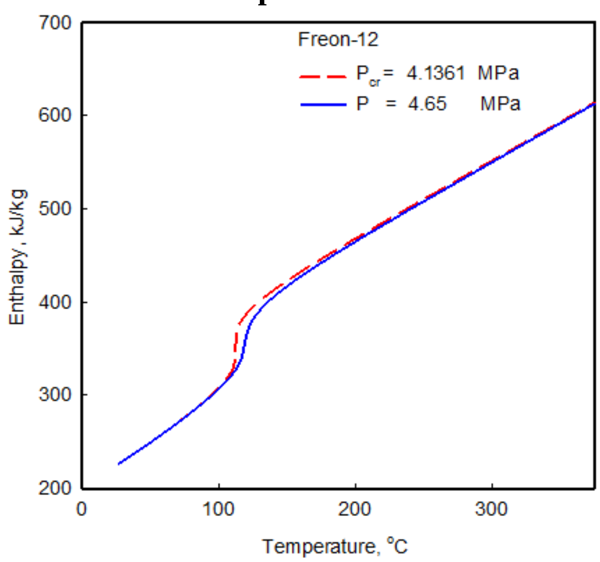


Figure 4. Enthalpy vs. Temperature.

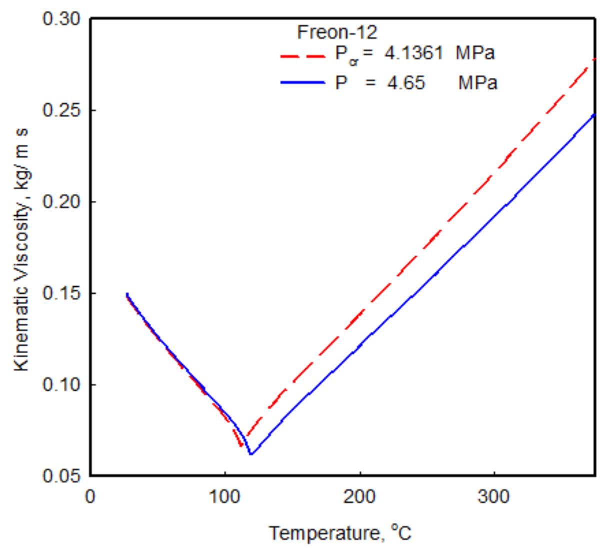


Figure 6. Kinematic viscosity vs. Temperature.

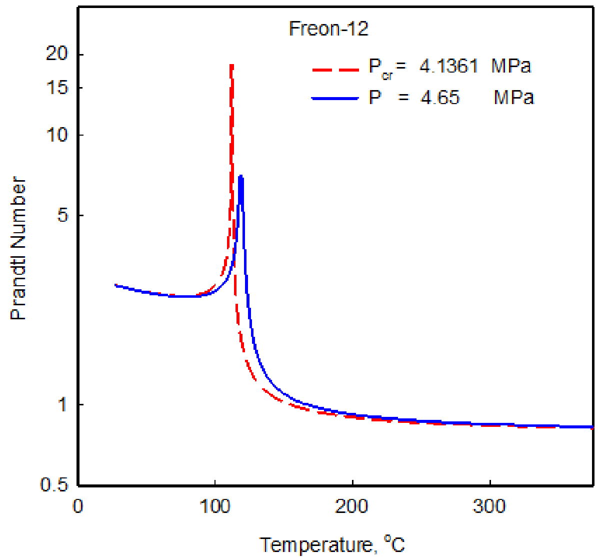


Figure 7. Prandlt number vs. Temperature.

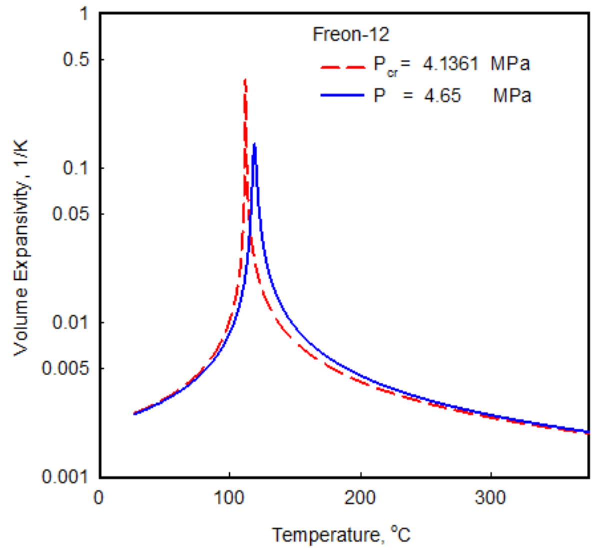


Figure 8. Volume expansivity vs. Temperature.

3. METHODOLOGY

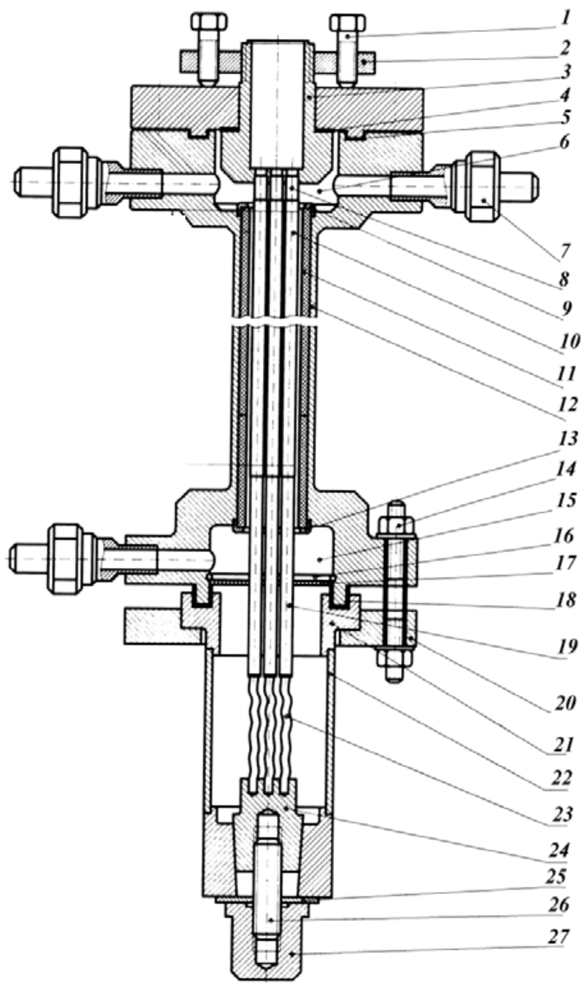
3.1 Experimental Setup

The experimental test section (see Figures 9 and 10) consists of a bare bundle with 7 circular elements installed in a hexagonal flow channel located inside a ceramic insert surrounded by a pressure tube. The bundle has 6 + 1 bare-element arrangement with each element being held at the ends to eliminate the use of spacers. Each of the 7 heating elements has a 9.5-mm outer diameter, and spaced one from another with a pitch of 11.29 mm. The total flow area is 374.0 mm^2, wetted perimeter – 318.7 mm, and hydraulic-equivalent diameter – 4.69 mm.

Main test-section components are cylindrical heated elements (10) installed tightly in the vertical hexagonal shell (12) (downward flow). The entire internal setup is contained by a cylindrical 40 × 4 mm pressure tube with welded flanges at the edges that form the upper (inlet) chamber (6) and lower (outlet) chamber (15), with a total heated length of 1000 mm. Four thermocouples installed into the top and bottom chambers were used to measure Freon-12 inlet and outlet temperatures. Basic parameters of the experimental setup are listed in Table 3.

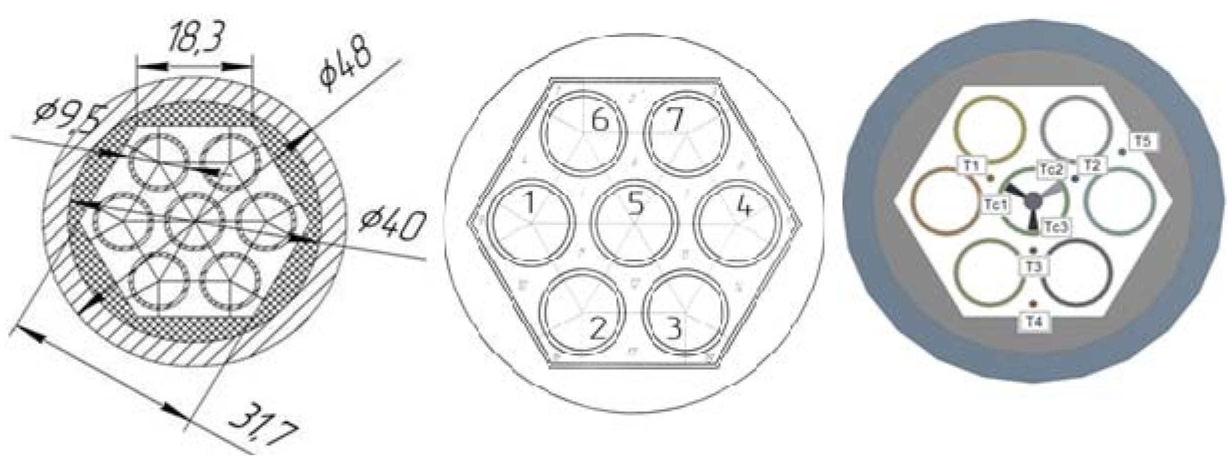
Table 3. Main experimental-setup parameters.

Pressure	Up to 5.0 MPa (equivalent to 25.5 MPa for water)
Temperature of Freon-12	Up to 120°C (400°C for heating elements)
Maximum mass-flow rate	20 m^3/h
Maximum pump pressure	1.0 MPa
Experimental test-section power	Up to 1 MW
Experimental test-section height	Up to 8 m
Data Acquisition System (DAS)	Up to 256 channels



1 – holding-down bolts;
2 – holding-down plate;
3 – upper current terminal;
4 – copper gasket;
5, 18 – insulators;
6 – upper chamber;
7 – union;
8 – copper-tube insert;
9, 13 – clamp rings;
10 – heated elements;
11 – ceramic sleeves;
12 – shell (flow tube);
14 – pin;
15 – lower chamber;
16 – check ring;
17 – Teflon spacer;
19 – copper rods;
20 – lower flange;
21 – adapter;
22 – can;
23 – flexible current leads;
24 – cone;
25 – gasket;
26 – pin;
27 – nut.

Figure 3. Experimental test-section schematic.

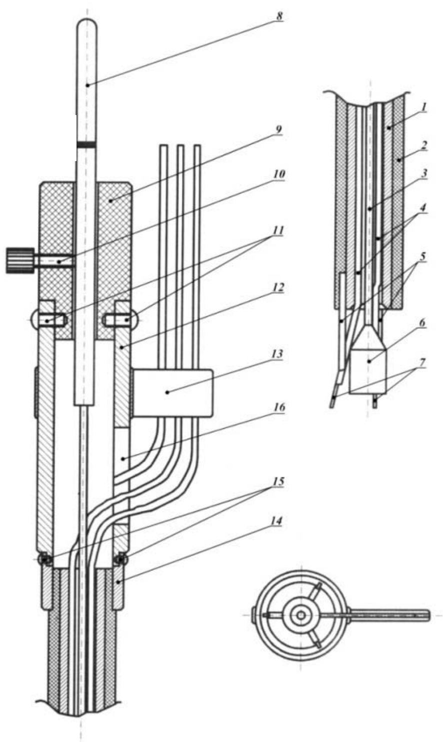


(a) (b) (c)

Figure 4. Flow-channel cross sections: (a) with dimensions; (b) with elements numbering, and (c) with thermocouple layout.

Measurements using this setup were only conducted after all necessary operating parameters have been reached and stabilized. These parameters include pressure, temperature, and mass-flow rate. All measurements were collected using DAS to ensure accuracy in control, monitoring, and processing of data. Temperature of the center heated-element sheath was measured using two sliding thermal probes connected to three chromel-copel thermocouples. These three thermocouples were placed at a 120° angle relative to each other as seen in Figure 11.

Increased reliability of temperature measurements was ensured through the use of two thermocouples installed at both the inlet and outlet chambers of the experimental section. At sections 5, 7, 8, 12, and 17 (Figure 10) cable microthermocouples (0.5 mm) were installed to monitor the temperature of the Freon-12 exiting the test section. Each thermocouple provided an uncertainty of ±0.3 – 0.5°C within a temperature range of 0 – 300°C. The outer surface temperature of the heat rejection system was calculated using correction for temperature differences across the sheath.



1 – thermal probe's tube
2 – insulator
3 – tie-rod
4 – thermocouple sheath
5 – tabs
6 – cone
7 – thermocouples
8 – tie-rod
9 – lock
10 – lock bolt
11 – coupling bolts
12 – thermal probe's shell
13 – flag indicator
14 – adapter
15 – coupling bolts
16 – slot for thermocouples' output

Figure 5. Sliding thermal probe for measuring sheath temperature.

The scaling factors listed in Table 2 were used to convert the Freon-12 data into the water-equivalent data with the mean-square error of 12.6%. A list of all sensor errors in the experimental setup is listed in Table 4.

Table 4. Uncertainties of measuring devices.

Sensor	Uncertainty
Thermocouple	±0.3 – 0.5°C
Pressure Gauge	±0.5 – 1%
Flow Meter	±0.11%
Power Sensor	±2.0%

The following three experiments have been performed:

1) Freon-12 bulk-fluid temperature was below the pseudocritical temperature along the whole heated length of the bundle (for details, see Figure 12);
2) Freon-12 bulk-fluid temperature was below the pseudocritical temperature at the inlet, but reached the pseudocritical temperature at the outlet of the bundle (for details, see Figure 13);
3) Freon-12 bulk-fluid temperature was above the pseudocritical temperature along the whole heated length of the bundle (for details, see Figure 14).

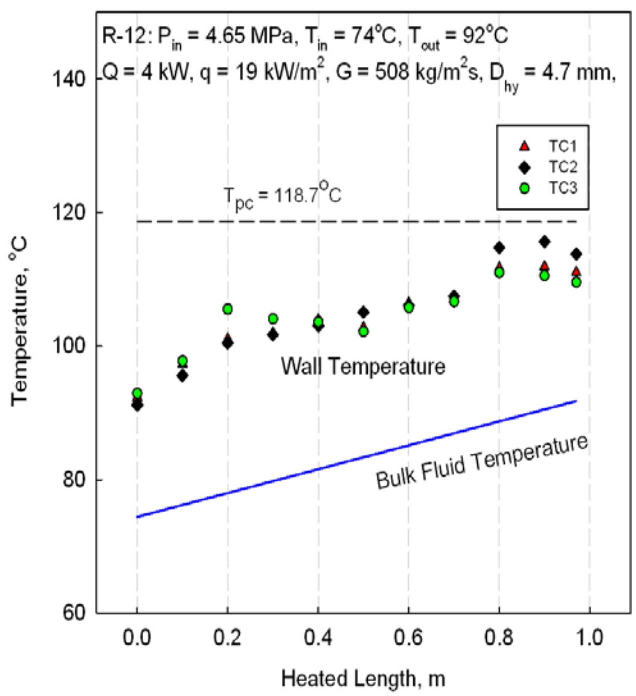


Figure 12. Experiment 1: Bulk-fluid and sheath-temperature profiles along bundle heated length.

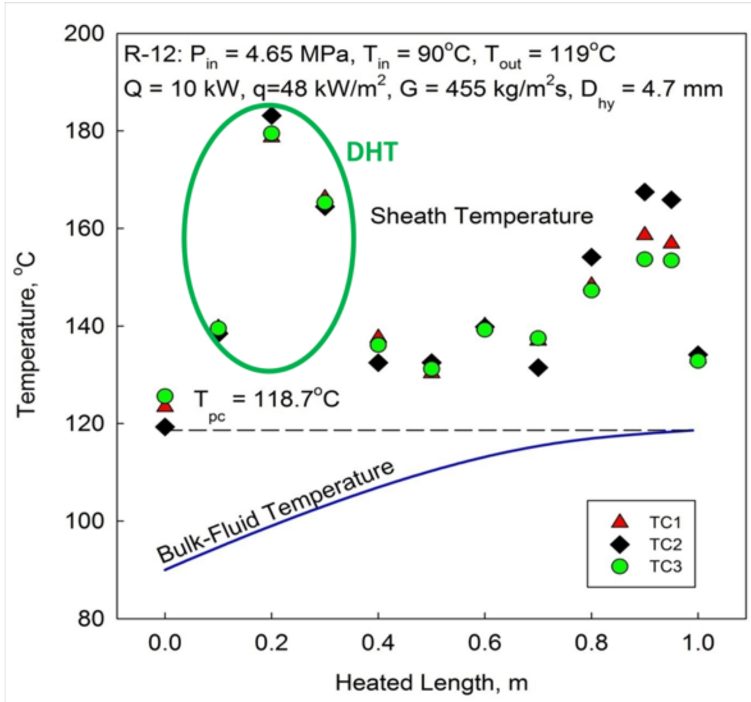


Figure 6. Experiment 2: Bulk-fluid and sheath-temperature profiles along bundle heated length.

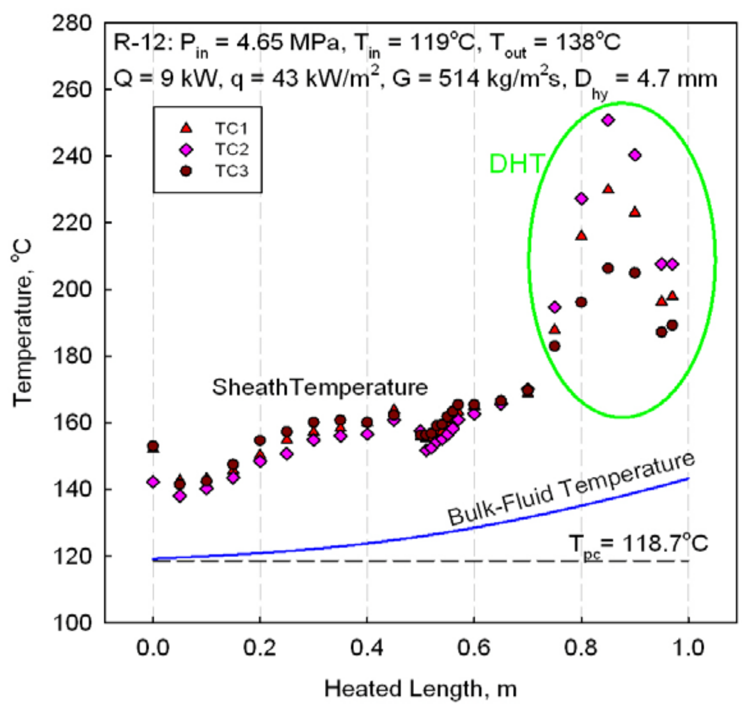


Figure 7. Experiment 3: Bulk-fluid and sheath-temperature profiles along bundle heated length.

Experiment 1 shows the normal heat-transfer regime. However, Experiments 2 and 3 show the normal and the Deteriorated Heat-Transfer (DHT) regimes within some part of the bundle. Experiment 2 shows the DHT regime near the entrance of the bundle, and Experiment 3 – at the outlet of the bundle.

4. Conclusions

The experiments have been conducted in a vertical 7-element bundle cooled with downward flow of supercritical Freon-12. The experiments showed that at certain operating conditions the deteriorated heat-transfer regime is possible not only in bare tubes, but also in “bare” bundles. This is the important statement, because previously the deteriorated heat-transfer regimes have not been encountered in supercritical water-cooled bundles with helical fins. This experimental work is in support of SCWRs.

5. Acknowledgments

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6. References

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[2] National Institute of Standards and Technology, 2007. NIST Reference Fluid Thermodynamic and Transport Properties-REFPROP. NIST Standard Reference Database 23, Ver. 8.0. Boulder, CO, U.S.: Department of Commerce.

[3] Pometko, R.S., Spanasenko, A.N., and Shelegov, A.S., Heat Exchange with the SuperCritical Parameters of the Heat-Transfer Agent in the Beam of the Rods, UDK621.039, Obninsk, Russia