STUDY OF HEAT TRANSFER IN A 7-ELEMENT BUNDLE COOLED WITH THE UPWARD FLOW OF SUPERCRITICAL FREON-12

by

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ABSTRACT

Experimental data on SuperCritical-Water (SCW) cooled bundles are very limited. Major problems with performing such experiments are: 1) small number of operating SCW experimental setups and 2) difficulties in testing and experimental costs at very high pressures, temperatures and heat fluxes. However, SuperCritical Water-cooled nuclear Reactor (SCWRs) designs cannot be finalized without such data. Therefore, as a preliminary approach experiments in SCW-cooled bare tubes and in bundles cooled with SC modeling fluids can be used. One of the SC modeling fluids typically used is Freon-12 (R-12) where the critical pressure is 4.136 MPa and the critical temperature is 111.97°C. These conditions correspond to a critical pressure of 22.064 MPa and critical temperature of 373.95°C in water.

A set of experimental data obtained in a Freon-12 cooled vertical bare bundle at the Institute of Physics and Power Engineering (IPPE, Obninsk, Russia) was analyzed. This set consisted of 20 cases of a vertically oriented 7-element bundle installed in a hexagonal flow channel. To secure the bundle in the flow channel 3 thin spacers were used. The dataset was obtained at equivalent parameters of the proposed SCWR concepts. Data was collected at pressures of about 4.65 MPa for several different combinations of wall and bulk-fluid temperatures that were below, at, or above the pseudocritical temperature. Heat fluxes ranged from 9 kW/m² to 120 kW/m² and mass fluxes ranged from 440 kg/m²s to 1320 kg/m²s. Also inlet temperatures ranged from 70°C – 120°C. The test section consisted of fuel 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 a combination of 8 different thermocouples.
The data was analyzed with respect to its temperature profile and heat transfer coefficient along the heated length of the test section. In a previous study it was confirmed that there is the existence of three distinct regimes for forced convention with supercritical fluids. (1) Normal heat transfer; (2) Deteriorated heat transfer, characterized by higher than expected temperatures; and (3) Improved heat transfer, characterized by lower than expected temperatures. All three regions were observed for the 7 rod bundle experiments. This work compares the experimental data to predictions based upon current 1-D correlations for heat transfer in supercritical fluids. Results show that no current 1-D correlation was able to accurately predict heat transfer coefficients within ±50%.

A parametric analysis of the data was also completed to determine if continuity in the experiment was present. Results of this study show that two distinct regions are present in the data. For cases with a mass flux below 1200 kg/m²s wall temperature profiles appear to be normal while in cases with mass flux above 1200 kg/m²s temperature given by the wall thermocouples were higher than normal. This phenomenon occurred regardless of heat flux-to-mass flux ratios.
ACKNOWLEDGMENTS

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I am thankful to my friends and family, especially my parents, Cyndy and Norm Richards and Cheryl and Steven Holmes for helping me through the difficult times and for being a source of inspiration during the course of my research and throughout my university education.

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NOMENCLATURE

\( A \)  area, \( m^2 \)

\( c_p \)  specific heat, \( \frac{J}{kg \cdot K} \)

\( \bar{c}_p \)  average specific heat, \( \frac{J}{kg \cdot K} \), \( \left( \frac{H_w-H_b}{T_w-T_b} \right) \)

\( D \)  diameter, \( m \)

\( g \)  gravity, \( \frac{m}{s^2} \)

\( G \)  mass flux, \( \frac{kg}{m^2.s} \)

\( H \)  enthalpy, \( \frac{J}{kg} \)

\( h \)  heat transfer coefficient, \( \frac{W}{m^2.K} \)

\( k \)  thermal conductivity, \( \frac{W}{m \cdot K} \)

\( L \)  length, \( m \)

\( \dot{m} \)  mass-flow rate, \( \frac{kg}{s} \)

\( P \)  perimeter, \( m \)

\( p \)  pressure, \( Pa \)

\( q \)  heat flux, \( kW/m^2 \)

\( \dot{Q} \)  total heat transfer rate, \( W \)

\( S \)  grid pitch, \( m \)

\( T \)  temperature, \( ^\circ C \)

\( V \)  Velocity, \( m/s \)

\( x \)  axial location, \( m \)
**Greek Letters**

<table>
<thead>
<tr>
<th>Symbol</th>
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<tr>
<td>$\alpha$</td>
<td>thermal diffusivity, $\frac{m^2}{s}$</td>
</tr>
<tr>
<td>$\beta$</td>
<td>expansion coefficient, $\frac{1}{K}$</td>
</tr>
<tr>
<td>$\delta$</td>
<td>thickness, mm</td>
</tr>
<tr>
<td>$\mu$</td>
<td>dynamic viscosity, Pa $\cdot$ s</td>
</tr>
<tr>
<td>$\nu$</td>
<td>viscosity, Pa $\cdot$ s</td>
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<tr>
<td>$\rho$</td>
<td>density, $\frac{kg}{m^3}$</td>
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**Dimensionless numbers**

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<tr>
<td>$Fr$</td>
<td>Froude number $\left( \frac{V}{\sqrt{gD_{hy}}} \right)$</td>
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<tr>
<td>$Gr$</td>
<td>Grashof number $\left( \frac{g\beta(T_w - T_b)D_{hy}^3}{\nu^2} \right)$</td>
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<tr>
<td>$Nu$</td>
<td>Nusselt number $\left( \frac{HTC \cdot D_{hy}}{k} \right)$</td>
</tr>
<tr>
<td>$Pr$</td>
<td>Prandtl number $\left( \frac{\mu c_p}{k} \right)$</td>
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<tr>
<td>$\bar{Pr}$</td>
<td>average Prandtl number $\left( \frac{\bar{\mu} \bar{c}_p}{k} \right)$</td>
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<tr>
<td>$Re$</td>
<td>Reynolds number $\left( \frac{G \cdot D_{hy}}{\mu} \right)$</td>
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**Subscripts and Superscripts**

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<td>$b$</td>
<td>bulk</td>
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<td>$B$</td>
<td>bundles</td>
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<td>$c$</td>
<td>cross section</td>
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<td>Abbreviation</td>
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<tr>
<td>CE</td>
<td>centre element</td>
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<td>wet</td>
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<tr>
<td>x</td>
<td>axial length along fuel-channel</td>
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**Acronyms**

<table>
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<th>Description</th>
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<tr>
<td>ACR</td>
<td>Advanced CANDU Reactor</td>
</tr>
<tr>
<td>AECL</td>
<td>Atomic Energy of Canada Limited</td>
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<tr>
<td>BWR</td>
<td>Boiling Water Reactor</td>
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CANDU CANada Deuterium Uranium
EURATOM European Atomic Energy Community
GFR Gas-cooled Fast Reactor
GIF Generation IV International Forum
IT Inner Tube
IPPE Institute of Physics and Power Engineering
HEC High Efficiency Channel
HTC Heat Transfer Coefficient
LFR Lead-cooled Fast Reactor
MATLAB MATrix LABoratory
MSR Molten Salt Reactor
Mtoe Million tonnes of oil equivalent
NIKIET Research and Development Institute of Power Engineering (Russian Abv.)
NIST National Institute of Standards and Technology
NPD Nuclear Power Demonstration
OT Outer Tube
PT Pressure Tube
PV Pressure Vessel
PWR Pressurized Water Reactor
RDIPE Research and Development Institute of Power Engineering
REC Re-Entrant Channel
REFPROP REFerence fluid thermodynamic and transport PROPerties
SCW SuperCritical Water
SCWR SuperCritical Water-cooled Reactor
SFR Sodium-cooled Fast Reactor
VHTR Very-High Temperature Reactor
Investigation of heat transfer to fluids at supercritical pressure began in the early 1930s. Schmidt et al. [1, 2] determined that the free convection Heat Transfer Coefficient (HTC) was higher for fluids surrounding the critical point. This finding began the use of single-phase thermosyphons with supercritical fluids [3].

The 1950s introduced supercritical ‘steam’ options to fossil-fuel power plants to increase thermal efficiencies. This is because at supercritical pressures there is no liquid-vapor transition eliminating Critical Heat Flux (CHF) or dryout phenomena. The USA and USSR intensely studied supercritical heat transfer from the 1950s until the 1980s, with research centered on supercritical water in circular tubes. This initiative was abandoned due to material constraints such as issues surrounding corrosion resistance of sheath materials at high temperatures, however the concept was revisited in the 1990s as a way to improve reactor efficiency and the investigation still continues [4, 5].

Current SuperCritical Water-cooled Reactor (SCWR) concepts use light water as their coolant with operating pressure of temperature about the critical point. The critical point of water is at a pressure of 22.064 MPa and temperature of 373.95°C. SCWRs offer many advantages over current reactor types. These benefits include:

1. An increase in thermal efficiency of the nuclear power plant from 33 – 35% to 40 – 45% which corresponds to current efficiencies in fossil-fuel power plants [4];
2. An expected decrease in capital and operating costs, therefore a decrease in electrical-energy costs;

3. A simplified flow circuit with the elimination of steam dryers and the possibility of steam generators;

4. Ability to facilitate steam based technologies such as thermochemical hydrogen cogeneration, desalination or district heating.

In recent years, a number of countries have begun to support the SCWR movement and have begun developing concepts. These countries include Canada, China, Germany, Japan, Korea, Russia, and the USA. Specifically, Canada has begun research into Pressure Tube (PT) designs at supercritical pressures. Canada currently predominantly uses a PT type reactor called the CANDU reactor, with heavy water coolant in the pressure range of 9.9 – 11.2 MPa where PT SCWR concepts use a light water coolant with pressures of approximately 25 MPa and inlet and outlet temperatures of 350ºC – 625ºC [6].

In support of the development of an SCWR, it is necessary to perform a heat transfer analysis. As a first step in this process, heat-transfer to supercritical water in bare vertical tubes can be investigated although obtaining data for supercritical water heated with bundles will provide a greater understanding of fluid behaviour and heat transfer phenomena. It has been confirmed that three heat transfer regimes exist for forced convective heat transfer to water flowing in tubes at supercritical pressures, however these have not been established for bundles. These three regimes are [7]:
1. Normal heat transfer regime

2. Deteriorated Heat Transfer (DHT) regime; characterized by lower than expected HTC values; and

3. Improved heat transfer regime; characterized by higher than expected HTC values.

Although a number of supercritical heat-transfer correlations are available in the open literature, comparison of the correlations show that there results can vary [4]. Also these correlations only take into account normal heat transfer regimes in bare tubes (with the exception of the correlation by Dyadyakin and Popov (1977) where a 7-element bundle with helical fins was used). To determine if these correlations are adequate for SCWR design purposes, they must be verified using experimental heat transfer data for bundles. Conducting experiments can be incredibly expensive and dangerous given that water temperatures of up to 625ºC and pressures as high as 25 MPa offer inherent risks. As an alternative, working fluids with lower critical temperatures and pressure can be used to reduce operating and capital costs of test facilities [8]. For the purposes of this thesis the primary working fluid that will be explored is Freon-12.

1.1 Objectives

To complement current knowledge of supercritical fluids, and heat transfer in supercritical fluids, a moderately sized set of experimental data, obtained at the IPPE in Russia, was analyzed. The dataset used Freon-12 as a working fluid and was obtained at equivalent parameters to that of the proposed SCWR concepts using fluid-fluid scaling discussed in Section 2.5.
The primary objective of this thesis is to analyze the experimental data with respect to heat transfer. This includes:

- determining if DHT phenomena occurs in bundles similar to that as observed in bare tubes;
- performing a parametric analysis of dataset to determine its validity as well as to observe any new phenomena that has not yet be observed.

Additional objectives of this work are as follows:

1. Comparing the Bishop et al., Mokry et al., Swenson et al., Gupta et al., Gorban et al., Dyadyakin and Popov, and Jackson et al. correlations and the experimental dataset;
2. Conducting a performance review of the current 1-D correlations in determining if they are adequate for design purposes; and
3. Creating a new 1-D correlation specifically for heat transfer in bundles cooled with supercritical Freon-12.

Chapter 2 of this thesis will describe the literature review with particular focus on SCWR type reactors, supercritical fluid properties, fluid-fluid scaling, and the general thermal hydraulic behaviour of supercritical fluids. Chapter 3 will discuss the methodology and the test facility in which the data was obtained. The results of the experiment are described in Chapter 4. This includes raw data obtained from the IPPE, predictions given using 1-D correlations, as well as detailed assessments of the correlations. Chapters 5 and 6 examine updates to current 1-D correlations and a parametric analysis of the data, respectively. Concluding remarks and future work are described in Chapters 8 and 9.
CHAPTER 2  BACKGROUND AND LITERATURE REVIEW

Nuclear Power Demonstration (NPD) which was a small scale prototype reactor commenced operation in 1962. The Douglas Point larger scale prototype was soon to follow, beginning operation in 1967. Both of these reactors were CANDU\textsuperscript{1} type reactors and were the first operational reactors in Canada. NPD and Douglas Point were known as Generation I reactors and laid the foundations for commercial CANDU reactors that currently provide electricity to the public.

The Pickering Nuclear Generating Station became the first multi-unit station in Ontario in 1972 and successfully demonstrated nuclear power on a commercial scale [9]. From the Pickering station design and operating experience the CANDU 6, Bruce A/B, and Darlington Units were designed. These units used natural uranium fuel, cooled and moderated with heavy water (D\textsubscript{2}O) in a PT design (separate coolant and moderator), where the coolant is at a pressure of approximately 10 MPa and temperatures of approximately 260\textdegree C and 310\textdegree C at the inlet and outlet, respectively.

Generation III reactors in the CANDU line have also been developed. These are the CANDU 3 and CANDU 9 reactor concepts. Both of these reactors have been designed, however neither has been built. Atomic Energy of Canada Limited (AECL) is currently in the process of developing a third Generation III design, the Enhanced CANDU 6 (EC6). It closely resembles the original CANDU 6 with the addition of newer technologies which give support to superior safety systems, operation, and performance.

\textsuperscript{1} CANDU\textsuperscript{®} (CANada Deuterium Uranium) is a registered trademark of Atomic Energy of Canada Limited.
AECL is also involved in the development of a Generation III+ reactor, the Advanced CANDU Reactor (ACR). This reactor will be light-water cooled and heavy water moderated with a primary goal of increasing efficiencies in the plant [11]. The purpose of EC6 and ACR designs are to be modest evolutions from the current CANDU 6 and Darlington designs. Major efficiency improvements are not expected and the inclusions of additional safety features are expected to increase the cost relative to the current fleet. A timeline of Canadian reactor technologies is shown in Figure 2-1 that shows the general trend towards Generation IV technology. As such, Canada and AECL are considering technologies that would be radically different in design and hence be able to achieve major efficiency improvements.
Figure 2-1: Canadian Nuclear Reactor Technologies [10, 11, 12, 13]
2.1 Generation IV Reactor Concepts

In 2001 the Generation IV International Forum (GIF) was formed to assist with the worldwide development of new reactor technologies. Countries associated with GIF include: Canada, Argentina, Brazil, France, Japan, the Republic of Korea, the Republic of South Africa, the United Kingdom, and the United States. The original members were later joined by Switzerland (2002), EURATOM (2003), China (2006) and Russia (2006).

The GIF has established the main objectives for Generation IV nuclear reactors which include further enhancements in sustainability, safety and reliability, economic viability, and, proliferation resistance and physical protection [14].

Target characteristics for Generation IV nuclear reactors:

* **Sustainability** – Generation IV nuclear reactors must provide sustainable energy generation that will meet clean-air objectives and support long term availability of systems and effective fuel utilization for worldwide energy production. Additionally, goals for minimization and management of nuclear waste and the reduction of the long term stewardship burden will improve protection for public health and the environment.

* **Economic Viability** – Generation IV nuclear energy systems will have a clear life cycle cost advantage over other energy sources. They will also have financial risk similar to other energy projects.
**Safety and Reliability** – Generation IV nuclear energy systems operations will surpass others in safety and reliability and will have a very low probability and degree of reactor core damage. This is to eliminate the need for offsite emergency response.

**Proliferation Resistance and Physical Protection** – Generation IV nuclear energy systems will ensure increased physical protection against acts of terrorism, as well as reinforce the unavailability of weapons-usable materials at the facility.

The above objectives work together to achieve three goals. First is to serve as a basis for developing criteria to assess and compare Generation IV reactor concepts. Second, to challenge and encourage the investigation of innovative nuclear energy systems in multiple areas of design; and lastly to motivate and direct research and development of Generation IV nuclear energy systems as a combined effort of GIF nations.

### 2.1.1 Description of Individual Reactor Concepts

Gas-cooled Fast Reactors (GFRs) and Very-High-Temperature Reactors (VHTRs) are two of the six Generation IV reactor concepts that are currently being evaluated by the GIF. These concepts are gas cooled and are not relevant to this study. This thesis contains work that could potentially affect design characteristics and are explained in more detail below.

- **Lead-cooled Fast Reactors (LFRs)** – The LFR is a lead-bismuth cooled reactor (400 – 420°C inlet temperature, 480 – 570°C outlet temperature; atmospheric operating
pressure) with a fast neutron spectrum. This reactor concept offers increased efficiency in electricity and hydrogen production as well as actinide management [15].

- **Molten Salt Reactors (MSRs)** – The MSR is a molten salt cooled reactor (565°C inlet temperature, up to 800°C outlet temperature) with a thermal neutron spectrum. Estimated at 1000 MWth, this reactor concept hold potential for hydrogen production. Unique to MSRs is the option to use solid fuels or fuel dissolved in the coolant [16, 17].

- **Sodium-cooled Fast Reactors (SFRs)** – The SFR is a liquid sodium cooled reactor (up to 530 - 550°C outlet temperatures; atmospheric operating pressure) with a thermal neutron spectrum. The main purpose for this reactor concept is to efficiently manage high-level wastes such as plutonium and other actinides as well as to produce electricity. There are three proposed sizes of SFRs: Large [600 – 1500 MW] loop type reactor; Intermediate [300 – 600 MW] pool type reactor; and Small [50 – 150 MW] modular type reactor [16, 18].

- **SuperCritical Water-cooled Reactors (SCWRs)** – The SCWR is a light water cooled reactor (280 – 350°C inlet temperature, 550 – 625°C outlet temperature; operating pressure of 25 MPa) with a thermal or fast neutron spectrum. The purpose of using supercritical water is to increase the thermal efficiency by operating above the thermodynamic critical point. Plant simplification is a benefit of this type of reactor as well as efficiencies in the range of 40 – 45% and the possible cogeneration with hydrogen [16, 19].
2.1.2 Supercritical Water-cooled Reactor Concepts

Out of the six Generation IV reactor concepts Canada is primarily focusing on the development of SCWRs. This concept can be broken into 2 main categories, Pressure Tube (PT) and Pressure Vessel (PV). The United States is currently researching this concept as it is analogous with current light water Pressurized Water Reactors (PWRs) (see Figure 2-2). Main concerns with this method of pressure containment is manufacturing of the PV. In cases where pressure is extremely high (25 MPa) the wall thickness of the PV can be 0.5 m or greater [4].

Canada (AECL) and Russia (Research and Development Institute of Power Engineering, RDIEPE/NIKIET and the Institute of Physics and Power Engineering, IPPE) are currently pursuing the design of a PT type SCWR (see Figure 2-3 and Figure 2-4) as it is analogous to current heavy water cooled nuclear power plants. This concept has been designed to be more flexible in terms of flow, flux and density changes compared to current PV reactors, and these advantages are to be carried into the design of the PT SCWR. Safety in the PT SCWR is also increased as the high pressure and temperature coolant is separated from the moderator. In a Loss of Coolant Accident the moderator will act as a secondary, passive heat sink (if the moderator is in liquid state). Also flexibility in moderator design can be achieved when separated from the coolant. Various materials are currently being investigated such as heavy water, graphite, beryllium oxide, and zirconium hydride [4, 20, 21].
Figure 2-2: Pressure Vessel Type SCWR [4]
Multiple products are key to sustainable future and competitive designs

Figure 2-3: Pressure Tube Type SCWR[4]

Figure 2-4: Vertically Oriented PT SCWR [22]
Although there are many different channel and bundle designs for PT SCWRs, which include the High Efficiency Channel (HEC), Re-Entrant Channel (REC), 43-, 54- and 64-element bundles, estimated pressure and temperatures are the same [23]. Operating pressures for the light water coolant is expected to be 25 MPa at the outlet, and inlet and outlet temperatures in the ranges of 280 – 350°C and 550 – 625°C, respectively [4, 24]. Operating at temperatures and pressure above the thermodynamic critical point, as well as the fact that SCWRs can operate on a direct cycle similar to Boiling Water Reactors (BWRs) and current supercritical water-cooled fossil fuel plants, will increase thermal efficiencies in the range of 40-45% [4]. SCWRs also have the ability to facilitate steam based technologies such as desalination, thermochemical hydrogen production and district heating [25].

Working fluids above critical point offer characteristics of both liquids and gases due to unique fluid properties of supercritical fluids. These properties will be examined in the following section.

2.2 Definition of Supercritical Terminology

Definitions of selected terms and expressions, related to heat transfer to fluids at critical and supercritical pressures, are listed below. For better understanding of these terms and expressions a graph is shown in Figure 2-5.
**Compressed fluid** is a fluid at a pressure above the critical pressure, but at a temperature below the critical temperature [4].

**Critical point** is the point where the distinction between the liquid and gas (or vapor) phases disappears, i.e., both phases have the same temperature, pressure, and volume. The *critical point* is characterized by the phase state parameters $T_{cr}$, $P_{cr}$, and $V_{cr}$, which have unique values for each pure substance [4].

**Deteriorated Heat Transfer (DHT)** is characterized with lower values of the wall heat transfer coefficient compared to those at the normal heat transfer. Similarly, higher values of wall temperature within the same part of the test section are also observed [4].

**Improved Heat Transfer (IHT)** is characterized with higher values of the wall heat transfer coefficient compared to those at the normal heat transfer. Similarly, lower values of wall temperature within the same part of the test section are also observed [4].

**Normal Heat Transfer (NHT)** can be characterized in general with wall heat transfer coefficients similar to those of subcritical convective heat transfer far from the critical or pseudocritical regions [4].

**Pseudocritical point** (characterized with $P_{pc}$ and $T_{pc}$) is a point at a pressure above the critical pressure and at a temperature ($T_{pc} > T_{cr}$) corresponding to the maximum value of the specific heat for this particular pressure [4].
**Supercritical fluid** is a fluid at pressures and temperatures that are higher than the critical pressure and critical temperature. However, in the current thesis, the term *supercritical fluid* includes both terms – *supercritical fluid* and *compressed fluid* [4].

**Superheated vapour** is at pressures below the critical pressure, but at temperatures above the critical temperature [4].

![Figure 2-5: Pressure-Temperature Diagram for Freon-12 surrounding the Critical Region](image-url)
2.3 Physical Properties of Supercritical Water

As the temperature and pressure of a fluid surpass the critical point, physical properties of the fluid are changing rapidly, as the distinction between liquid and gas phases disappears. Critical parameters for water are shown in Table 2-1.

<table>
<thead>
<tr>
<th>Critical Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Critical Pressure</td>
<td>22.064 MPa</td>
</tr>
<tr>
<td>Critical Temperature</td>
<td>373.95°C</td>
</tr>
<tr>
<td>Critical Density</td>
<td>322.0 kg/m³</td>
</tr>
</tbody>
</table>

At the critical point the highest value of specific heat is reached. The critical point is shown in Figure 2-6 as well as the pseudocritical points when the pressure is about 22.064 MPa. The pseudocritical point is characterized by the peak in specific heat at pressures and temperatures above the critical pressure. These oscillating peaks for Specific Heat are not believed to be physical in nature and only occur directly surrounding the critical point ± 1°C. This is most likely due to interpolation techniques used by NIST REFPROP. For the purpose of this thesis these peaks were not encountered as fluid parameters were well above the critical point. For further details on issues with NIST REFPROP at the critical point please see Appendix 1.
Additionally, all other fluid properties undergo significant changes surrounding the critical and pseudocritical points. Figure 2-7 to Figure 2-14 show trends of important thermophysical properties at the critical pressure and proposed operating pressure of a Canadian SCWR [4, 26]. Density and dynamic viscosity of the fluid undergo a significant drop near the critical point. The changes are nearly instantaneous as the drops are near vertical. As pressure increases the changes become more gradual. Enthalpy and kinematic viscosity on the other hand experience sharp increases around the critical point. Specific heat, volume expansivity, thermal conductivity and Prandtl number have a distinct peak at the critical and pseudocritical points. In all cases the intensity of the property change will diminish as the difference in pressure between the critical point and the test pressure increases.
Figure 2-6: Specific Heat Dependence on Temperature and Pressure [26]
Figure 2-7: Specific Heat of Water within the Critical/Pseudocritical regions

Figure 2-8: Density of Water within the Critical/Pseudocritical regions
Figure 2-9: Thermal Conductivity of Water within the Critical/Pseudocritical regions

Figure 2-10: Kinematic Viscosity of Water within the Critical/Pseudocritical regions
Figure 2-11: Dynamic Viscosity of Water within the Critical/Pseudocritical regions

Figure 2-12: Specific Enthalpy of Water within the Critical/Pseudocritical regions
Figure 2-13: Volume Expansivity of Water within the Critical/Pseudocritical regions

Figure 2-14: Prandtl Number of Water within the Critical/Pseudocritical regions
Figure 2-15 shows selected fluid properties of water at the pseudocritical point at 25 MPa (the predicted operating pressure of a Canadian SCWR). It is shown that the significant changes in fluid properties are found within ±25°C surrounding the pseudocritical point. Also it should be noted that no phase change occurs at this point, and the fluid will have properties similar to that of gases, however, the fluid is still in a fully liquid state.

Figure 2-15: Selected Properties of Supercritical Water [25 MPa] within the Critical/Pseudocritical regions
2.4 Alternative Working Fluids

As stated in section 2.1.2, 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) [4, 24]. Design and operation of a facility capable of accurately and safely conducting experiments with SCW is a very expensive task. Major costs derive from the large electrical load required to heat water up to the required temperatures as well as the special pumps designed for the high pressures and temperatures associated with supercritical water in the loop. Testing with high temperature and pressure fluids increase the cost of simple components such as piping as well as the safety procedures associated with the test loop.

Operating conditions can be modeled with lower critical pressure and temperature fluids such as Freons as a preliminary approach to complement our knowledge of supercritical fluids. Freon-12 was widely used in industry some time ago as a refrigerant for air-conditioning systems. Therefore, its thermophysical properties are well known within a wide range of conditions including the supercritical-pressure region. Using an alternative working fluid will lower capital and operation costs, and reduce the risks associated with operation at full pressure and temperature.

2.4.1 Physical Properties of Supercritical Freon-12

Freon-12 properties follow similar trends to that of water surrounding the critical point. The primary difference is that critical parameters of Freon-12 are much more desirable than that of water for testing purposes. As shown in Table 2-2, critical pressure and
temperature are reduced by 81% and 70% respectively and critical density in increased 2.55 times over that of water.

All fluid properties undergo significant changes surrounding the critical and pseudocritical points similar to that of water. Figure 2-16 – Figure 2-23 show trends of important thermophysical properties of Freon-12 at the critical pressure and operating pressure of the experiments later to be analyzed [26]. Density and dynamic viscosity of the fluid undergo a significant drop near the critical point. The changes are nearly instantaneous as the drops are close to vertical. It should be noted that the changes are continuous, not distinct as commonly seen in phase changes in subcritical fluids. Enthalpy and kinematic viscosity on the other hand experience sharp increases around the critical point. Specific heat, volume expansivity, thermal conductivity and Prandtl number have similar peaks to that of water.

<table>
<thead>
<tr>
<th>Critical Parameters for Freon-12 [26]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Critical Pressure</strong></td>
</tr>
<tr>
<td><strong>Critical Temperature</strong></td>
</tr>
<tr>
<td><strong>Critical Density</strong></td>
</tr>
</tbody>
</table>
Figure 2-16: Specific Heat of Freon-12 within the Critical/Pseudocritical regions

Figure 2-17: Density of Freon-12 within the Critical/Pseudocritical regions
Figure 2-18: Thermal Conductivity of Freon-12 within the Critical/Pseudocritical regions

Figure 2-19: Kinematic Viscosity of Freon-12 within the Critical/Pseudocritical regions
Figure 2-20: Dynamic Viscosity of Freon-12 within the Critical/Pseudocritical regions

Figure 2-21: Specific Enthalpy of Freon-12 within the Critical/Pseudocritical regions
Figure 2-22: Volume Expansivity of Freon-12 within the Critical/Pseudocritical regions

Figure 2-23: Prandtl Number of Freon-12 within the Critical/Pseudocritical regions
Figure 2-24 shows selected fluid properties of water at the pseudocritical point at 4.65 MPa (approximate equivalent pressure of the predicted operating pressure of a Canadian SCWR for Freon-12). The peak of specific heat at 4.65 MPa occurs at a temperature of 118.7°C. Similarly to water, the properties of Freon-12 experience the majority of changes within ±25°C from the pseudocritical point. The drastic changes in fluid properties surrounding the pseudocritical point greatly affect how subcritical 1-dimensional correlations predict heat transfer in this area. Supercritical heat transfer correlations need to take into account the changing of fluid properties as they have the potential to be the dominating parameters characterizing heat transfer. Further comparison and verification of water/Freon-12 scaling will be addressed in the following section.
Operating conditions of SCWRs 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 2-3 [4, 8]. In addition, scaling factors for the conversion of data from Freon-12 to water at supercritical conditions can be found in Table 2-4. This table represents Table 2-3 with the input of critical parameters of water and Freon-12. Using these scaling factors it can...
be determined that the test pressure of \(~4.65\) MPa with Freon-12 in the experiments that are analyzed in the later chapters of this thesis are equivalent to \(24.9\) MPa in water; similar to that of the proposed operating pressure of a SCWR.

Table 2-3: Major scaling parameters for fluid-to-fluid modeling at supercritical conditions based on inlet-conditions approach. [8]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure</td>
<td>(\left(\frac{p}{p_{cr}}\right)<em>w = \left(\frac{p}{p</em>{cr}}\right)_f)</td>
</tr>
<tr>
<td>Bulk-Fluid Temperature</td>
<td>(\left(\frac{T}{T_{cr}}\right)<em>w = \left(\frac{T}{T</em>{cr}}\right)_f)</td>
</tr>
<tr>
<td>Heat Flux</td>
<td>(\left(\frac{q D}{k_b}\right)_w = \left(\frac{q D}{k_b}\right)_f)</td>
</tr>
<tr>
<td>Mass Flux</td>
<td>(\left(\frac{G D}{\mu_b}\right)_w = \left(\frac{G D}{\mu_b}\right)_f)</td>
</tr>
</tbody>
</table>

Table 2-4: Scaling factors for Freon-12 to water at supercritical conditions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure</td>
<td>(\frac{p_W}{p_F} = 5.37)</td>
</tr>
<tr>
<td>Temperature</td>
<td>(\frac{T_w}{T_F} = 3.3)</td>
</tr>
<tr>
<td>Heat Flux</td>
<td>(\frac{q_W}{q_F} = 20)</td>
</tr>
<tr>
<td>Temperature difference</td>
<td>(\frac{\Delta T_W}{\Delta T_F} = 15.4 \left(\frac{k_W}{k_F}\right)^{0.66})</td>
</tr>
</tbody>
</table>
When looking at fluid properties of multiple working fluids, trends begin to emerge. In Figure 2-25, the maximum value of specific heat was taken at different pressures surrounding the critical point of the fluid. Water, as shown on the right hand side in pink, follows specific trends with CO₂, R-134a, Freon-22 and Freon-12.

Although visually it appears that trends for specific heat are identical for a number of different working fluids, a more detailed approach is needed to verify the visual trends. To accomplish this, the fluid property as well as temperature and pressure must be normalized to accurately compare the fluids to one another. When comparing fluids around the critical point it is common to normalize properties by creating dimensionless fluid properties; for example, using a ratio with the property and the property at the critical point of the fluid.

Figure 2-28 shows the comparison between Freon-12 and water for specific heat. In this case, the value was divided by its value at the critical point. For example, specific heat at the critical pressure is calculated for temperatures surrounding the supercritical temperature. This array is then formed into a ratio with the value of specific heat at both critical pressure and temperature in the form of $T/T_{cr}$ or $c_p/c_{p,cr}$. When comparing the dimensionless specific heat of both water and Freon-12 plotted vs. dimensionless temperature trends between Freon-12 and water are very similar [26, 8]. This trend also is the same for other major fluid properties such as density and Prandtl number, shown below.
Figure 2-25: Specific Heat comparison of various working fluids (R134a, Freon-12, Freon-22, CO₂, and Water)

Figure 2-26: Specific Heat comparison between Freon-12 and Water within the critical region
Figure 2-27: Density comparison between Freon-12 and Water in the critical region

Figure 2-28: Prandtl Number comparison between Freon-12 and Water in the critical region
2.6 Heat Transfer Correlations for use with Supercritical Fluids

The ultimate goal is to obtain a heat transfer correlation valid for SCW type nuclear power reactors, in other words a correlation designed specifically for bundle geometries. Most of the data and correlations developed to date are for pipe flow geometries.

Currently, there is only a single Nusselt correlation for use with bundles cooled with supercritical fluids. This heat transfer correlation was developed by Dyadyakin and Popov in 1977 [27].

\[
\text{Nu}_x = 0.0021 \ Re_x^{0.8} \ Pr_x^{0.7} \left( \frac{\rho_w}{\rho_b} \right)_x^{0.45} \left( \frac{\mu_b}{\mu_{in}} \right)_x^{0.2} \left( \frac{\rho_b}{\rho_{in}} \right)_x^{0.1} \left( 1 + 2.5 \frac{D_{hy}}{x} \right)
\]  \[2-1\]

Where \( x \) is the axial location along the heated length of the test section in meters and \( D_{hy} \) is the hydraulic-equivalent diameter. \( D_{hy} \) calculated using the equation below:

\[
D_{hy} = \frac{4 \cdot A_{fl}}{\rho_{wet}}
\]  \[2-2\]

This correlation along with the other correlations included in this thesis use different dimensionless terms in an attempt to predict heat transfer. Reynolds number is used to take into account flow effects, Prandtl number to take into account changing fluid properties as well as other fluid property ratios to further refine the correlation. The
exponent associated with each term represents the level of effect the parameter has on heat transfer.

This particular correlation was developed by experimentation with a tight-lattice 7-element bundle with helical fins. In all cases for this experiment the selected coolant was water. Five different bundle configurations were used to develop the correlation; the parameters are provided in Table 2-5.

<table>
<thead>
<tr>
<th>Test Section #</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_n$, mm$^2$</td>
<td>112</td>
<td>134</td>
<td>113</td>
<td>121</td>
<td>102</td>
</tr>
<tr>
<td>$D_{hy}$, mm</td>
<td>2.35</td>
<td>2.77</td>
<td>2.38</td>
<td>2.53</td>
<td>2.15</td>
</tr>
</tbody>
</table>

The most widely used heat transfer correlation at sub-critical pressures is the Dittus-Boelter correlation (1930). The form below was proposed by McAdams (1942) for forced convective heat transfer for turbulent flow at sub-critical pressure.

$$\text{Nu}_b = 0.0243 \text{Re}_b^{0.8} \text{Pr}_b^{0.4} \quad [2-3]$$

In 1976, Schnurr et al. showed good agreement with experiments using supercritical water, however also noted that for some flow conditions the correlation could fabricate unrealistic results due to its sensitivity to changes in fluid properties. Generally, this
correlation is the basis for modern heat transfer correlations for use with supercritical fluids [28].

Bishop et al. used supercritical water flowing upward through bare tube and annuli to at the following parameters to develop his own Nusselt correlation. Operating parameters: pressure: 22.8 – 27.6 MPa; bulk-fluid temperature: 282 – 527°C; mass flux: 651 – 3662 kg/m²s; and heat flux: 0.31 – 3.46 MW/m². The experimental data fit the following correlation to ±15% [29].

\[
N_u_b = 0.0069 \, Re_b^{0.9} \, Pr_b^{0.66} \left( \frac{\rho_w}{\rho_b} \right)^{0.43} \left( 1 + 2.4 \frac{D}{x} \right) \tag{2-4}
\]

Where \( x \) is the axial location along the heated along length, \( \rho_w \) is the density of the fluid at the wall of the heated surface, \( \rho_b \) is the density at the bulk-fluid temperature, and \( \left( 1 + 2.4 \frac{D}{x} \right) \) accounts for the entrance region into the test section.

For the purposes of this thesis, all fluid regimes were considered to be fully developed due to the particular test section design, therefore the Bishop et al. correlation was used in the following form:

\[
N_u_b = 0.0069 \, Re_b^{0.9} \, Pr_b^{0.66} \left( \frac{\rho_w}{\rho_b} \right)^{0.43} \tag{2-5}
\]

In using the Dyadyakin and Popov correlation the entrance term was also removed.
Swenson et al. determined that correlations based mainly on properties at bulk-fluid temperatures produced poor results when used with supercritical fluids. They suggested the flowing correlation using primarily properties based on wall temperature:

\[
\text{Nu}_w = 0.00459 \text{ Re}_w^{0.923} \text{ Pr}_w^{0.613} \left(\frac{\rho_w}{\rho_b}\right)^{0.231}
\]  

Swenson et al. obtained their correlation at the following conditions: pressure: 22.8 – 41.4 MPa; bulk-fluid temperature: 75 – 576°C; wall temperature 93 – 649°C; and mass flux: 542 – 2150 kg/m²s. It predicated the experimental data within ±15% [30].

Heat transfer experiments were performed, by Gorban et al., for water and Freon-12 flowing inside circular tubes at a temperature above the critical temperature. As a result, Gorban et al. developed two correlations for water [4, 31].

**Water:**  \[
\text{Nu}_b = 0.0059 \text{ Re}_b^{0.9} \text{ Pr}_b^{-0.12}
\]

**Freon-12:**  \[
\text{Nu}_b = 0.0094 \text{ Re}_b^{0.86} \text{ Pr}_b^{-0.15}
\]

For this thesis, only the correlation for Freon-12 was used as experiment was conducted using Freon-12 as the working fluid.
Jackson modified the original Krasnoshchekov *et al.* correlation for forced convective heat transfer in water and carbon dioxide to translate it to the Dittus-Boelter, \(\text{Nu}_o\) form [32].

\[
\text{Nu}_w = 0.0183 \, \text{Re}_b^{0.82} \, \text{Pr}_b^{0.5} \left( \frac{\rho_w}{\rho_b} \right)^{0.3} \left( \frac{c_p_b}{c_p_w} \right)^n
\]  

[2-9]

Where \(n\) is determined by:

\[
n = 4; \quad \text{for: } T_b < T_w < T_{pc} \; \& \; 1.2 \, T_{pc} < T_b < T_w;
\]

\[
n = 0.4 + 0.2 \left( \frac{T_w}{T_{pc}} - 1 \right); \quad \text{for: } T_b < T_{pc} < T_w;
\]

\[
n = 0.4 + 0.2 \left( \frac{T_w}{T_{pc}} - 1 \right) \left[ 1 - 5 \left( \frac{T_b}{T_{pc}} - 1 \right) \right] \quad \text{for: } T_{pc} < T_b < 1.2 \, T_{pc} \; \& \; T_b < T_w
\]

The following correlation (equation 2-10) was proposed by Mokry *et al.* (2009) and calculates the Nusselt number at supercritical conditions. The experimental data, based on which the correlation was developed, was obtained within conditions similar to those of proposed SCWR concepts; supercritical water flowing upward in a 4-m-long vertical bare tube. The data was collected at a pressure of approximately 24 MPa for several combinations of wall and bulk fluid temperatures. These temperature values were above, below, or on par with the pseudocritical temperature. The mass flux ranged from 200 – 1500 kg/m²·s with coolant inlet temperature varying from 320 – 350°C, and heat flux up to 1250 kW/m² [20].

\[
\text{Nu}_b = 0.0061 \, \text{Re}_b^{0.904} \, \text{Pr}_b^{0.684} \left( \frac{\rho_w}{\rho_b} \right)^{0.564}
\]  

[2-10]
Experimental conditions for the Gupta et al. correlation were the same as for the Mokry et al. correlation however the correlation was developed using the Swenson et al. model.

\[
Nu_w = 0.004 Re_w^{0.923} Pr_b^{0.773} \left( \frac{\mu_w}{\mu_b} \right)^{0.366} \left( \frac{\rho_w}{\rho_l} \right)^{0.186}
\] \hspace{1cm} [2-11]

In general, a total of 7 different empirical correlations were used: 1 correlation specifically designed for use with supercritical Freon-12, 1 correlation used for bundles, and 6 correlations based on supercritical water in bare tubes/annuli.

Since each correlation was derived from a different set of experimental data, their ranges of applicability vary. Shown below in Figure 2-29 is a graphical comparison of the parameters of which each correlation was developed. The dataset that is analyzed in this thesis is shown in pink and overlaps a number of ranges for different correlations.
Figure 2-29: Comparison of the applicability of 7, 1-D correlations

**these studies used Freon-12 as the working fluid. All other studies shown used water.
2.7 Deteriorated Heat Transfer

Deteriorated Heat Transfer (DHT) is the reduction in the wall HTC, which consequently increases the wall temperature. Heat flux, mass flux, and flow geometry are the three factors that contribute the most to DHT; many authors have identified the ratio of heat flux to mass flux as the determining factor for the appearance of DHT. Freon-12 was tested in a vertical tube, with an upward flow direction, at supercritical conditions. These experiments were performed by Pometko et al. and based on their experiments, the boundary of the DHT can be determined with the equation below, which indicates that the ratio of the heat flux to mass flux should be greater than 0.07 to 0.1 kJ/kg in order for a DHT to occur [33].

$$\frac{q}{G} \geq 0.07 - 0.1, \text{ kJ/kg}$$  \[2-12\]

In 1967, Vikhev et al. conducted experiments with SCW and discovered two types of DHT at a mass flux of 495 kg/m²·s. The first DHT type appeared in the entrance region of the tube where, $\frac{L}{D} \leq 40 - 60$. This type occurred at low mass fluxes and high heat fluxes; however, the DHT disappeared at high mass fluxes. The second DHT type appeared when the sheath temperature exceeded the pseudocritical temperature. According to Vikhev et al., DHT appears when $\frac{q}{G} \geq 0.4, \text{ kJ/kg}$ [4]. The value of heat flux to mass flux ratio is even lower for CO₂. The expression for calculating the boundary of DHT in CO₂ is shown below [34].

$$\frac{q}{G} \geq 0.2 - 0.3, \text{ kJ/kg}$$  \[2-13\]
DHT has previously only been observed in bare tube bundles. The accepted theory is that the increase of fuel elements eliminates the risk of reduced heat transfer in bundle geometries. This theory will be tested in the later chapters of this thesis.
CHAPTER 3  METHODOLOGY

All experimental data included in this current thesis were obtained at the State Scientific Center of Russian Federation – Institute for Physics and Power Engineering Supercritical-Test Facility in Obninsk, Russia. The set of data was obtained using a Freon-12 working fluid at similar parameters as the proposed conditions of Canadian SCWRs (using for mentioned scaling laws). The Supercritical-Pressure Test Facility STF is designed to gain further knowledge of heat transfer to supercritical water in bundles by using an alternative working fluid, Freon-12, within a wide range of parameters.

This chapter presents the details of the experimental test facility, the individual test section used in the cases examined as well as the methods that were used in the theoretical analysis.

3.1 Experimental Apparatus

The schematic diagram of the STF, Freon-12 test loop is shown in Figure 3-1 on the following page. The loop consists of a number of basic components including: two circulating pumps (5), preheater (6), two test sections (1), heat exchangers (2, 4), recuperator (3), deaerator (7), level indicator (8), two Freon-12 storage tanks (9) and filters (10). All components and piping in the test facility were made of stainless steel with an internal diameter of 50 mm (where applicable); also the unit is designed to operate up to pressure of 5.0 MPa.
The circulating pumps (5) are able to operate in series, parallel, or independently of one another. Each pump has a capacity of 20 m$^3$/h and a pressure of 1.0 MPa. The preheater (6) is manufactured as an electrically heated tube. Electrical power of 160 kW can be applied with the preheater, however, if this is insufficient for any reason heat exchangers (2) can be used for additional preheating of the coolant. The heat exchangers are supplied with either hot or cold water in a secondary loop not shown in Figure 3-1.
Figure 3-1: Schematic drawing of STF, Freon-12 Test Loop (courtesy of Dr. Kirillov, IPPE)
There are two different test channels (1) presented in the STF schematic. In most situations a single channel is used for testing while the other is being prepared for a different experiment. In cases where higher power is needed the leftmost channel is used with the heat exchangers to remove excess heat. The Freon tanks (9) are placed below the level of test loop and are also used as pressurizers during experiments with the testing loop. Additionally there are electrical heaters in the Freon tanks to serve as a first stage preheater as well as to provide pressure control in the system. Each tank has a total volume of 0.25 m$^3$.

The power supply of the test channel is provided by alternating current. The maximum power input to the test channel is 200 kW. The electrical supply of the test channel can be provided by a direct current generator of capacity with 540 kW, this is equivalent to 8 MW for water. Main parameters of the STF test facility are provided in Table 3-1.

**Table 3-1: Main experimental-setup parameters for Freon-12 heat transfer experiments.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure</td>
<td>Up to 5.0 MPa</td>
</tr>
<tr>
<td>Temperature of Freon-12</td>
<td>Up to 120°C (400°C heating elements)</td>
</tr>
<tr>
<td>Maximum mass-flow rate</td>
<td>20 + 20 m$^3$/h</td>
</tr>
<tr>
<td>Maximum pump pressure</td>
<td>1.0 + 1.0 MPa</td>
</tr>
<tr>
<td>Experimental test-section power</td>
<td>Up to 1 MW</td>
</tr>
<tr>
<td>Experimental test-section height</td>
<td>Up to 8 m</td>
</tr>
<tr>
<td>Data Acquisition System (DAS)</td>
<td>Up to 256 channels</td>
</tr>
</tbody>
</table>
### 3.2 Test Section Design

The experimental test section (Figure 3-2) consists of a housing and a seven-element bundle. The housing is a round tube, Ø40x4 mm, with welded flanges to form the test channel. Bushings are placed inside the round tube creating a hexagonal coolant flow channel with a side length of 18.3 mm. The bushings are manufactured from Al₂O₃ with high temperature treatments and also provide electric insulation between the electric heater elements (bundle) and the housing. Heated elements are stainless steel tubes of Ø9.5x0.6 mm. They are arranged in a 6 + 1 arrangement inside the hexagonal flow channel as shown in Figure 3-3. Figure 3-4 shows the thermocouple layout while Figure 3-5 gives dimensions for key parameters of the bundle and flow channel.
Figure 3-2: Schematic of Experimental test-section used by Shelegov et al. [35]
Figure 3-3: Test-section cross section with Element/Subchannel Numbering

Figure 3-4: Test-section cross section with Thermocouple Layout

Figure 3-5: Test-section cross section with Dimensions
The seven elements are kept in position through the use of three spacer grids as shown in Figure 3-6.

Figure 3-6: Spacer Grid Locations (courtesy of Dr. Kirillov, IPPE)

Dimensions of the three spacers are shown in Figure 3-7.

Figure 3-7: Spacer Grid (courtesy of Dr. Kirillov, IPPE)
Parameters of the seven-element bundle are shown below in Table 3-2. Incorporated in this table are detailed measurements of all components including flow areas of each subchannel, other geometry of the bundle and parameters of the electric heaters.

**Table 3-2: 7-Element Bundle Parameters**

<table>
<thead>
<tr>
<th>Flow area, $A_{fl}$, mm$^2$</th>
<th>Geometry of 7-element Bundle</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of subchannel</td>
<td>Value</td>
</tr>
<tr>
<td>1</td>
<td>9.45</td>
</tr>
<tr>
<td>2</td>
<td>33.1</td>
</tr>
<tr>
<td>3</td>
<td>9.45</td>
</tr>
<tr>
<td>4</td>
<td>33.1</td>
</tr>
<tr>
<td>5</td>
<td>19.8</td>
</tr>
<tr>
<td>6</td>
<td>19.8</td>
</tr>
<tr>
<td>7</td>
<td>19.8</td>
</tr>
<tr>
<td>8</td>
<td>33.1</td>
</tr>
<tr>
<td>9</td>
<td>9.45</td>
</tr>
<tr>
<td>10</td>
<td>33.1</td>
</tr>
<tr>
<td>11</td>
<td>19.8</td>
</tr>
</tbody>
</table>
The data acquisition system used for the STF facility is equipped with more than 100 measuring channels. The system includes a control panel, high-speed multiplexers, AD converter, and instruments for the measurement of temperature, pressure, flow rate, current, and voltage. The data are sampled with a frequency of 300 Hz and subsequently averaged.

To measure wall temperature on the central element two movable thermoelectric probes were used with three chromel-copel thermocouples installed at 120° with respect to each other. The design of the movable thermometric probe is shown in Figure 3-8. Two chromel-copel thermocouples were placed in both the inlet and outlet chambers of the test section. Coolant temperature at the outlet was also measured by cable chromel-copel thermocouples at the centers of subchannels 5, 7, 8, 12, and 17. Each individual thermocouple was calibrated providing an accuracy of ± 0.3 – 0.5°C for temperatures between 0°C and 300°C.
Figure 3-8: Design of movable thermometric probe to measure temperature of the central element [35].

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
The three movable thermocouples are in contact with the inner wall of the central heated element. External wall temperature is calculated using the equation below:

\[ T_{w}^{ext} = T_{w}^{int} - \frac{q_{v}d_{ext}}{2k} \left( \frac{1}{2} - \frac{d_{int}^{2}}{d_{ext}^{2} - d_{int}^{2}} \right) \ln \left( \frac{d_{ext}}{d_{int}} \right) \]  

Equation 3-1 uses the internal wall temperature measured from the thermocouple located on the inside of the stainless steel heater rod based upon conduction through a cylindrical pipe when the interior is not cooled (based upon \(-k\Delta T\)) assuming that the wall thickness is sufficient to have an effect on the heat transfer to the wall’s external surface. This equation is used to calculate the external wall temperature using the thickness of the heater rod \((d_{ext} - d_{int})\), the heat applied from electric current \((q_{v})\), and the thermal conductivity through the wall \((k)\). This equation is only valid for internal heating through a cylindrical wall.

Pressure was measured in the test section inlet and outlet using Sapfir-22DI transducers with an accuracy of ±0.25%. Each transducer was individually calibrated with an accuracy of up to ±0.5 – 1%. Pressure drop in the test channel was calculated using Sapfir-22DD transducers and confirmed using the difference between the transducers at the inlet and outlet.

Coolant flow rate was measured using orifice flow meters and a Sapfir-22DD pressure difference transducer. The flow meter was calibrated in water with the volume-time method certified by State Standard Service of Russian Federation with a measurement
accuracy of ±0.11%. The approximate relative relationship for flow rate has a relative error of ±0.4%. Supercritical Freon-12 was used as the coolant in the test section in all cases. The coolant flowed upward, entering the heated region at the bottom of the channel.

Electrical current for the heated elements was measured using calibrated shunts with an accuracy of ±0.5%. Voltages were measured using dividers with an accuracy of ±0.1%.

Power addition though the heater rods were calculated from the electrical current and voltages measured. Using the Kline and McClintock [37] method of uncertainty propagation shown in equation 3-2, electrical power was calculated to have a total relative error of no more than ±2%.

\[
W_R = \left[ \left( \frac{\partial R}{\partial x_1} w_1 \right)^2 + \left( \frac{\partial R}{\partial x_2} w_2 \right)^2 + \ldots + \left( \frac{\partial R}{\partial x_n} w_n \right)^2 \right]^{1/2}
\]  

[3-2]

Using the same method of uncertainty analysis, heat transfer coefficient has a total uncertainty of no more than 4%.

3.3 Thermalhydraulic Analysis

The thermalhydraulic analysis of the experimental data can be completed in three modules:
1) Analysis of experimental data;

2) Theoretical evaluation of HTC and heated surface temperatures using different available Nusselt correlations;

3) Comparison of experimental data to theoretical data.

All isobaric fluid parameters, such as specific heat and dynamic viscosity, utilized in calculations were extracted from REFPROP: a digital scientific and technical software database of fluid properties created by the National Institute of Standards and Technology (NIST). Microsoft Excel spreadsheets and MATLAB were used to simultaneously reference REFPROP, extracting all the necessary thermophysical properties of the coolant (Freon-12) for the purposes of completing the required calculations.

All calculations were done in 1 mm intervals along the heated length, or done at the intervals defined in the experimental data. Calculations were verified by comparing results of spreadsheet analysis to those of the MATLAB program written (See program in Appendix B), and further verified by comparing random values to hand calculated results.

For the purposes of calculating surface temperatures and HTC of the bundle and tube setup, a temperature profile of the coolant must first be established. Using the inlet temperature of coolant for each experiment, the temperature rise was calculated for each 1 mm interval along the heated length. This method is widely used in this field of study and was described in Cengel et al., and Incorpera et al. [38, 39]. The method uses heat balance to determine the temperature rise at each 1 mm interval as shown in equation 3-2.
Using the experimental coolant and heated surface temperatures, the experimental HTC was calculated using equation 3-3. The results of this analysis are used in determining where areas of DHT/IHT occur and how well 1-D correlations perform in modeling the conditions of the experiment.

\[ h_{exp} = \frac{q}{T_c - T_{bulk}} \quad [3-4] \]

The temperature profile for coolant was also used to establish two dimensionless heat transfer parameters along the heated length which are needed for theoretical correlations: Prandtl number and Reynolds number.

\[ Pr = \frac{c_p \mu}{k} \quad [3-5] \]

\[ Re = \frac{G \cdot D_{by}}{\mu} \quad [3-6] \]

These dimensionless parameters were used to calculate Nusselts number, using the one of the correlations given in chapter 2.

For some specific Nusselt number correlations, average thermal hydraulic parameters, such as average specific heat and average Prandtl number were used.

\[ \bar{c}_p = \frac{H_w - H_b}{T_w - T_b} \quad [3-7] \]
\[ \overline{Pr} = \frac{c_p \mu}{k} \]  

[3-8]

Iterations had to be used to simultaneously determine a Nusselt number and surface temperature that satisfied the scenario. These iterations were completed in MATLAB (See program in Appendix B) using a stopping criteria of ±1°C. Each Nusselt correlation was used to determine the HTC and heated length surface temperature. Equations for HTC and temperature are shown below.

\[ h_{theo} = \frac{Nu \cdot k}{D_{hy}} \]  

[3-9]

\[ T_{surface} = T_{in} + \frac{q}{h} \]  

[3-10]

Since this analysis is 1-dimensional, effects such as subchannel mixing and radiation between heating elements cannot be captured by the model. The bundle in this test dataset is reduced to tube geometry for use in the model through the calculation of the hydraulic diameter.

Figure 3-9 depicts the process leading towards the development of a new 1-D correlation. Inputs from each step to the next allow for a more accurate final correlation taking into account information discovered in each step.

Methods described in this thesis are used in the analysis of the experimental data described in the following chapters.
Figure 3-9: Flow chart representing the process towards correlation development.
CHAPTER 4 EXPERIMENTAL RESULTS

Discussed in this chapter are the details of the experimental dataset which include the different divisions of the experimental dataset. Also presented is the unprocessed data with predictions given by 1-D correlations\(^2\) as well as a correlation performance review.

4.1 Experimental Dataset

A total of 20 runs were done using the experimental setup; however this dataset can be broken down into three major categories:

Below-pseudocritical point: The Freon-12 bulk-fluid temperature was below the pseudocritical temperature along the whole heated length of the bundle.

Crossing the pseudocritical point: The Freon-12 bulk-fluid temperature was below the pseudocritical temperature at the inlet, but reached the pseudocritical temperature before the outlet of the bundle.

Above-pseudocritical point: The Freon-12 bulk-fluid temperature was above the pseudocritical temperature along the entire heated length of the bundle.

The three major categories can be further divided into smaller groups by the mass flux at which the Freon-12 working fluid is cooling the heated elements. These are:

\(^2\) 1-Dimensional correlations presented in section 2.6: Heat Transfer Correlations for use with Supercritical Fluids on page 34
o Low Mass Flux: 440 – 520 kg/m²s;

o Moderate Mass Flux: 990 – 1030 kg/m²s; and

o High Mass Flux: 1190 – 1320 kg/m²s

Tabular and graphical comparisons of all experiments acquired are shown in Table 4-1 and Figure 4-1, respectively. This data was obtained from Shelegov et al. [40] at the IPPE.

Table 4-1: Summary of Experimental Data obtained by Shelegov et al. [40]

<table>
<thead>
<tr>
<th>№</th>
<th>q [kW/m²]</th>
<th>G [kg/m²s]</th>
<th>P_in [MPa]</th>
<th>P_out [MPa]</th>
<th>T_in [°C]</th>
</tr>
</thead>
<tbody>
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<td>1</td>
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<td>4.63</td>
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</tr>
</tbody>
</table>

Bulk fluid Temperature is BELOW pseudocritical temperature
Bulk fluid Temperature is CROSSING pseudocritical temperature
Bulk fluid Temperature is ABOVE pseudocritical temperature
Using scaling laws discuss in section 2.5, Table 4-2 was created to summarize the experimental data in water equivalent values.

Table 4-2: Summary of Experimental Data with water equivalent values calculated using scaling laws from section 2.5

<table>
<thead>
<tr>
<th>№</th>
<th>$q$ [kW/m²]</th>
<th>$G$ [kg/m²s]</th>
<th>$P_{in}$ [MPa]</th>
<th>$P_{out}$ [MPa]</th>
<th>$T_{in}$ [°C]</th>
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<tr>
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<td>1228.4</td>
<td>24.9</td>
<td>24.9</td>
<td>304.3</td>
</tr>
</tbody>
</table>

Bulk fluid Temperature is BELOW pseudocritical temperature

Bulk fluid Temperature is CROSSING pseudocritical temperature

Bulk fluid Temperature is ABOVE pseudocritical temperature
Figure 4-1: Summary of Experimental Dataset (each line corresponds to a single case performed by Shelegov et al.) [40]
Figure 4-1 represents an experiment-by-experiment comparison of the parameters of each case. An individual case is characterized by a single vertical line with points at each end. The lower point of each line represents the inlet temperature into the heated section; whereas the upper most point represents the outlet temperature (both to be read with the temperature axis at the left of the graph). The blue plane signifies the pseudocritical temperature of 118.7ºC at 4.65 MPa.\(^3\) Cases move from left to right with increasing mass flux and from back to front with increasing power applied to the test section.

In total nine cases were entirely below the pseudocritical temperature. In nine cases the bulk fluid temperature crossed the pseudocritical point. For two cases the bulk fluid temperature was entirely above the pseudocritical point.

Raw data from the three central thermocouples for selected cases are in Figure 4-2, Figure 4-3, and Figure 4-4, while the full experimental data set is shown in Appendix C. The figures also show calculated bulk fluid temperature for each case as well as calculated values for HTC for each thermocouple measurement. Theoretical values for sheath temperature and HTC for seven heat transfer correlations are shown in the figures below. These correlations are explored in Section 2.6: Heat Transfer Correlations for use with Supercritical Fluids. Finally, grid spacer locations are shown on each figure to assist in determining if the spacers have an effect on heat transfer in the test section.

\(^3\) Although 4.65 MPa is not the exact pressure used in each case the corresponding pseudocritical temperature of 118.7ºC can be assumed for all cases. This value will change less than 1ºC when using exact pressure for each case in the dataset.
In general all experimental cases, with the exception of Case 20, were completed successfully. During the experimental test of case 20 there was a technical issue with the experimental setup and the complete (0-1 m) set of data could not be recorded. For that reason, results for Case 20 were limited to data recorded at axial locations between 0 m and 0.45 m.
7-Element Bundle; Vertical; Upward flow
R-12: $P_{in} = 4.64$ MPa, $T_{in} = 74^\circ$C, $H_{PC} = 353$ kJ/kg
$q = 67.1$ kW/m$^2$, $G = 517$ kg/m$^2$s, $D_{hy} = 4.7$ mm

**Figure 4-2:** Case 5 with predictions from 7 correlations

*Correlations Identified in section 2.6*
7-Element Bundle; Vertical; Upward flow

R-12: $P_{in} = 4.64$ MPa, $T_{in} = 100^\circ C$, $H_{PC} = 353$ kJ/kg

$q = 96.4$ kW/m$^2$, $G = 1003$ kg/m$^2$s, $D_{hy} = 4.7$ mm

Figure 4-3: Case 14 with predictions from 7 correlations

*Correlations Identified in section 2.6
7-Element Bundle; Vertical; Upward flow

R-12: $P_{\text{in}} = 4.63$ MPa, $T_{\text{in}} = 119^\circ$C

$q = 33.5$ kW/m$^2$, $G = 517$ kg/m$^2$s, $D_{\text{hy}} = 4.7$ mm

<table>
<thead>
<tr>
<th>Temperature, $^\circ$C</th>
<th>HT$C$, kW/m$^2$K</th>
</tr>
</thead>
<tbody>
<tr>
<td>110</td>
<td>0.5</td>
</tr>
<tr>
<td>120</td>
<td>1.0</td>
</tr>
<tr>
<td>130</td>
<td>1.5</td>
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<tr>
<td>140</td>
<td>2.0</td>
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<tr>
<td>150</td>
<td>2.5</td>
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<tr>
<td>160</td>
<td>3.0</td>
</tr>
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<td>170</td>
<td>3.5</td>
</tr>
<tr>
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</tr>
<tr>
<td>190</td>
<td>4.5</td>
</tr>
<tr>
<td>200</td>
<td>5.0</td>
</tr>
</tbody>
</table>

Bulk Fluid Enthalpy, kJ/kg

355 360 365 370 375 380 385 390 395

Figure 4-4: Case 8 with predictions from 7 correlations

*Correlations Identified in section 2.6
In the cases explored DHT was observed in all but three. In these cases (1, 3, and 4) only normal or improved heat transfer regimes were observed. The three cases were primarily conducted at low heat flux and mass flux with inlet temperatures less than 90°C. In all of these cases the bulk-fluid temperature was below the pseudocritical point during the entire test. More importantly thermocouple measurements at the wall of the central element indicate that fluid temperatures at the wall were all below the pseudocritical point.

Cases in which a single area of DHT was observed include Cases: 7–15, and 18–20. This phenomenon can be observed in Figure 4-3 and Figure 4-4 with areas of high wall temperature (and low HTC) values nearing the outlet of the heated region. These sets of data contain cases with high, moderate, and low heat and mass fluxes as well as include three ranges of bulk-fluid temperature. Fluid temperatures at the wall of the central element were crossing or above the pseudocritical point in all cases experiencing DHT. In general the area of DHT was experienced predominantly towards the end of the heat section. In most cases this was between 0.8 m and 1 m (axial location). This general location along the heated length includes the final spacer region. The spacer could be a cause of the DHT regime if it is restricting subchannel mixing and causing flow in this region to become less turbulent.

In the remaining five cases (Cases 2, 5, 6, 16, and 17) two areas of DHT were observed clearly observed in Figure 4-2. The first area of DHT in all five cases developed at approximately 0.2 m after the inlet to the heated section. This location corresponds to the
location immediately after the first spacer in the test section. The second area of DHT in the cases was similar to the other twelve cases experiencing DHT, developing near the end of the heater section near the location of the final spacer in the heated channel.

Preliminary analysis of this data shows that the spacer grids could have a large effect on HTC. This effect was confirmed in 10 out of 20 cases, although in some cases the effect was minimal. The presence of spacers could influence more than 10 cases however the effect could be masked by other phenomena such as DHT/IHT. Occurrences of spacer effects can be visualized in Figure 4-3 and Figure 4-4 at an axial location of 0.5 m as there are areas of reduced wall temperature in the immediate vicinity. In general the effect was only observed in cases where mass flux was over 515 kg/m²s. Also the phenomena effect was greater as mass flux increased however over 1200 kg/m²s the amount of heat transfer improvement was less. The effects of the spacers have been observed to either enhance or deteriorate heat transfer depending on specific parameters of the individual test. This has previously been observed by Lim et al. in finned fuel bundles cooled with R-134a using real-time neutron radiography [41].

4.2 Assessment of Current 1-Dimensional Correlations

Assessment of correlations was performed to determine if current 1-D correlations are accurate enough to provide sufficient confidence in their results to aid in the research and development of a SCWR fuel channel. To determine correlation performance, HTC calculated with the correlation was graphed versus the experimentally calculated HTC.
Graphs for the HTC calculated with the seven correlations explored (Mokry et al., Bishop et al., Swenson et al., Gorban et al., Gupta et al., Dyadyakin and Popov, and Jackson et al.) versus HTC calculated experimentally are shown in Figure 4-5 – Figure 4-11. In the following figures reference lines are shown for 0%, ±25% and ±50%. The reference lines aid in determining general patterns for each correlation’s performance and how well each correlation follows the desired trends. For the purposes of this thesis HTC calculations were grouped by temperature to determine if this is the cause of correlation not being able to predict heat transfer. Many other sub-groups could be used such as: mass flux, heat flux, or pressure drop.

Correlation of Mokry et al.:

The correlation of Mokry et al. could not predict experimental data within ±50%. This correlation also did not capture the trends for the data as shown in Figure 4-5. Individual cases appear horizontally across the figure demonstrating the scattering in predictions relative to the experimentally calculated HTC. This proves that this correlation is not useful in predicting experimental heat transfer data in bundles. Zahlan et al. [42] reports that the correlation of Mokry et al. performed the best for a number of published correlations for supercritical heat transfer; however this study did not take into account heat transfer in bundles.

The correlation of Mokry et al. is based on a very large set of data in vertical bare tubes. This correlation is highly specialized to bare tubes and the trends/phenomena associated with bundles are not captured by the correlation.
Currently it is unclear what the causes of these phenomena are as it could be a flow effect, fluid property change, or a combination of both.

Correlation of Bishop et al.:

Since the correlation of Mokry et al. is a modified correlation of Bishop et al.; the correlation of Bishop et al. presents similar trends to that of Mokry et al. There are high amounts of scattering (outside ±50%) with the predictions given by this correlation. The correlation of Bishop et al. captured more trends than the correlation of Mokry et al. since it is not as highly specialized for bare tubes; as shown in Figure 4-6. Although it is better than the correlation of Mokry et al. with respect to the trends captured it is not sufficient to use for further investigation into heat transfer for bundles in SCWR applications.

Correlation of Swenson et al.:

The correlation of Swenson et al. consistently over predicts HTC for the data provided, as shown in Figure 4-7. In some cases this could be as high as +100%. In general this correlation showed improvements in capturing the appropriate trends however it would need large amounts of modification to reduce the scattering of the predictions and align the trends with the 0% reference line.

Correlation of Gorban et al.:

The correlation of Gorban et al. consistently under predicted the optimal result by greater than 50%, as shown in Figure 4-8. Trends were also not captured showing that this correlation is not adequate for further studies in SCWR applications.
Correlation of Gupta et al.:

This correlation is constructed in a similar for that of the correlation of Swenson et al.. Similar to the correlation of Swenson et al. some trends are capture in the predictions however highly scattered results (greater than $\pm 50\%$ as shown in Figure 4-9). These results are not accurate enough to use for more complex geometries or for design purposes in fuel channel designs.

Correlation of Dyadyakin and Popov:

The correlation of Dyadyakin and Popov is the only Nusselt Correlation that was developed with bundle data cooled with supercritical water. Even though it is designed for use with a similar bundle, predictions were highly scattered with no evident trends immergeing (Figure 4-10). This correlation is inadequate for design purposes in SCWRs.

Correlation of Jackson et al.:

Lastly, the correlation of Jackson et al. follows the same pattern as the other correlations examined as shown in Figure 4-11. Little to no trending is evident and large amounts of scattering are present. Predictions using this correlation were outside $\pm 50\%$ of the experimentally calculated HTC values.
Figure 4-5: Experimental Heat Transfer Coefficient compared to predictions from the Mokry et al. correlation.
Figure 4-6: Experimental Heat Transfer Coefficient compared to predictions from the Bishop et al. correlation
Figure 4-7: Experimental Heat Transfer Coefficient compared to predictions from the Swenson et al. correlation
Figure 4-8: Experimental Heat Transfer Coefficient compared to predictions from the Gorban et al. correlation
Figure 4-9: Experimental Heat Transfer Coefficient compared to predictions from the Gupta et al. correlation
Figure 4-10: Experimental Heat Transfer Coefficient compared to predictions from the Dyadyakin and Popov correlation
Figure 4-11: Experimental Heat Transfer Coefficient compared to predictions from the Jackson et al. correlation
In general, no single existing Nusselt correlation is able to accurately predict the experimental data for all cases. The correlations were not able to come within ± 50% of the experimental heat transfer coefficient. For specific cases some correlations were able to closely approximate some trends for heat transfer coefficient in the normal regime, however deteriorated/improved heat transfer regimes could not be predicted. It can be concluded that no single 1-D correlation can be used for SCWR design purposes. Although Swenson et al. and Gupta et al. were able to capture some trends present in the experimental data the level of accuracy is not adequate.
To determine if the provided dataset is consistent or not, a parametric analysis was performed. Cases were compared with each other based on bulk-fluid temperature. Axial length was manually adjusted for each case using corresponding inlet and outlet temperatures. For example, bulk-fluid inlet and outlet temperatures of Case 15 are 73°C and 86.3°C, respectively. Case 1 has an inlet temperature of 86.1°C; therefore this case was shifted to align the outlet temperature of Case 15 with the inlet temperature of Case 1. To clarify, axial locations of Case 15 are placed from 0–1000mm while Case 1 is placed at axial locations of 1000–2000mm. This approximation enables Case 15 and Case 1 to be treated as a single set of data simulating a total heated region of 2000mm.

Shown in Figure 5-1 is a comparison of bulk-fluid temperatures for all cases. The ratio of heat flux to mass flux \( \frac{q}{G} \) proved to be significant. As the slope of the bulk-temperature increased, this ratio increased as well which is expected since temperature is increasing at a faster rate as more energy is deposited into the working fluid compared to the flow rate of the fluid. Consistency in the data demonstrates that the experiments were conducted properly and show expected results with the given operating parameters (heat flux, mass flux, pressure, and bulk-fluid temperature).

Two clearly identifiable sub-sets of data are evident where bulk-fluid temperatures align from the inlet to well above the pseudocritical point. As shown in Figure 5-2, subset #1 is composed of Cases 10, 19, 20, 7, and 8 (listed in order of \( \frac{q}{G} \)) and the subset #2 includes Cases 11, 17, 9, and 14. These sub-sets were used to check the consistency of sheath temperatures recorded on the central element.
Figure 5-1: Bulk-fluid Temperature Trend Analysis of Bulk-Fluid Temperature
Figure 5-2: Selected cases for sheath temperature consistency analysis.
First, Subset #1 was examined to check the consistency of sheath temperatures. Bulk-fluid temperature was plotted in a similar fashion to Figure 5-1 with the addition of average sheath temperatures from the 3 thermocouples on the central element. Trends emerge in the sheath temperatures from Cases 10, 7, and 8, however Cases 19, and 20 do not follow the same pattern as shown in Figure 5-3. This is an odd result as heat flux-to-mass flux ratio for each case is approximately the same.

Subset #2 was analyzed by the same method. A similar trend was observed with Cases 11, 9 and 14; with sheath temperatures for Case 17 being higher than the other three.

Even though the heat flux-to-mass flux ratio is approximately the same in each subset, there must be a unique phenomena occurring when mass flux exceeds approximately 1200 kg/m²s as this is the only similarity between Cases 17, 19 and 20. From this analysis is it clear that two unique sets of data are included in these 20 cases. The first being where mass flux is less than 1200 kg/m²s and the second where mass flux is greater than 1200 kg/m²s. Since the heat flux to mass flux ratio is the same in each case there is also the possibility that there is a contribution from high heat fluxes causing surface phenomena on the heated element.
Figure 5-3: Sheath Temperature Trend Analysis for Subset #1

Figure 5-4: Sheath Temperature Trend Analysis for Subset #2
Using Figure 5-3 and Figure 5-4 as a base, sheath temperature predictions from the 1-D correlations were plotted to determine how well they predicted the temperature the different family of curves. While most correlations were somewhere in the middle of the two subsets (over-predicting when $G<1200$ kg/m$^2$s, and under-predicting when $G>1200$ kg/m$^2$s), the correlation of Gupta et al. and Swenson et al. correlation captured the trends very well when mass flux was less than 1200 kg/m$^2$s. This is evident in Figures 5–5 and 5–6.

To confirm the visual evidence, $HTC_{exp}$ was compared to $HTC_{theo}$ for cases with mass fluxes less than 1200 kg/m$^2$s similar to the method in Chapter 4. The Gupta et al. correlation and Swenson et al correlation were re-evaluated since they showed the best agreement. The Dyadyakin and Popov correlation was also re-evaluated since it was the only correlation developed in bundles. As shown in Figure 5-7, Figure 5-8, and Figure 5-9, error is greatly reduced with all three correlations. The significance of this is that it is not only the heat flux to mass flux ratio that affects heat transfer, however, both individually induce fluid phenomena that influence heat transfer and heat transfer and its deterioration.
Figure 5-5: Re-evaluation of 1-D correlations with cases 7, 8, 10, 19, and 20.
Figure 5-6: Re-evaluation of 1-D correlations with cases 9, 11, 14, and 17.
Figure 5-7: Re-evaluation of the Swenson et al. Correlation with the removal of DHT and cases with mass flux above 1200 kg/m²s
Figure 5-8: Re-evaluation of the Gupta et al. Correlation with the removal of DHT and cases with mass flux above 1200 kg/m²s
Figure 5-9: Re-evaluation of the Dyadyakin and Popov Correlation with the removal of DHT and cases with mass flux above 1200 kg/m²s
Even when cases with mass flux greater than 1200 kg/m$^2$s were isolated from the analysis no current correlation was able to capture the trends adequately to allow the use for modeling heat transfer under supercritical conditions.
CHAPTER 6  Updated Correlation

No current correlation was able to replicate the data for all the experiments performed. The majority of newer correlations (from approximately 1990-present) are highly specialized to the data for which they were created, (in most cases bare tubes) that they do not produce accurate results for datasets with slight changes to geometries or operating conditions.

Through analysis and consideration, it is clear that there are needs for a reliable, accurate and wide range supercritical fluid heat transfer correlation for use with bundles for:

1. thermalhydraulics calculations of supercritical-fluid-cooled fuel bundles as a conservative approach in relation to SCWRs;

2. the verification of computer codes for SCWR core thermalhydraulics; and

3. the verification of scaling parameters between water and modeling fluids (CO₂, refrigerants, etc.).

From results of Chapter 5, only cases which were shown to follow similar trends were considered for correlation development. Using the remaining cases would skew the results of the correlation and would eliminate all data that could be used for correlation verification.
6.1 Dimensional Analysis

It is established that the most common form of empirical correlations is:

\[ y = x \cdot A^a \cdot B^b \cdots N^n \]  \[\text{[6-1]}\]

where capital letter denotes various parameters that affect heat transfer and lower case letter represent various coefficients and exponents.

To obtain a general empirical correlation, first the correct form (with specific parameters) must be found. Dimensional analysis was conducted to finalize this form. It is known that HTC is a dependant variable that is affected by fluid parameters such as velocity, hydraulic diameter and thermophysical fluid properties. A review of trends in correlating heat transfer data at supercritical pressures determined that there are nine primary parameters that affect heat transfer [4]. These parameters are shown in Table 6-1.

**Table 6-1: Various Parameters of Heat Transfer**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>SI Units</th>
<th>Dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>HTC</td>
<td>Heat Transfer Coefficient</td>
<td>W / m² · K</td>
<td>M T⁻³ K⁻¹</td>
</tr>
<tr>
<td>(D_{hy})</td>
<td>Hydraulic Diameter</td>
<td>m</td>
<td>L</td>
</tr>
<tr>
<td>(\rho_b)</td>
<td>Density of the Bulk Fluid</td>
<td>kg / m³</td>
<td>M L⁻³</td>
</tr>
<tr>
<td>(\rho_w)</td>
<td>Density of the Fluid at the Wall</td>
<td>kg / m³</td>
<td>M L⁻³</td>
</tr>
<tr>
<td>(\mu_b)</td>
<td>Dynamic Viscosity of the Bulk Fluid</td>
<td>Pa · s</td>
<td>M L⁻¹ T¹</td>
</tr>
<tr>
<td>(\mu_w)</td>
<td>Dynamic Viscosity of the Fluid at the Wall</td>
<td>Pa · s</td>
<td>M L⁻¹ T¹</td>
</tr>
<tr>
<td>(k_b)</td>
<td>Thermal Conductivity of the Bulk Fluid</td>
<td>W / m · K</td>
<td>M L T⁻³ K⁻¹</td>
</tr>
<tr>
<td>(k_w)</td>
<td>Thermal Conductivity of the Fluid at the Wall</td>
<td>W / m · K</td>
<td>M L T⁻³ K⁻¹</td>
</tr>
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</table>
Using the Buckingham $\Pi$-theorem, dimensionless $\Pi$ terms are found and are used in the development of the correlation. The theorem is based on dimensional homogeneity, in which $\Pi$-terms can be formed from the desired parameters, in this case, parameters found in Table 6-1. The following expression was produced for HTCs as a function of the identified heat-transfer parameters:

$$\text{HTC} = f(D_{hy}, \rho_b, \rho_w, \mu_b, \mu_w, k_b, k_w, c_p, V)$$ \[6-2\]

Each parameter is broken into four primary dimensions; mass (M), length (L), time (T) and temperature (K). Six unique dimensionless $\Pi$-terms, listed in Table 6-2, were created from the original nine parameters.

**Table 6-2: $\Pi$-terms of the Empirical Correlation**

<table>
<thead>
<tr>
<th>$\Pi$-terms</th>
<th>Dimensionless Group</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Pi_1$</td>
<td>$\frac{\text{HTC} \cdot D}{k_b}$</td>
<td>Nusselt Number</td>
</tr>
<tr>
<td>$\Pi_2$</td>
<td>$\frac{\rho \cdot V \cdot D}{\mu_b}$</td>
<td>Reynolds Number</td>
</tr>
<tr>
<td>$\Pi_3$</td>
<td>$\frac{c_p \cdot \mu_b}{k_b}$</td>
<td>Prandtl Number</td>
</tr>
<tr>
<td>$\Pi_4$</td>
<td>$\frac{c_{pw}}{c_{pb}}$</td>
<td>Specific Heat Ratio</td>
</tr>
<tr>
<td>$\Pi_5$</td>
<td>$\frac{\rho_w}{\rho_b}$</td>
<td>Density Ratio</td>
</tr>
<tr>
<td>$\Pi_6$</td>
<td>$\frac{k_w}{k_b}$</td>
<td>Thermal Conductivity Ratio</td>
</tr>
<tr>
<td>$\Pi_7$</td>
<td>$\frac{\mu_w}{\mu_b}$</td>
<td>Viscosity Ratio</td>
</tr>
</tbody>
</table>
The resulting relationship based on the Buckingham $\Pi$-theorem is as follows:

$$\Pi_1 = f (\Pi_2, \Pi_3, \Pi_4, \Pi_5, \Pi_6, \Pi_7)$$  \[6-3\]

or

$$Nu_b = C \cdot Re_b^{n_1} \cdot Pr_b^{n_2} \cdot \left(\frac{c_{pw}}{c_{pb}}\right)^{n_3} \cdot \left(\frac{\rho_w}{\rho_b}\right)^{n_4} \cdot \left(\frac{k_w}{k_b}\right)^{n_5} \cdot \left(\frac{\mu_w}{\mu_b}\right)^{n_6}$$  \[6-4\]

This equation provides a starting point for the development of a correlation, where HTC can be calculated from the following equation:

$$HTC = \frac{Nu \cdot k_b}{D_{hy}}$$  \[6-5\]

A number of correlations at supercritical pressures use an averaged specific heat and Prandtl number. As previously discussed, significant peaks in thermophysical properties occur within the pseudocritical range. Thus, averaging specific heat and Prandtl number over the ranges accounts for these thermophysical properties variations.

The average Prandtl number ($\overline{Pr}$) and average specific heat are given by the equations below:

$$\overline{Pr} = \frac{\mu_b \cdot \overline{c_p}}{k_b}$$  \[6-6\]

$$\overline{c_p} = \frac{H_w - H_b}{T_w - T_b}$$  \[6-7\]

Since the Swenson et al. and Gupta et al. correlations offered the best predictions for HTC, the same model was chosen for the development of the correlation. The main difference from these correlations to the other five is that some fluid properties, such as Prandtl number, were calculated using fluid temperature at the wall of the heated element.
6.2 Manual Iterations

In order to determine the coefficients in the general correlation relationship, manual iterations were performed. The experimental dataset, with removed DHT was compiled into an MS Excel spreadsheet. The required thermophysical properties data were retrieved using NIST (2002) software. Scatter plots were then created and analyzed using linear regression on a log-log scale. The resulting slope of this regression line provided the exponent for the associated scatter plot.

The first step of the iterative process was performed using the first two $\Pi$-terms.

**Manual Iteration Step 1:** $Nu_b$ vs. $Re_b$

In Figure 6-1 the scatter plot for the first iteration is shown.
The slope of the linear regression line (in this case 0.4042) becomes the exponent for the $\text{Re}_b$ term in the correlation. The statistical R-squared value (.4590) indicates how well the regression was able to approximate the data. In this case the R-squared value shows that linear regression was able to capture the trends in the data but not in a highly accurate manor.

The next step was to determine the exponent for the Prandtl number at the wall through the creation of a second scatter plot. At this point, the effect of $\text{Re}_b$ can be accounted for in this second plot.
Manual Iteration Step 2: \( \frac{N_{ub}}{Re_b^{0.4024}} \text{ vs. } Pr_w \)

Similar to the first plot, the second plot uses \( \Pi \)-terms, \( \Pi_1 \) and \( \Pi_2 \) graphed with respect to \( \Pi_3 \). Once again, linear regression is used to determine the exponent of the \( \Pi_3 \) term. The scatter plot used for the second iteration is shown in Figure 6-2. Displayed in the scatter plot is the slope of the linear regression (exponent for the effect of Prandtl number) and the r-squared value.

![Figure 6-2: Scatter Plot for \( Pr_w \) versus \( \frac{N_{ub}}{Re_b^{0.4024}} \)](image_url)

Slope = 1.096

\( r^2 = 0.4646 \)
Manual Iteration Step 3:

\[
\frac{N_{ub}}{Re_b^{0.4042}Pr_w^{1.096}} \nu S \cdot \frac{c_{p,w}}{c_{p,b}}
\]

The third step was to obtain the exponent for the ratio of specific heat of the coolant at the wall and the bulk fluid temperatures Figure 6-3. The effects of Reynolds number and Prandtl number were included in this step. The resulting slope was determined to be 0.2006.

![Figure 6-3: Scatter Plot for \( \frac{c_{p,w}}{c_{p,b}} \) versus \( \frac{N_{ub}}{Re_b^{0.4042}Pr_w^{1.096}} \nu S \cdot \frac{c_{p,w}}{c_{p,b}} \)]
The remaining steps were completed using the same technique. For each subsequent iterative step the next $\Pi$-term was added to find an approximate exponent. Manual Iterations 4 through 6 are shown below. As shown in Figure 6-4, Figure 6-5, and Figure 6-6 there are no trends present using the ratios for density, dynamic viscosity or thermal conductivity in the correlation. Also the r-squared values are very low. For these reasons these fluid property ratios were not used in the remaining manual iteration steps.

Manual Iteration Step 4:

$$\frac{N_{ub}}{Re_b^{0.4042}Pr_w^{1.096}(\frac{c_{p,w}}{c_{p,b}})^{0.2006}} \text{ vs. } \frac{\rho_b}{\rho_w}$$
Manual Iteration Step 5:

\[
\frac{N_{ub}}{Re_b^{0.4042} Pr_w^{1.096}} \left( \frac{c_{pw}}{c_{pb}} \right)^{0.2006} \text{ vs. } \frac{\mu_w}{\mu_b}
\]

Figure 6-5: Scatter Plot for \( \frac{\mu_w}{\mu_b} \) versus \( \frac{N_{ub}}{Re_b^{0.4042} Pr_w^{1.096}} \left( \frac{c_{pw}}{c_{pb}} \right)^{0.2006} \)

Slope = -0.1149

\( r^2 = 0.1892 \)
Manual Iteration Step 6:

\[
\frac{Nu_b}{Re_b^{0.4042} Pr_w^{1.096} \left( \frac{c_p w}{c_p b} \right)^{0.2006}} \quad \text{v.s.} \quad \frac{k_b}{k_w}
\]

Figure 6-6: Scatter Plot for \( \frac{k_b}{k_w} \) versus \( \frac{Nu_b}{Re_b^{0.4042} Pr_w^{1.096} \left( \frac{c_p w}{c_p b} \right)^{0.2006}} \)

Slope = -0.3758

\( r^2 = 0.2296 \)
The initial iteration leaves the following empirical correlation for the data:

\[ \text{Nu}_b = 0.075 \text{Re}_b^{0.4024} \text{Pr}_w^{1.096} \left( \frac{c_{pw}}{c_{pb}} \right)^{0.2006} \]

A number of additional \( \Pi \)-Terms were also considered to see if any trends would emerge. The added terms were the Grashof number and Froude number. The Grashof number takes into account the fluids buoyant forces which could affect heat transfer. Froude number is a measure of the gravitational effect. Figures for these additional terms were not included in this thesis however a summary of \( R^2 \) values for each step is shown in Table 6-3.

Table 6-3: Summary of Manual Iteration including exponents and \( R^2 \) Values

<table>
<thead>
<tr>
<th>( \Pi )-Term</th>
<th>Slope/Exponent</th>
<th>( R^2 )-Squared Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>( Re_b )</strong></td>
<td>0.40</td>
<td>0.46</td>
</tr>
<tr>
<td><strong>( Pr_w )</strong></td>
<td>1.10</td>
<td>0.47</td>
</tr>
<tr>
<td>( \frac{c_{pw}}{c_{pb}} )</td>
<td>0.20</td>
<td>0.34</td>
</tr>
<tr>
<td>( \frac{k_w}{k_b} )</td>
<td>-0.38</td>
<td>0.23</td>
</tr>
<tr>
<td>( \frac{\mu_w}{\mu_b} )</td>
<td>-0.12</td>
<td>0.19</td>
</tr>
<tr>
<td>( \frac{\rho_w}{\rho_b} )</td>
<td>-0.16</td>
<td>0.23</td>
</tr>
<tr>
<td><strong>( Gr )</strong></td>
<td>0.018</td>
<td>&lt;0.02</td>
</tr>
<tr>
<td><strong>( Fr )</strong></td>
<td>0.13</td>
<td>&lt;0.02</td>
</tr>
</tbody>
</table>
A second manual iteration was used to converge on more steady values.

**Manual Iteration 2 – Step 1:**

\[ \frac{N_u}{P_r^{1.096} \left( \frac{c_{p, w}}{c_{p, b}} \right)^{0.2006}} \text{ vs. } Re_b \]

![Figure 6-7: Scatter Plot for Re_b versus \( \frac{N_u}{P_r^{1.096} \left( \frac{c_{p, w}}{c_{p, b}} \right)^{0.2006}} \)](image.png)

Slope = 0.3098

\[ r^2 = 0.4796 \]
Manual Iteration 2 – Step 2:

\[
\frac{Nu_b}{Re_b^{0.3098}(\frac{c_{p,w}}{c_{p,b}})^{0.2006}} \text{ vs } Pr_b
\]

Figure 6-8: Scatter Plot for Pr_w versus 
\[
\frac{Nu_b}{Re_b^{0.4042}(\frac{c_{p,w}}{c_{p,b}})^{0.2006}}
\]

Slope = 1.131
\[r^2 = 0.6210\]
Manual Iteration 2 – Step 3:

$$\frac{Nu_b}{Re_b^{0.3098}Pr_w^{1.131}} \text{ vs } \frac{c_{p,w}}{c_{p,b}}$$

Figure 6-9: Scatter Plot for $\frac{c_{p,w}}{c_{p,b}}$ versus $\frac{Nu_b}{Re_b^{0.3098}Pr_w^{1.131}}$
The second iteration leaves the following empirical correlation for the data:

\[ \text{Nu}_b = 0.696 \text{Re}_b^{0.31} \text{Pr}_w^{1.13} \left( \frac{c_{pw}}{c_{pb}} \right)^{0.17} \]

A summary of R-squared values for each step is shown in Table 6-3.

<table>
<thead>
<tr>
<th>Π-Term</th>
<th>Slope/Exponent</th>
<th>R-Squared Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Re_b</td>
<td>0.31</td>
<td>0.48</td>
</tr>
<tr>
<td>Pr_w</td>
<td>1.13</td>
<td>0.62</td>
</tr>
<tr>
<td>( \frac{c_{pw}}{c_{pb}} )</td>
<td>0.17</td>
<td>0.28</td>
</tr>
</tbody>
</table>

To continue the iterative process, the dynamic fit wizard of Sigmaplot was used. This program took a total of 34 iterations to converge on the following correlation with a tolerance of 1e\(^{-1}\) and a total r\(^2\) value of 0.607.

\[ \text{Nu}_b = 9.23 \text{Re}_b^{0.3} \text{Pr}_w^{1.1} \left( \frac{c_{pw}}{c_{pb}} \right)^{0.165} \]

This correlation is valid for the normal heat transfer regime with Freon-12 mass fluxes less than 1200 kg/m\(^2\)s and temperatures in the range of 70–140°C.

Figure 6-10 and Figure 6-11 show the newly created correlation compared to 2 alternative cases to verify that the correlation can more accurately predict heat transfer.
7-Element Bundle; Vertical; Upward flow
R-12: $P_{in} = 4.64$ MPa, $T_{in} = 112^\circ$C
$q = 33.4$ kW/m$^2$, $G = 517$ kg/m$^2$s, $D_{hy} = 4.7$ mm

\[ H_{PC} = 353 \text{ kJ/kg} \]

Figure 6-10: Case 7 with predictions from the modified correlation
7-Element Bundle; Vertical; Upward flow
R-12: \( P_{in} = 4.64 \) MPa, \( T_{in} = 100^\circ C \), \( H_{PC} = 353 \) kJ/kg
\( q = 96.4 \) kW/m², \( G = 1003 \) kg/m²s, \( D_{hy} = 4.7 \) mm

Figure 6-11: Case 14 with predictions from the modified correlation
As shown in Figure 6-10 and Figure 6-11 this new correlation fits the data for a number of cases fairly well. This is expected as the correlation was developed from this data. To further verify and validate the correlation, it must be used to assess an independent dataset.
20 cases of experimental data were collected at the IPPE in Obninsk, Russia and were analyzed with respect to heat transfer as a preliminary study towards understanding fluid phenomena at supercritical conditions in the support of SCWR development.

- Deteriorated Heat Transfer was observed in 17 of 20 cases proving that DHT can occur in bundles cooled with supercritical fluids. This phenomenon has previously only occurred in tube geometries and has not been encountered in studies conducted with bundles.

- A parametric analysis has been conducted on the experimental dataset confirming that regardless of the heat flux-to-mass flux ratio DHT can occur in cases with mass fluxes higher than 1200 kg/m²s. Also there is a dramatic increase of sheath temperatures when mass fluxes are above this point even in areas where DHT does not seem to be present indicating that a new family of curves is present at mass fluxes greater than 1200 kg/m²s.

- Current 1-Dimensional correlations are inadequate for design purposes in support of SCWRs. No current correlation can predict this heat transfer data within ±50%. When all outliers, areas of DHT, and cases where mass flux was higher than 1200 kg/m²s were removed, correlation performance improved however not to the point where accuracy was within ±50%.
• A new 1-D correlation was developed using the dataset provide by the IPPE. Initial signs show that this correlation will perform better than current 1-D correlations since it has been designed specifically for use with bundles cooled with supercritical fluids. This is the first correlation developed in bundles geometries since Dyadyakin and Popov in 1977.

• Analysis of this data through the development of a new correlation show that in bundle geometries Reynolds number has a lesser effect than tube data has previously indicated. Fluid properties such as Prandtl Number have a greater effect on heat transfer as there are many property changes occurring surrounding the pseudocritical point.
Future work should also include the collection of new heat transfer data with bundles cooled with supercritical fluids. This would enable:

- the verification of scaling laws,
- verification of datasets/correlations such as the one explored in this thesis,
- the determination of the cause of DHT/IHT and

Further investigation of the influence of high mass flux on heat transfer characteristics would be useful in other experimental work as well as when conducting future experiments on supercritical fluids. The cause of unique phenomena when mass flux is greater than 1200 kg/m²s needs to be determined as this is critical in the understanding of how heat transfer is governed in supercritical fluids.


Technology, Oshawa, Canada, 2009.


[28] N. M. Schnurr, V. S. Sastry and A. B. Shapiro, "A numerical analysis of heat


[37] S. J. Kline and F. A. McClintock, "Describing uncertainties in single sample


10.1 Appendix A: Issues in NIST RefPROP

While trying to determine if various fluids (Water, R12, R22, R134a, and CO₂) were scalable with regards to specific heat, a number of issues arose from the values of specific heat from NIST REFPROP. The maximum value for specific heat at pressure increments of 1 kPa were taken from NIST via MATLAB to develop an accurate representation of specific heat at pressures surrounding the pseudocritical point. For each pressure, the maximum value of specific heat was determined using a large temperature array over the entire range of available in NIST in 0.1K increments.

The values from MATLAB were compared directly from values in NIST to ensure that there was no error in the extraction of data through the MATLAB program. The values from NIST seem to be unrealistic and physically impossible. For each of the five fluids examined a similar trend was found. When calculating specific heat at specific temperatures and pressures, there are many peaks and oscillations surrounding the pseudocritical point which seem to be physically impossible. In the case of water at the supercritical point, three, 1 kPa increases cause a peak from 3861.2155 kJ/kg-K to 38396.0610 kJ/kg-K to 3261.4867 kJ/kg-K. Pressure increases of 1kPa could not cause changes in the specific heat of up to 35134.5743 kJ/kg-K.
Either the method that NIST used to retrieve data for specific heat was incorrect or was done through inaccurate interpolation between data points, as small increments for pressure reveal oscillations that are not physically possible. To further investigate specific heat issues, one parameter remained constant while the increment of the other was decreased. In the case of constant temperature increments the increment remained at 0.01K while the pressure increments changed. The increments which were examined were: 10 kPa, 1 kPa, 0.5 kPa, 0.1 kPa, and 0.05 kPa. Pressure increments of 0.01 kPa were also examined however, nearing the critical point the following error message occurred:

??? Error using ==> refpropm
[TPFLSH error 214] vapor density iteration did not converge: [TPRHO error 203] vapor iteration has not converged for T = 647.09 K, P = 22.062 MPa, rho (last guess) = 16.981 mol/L,
x (mol frac) = 1.00000

Error in ==> GRAD_cp_compare at 32
   cp(j,i) = refpropm('C', 'T', temp_calc(i), 'P', pressure(j), 'water');

Figure 10-1 shows the oscillations with varying pressure increments. As the pressure increment decreases the amount of oscillations increase.
The opposite occurs when holding the pressure increment constant and varying the temperature increment. The pressure increment remained at a constant 1kPa while the temperature increments were 1 K, 0.5 K, 0.1 K, 0.01 K, 0.001 K, 0.0001 K, 0.0005 K. As the temperature increment decreased the amount of oscillations also decreased as shown in Figure 10-2. Other properties such as density, viscosity, thermal conductivity, and enthalpy were extracted from NIST nearing the critical point. This data is shown in Figure 10-3.

**Figure 10-1: Varying pressure increment**
Figure 10-2: Varying Temperature Increment

Figure 10-3: Other properties surrounding the critical point
Data from NIST was also extracted surrounding 24MPa and 25MPa to determine if the work of others would be affected by the oscillations. Other properties were also extracted such as density, thermal conductivity, enthalpy, and viscosity to determine if these properties affect the work of others. Figure 10-4, Figure 10-5 and Figure 10-6 Figure 10-7 show specific heat as well as the other properties for 24 MPa and 25 MPa, respectively.

Figure 10-4: 24 MPa, specific heat
Figure 10-5: 24 MPa, other properties

Figure 10-6: 25 MPa, specific heat
Although there appear to be oscillations with the other properties examined the differences between the peaks and the valleys are not great enough to cause major issues in other work.

There seems to only be inconsistencies in NIST immediately surrounding the critical point of the fluid as surrounding 24 and 25 MPa there is a nearly linear relationship between pressure and specific heat. Therefore NIST seems to be reliable at all pressures except for immediately surrounding the critical pressure.
Varying Fluid – 1 kPa, 0.1 K

Figure 10-8: Water - max Cp vs. pressure
Figure 10-9: R134a - max Cp vs. pressure

Figure 10-10: R12 - max Cp vs. pressure
Figure 10-11: R22 - max $C_p$ vs. pressure

Figure 10-12: $CO_2$ - max $C_p$ vs. pressure
Appendix B: MATLAB Code

clc
clear all;

L_hex = 18.3 * 10^-3;
OD = 9.5 * 10^-3;
A_hex = 6 * 0.5 * L_hex^2 * cosd(30);
A_FB = 7 * (pi * OD^2)/4;
A_fl = .00037402; %A_hex - A_FB;
p_FB = pi * OD * 7;
A_FB = p_FB * 1;
n = 1000; % input('into how many segments do you want to divide the fuel-channel? ');
temp_pc = 118 + 273;

pressure = 4.64 * 1000; % kPa
T_in = 86.13 + 273.15; % Table 2 >> 74.42 Table 3 >> 90
Table 4 >> 119.26
Q = 2.05 * 1000; % W Table 2 >> 4050
Table 3 >> 10000 Table 4 >> 9000
m = 549.20 / 3600; % kg/s % kg/h / 60 = kg/s
........ Q from table

G = m/A_fl; %kg/m2s
q = Q/A_FB;

T_c = T_in * ones(1,n);
Cp(1)= refpropm('C','T',T_in,'P',pressure,'R12');
p_wetted = pi * ( 7 * OD )+ 6*L_hex;
Dhy = 4 * A_fl / p_wetted;

x = linspace(0,1,n);
L=zeros;
%Cp = zeros;

for i =1:n-1
    L(i)= (x(i+1)-x(i));
end
L1 = [L,L(1)];

for i =1:n-1
    Cp(i+1)= refpropm('C','T',T_c(i),'P',pressure,'R12');
    T_c(i+1) = T_c(i)+ (q*p_FB * L1(i))/( m*Cp(i));
end

delta_T = 10;
\[ T_w = T_c + 100; \]
\[ T_{pc} = 118 + 273; \]

\[
T_{w\_new} = \text{zeros;}
\]
\[
k_c = \text{zeros;}
\]
\[
Cp_c = \text{zeros;}
\]
\[
mu_c = \text{zeros;}
\]
\[
mu_w = \text{zeros;}
\]
\[
density_c = \text{zeros;}
\]
\[
density_w = \text{zeros;}
\]
\[
enthalpy_c = \text{zeros;}
\]
\[
enthalpy_w = \text{zeros;}
\]
\[
Cp_{avg} = \text{zeros;}
\]
\[
Pr_{avg} = \text{zeros;}
\]

\[
Pr = \text{zeros;}
\]
\[
Re = \text{zeros;}
\]

\[
k_w = \text{zeros;}
\]
\[
Cp_w = \text{zeros;}
\]

\[
Pr_w = \text{zeros;}
\]
\[
Re_w = \text{zeros;}
\]
\[
Pr_{avg\_w} = \text{zeros;}
\]
\[
h = \text{zeros;}
\]
\[
Nu = \text{zeros;}
\]

\[\text{while} (\Delta T > 1)\]

\[\text{for} \ i = 1:n\]
\[
\% \quad T_m(i) = (T_w(i)+T_c(i))/2;
\]
\[
k_c(i) = \text{refpropm('L','T',T_c(i),'p',pressure,'R12');}
\]
\[
Cp_c(i) = \text{refpropm('C','T',T_c(i),'p',pressure,'R12');}
\]
\[
mu_c(i) = \text{refpropm('V','T',T_c(i),'p',pressure,'R12');}
\]
\[
mu_w(i) = \text{refpropm('V','T',T_w(i),'p',pressure,'R12');}
\]
\[
density_c(i) = \text{refpropm('D','T',T_c(i),'p',pressure,'R12');}
\]
\[
density_w(i) = \text{refpropm('D','T',T_w(i),'p',pressure,'R12');}
\]
\[
enthalpy_c(i) = \text{refpropm('H','T',T_c(i),'p',pressure,'R12');}
\]
\[
enthalpy_w(i) = \text{refpropm('H','T',T_w(i),'p',pressure,'R12');}
\]
\[
Cp_{avg}(i) = (enthalpy_w(i) - enthalpy_c(i))/(T_w(i)-T_c(i));
\]
\[
Pr_{avg}(i) = \text{Cp}_{avg}(i) * mu_c(i)/k_c(i);
\]
\[Pr(i) = \text{mu_c(i)}*Cp_c(i)/k_c(i);\]
\[Re(i) = G*D_{hy}/mu_c(i);\]
\[k_w(i) = \text{refpropm('L','T',T_w(i),'p',pressure,'R12');}\]
\[Cp_w(i) = \text{refpropm('C','T',T_w(i),'p',pressure,'R12');}\]
\[Pr_w(i) = mu_w(i)*Cp_w(i)/k_w(i);\]
\[Re_w(i) = G*D_{hy}/mu_w(i);\]
\[Pr_{avg\_w}(i) = \text{Cp}_{avg}(i) * mu_w(i)/k_w(i);\]
\[
\% \quad Nu(i) = 0.0064 * Re(i) ^ 0.86 * Pr(i) ^ -0.15;
\]
\[
\% \quad if ((T_c(i)<T_w(i)) \&\& (T_w(i)<T_{pc})) \ || \ ((T_{pc}<T_c(i))\&\&(T_c(i)<T_w(i)))
\]
\[ p = 0.4; \]
\[
\text{elseif } ((T_c(i) < T_{pc}) \&\& (T_{pc} < T_w(i))) \]
\[
p = 0.4 + 0.2 \times \frac{(T_w(i))/T_{pc} - 1}{1 - 5 \times (T_c(i)/T_{pc} - 1)}; \]
\[
\text{elseif } ((T_{pc} < T_c(i) \&\& T_c(i) < 1.2 \times T_{pc}) \&\& (T_c(i) < T_w(i))) \]
\[
p = 0.4 + 0.2 \times \frac{(T_w(i))/T_{pc} - 1}{1 - 5 \times (T_c(i)/T_{pc} - 1)}; \]
\end{verbatim}

% Mokry
\[
\text{Nu}(i) = 0.0061 \times \text{Re}(i)^{0.904} \times \text{Pr}_{avg}(i)^{0.684} \times \left( \frac{\text{density}_w(i)}{\text{density}_c(i)} \right)^{0.564}; \]

% Bishop
\[
\text{Nu}(i) = 0.0069 \times \text{Re}(i)^{0.9} \times \text{Pr}_{avg}(i)^{0.66} \times \left( \frac{\text{density}_w(i)}{\text{density}_c(i)} \right)^{0.43}; \]

% Swenson
\[
\text{Nu}(i) = 0.00459 \times \text{Re}_w(i)^{0.923} \times \text{Pr}_{avg}_w(i)^{0.613} \times \left( \frac{\text{density}_w(i)}{\text{density}_c(i)} \right)^{0.23} \]
\[
\text{Nu}(i) = 0.0094 \times \text{Re}(i)^{0.86} \times \text{Pr}(i)^{-0.15}; \]

% Gupta
\[
\text{Nu}(i) = 0.004 \times \text{Re}_w(i)^{0.923} \times \text{Pr}_{avg}_w(i)^{0.773} \times \left( \frac{\text{mu}_w(i)}{\text{mu}_c(i)} \right)^{0.366} \times \left( \frac{\text{density}_w(i)}{\text{density}_c(i)} \right)^{0.186}; \]

% Popov
\[
\text{Nu}(i) = 0.021 \times \text{Re}(i)^{0.8} \times \text{Pr}_{avg}(i)^{0.7} \times \left( \frac{\text{density}_w(i)}{\text{density}_c(i)} \right)^{0.45} \times \left( \frac{\text{mu}_c(i)}{\text{mu}_c(1)} \right)^{0.2} \times \left( 1 + 2.5 \times \text{HD}/x(j) \right); \]

% Jackson
\[
\text{Nu}(i) = 0.0183 \times \text{Re}(i)^{0.82} \times \text{Pr}(i)^{0.5} \times \left( \frac{\text{density}_w(i)}{\text{density}_c(i)} \right)^{0.3} \times \left( \frac{\text{Cp}_{avg}(i)}{\text{Cp}_c(i)} \right)^p; \]
\[
h(i) = \text{Nu}(i) \times k_c(i)/D_hy; \]
\[
T_{w\_new}(i) = T_c(i) + q/h(i); \]
\[
\text{delta}_T = \text{abs}(T_{w\_new}(i) - T_w(i)); \]
\[
T_w(i) = \text{min}(T_{w\_new}(i), T_w(i)) + \text{delta}_T/2; \]
\end{verbatim}

end

plot(x, T_w-273.15)

XX = x';
T_ww = (T_w-273.15)';
T_cc = (T_c - 273.15)';
KC = k_c';
CP = Cp_c';
MU_c = mu_c';
MU_w = mu_w';
DENSITY_C = density_c';
DENSITY_W = density_w';
PR = Pr_avg';
RE = Re_w';
NU = Nu';
HTC = h'/1000;
COPY = [mu_w',DENSITY_W];
10.3 Appendix C: Full Experimental Dataset

7-Element Bundle; Vertical; Upward flow
R-12: $P_{in} = 4.64$ MPa, $T_{in} = 86^\circ$C, $H_{PC} = 353$ kJ/kg
$q = 9.8$ kW/m$^2$, $G = 441$ kg/m$^2$s, $D_{hy} = 4.7$ mm

Figure 10-13: Case 1 with predictions from 7 correlations
7-Element Bundle; Vertical; Upward flow
R-12: $P_{in} = 4.63 \text{ MPa}, T_{in} = 90^\circ \text{C}$
$q = 47.8 \text{ kW/m}^2, G = 447 \text{ kg/m}^2\text{s}, D_{hy} = 4.7 \text{ mm}$

**Figure 10-14: Case 2 with predictions from 7 correlations**

*Correlations Identified in section 2.6*
7-Element Bundle; Vertical; Upward flow
R-12: $P_{in} = 4.65$ MPa, $T_{in} = 74^\circ$C, $H_{PC} = 353$ kJ/kg
$q = 19.4$ kW/m$^2$, $G = 508$ kg/m$^2$s, $D_{hy} = 4.7$ mm

Figure 10-15: Case 3 with predictions from 7 correlations

*Correlations Identified in section 2.6
7-Element Bundle; Vertical; Upward flow
R-12: \( P_{in} = 4.679 \text{ MPa}, T_{in} = 78^\circ\text{C}, H_{PC} = 353 \text{ kJ/kg} \)
\( q = 52.3 \text{ kW/m}^2, G = 511 \text{ kg/m}^2\text{s}, D_{hy} = 4.7 \text{ mm} \)

**Figure 10-16: Case 4 with predictions from 7 correlations**

*Correlations Identified in section 2.6*
7-Element Bundle; Vertical; Upward flow
R-12: $P_{in} = 4.64$ MPa, $T_{in} = 74^\circ$C, $H_{PC} = 353$ kJ/kg
$q = 67.1$ kW/m$^2$, $G = 517$ kg/m$^2$s, $D_{hy} = 4.7$ mm

Figure 10-17: Case 5 with predictions from 7 correlations

*Correlations Identified in section 2.6
7-Element Bundle; Vertical; Upward flow
R-12: \( P_{in} = 4.63 \text{ MPa}, T_{in} = 73^\circ\text{C}, H_{PC} = 353 \text{ kJ/kg} \)
\( q = 81.4 \text{ kW/m}^2, G = 516 \text{ kg/m}^2\text{s}, D_{hy} = 4.7 \text{ mm} \)

**Figure 10-18: Case 6 with predictions from 7 correlations**

*Correlations Identified in section 2.6*
7-Element Bundle; Vertical; Upward flow
R-12: $P_{in} = 4.64 \text{ MPa}, T_{in} = 112^\circ \text{C}$
$q = 33.4 \text{ kW/m}^2, G = 517 \text{ kg/m}^2\text{s}, D_{hy} = 4.7 \text{ mm}$

**Figure 10-19: Case 7 with predictions from 7 correlations**

*Correlations Identified in section 2.6*
7-Element Bundle; Vertical; Upward flow
R-12: $P_{in} = 4.63$ MPa, $T_{in} = 119^\circ C$
$q = 33.5$ kW/m$^2$, $G = 517$ kg/m$^2$s, $D_{hy} = 4.7$ mm

Figure 10-20: Case 8 with predictions from 7 correlations

*Correlations Identified in section 2.6
7-Element Bundle; Vertical; Upward flow
R-12: $P_{in} = 4.65$ MPa, $T_{in} = 119^\circ$C, $H_{PC} = 353$ kJ/kg
$q = 43.5$ kW/m$^2$, $G = 516$ kg/m$^2$s, $D_{hy} = 4.7$ mm

**Figure 10-21: Case 9 with predictions from 7 correlations**

*Correlations Identified in section 2.6*
7-Element Bundle; Vertical; Upward flow
R-12: $P_{in} = 4.64$ MPa, $T_{in} = 79^\circ$C, $H_{PC} = 353$ kJ/kg
$q = 52.8$ kW/m$^2$, $G = 1024$ kg/m$^2$s, $D_{hy} = 4.7$ mm

Figure 10-22: Case 10 with predictions from 7 correlations

*Correlations Identified in section 2.6
7-Element Bundle; Vertical; Upward flow
R-12: $P_{in} = 4.63$ MPa, $T_{in} = 80^\circ$C, $H_{PC} = 353$ kJ/kg
$q = 80.9$ kW/m$^2$, $G = 1020$ kg/m$^2$s, $D_{hy} = 4.7$ mm

**Figure 10-23: Case 11 with predictions from 7 correlations**

*Correlations Identified in section 2.6*
7-Element Bundle; Vertical; Upward flow
R-12: $P_{in} = 4.64$ MPa, $T_{in} = 80^\circ$C, $H_{PC} = 353$ kJ/kg
$q = 119.7$ kW/m$^2$, $G = 1019$ kg/m$^2$s, $D_{hy} = 4.7$ mm

- Bulk Fluid Enthalpy, kJ/kg
- Temperature, oC
- Heat Transfer Coefficient, kW/m$^2$K
- Bulk-Fluid Temperature
- Sheath Temperature
- Spacer Grid Locations; Grid Length=19 mm

**Figure 10-24: Case 12 with predictions from 7 correlations**

*Correlations Identified in section 2.6*
7-Element Bundle; Vertical; Upward flow
R-12: $P_{in} = 4.63$ MPa, $T_{in} = 100^\circ$C, $H_{PC} = 353$ kJ/kg
$q = 46.4$ kW/m$^2$, $G = 998$ kg/m$^2$s, $D_{hy} = 4.7$ mm

Figure 10-25: Case 13 with predictions from 7 correlations
*Correlations Identified in section 2.6
7-Element Bundle; Vertical; Upward flow

R-12: $P_{in} = 4.64 \text{ MPa}$, $T_{in} = 100^\circ\text{C}$, $H_{PC} = 353 \text{ kJ/kg}$

$q = 96.4 \text{ kW/m}^2$, $G = 1003 \text{ kg/m}^2\text{s}$, $D_{hy} = 4.7 \text{ mm}$

**Figure 10-26: Case 14 with predictions from 7 correlations**

*Correlations Identified in section 2.6*
7-Element Bundle; Vertical; Upward flow
R-12: $P_{in} = 4.65$ MPa, $T_{in} = 73^\circ$C
$q = 33.9$ kW/m$^2$, $G = 1220$ kg/m$^2$s, $D_{hy} = 4.7$ mm

Figure 10-27: Case 15 with predictions from 7 correlations
*Correlations Identified in section 2.6
7-Element Bundle; Vertical; Upward flow
R-12: $P_{in} = 4.64$ MPa, $T_{in} = 73^\circ C$, $H_{PC} = 353$ kJ/kg
$q = 86.3$ kW/m$^2$, $G = 1197$ kg/m$^2$s, $D_{hy} = 4.7$ mm

**Figure 10-28: Case 16 with predictions from 7 correlations**

*Correlations Identified in section 2.6*
7-Element Bundle; Vertical; Upward flow
R-12: $P_{in} = 4.64$ MPa, $T_{in} = 74^\circ$C, $H_{PC} = 353$ kJ/kg
$q = 96.0$ kW/m$^2$, $G = 1210$ kg/m$^2$s, $D_{hy} = 4.7$ mm

**Figure 10-29:** Case 17 with predictions from 7 correlations

*Correlations Identified in section 2.6*
7-Element Bundle; Vertical; Upward flow
R-12: \( P_{in} = 4.62 \) MPa, \( T_{in} = 101^\circ C \), \( H_{PC} = 353 \) kJ/kg
\( q = 47.9 \) kW/m\(^2\), \( G = 1225 \) kg/m\(^2\)s, \( D_{hy} = 4.7 \) mm

**Figure 10-30: Case 18 with predictions from 7 correlations**

*Correlations Identified in section 2.6*
7-Element Bundle; Vertical; Upward flow

R-12: $P_{\text{in}} = 4.65$ MPa, $T_{\text{in}} = 99^\circ\text{C}$, $H_{\text{PC}} = 353$ kJ/kg

$q = 66.3$ kW/m², $G = 1219$ kg/m²s, $D_{\text{hy}} = 4.7$ mm

Figure 10-31: Case 19 with predictions from 7 correlations

*Correlations Identified in section 2.6
7-Element Bundle; Vertical; Upward flow
R-12: $P_{\text{in}} = 4.64$ MPa, $T_{\text{in}} = 91^\circ\text{C}$, $H_{\text{PC}} = 353$ kJ/kg
$q = 77.6$ kW/m$^2$, $G = 1316$ kg/m$^2$s, $D_{\text{hy}} = 4.7$ mm

Figure 10-32: Case 20 with predictions from 7 correlations
*Correlations Identified in section 2.6
10.4 Appendix D: Publications Related to the Work (in order of date)


