APPENDIX D: SAMPLE OF UNCERTAINTY ANALYSIS


The proposed uncertainty analysis\(^1\) is based on our current experience with heat-transfer and pressure-drop experiments in supercritical water (Kirillov et al. 2005; Pis’menny et al. 2005) and carbon dioxide (Pioro and Khartabil 2005) and on our long-term experience in conducting heat-transfer experiments at subcritical pressures (Guo et al. 2006; Bezrodny et al. 2005; Leung et al. 2003; Pioro et al. 2002a,b, 2001, 2000; Pioro 1999, 1992; Pioro and Pioro 1997; Kichigin and Pioro 1992; Pioro and Kalashnikov 1988; Pioro 1982). Also, basic principles of the theory of thermophysical experiments and their uncertainties were applied (Coleman and Steel 1999; Hardy et al. 1999; Guide… 1995; Holman 1994; Moffat 1988; Gortyshov et al. 1985; Topping 1971).

In general, an uncertainty analysis is quite complicated process in which some uncertainties\(^2\) (for example, uncertainties of thermophysical properties (for details, see NIST (2002)), uncertainties of constants, etc.) may not be known or may not be exactly calculated. Therefore, applying the engineering judgement is the only choice in some uncertainty calculations.

This section summarizes instrument calibrations and uncertainty calculations for the measured parameters such as temperature, pressure, pressure drop, mass-flow rate, power, tube dimensions, etc. and for the calculated parameters such as mass flux, heat flux, etc. in supercritical heat-transfer and pressure-drop tests. Uncertainties for these parameters are based on the RMS of component uncertainties. All uncertainty values are at the 2\(\sigma\) level, unless otherwise specified.

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\(^1\) The authors of the current monograph express their appreciation to D. Bullock and Y. Lachance (CRL AECL) for their help in preparation of this uncertainty analysis.

\(^2\) Uncertainty refers to the accuracy of measurement standards and equals the sum of the errors that are at work to make the measured value different from the true value. The accuracy of an instrument is the closeness with which its reading approaches the true value of the variable being measured. Accuracy is commonly expressed as a percentage of a measurement span, measurement value or full-span value. Span is the difference between the full-scale and the zero scale value (Mark’s Standard Handbook for Mechanical Engineers 1996).
Calibration of the instruments used in the tests was performed either in situ, e.g., power measurements, test-section thermocouples, etc., or at an instrumentation shop, e.g., pressure transducers and bulk-fluid temperature thermocouples. In general, instruments were tested against a corresponding calibration standard.

When the same calibration standard is used for serial instruments, the calibration standard uncertainty is treated as a systematic uncertainty. In general, high accuracy calibrators were used, hence systematic errors for calibrated instruments are considered to be negligible. All other uncertainties are assumed to be random. Also, errors correspond to the normal distribution. Usually, the uncertainties have to be evaluated for three values of the corresponding parameter: minimum, mean and maximum value within the investigated range.

Uncertainties are presented below for instruments, which are commonly used in heat-transfer and pressure-drop experiments. It is important to know the exact schematics for sensor signal processing. Some commonly used cases, which are mainly based on a DAS recording, are shown in Figure D1 for thermocouples and in Figure D2 for RTDs, pressure cells and differential pressure cells.

Figure D2. Schematic of signal processing for temperature (based on RTD), absolute pressure and differential pressure. Numbers in figure identify uncertainty of particular device in measuring circuit: 1 – sensor uncertainty, 2 – uncertainty due to temperature effect, 3 – A/I uncertainty, 4 – A/D conversion uncertainty, and 5 – DAS algorithm uncertainty; for RTD and both types pressure cells – DAS algorithm uncertainty is usually 0 due to linear fit.

Also, absolute and relative errors for commonly used functions are listed in Table D1 for reference purposes.

**Table D1. Absolute and relative errors for commonly used functions (based on Gortyshov et al. (1985)).**

<table>
<thead>
<tr>
<th>Function</th>
<th>Absolute error</th>
<th>Relative error</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Y = X_1 + X_2 + ... + X_n$</td>
<td>$\pm \sqrt{\Delta X_1^2 + \Delta X_2^2 + ... + \Delta X_n^2}$</td>
<td>$\pm \sqrt{\Delta X_1^2 + \Delta X_2^2 + ... + \Delta X_n^2}$</td>
</tr>
<tr>
<td>$Y = \frac{X_1 + X_2 + ... + X_n}{n}$</td>
<td>$\pm \sqrt{\frac{\Delta X_1^2 + \Delta X_2^2 + ... + \Delta X_n^2}{\sqrt{n}}}$</td>
<td>$\pm \sqrt{n \cdot \sqrt{\Delta X_1^2 + \Delta X_2^2 + ... + \Delta X_n^2}} \frac{X_1 + X_2 + ... + X_n}{X_1 + X_2 + ... + X_n}$</td>
</tr>
<tr>
<td>$Y = X_1 - X_2$</td>
<td>$\pm \sqrt{\Delta X_1^2 + \Delta X_2^2}$</td>
<td>$\pm \sqrt{\Delta X_1^2 + \Delta X_2^2}$</td>
</tr>
<tr>
<td>( Y = X_1 \cdot X_2 )</td>
<td>( \pm \sqrt{(X_1 \cdot \Delta X_2)^2 + (X_2 \cdot \Delta X_1)^2} )</td>
<td>( \pm \sqrt{(\frac{\Delta X_1}{X_1})^2 + (\frac{\Delta X_2}{X_2})^2} )</td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>( Y = a \cdot X )</td>
<td>( \pm a \cdot \Delta X )</td>
<td>( \pm \frac{\Delta X}{X} )</td>
</tr>
<tr>
<td>( Y = X^n )</td>
<td>( \pm n \cdot X^{n-1} \Delta X )</td>
<td>( \pm \frac{n \cdot \Delta X}{X} )</td>
</tr>
<tr>
<td>( Y = \sin X )</td>
<td>( \pm \cos X \cdot \Delta X )</td>
<td>( \pm \cot X \cdot \Delta X )</td>
</tr>
<tr>
<td>( Y = \cos X )</td>
<td>( \pm \sin X \cdot \Delta X )</td>
<td>( \pm \tan X \cdot \Delta X )</td>
</tr>
<tr>
<td>( Y = \tan X )</td>
<td>( \pm \frac{\Delta X}{\cos^2 X} )</td>
<td>( \pm \frac{2 \cdot \Delta X}{\sin(2 \cdot X)} )</td>
</tr>
<tr>
<td>( Y = \cot X )</td>
<td>( \pm \frac{\Delta X}{\sin^2 X} )</td>
<td>( \pm \frac{2 \cdot \Delta X}{\sin(2 \cdot X)} )</td>
</tr>
</tbody>
</table>

### D.1 Temperature

For the calibrated thermocouples, the following linear characteristics were found:

\[
V_{act} = a \cdot V_{meas} + b, \quad (D1)
\]

where \( V_{act} \) is the “actual” value\(^3\) of the given parameter, \( V_{meas} \) is the value measured by the given instrument, and \( a \) and \( b \) are the calibration coefficients.

#### D.1.1 Measured Bulk-Fluid Temperature

The test section (see Figures 10.5 and 10.6) has three thermocouples to measure the inlet and outlet bulk-fluid temperatures. Also, the temperature at the flowmeter is monitored by thermocouple for fluid density calculations.

The test-section inlet and outlet bulk-fluid temperatures were measured with sheathed K-type thermocouples (for thermocouple signal processing, see Figure D1). These thermocouples

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\(^3\) The value obtained from the calibration standard.
were calibrated against the temperature standard RTD over the temperature range from 0 to 100 ºC. For the reference RTD, the maximum error was ±0.3 ºC. The maximum uncertainty of a data fit for inlet and outlet bulk-fluid temperature measurements is listed in Table D2.

Table D2. Linear coefficients for inlet and outlet temperature thermocouples (from instrument calibration records).

<table>
<thead>
<tr>
<th>TC</th>
<th>Coefficient</th>
<th>Uncertainty, ºC</th>
<th>Number of points</th>
</tr>
</thead>
<tbody>
<tr>
<td>–</td>
<td>a</td>
<td>b</td>
<td>Maximum (2σ)</td>
</tr>
<tr>
<td>TE-1</td>
<td>1.000</td>
<td>–0.1798</td>
<td>0.12</td>
</tr>
<tr>
<td>TE-2</td>
<td>0.9980</td>
<td>0.1502</td>
<td>0.12</td>
</tr>
<tr>
<td>TE-3</td>
<td>0.9985</td>
<td>0.0980</td>
<td>0.12</td>
</tr>
</tbody>
</table>

The inlet and outlet bulk-fluid measurement uncertainties are as follows:

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Calibration system uncertainty</td>
<td>±0.3 ºC</td>
</tr>
<tr>
<td>Thermocouple sensor accuracy after linear fit</td>
<td>±0.12 ºC</td>
</tr>
<tr>
<td>A/I accuracy</td>
<td>±0.06 ºC, i.e., ±0.025% of f.s.; $\left( = \pm \frac{0.00025 \cdot 10 \text{ mV}}{0.045 \text{ mV} / ^\circ \text{C}} \right)$;</td>
</tr>
<tr>
<td>where f.s. is the full scale</td>
<td></td>
</tr>
<tr>
<td>A/D resolution accuracy (minimum 1 bit)</td>
<td>±0.03 ºC $\left( = \pm \frac{10 \text{ mV (f.s.)}}{8192 \text{ counts} \cdot 0.045 \text{ mV} / ^\circ \text{C}} \right)$, where 0.045 mV/ºC is the conversion rate, i.e., 4.509 mV for 100ºC (The Temperature Handbook 2000)</td>
</tr>
<tr>
<td>Reference junction</td>
<td>±0.4 ºC</td>
</tr>
</tbody>
</table>

---

4 All inputs are from instrument calibration records and device manuals unless otherwise specified.
For a given test-section inlet or outlet temperature $t$, the uncertainty $\Delta t$ is given by

$$\frac{\Delta t}{t} = \sqrt{\left(\frac{0.3}{t}\right)^2 + \left(\frac{0.12}{t}\right)^2 + \left(\frac{0.03}{t}\right)^2}.$$  \hspace{1cm} (D2)

The first term is the maximum error of the calibration system ($\pm0.3^\circ C$). The second term is the maximum error for the sheathed thermocouple ($\leq100^\circ C$), obtained from the calibration. The third term is the uncertainty introduced by the DAS, i.e., the A/D resolution uncertainty ($\pm0.03^\circ C$). Note that since the calibration was done in situ using the DAS as the measuring system for the RTD and for the calibrated thermocouples, the uncertainty introduced by the reference junction and the A/I accuracy was included in calibration curves.

All bulk-fluid temperature thermocouples were calibrated in situ, only within the range of $0 - 100^\circ C$. Therefore, individual correction factors were implemented for each thermocouple within the range of $0 - 100^\circ C$ (see Table D2). For this range of temperatures, the uncertainty $\Delta t$ is

- for $t_{min} = 20^\circ C$ \hspace{1cm} $\Delta t = \pm0.32^\circ C$ (or $\pm1.62\%$), and
- for $t = 100^\circ C$ \hspace{1cm} $\Delta t = \pm0.32^\circ C$ (or $\pm0.32\%$).

Beyond this range, thermocouple uncertainties were taken as per The Temperature Handbook (2000), i.e., $\pm2.2^\circ C$.

Thermocouple installed near the flowmeter was calibrated using another calibrating system and procedure. All inputs below are from instrument calibration record and device manuals unless otherwise specified.

Calibration system uncertainty:
$\pm0.5^\circ C$, i.e., \hspace{1cm} $\pm\sqrt{0.06^2 + 0.5^2 + 0.041^2}$, where the first term is the accuracy of standard RTD, the second term is the accuracy of thermocouple signal measuring device and the third term is the accuracy of RTD signal measuring device (all uncertainties are in $^\circ C$).
### Table

<table>
<thead>
<tr>
<th>Accuracy Description</th>
<th>Accuracy Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy $^5 (&gt;2\sigma)$ within 0.0 – 45.0°C</td>
<td></td>
</tr>
<tr>
<td>A/I accuracy</td>
<td>$\pm 0.06^\circ C$, i.e., $\pm 0.025%$ of f.s.</td>
</tr>
<tr>
<td></td>
<td>$= \pm \frac{0.00025 \cdot 10 \text{ mV}}{0.045 \text{ mV/}^\circ C}$</td>
</tr>
<tr>
<td>A/D resolution accuracy (minimum 1 bit)</td>
<td>$\pm 0.03^\circ C$ $= \pm \frac{10 \text{ mV (f.s.)}}{8192 \text{ counts} \cdot 0.045 \text{ mV/}^\circ C}$, where</td>
</tr>
<tr>
<td></td>
<td>$0.045 \text{ mV/}^\circ C$ is the conversion rate, i.e., 4.509 mV for 100°C (The Temperature Handbook 2000)</td>
</tr>
<tr>
<td>Reference junction accuracy</td>
<td>$\pm 0.02^\circ C$</td>
</tr>
</tbody>
</table>

For a given flowmeter bulk-fluid temperature $t_{fm}$, the uncertainty $\Delta t_{fm}$ is given by

$$\left( \frac{\Delta t_{fm}}{t_{fm}} \right)_{TC} = \pm \sqrt{\left( \frac{0.5}{t_{fm}} \right)^2 + \left( \frac{0.53}{t_{fm}} \right)^2 + \left( \frac{0.06}{t_{out}} \right)^2 + \left( \frac{0.03}{t_{out}} \right)^2 + \left( \frac{0.02}{t_{out}} \right)^2}.$$  \hspace{1cm} (D3)

Therefore, the flowmeter bulk-fluid temperature uncertainty is:

- for $t_{fm \min} = 19^\circ C$ \hspace{1cm} $\Delta t_{fm} = \pm 0.74^\circ C$ (or $\pm 3.9\%$), and
- for $t_{fm \max} = 35^\circ C$ \hspace{1cm} $\Delta t_{fm} = \pm 0.74^\circ C$ (or $\pm 2.1\%$).

Additional uncertainties due to thermocouple installation and possible electrical pickup have been minimized by using good engineering practices.

If a bulk-fluid temperature is measured with an RTD, then the following will apply.

The bulk-fluid temperature measurement uncertainties at the 2$\sigma$ level are characterized with the following for an RTD (for RTD signal processing, see Figure D2):

$^5$ The TC calibration accuracy is the maximum difference in $^\circ C$ between what the calibration standard measured and what TC indicated.
Calibration system uncertainty in °C (from the instrument calibration record):
\[
\text{Cal. Sys. Unc.} = \pm \sqrt{\left(0.01\% \text{ of Reading} \cdot \frac{16 \text{ mA}}{100 \degree \text{C}} + 0.015\% \text{ of f.s.} \right)^2 + (0.05 \degree \text{C})^2} \approx 0.06 \degree \text{C},
\]
where the first term is the accuracy of calibrator in which reading is in °C and f.s. is 30 mA and a conversion rate is 16 mA for 100 °C; and the second term is the accuracy of standard RTD.

The RTD accuracy after linear fit, i.e., maximum deviation (from the instrument calibration record), is about ±0.08 °C;

A/I accuracy (from the device manual):

\[
\pm 0.032 \degree \text{C} (\pm 0.025\% \text{ of f.s.}), \text{ i.e., } \pm \frac{0.00025 \cdot 5.12 \text{ V (f.s.)}}{0.04 \degree \text{C}}.
\]

A/D conversion accuracy (minimum 1 bit accuracy) (from the device manual):

\[
\pm 0.016 \degree \text{C}, \text{ i.e., } \pm \frac{5.12 \text{ V (f.s.)}}{8192 \text{ counts} \cdot 0.04 \degree \text{C}}, \text{ where } 0.04 \degree \text{C is the conversion rate, i.e., } 4 \text{ V for 100} \degree \text{C (from the instrument calibration record).}
\]

DAS algorithm uncertainty is 0 due to a linear fit.

Therefore, for a given test-section inlet temperature, its uncertainty (Δt) is given by

\[
\frac{\Delta t}{t} = \pm \sqrt{\left(\frac{\text{Cal. Sys. Unc.}}{t}\right)^2 + \left(\frac{0.08}{t}\right)^2 + \left(\frac{0.032}{t}\right)^2 + \left(\frac{0.016}{t}\right)^2}.
\] (D4)

The resulting uncertainties in the bulk-fluid temperature are

- For \( t = 10 \degree \text{C} \) \( \Delta t = \pm 0.10 \degree \text{C} \) (or ±1.2%); and
- For \( t = 50 \degree \text{C} \) \( \Delta t = \pm 0.11 \degree \text{C} \) (or ±0.2%).

If the bulk-fluid temperature is measured with several devices installed in a one cross section (for example, two RTDs and one thermocouple), the following equation may apply:
In this case, the resulting uncertainty will be close to the larger uncertainty, i.e., the thermocouple uncertainty. Therefore, if several devices have to be used for measuring a non-uniform temperature or any other parameter, they have to be with a similar accuracy.

D.1.2 External Wall Temperature

Temperatures for the test-section external surface (see Figure 10.6) were measured using fast-response K-type thermocouples (see Figure D3). In general, thermocouple uncertainties for K-type thermocouples are ±2.2°C within a range of 0 – 277°C (The Temperature Handbook, 2000). However, all fast-response thermocouples were calibrated in situ within a range of 0 – 100°C prior to use (for details, see below). Therefore, individual correction factors were implemented for each thermocouple within the range of 0 – 100°C. Beyond this range, thermocouple uncertainties were taken as per The Temperature Handbook (2000), i.e., ±2.2°C.

Figure D3. Sketch drawing of fast-response K-type thermocouple.

All K-type thermocouples were calibrated against the temperature calibration standard (i.e., the reference RTD) over the temperature range from 0 to 100°C. These thermocouple
assemblies were immersed in a liquid bath thermostat together with the RTD. For the reference RTD, the maximum uncertainty is ±0.3ºC. The combined uncertainty for wall temperature measurements is as follows:

<table>
<thead>
<tr>
<th>Calibration system accuracy</th>
<th>±0.3°C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermocouple sensor accuracy after linear fit</td>
<td>±0.16ºC max at values ≤100ºC</td>
</tr>
<tr>
<td>A/I accuracy</td>
<td>±0.06ºC, i.e., ±0.025% of f.s. $= \pm \frac{\text{0.00025} \cdot 10 \text{ mV}}{0.045 \degree\text{C}}$</td>
</tr>
<tr>
<td>A/D resolution accuracy (minimum 1 bit)</td>
<td>±0.03ºC $= \pm \frac{10 \text{ mV (f.s.)}}{8192 \text{ counts} \cdot 0.045 \text{ mV/} \degree\text{C}}$, where 0.045 mV/ºC is the conversion rate, i.e., 4.509 mV for 100ºC (The Temperature Handbook 2000)</td>
</tr>
</tbody>
</table>

For a given test-section wall temperature $t$, the uncertainty $\Delta t$ is given by

$$\frac{\Delta t}{t} = \sqrt{\left(\frac{0.3}{t}\right)^2 + \left(\frac{0.16}{t}\right)^2 + \left(\frac{0.03}{t}\right)^2}. \tag{D6}$$

The first term is the maximum error of the calibration system (±0.3ºC). The second term is the maximum error of the sheathed thermocouple (≤100ºC), obtained from the calibration. The third term is the uncertainty introduced by the DAS, i.e., the A/D resolution uncertainty (±0.03ºC). Note that since the calibration was done in situ using the DAS as the measuring system for the RTD and the calibrated thermocouples, the uncertainty introduced by the reference junction and the A/I accuracy was included in calibration curves.

Within the calibrated range of measured temperatures, i.e., from 0 to 100ºC, the

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6 All inputs are from instrument calibration records and device manuals unless otherwise specified.
uncertainty $\Delta t$ is

- for $t_{\text{min}} = 25^\circ\text{C}$ \hspace{1cm} $\Delta t = \pm 0.34^\circ\text{C}$ (or $\pm 1.36\%$), and
- for $t = 100^\circ\text{C}$ \hspace{1cm} $\Delta t = \pm 0.34^\circ\text{C}$ (or $\pm 0.34\%$).

Also, the external wall temperatures measured with fast-response thermocouples were compared to the inlet and outlet bulk-fluid temperatures measured with sheathed thermocouples, at 0 power and 0 mass flux through the test section (see Figure D4). The comparison showed that, in general, all measured temperatures were within $\pm 0.3^\circ\text{C}$.

![Figure D4. Temperature profile along test section at 0 power and 0 mass flux values.](image)

### D.2 Absolute Pressure

A high-accuracy gauge pressure cell with a range of $0 – 10,000$ kPa ($0 – 10$ MPa) was used for the outlet-pressure measurements (for pressure signal processing, see Figure D2). A small correction (77.2 kPa) is applied in the DAS program for the elevation difference between the pressure tap and transmitter. The combined uncertainty for absolute pressure measurements is as follows.
Accuracy of gauge pressure cell (from the calibration record) is \( \pm 0.1\% \) of calibrated span (10,000 kPa), and this accuracy was verified during the calibration check.

Calibration system uncertainty in kPa (from the instrument calibration record):

\[
\text{Cal. Sys. Unc.} = \pm \sqrt{\left(0.015\% \text{ of reading} \frac{16 \text{ mA}}{10000 \text{ kPa}} + 0.015\% \text{ of f.s.} \frac{10000 \text{ kPa}}{16 \text{ mA}} \right)^2 + (0.1\% \text{ of reading})^2},
\]

where the first term is the accuracy of calibrator in which reading is in kPa and f.s. is 30 mA and conversion rate is 16 mA for 10000 kPa; and the second term is the accuracy of tester.

Uncertainty due to temperature effect in 250-\(\Omega\) resistor:

\( \pm 0.1\% \).

A/I accuracy (from the device manual):

\[
\pm 3.2 \text{ kPa}, \text{ i.e., } \pm 0.025\% \text{ of f.s., i.e., 5.12 V } = \pm \frac{0.00025 \cdot 5.12 \text{ V}}{0.0004 \text{ V/kPa}}.
\]

A/D conversion accuracy (minimum 1 bit accuracy) (from the device manual):

\[
\pm 1.56 \text{ kPa} \left( = \pm \frac{5.12 \text{ V (f.s.)}}{8192 \text{ counts} \cdot 0.0004 \text{ V/kPa}} \right),
\]

where 0.0004 V/kPa is the conversion rate, i.e., 4 V for 10,000 kPa (from the instrument calibration record).

For a given test-section outlet pressure \( p \), the uncertainty \( \Delta p \) is given by

\[
\frac{\Delta p}{p} = \pm \sqrt{\left(\frac{0.001 \cdot 10000}{p} \right)^2 + \left(\frac{0.1}{100} \right)^2 + \left(\frac{\text{A/I}}{p} \right)^2 + \left(\frac{\text{A/D}}{p} \right)^2},
\]

(D7)

For the range of \( p \) from 7.6 to 8.8 MPa, the uncertainty \( \Delta p \) is given by

- for \( p_{\text{min}} = 7600 \text{ kPa} \) \( \Delta p = \pm 13.1 \text{ kPa} \text{ (or } \pm 0.17\%) \),
- for \( p = 8400 \text{ kPa} \) \( \Delta p = \pm 13.5 \text{ kPa} \text{ (or } \pm 0.16\%) \),
- for \( p_{\text{max}} = 8800 \text{ kPa} \) \( \Delta p = \pm 13.8 \text{ kPa} \text{ (or } \pm 0.16\%) \).
D.3 Differential-Pressure Cells

Five differential-pressure transducers for measuring test-section pressure drops (for differential-pressure signal processing, see Figure D2) were connected to the corresponding pressure taps installed as shown in Figure 10.6. They were used for measuring the test-section axial pressure gradient and the overall pressure drop. Also, one differential-pressure transducer was used to measure a pressure drop across the flowmeter (see Figure 10.5). All these pressure drops were measured using pressure transmitters.

A calibrator and a pressure module were used for the calibration check of the differential-pressure transducers. Basic characteristics of the test-section and flowmeter differential-pressure cells are listed in Table D3.

Table D3. Basic characteristics of differential-pressure cells.

<table>
<thead>
<tr>
<th>Instrument Name</th>
<th>Description</th>
<th>Output</th>
<th>Output</th>
<th>Span</th>
<th>Accuracy ±% of span</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDT-1</td>
<td>Total test-section pressure drop</td>
<td>10–50 mV</td>
<td>0–300</td>
<td>300</td>
<td>0.5</td>
</tr>
<tr>
<td>PDT-2</td>
<td>Test-section pressure drop</td>
<td>1–5 V</td>
<td>0–50</td>
<td>50</td>
<td>0.5</td>
</tr>
<tr>
<td>PDT-3</td>
<td>Test-section pressure drop</td>
<td>1–5 V</td>
<td>0–50</td>
<td>50</td>
<td>0.5</td>
</tr>
<tr>
<td>PDT-4</td>
<td>Test-section pressure drop</td>
<td>1–5 V</td>
<td>0–50</td>
<td>50</td>
<td>0.5</td>
</tr>
<tr>
<td>PDT-5</td>
<td>Test-section pressure drop</td>
<td>1–5 V</td>
<td>0–50</td>
<td>50</td>
<td>0.5</td>
</tr>
<tr>
<td>PDT-FM-1</td>
<td>Orifice-plate pressure drop</td>
<td>10–50 mV</td>
<td>0–37</td>
<td>37</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Accuracy, includes combined effects of linearity, hysteresis and repeatability in % of a calibrated span are listed in Table D3.

Calibration system uncertainty in kPa (from instrument calibration records):

\[ \text{Cal. Sys. Unc.} = \pm \sqrt{\left(0.015\% \text{ of Reading} \cdot \frac{16 \text{ mA}}{\text{Span} \text{ kPa}} + 0.015\% \text{ of f.s.} \right)^2 + \left(0.05\% \text{ of f.s.} \right)^2}, \]

where the
first term is the accuracy of process calibrator in which reading is in kPa, f.s. is 30 mA and conversion rate is 16 mA for span in kPa; and the second term is the accuracy of calibrator in which f.s. is 690 kPa (100 psig).

Uncertainty due to temperature effect in 250-Ω resistor: ±0.1%.

A/I accuracy (from a device manual):

\[ \pm 0.025\% \text{ of f.s., i.e., } \frac{0.00025 \times 5.12 \text{ V}}{\text{4 V}} = \frac{5.12 \text{ V (f.s.)}}{8192 \text{ counts} \cdot \frac{4 \text{ V}}{\text{Span kPa}}} \].

A/D conversion accuracy (minimum 1 bit accuracy) (from a device manual):

\[ \pm 0.25 \% \text{ of f.s., i.e., } \frac{0.00025 \times 5.12 \text{ V}}{\text{8192 counts} \cdot \frac{4 \text{ V}}{\text{Span kPa}}} \].

For a given pressure drop (\(\Delta p\)) for PDT-1, PDT-2 to PDT-5 and PDT-FM-1, the uncertainty \(\Delta(\Delta p)\) is given by

\[ \frac{\Delta(\Delta p)}{\Delta p} = \pm \left[ \left( \frac{\% \text{ of span in kPa}}{\Delta p} \right)^2 + \left( \frac{0.1}{100} \right)^2 + \left( \frac{\text{A/I}}{\Delta p} \right)^2 + \left( \frac{\text{A/D}}{\Delta p} \right)^2 \right]^{1/2}. \quad (D8) \]

For the range of the total \(\Delta p\) from 5 to 70 kPa, the uncertainty \(\Delta(\Delta p)\) for PDT-1 is given by

- for \(\Delta p_{\text{min}} = 5\) kPa \(\Delta(\Delta p) = \pm 1.50\) kPa (or ±30.1%), and
- for \(\Delta p_{\text{max}} = 70\) kPa \(\Delta(\Delta p) = \pm 1.51\) kPa (or ±2.2%).

For the range of the local \(\Delta p\) from 5 to 30 kPa, the uncertainty \(\Delta(\Delta p)\) for PDT-2 – PDT-5 is given by

- for \(\Delta p_{\text{min}} = 5\) kPa \(\Delta(\Delta p) = \pm 0.25\) kPa (or ±5.0%), and
- for \(\Delta p_{\text{max}} = 30\) kPa \(\Delta(\Delta p) = \pm 0.25\) kPa (or ±0.84%).

For the local \(\Delta p\) equals to 37 kPa, the uncertainty \(\Delta(\Delta p)\) for PDT-FM-1 is given by

- for \(\Delta p_{\text{min}} = 1.5\) kPa \(\Delta(\Delta p) = \pm 0.19\) kPa (or ±12.5%), and
- for \(\Delta p_{\text{max}} = 16.9\) kPa \(\Delta(\Delta p) = \pm 0.19\) kPa (or ±1.1%).
D.4 Mass-Flow Rate

The loop mass-flow rate $F_{M-1}$ (see Figure 10.5) is measured by a small orifice plate\(^7\) with an orifice diameter of 0.308", and monitored by a differential-pressure cell with the range of 0 – 37 kPa. This cell has a square root output, with an accuracy of ±0.5% of full scale. The square root output is converted in the program to obtain kPa for use in the following flow equation, for a mass-flow rate of 0 – 0.24 kg/s (see Figure D4):

$$m = C_{fl} \sqrt{\rho \Delta p},$$

(D9)

where $C_{fl} = 0.00130$ is the constant (White 1994), $\rho$ is the density at the orifice plate in kg/m\(^3\), and $\Delta p$ is the pressure drop across the orifice plate in kPa. It is known that orifice-plate flowmeters usually have a working range within (0.3 and 1)\(\cdot m_{max}\), i.e., 0.08 – 0.24 kg/s (The Flow and Level Handbook 2001).

In general, the constant $C_{flow}$ is a function of Reynolds number (see Figure D5). However, this effect is minor within the investigated range of Reynolds numbers ($Re = 57,000 – 1,130,000$).

---

\(^7\) This small diameter orifice plate is a non-standard orifice plate, because International Standard ISO 5167-2:2003(E), “Measurement of fluid flow by means of pressure differential devices inserted in circular-cross section conduits running full – Part 2: Orifice Plates”, applies only to orifice plates with a diameter not less than 12.5 mm.
We attempted to calibrate the flowmeter FM-1 with water using the direct weighting method (Hardy et al. 1999) within the supercritical CO₂ investigated Reynolds numbers range. Due to significantly different values of water dynamic viscosity compared to those of supercritical carbon dioxide and restrictions applied to the maximum water flow and its temperature, the flowmeter was calibrated (see Figure D6) within a lower range of Reynolds numbers ($\text{Re} = 2,700 – 27,000$) compared to those of supercritical carbon dioxide ($\text{Re} = 57,000 – 1,130,000$).
However, the calibration results showed that Equation (D9) is reasonably accurate (a mean error is \(-0.15\%\) and an RMS error is \(0.5\%\)) for flows that are not less than \(0.045\) kg/s. This finding is consistent with heat-balance error data obtained in supercritical CO\(_2\). However, the heat-balance error data for \(m < 0.045\) kg/s show the opposite trend, i.e., steeper slope than that shown in Figure D6b. Mass-flow rates lower than \(0.045\) kg/s were calculated using:

\[
m = \frac{POW}{H_{\text{out}} - H_m}.
\]  

In general, flow-rate measurement uncertainty within the range of \(m = 0.045 - 0.24\) kg/s is given by:

\[
\frac{\Delta m}{m} = \sqrt{\left(\frac{\Delta C_1}{C_1}\right)^2 + \left(0.5 \frac{\Delta \rho}{\rho}\right)^2 + \left(0.5 \frac{\Delta (\Delta \rho)}{\Delta \rho}\right)^2}.
\]  

The estimated uncertainty in the constant \(C_1\) is \(\pm 0.08\%\) as a result of the minor effect of Reynolds number on the constant within the investigated range (White 1994).

Temperature, pressure (see Figure 10.5) and NIST software (2002) were used for the CO\(_2\) density calculation. At pressures up to 30 MPa and temperatures up to 249.9°C (523 K), the estimated uncertainty in density (NIST 2002) varies up to \(0.05\%\). Also, additional uncertainty in density arises from variations in density within the measured temperature uncertainty of \(\pm 1.1\)°C. This additional uncertainty is about \(\pm 1.1\%\) at \(p = 8.36\) MPa and \(t = 19\)°C, and \(\pm 5.0\%\) at \(p = 8.8\) MPa and \(t = 35\)°C. Therefore, the total uncertainty in density is

\[
\frac{\Delta \rho}{\rho} = \sqrt{\left(\frac{0.05}{100}\right)^2 + \left(\frac{1.1}{100}\right)^2} = 0.011 \text{ at } p = 8.36\text{ MPa and } t = 19\text{°C}
\]  

(D12)
and

$$\frac{\Delta \rho}{\rho} = \sqrt{\left(\frac{0.05}{100}\right)^2 + \left(\frac{5.0}{100}\right)^2} = 0.05 \text{ at } p = 8.8 \text{ MPa and } t = 35^\circ\text{C.} \quad \text{(D13)}$$

However, the vast majority of the experimental data were obtained at pressure of 8.36 MPa. Therefore, the uncertainty value of 0.011 was used below.

Pressure-drop measurement uncertainties for PDT-FT-1/1 are according to Section D.3. Hence,

- for $m_{\text{min}} = 46 \text{ g/s} \ \Delta m = \pm 5.7 \text{ g/s (or } \pm 12.5\%) \text{ at } t = 19^\circ\text{C} \text{ and } p = 8.36 \text{ MPa},$ and
- for $m_{\text{max}} = 155 \text{ g/s} \ \Delta m = \pm 2.4 \text{ g/s (or } \pm 1.6\%) \text{ at } t = 19^\circ\text{C} \text{ and } p = 8.36 \text{ MPa}.$

**D.5 Mass Flux**

Mass flux, $G$, is based on mass-flow rate measurements. The uncertainty, $\Delta G$, includes an error in the estimation of the cross-sectional flow area, $A_{fl} = 5.1 \ 10^{-5} \text{ m}^2$. The test section is a tube of 8.058 mm ID and 10 mm OD, made of Inconel 600, with tolerances of $\pm 0.02$ mm. The uncertainties are as follows:

For ID $\quad \Delta D = \pm 0.02 \text{ mm (or } \pm 0.25\%)$,  
For OD $\quad \Delta D_{\text{ext}} = \pm 0.02 \text{ mm (or } \pm 0.20\%)$, and  
For $A_{\text{flow}}$ $\quad \Delta A_{fl} = \frac{\pi D \Delta D}{2} = \pm 0.253 \text{ mm}^2 (\text{or } \pm 0.50\%)$.

The uncertainty, $\Delta G$, is obtained from the following equation:

$$\frac{\Delta G}{G} = \sqrt{\left(\frac{\Delta m}{A_{fl} G}\right)^2 + \left(\frac{m \Delta A_{fl}}{A_{fl}^2 G}\right)^2} = \sqrt{\left(\frac{\Delta m}{m}\right)^2 + \left(\frac{\Delta A_{fl}}{A_{fl}}\right)^2}. \quad \text{(D14)}$$
For the range of interest, the uncertainties, \( \Delta G \), are

for \( G_{\text{min}} = 902 \text{ kg/m}^2 \cdot \text{s} \ (m_{\text{min}} = 46 \text{ g/s}) \) \( \Delta G = \pm 112.8 \text{ kg/m}^2 \cdot \text{s} \) (or \( \pm 12.5\% \)), and for \( G_{\text{max}} = 3039 \text{ kg/m}^2 \cdot \text{s} \ (m_{\text{max}} = 155 \text{ g/s}) \) \( \Delta G = \pm 49.8 \text{ kg/m}^2 \cdot \text{s} \) (or \( \pm 1.6\% \)).

D.6 Electrical Resistivity

Electrical resistivity is a calculated value (for details, see Equation (C2)) that is based on measured values of electrical resistance, heated length and tube diameters.

The accuracy of the micro-ohmmeter used in test-section electrical resistance measurements is \( \pm 0.04\% \) of the reading (its readings are in milliohms). The uncertainties in ID and OD are \( \Delta D = \Delta D_{\text{ext}} = \pm 0.02 \text{ mm} \), and in \( L \) it is \( \Delta L = \pm 0.5 \text{ mm} \).

For a given electrical resistivity, the uncertainty \( \Delta \rho \) is given by

\[
\frac{\Delta \rho_{\text{el}}}{\rho_{\text{el}}} = \sqrt{\left( \frac{0.04}{100} \right)^2 + \left( \frac{\Delta D_{\text{ext}}}{D_{\text{ext}}} \right)^2 + \left( \frac{\Delta D}{D} \right)^2 + \left( \frac{\Delta L}{L} \right)^2}.
\]

(D15)

The uncertainty in \( \Delta \rho_{\text{el}} \) \( (\rho_{\text{el}} = 104.3 \cdot 10^{-8} \text{ Ohm} \cdot \text{m}) \) is

- for \( L = 2461 \text{ mm} \) \( \Delta \rho_{\text{el}} = \pm 0.212 \cdot 10^{-8} \text{ Ohm} \cdot \text{m} \) (or \( \pm 0.20\% \)).

D.7 Total Test-Section Power

The total test-section power is obtained by measuring the current through a 2000 A/100 mV current shunt and the voltage across the test section. These signals are fed into a power-measuring unit (PMU), where the test-section voltage is scaled down to a 1-V level. Both the voltage and current signals are fed into isolation amplifiers and then into instrumentation amplifiers with outputs of 0 – 10 V. The amplifier outputs are fed to the computer analog inputs and represent a full-scale voltage of 175 V and a full-scale current of 2000 A. These signals are multiplied in the computer program to represent a 0 – 350 kW power level.
Calibration of the power measurement unit was performed in situ. Test-section voltage and current inputs were removed from the PMU. Simulated inputs were used to check the calibration of the unit. A comparison between the computer readings and the calibrated simulated inputs was used to create a curve fit for the DAS to correct for the differences. The voltage input from 0 – 110 V DC was simulated with a DC power supply and verified with a multimeter. The current shunt input was simulated with a calibrator for inputs from 10 to 100 mV, which represents 200 – 2000-A range:

<table>
<thead>
<tr>
<th>Accuracy of current shunt</th>
<th>±0.25% of reading</th>
</tr>
</thead>
<tbody>
<tr>
<td>Error due to current shunt resistance change</td>
<td>±0.02%</td>
</tr>
<tr>
<td>A/D accuracy</td>
<td>±0.025% of f.s., 10.00 V</td>
</tr>
</tbody>
</table>

The uncertainty, \( \Delta POW_{TS} \), in power measurements (the power is a product of \( U \) and \( I \)) is given by

\[
\frac{\Delta POW_{TS}}{POW_{TS}} = \sqrt{\left(\frac{0.25}{100}\right)^2 + \left(\frac{0.02}{100}\right)^2 + \left(\frac{0.1}{100}\right)^2 + \left(\frac{0.09}{100}\right)^2 + \left(\frac{\Delta I}{I}\right)^2 + \left(\frac{\Delta U}{U}\right)^2}. \quad (D16)
\]

The first term is the accuracy of the current shunt, the second term is the effect of a temperature change on the current shunt, the third term is the error in the test-section voltage drop from the PMU output of \( \Delta U = +0.1\% \) (0.10 V) up to 100 V, the fourth term is the error in the test-section current from the PMU output with a maximum offset of \( \Delta I = +0.09\% \) (0.75 A) at 800 A, and the fifth and sixth terms are the ±0.025% uncertainties introduced by the AC/DC conversion process for reading the current (\( \Delta I = ±0.5 \) A) and (\( \Delta U = ±0.04 \) V) for reading the voltage, respectively.

For the power range, \( POW_{TS} \), from 3.0 to 35.0 kW, and for \( L = 2.208 \) m, the corresponding values of voltage drop and current are

- \( POW_{TS\ min} = 3000 \) W  \( U = 16.0 \) V, \( I = 188 \) A, and
- \( POW_{TS\ max} = 35,000 \) W  \( U = 54.6 \) V, \( I = 641 \) A.

The uncertainty in \( \Delta POW_{TS} \) is as follows:

- For \( POW_{TS\ min} = 3000 \) W  \( \Delta POW_{TS} = ± \) 13.9 W (or ±0.46%), and
• For \( POW_{TS_{\text{max}}} = 35,000 \text{ W} \) \( \Delta POW_{TS} = \pm106.4 \text{ W (or } \pm0.30\%\).}

### D.8 Average Heat Flux

The uncertainty in heat flux, \( \Delta q_{\text{ave}} \), involves the uncertainties in the total test-section power (see Section D.7) and in the heated area measurements, \( \Delta A_h \), where \( A_h = \pi D L \). The uncertainty in ID is \( \Delta D = \pm0.02 \text{ mm} \), and in \( L \) it is \( \Delta L = \pm0.5 \text{ mm} \). Thus, \( \Delta A_h \) can be calculated from

\[
\frac{\Delta A_h}{A_h} = \sqrt{\left(\frac{\Delta D}{D}\right)^2 + \left(\frac{\Delta L}{L}\right)^2}.
\]

(D17)

The uncertainty in \( A_h \) (\( A_h = 55,895.4 \text{ mm}^2 \)) is

- for \( L = 2208 \text{ mm} \) and \( D = 8.058 \text{ mm} \) \( \Delta A_h = \pm78.3 \text{ mm}^2 \) (or \( \pm0.14\%\).)

Then, the uncertainty in \( q_{\text{ave}} \) can be computed from

\[
\frac{\Delta q_{\text{ave}}}{q_{\text{ave}}} = \sqrt{\left(\frac{\Delta POW_{TS}}{POW_{TS}}\right)^2 + \left(\frac{\Delta A_h}{A_h}\right)^2}.
\]

(D18)

which, for the given power values, results in

- \( q_{\text{ave min}} = 53.7 \text{ kW (} POW_{TS} = 3.0 \text{ kW} \) \( \Delta q = \pm0.28 \text{ kW/m}^2 \) (or \( \pm0.53\%\)), and

- \( q_{\text{ave max}} = 626.2 \text{ kW (} POW_{TS} = 35.0 \text{ kW} \) \( \Delta q = \pm2.46 \text{ kW/m}^2 \) (or \( \pm0.39\%\)).

However, Equation (D18) does not account for the uncertainties related to the heat loss, which are subtracted from the applied heat flux (for details, see Section 10.3.8), because the heat loss was negligible, i.e., less than 0.5%.

### D9 Uncertainties in Heat-Transfer Coefficient
Local HTC is as follows:

\[ HTC = \frac{q}{t_{\text{w}}^{\text{int}} - t_b} \]  \hspace{1cm} (D19)

Uncertainty in the temperature difference is

\[ \frac{\Delta(t_{\text{w}}^{\text{int}} - t_b)}{t_{\text{w}}^{\text{int}} - t_b} = \pm \sqrt{\left(\frac{\Delta t_{\text{w}}^{\text{int}}}{t_{\text{w}}^{\text{int}} - t_b}\right)^2 + \left(\frac{\Delta t_b}{t_{\text{w}}^{\text{int}} - t_b}\right)^2} \]  \hspace{1cm} (D20)

where uncertainty in \( t_{\text{w}}^{\text{int}} \) is taken as uncertainty in \( t_{\text{w}}^{\text{ext}} \) and uncertainty in \( t_b \) is taken as uncertainty in \( t_{\text{out}} \).

And uncertainty \( \Delta HTC \) is:

\[ \frac{\Delta HTC}{HTC} = \sqrt{\left(\frac{\Delta q}{q}\right)^2 + \left(\frac{\Delta(t_{\text{w}}^{\text{int}} - t_b)}{t_{\text{w}}^{\text{int}} - t_b}\right)^2} \]  \hspace{1cm} (D21)

\section*{D.10 Uncertainties in Thermophysical Properties near Pseudocritical Point}

Uncertainties in thermophysical properties (NIST 2002) near the pseudocritical point within the uncertainty range of the measured value of bulk-fluid temperature \( \Delta t = \pm 0.4^\circ \text{C} \) are as follows (for example, at \( p = 8.38 \text{ MPa} \) \( t_{\text{pc}} = 36.7^\circ \text{C} \)):

\( \Delta \rho = \pm 7\% \); \( \Delta H = \pm 2.5\% \); \( \Delta c_p = 4.5\% \); \( \Delta k = \pm 2\% \), and \( \Delta \mu = \pm 7\% \).

\section*{D.11 Heat-Loss Tests}

Heat loss is an important component of the total heat-balance analysis. Heat loss from the test section, \( HL_{\text{TS}} \), to the surrounding area was measured at various wall temperatures, with electrical power applied to the test section (the loop was previously evacuated to minimise heat removal through the coolant). This test provided (i) an indication of the difference between the measured external wall temperatures and ambient temperature, and (ii) data (voltage and current applied to the test section) to calculate the heat loss from the test section.
To perform the heat loss power test, a small power supply was used.

The temperature difference between the external wall temperatures and ambient temperature at zero power was found to be ±0.2ºC (i.e., within the accuracy range for the thermocouples); with an increase in power to the test section, the difference \( \Delta t = t_{\text{ave}} - t_{\text{amb}} \) increases. This temperature difference permits the evaluation of the heat loss from the test section to the surrounding area as follows:

\[
HL_{TS} = POW_{TS} = f(\Delta t),
\]

\[\text{(D22)}\]

or, as calculated,

\[
HL_{TS} = POW_{TS} = U\ I,
\]

\[\text{(D23)}\]

where \( U \) is the voltage drop over the test section, and \( I \) is the current through the test-section wall. This heat loss test, compared to the usual zero-power test, eliminates uncertainties that are related to the estimation of the thermophysical properties of \( \text{CO}_2 \). This test also eliminates flow-measurement uncertainties and uncertainties that are incurred when measuring very small temperature differences (0.5 – 1ºC) between the inlet and outlet bulk-fluid temperatures.

The heat-loss power test was performed with the insulated reference test section (heated length of 2.208 m). The heat loss assessed from these tests, as a function of the wall-ambient temperature difference, \( (t_{\text{ave}} - t_{\text{amb}}) \), is shown in Figure D7, and can be approximated by the following equation:

\[
HL_{TS} = 0.47 \ (t_{\text{ave}} - t_{\text{amb}}) \ [\text{W}].
\]

\[\text{(D24)}\]

There were some non-uniformities in the temperature distribution along the heated length. These non-uniformities were caused by the power clamps and structural support elements for the test section, which acted as heat sinks. Therefore, a conservative approach (maximum possible heat loss and therefore, minimum HTC value) was taken, i.e., only two external wall thermocouples (TEC01 and TEC24), which are located in the same cross-sections
as TEC02 and TEC23, respectively, but 180° apart, were not taken into account (see Figure 10.6).

For local heated lengths, the following formula would apply:

\[ HL_{TS} \mid_{L_{T}} = HL_{TS} \mid_{L=2.208m} \frac{L_{T}}{2.208} \ [kW], \]  

(D25)

where \( L_{T} \) is in metres.

In general, heat loss was negligible, i.e., less than 0.5%.
Figure D7. Heat loss from test section: Direct electrical heating of test section, heated length of 2.208 m, and loop vacuumed.

D.12 Heat-Balance Evaluation near Pseudocritical Region

For each run, an error in the heat balance was calculated using the following expression:

\[ \Delta_{hb} = \frac{POW - HL - m (H_{out} - H_{in})}{POW} \cdot 100\% . \]  

(D26)
In general, an analysis of errors in the heat-balance data shows that, at mass-flux values equal to or higher than 900 kg/m$^2$s, at medium and high values of power ($POW \geq 5$ kW) and at the inlet and outlet bulk-fluid temperatures below or beyond the pseudocritical region (i.e., $t_{in}$ and $t_{out} < t_{pc} - 2^\circ C$ or $t_{in}$ and $t_{out} > t_{pc} + 2^\circ C$), these errors are within ±4%.

Increased values of heat-balance error (i.e., more than ±4%) at lower values of power ($POW < 5$ kW) and at inlet or outlet bulk-fluid temperatures within the pseudocritical region (i.e., $t_{pc} - 2^\circ C < t_{in} < t_{pc} + 2^\circ C$ or $t_{pc} - 2^\circ C < t_{out} < t_{pc} + 2^\circ C$) can be explained with the following (see Table D4 and Figure D8).

At lower values of power, the increase in bulk-fluid enthalpy is relatively small. However, uncertainties in bulk-fluid enthalpy within the pseudocritical region are larger for the same uncertainty range in bulk-fluid temperature, compared to the enthalpy values’ uncertainties that correspond to temperatures far from the pseudocritical region.

Table D4. Maximum uncertainties in $\Delta H$ calculations near pseudocritical point ($p_{out}=8.36$ MPa, $t_{pc}=36.7^\circ C$, $t_{in}=21^\circ C$, $m=0.1$ kg/s, and $G=2000$ kg/m$^2$s).

<table>
<thead>
<tr>
<th>$t_b$ (°C)</th>
<th>$H_b$ (kJ/kg)</th>
<th>Uncertainty in $H_b$ at $\Delta t_b=+0.4^\circ C$ (kJ/kg)</th>
<th>Uncertainty in $H_b$ at $\Delta t_b=-0.4^\circ C$ (kJ/kg)</th>
<th>$\Delta H_b=H_{out}-H_{in}$ (kJ/kg)</th>
<th>Max uncertainty in $\Delta H_b$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>21</td>
<td>248.94</td>
<td>1.18</td>
<td>-1.19</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>35</td>
<td>313.72</td>
<td>4.29</td>
<td>-5.04</td>
<td>64.78</td>
<td>14.4</td>
</tr>
<tr>
<td>37</td>
<td>349.26</td>
<td>8.51</td>
<td>-7.82</td>
<td>100.32</td>
<td>16.3</td>
</tr>
<tr>
<td>41</td>
<td>395.75</td>
<td>2.56</td>
<td>-2.4</td>
<td>144.41</td>
<td>3.4</td>
</tr>
</tbody>
</table>

Also, an additional error in the heat balance appears at mass-flux values below 900 kg/m$^2$s (see Figure D6), where the flow-measuring curve is steep. Therefore, lower values of mass flux should be measured with a smaller diameter orifice flowmeter\(^8\) or other type.

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\(^8\) However, orifice-plate flowmeters with a diameter of the orifice less than 12.5 mm is considered a non-standard type.
flowmeters.

Figure D8 shows an example of the heat-balance evaluation near the pseudocritical region. This graph shows that, at lower power values (\(P_{OW} < 5\) kW) and at the outlet bulk-fluid temperature within the pseudocritical region, variations in bulk-fluid enthalpy difference can be up to 11.5\% within the nominal uncertainty range for bulk-fluid temperatures (i.e., ±0.4°C).

**Figure D8. Heat-balance evaluation near pseudocritical region.**
SYMBOLS AND ABBREVIATIONS

\(A\) area, \(m^2\)
\(A_{fl}\) flow area, \(m^2\)
\(c_p\) specific heat at constant pressure, \(J/kg \, K\)
\(\bar{c}_p\) averaged specific heat within the range of \((T_w - T_b)\); \(\left( \frac{H_w - H_b}{T_w - T_b} \right)\), \(J/kg \, K\)
\(D\) inside diameter, \(m\)
\(D_{ext}\) external diameter, \(m\)
\(D_{hy}\) hydraulic diameter, \(m\); \(\left( \frac{4 \, A_{fl}}{P_{wetted}} \right)\)
\(f\) friction factor; \(\left( \frac{\sigma_w}{G^2} \right) \left( \frac{8 \, \rho}{P_{wetted}} \right)\)
\(f_d\) drag coefficient
\(G\) mass flux, \(kg/m^2 \, s\); \(\left( \frac{m}{A_{fl}} \right)\)
\(g\) gravitational acceleration, \(m/s^2\)
\(H\) specific enthalpy, \(J/kg\)
\(h\) heat transfer coefficient, \(W/m^2 \, K\)
\(HL\) heat loss, \(W\)
\(I\) current, \(A\)
\(k\) thermal conductivity, \(W/m \, K\)
\(L\) heated length, \(m\)
\(L_{tot}\) total length, \(m\)
\(m\) mass-flow rate, \(kg/s\); \(\left( \rho \, V \right)\)
\(p\) pressure, \(MPa\)
\(POW\) power, \(W\)
\(Q\) heat-transfer rate, \(W\)
\( q \) heat flux, W/m\(^2\): \( \frac{Q}{A_h} \)

\( q_v \) volumetric heat flux, W/m\(^3\): \( \frac{Q}{V_h} \)

\( R \) molar gas constant, 8.31451 J/mol K

\( R_{\text{a}} \) arithmetic average surface roughness, \( \mu \)m

\( R_{\text{bend}} \) radius of bending (for tube)

\( R_{\text{el}} \) electrical resistance, Ohm

\( r \) radial coordinate or radius, m; regression coefficient

\( T \) temperature, K

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

\( U \) voltage, V

\( u \) axial velocity, m/s

\( V \) volume, m\(^3\) or volumetric flow rate, m\(^3\)/s

\( V_m \) molar volume, m\(^3\)/mol

\( v \) radial velocity, m/s

\( x \) axial coordinate, m

\( y \) radial distance; (\( r_0 - r \)), m

\( z \) axial coordinate, m

**Greek Letters**

\( \alpha \) thermal diffusivity, m\(^2\)/s; \( \frac{k}{c_p \rho} \)

\( \beta \) volumetric thermal expansion coefficient, 1/K

\( \Delta \) difference

\( \Delta_{\text{HB}} \) error in heat balance, %

\( \delta \) thickness, mm

\( \varepsilon \) dissipation of turbulent energy

\( \mu \) dynamic viscosity, Pa s

\( \pi \) reduced pressure; \( \frac{p}{p_{\text{cr}}} \)
\( P \) perimeter, m
\( \rho \) density, kg/m\(^3\)
\( \rho_{el} \) electrical resistivity, Ohm·m
\( \sigma \) dispersion
\( \sigma_w \) viscous stress, N/m\(^2\)
\( \nu \) kinematic viscosity, m\(^2\)/s
\( \zeta \) friction coefficient

**Non-dimensional Numbers**

\( \text{Ga} \) Galileo number; \( \left( \frac{g}{\nu^2} \cdot \frac{D^3}{g} \right) \)

\( \text{Gr} \) Grashof number; \( \left( \frac{g \beta \Delta T \cdot D^3}{\nu^2} \right) \)

\( \text{Gr}_q \) modified Grashof number; \( \left( \frac{g \beta q_w \cdot D^4}{k \nu^2} \right) \)

\( \text{Nu} \) Nusselt number; \( \left( \frac{h \cdot D}{k} \right) \)

\( \text{Pr} \) Prandtl number; \( \left( \frac{\mu \cdot c_p}{k} \right) = \left( \frac{\nu}{\alpha} \right) \)

\( \overline{\text{Pr}} \) averaged Prandtl number within the range of \((t_w - t_b)\); \( \left( \frac{\mu \cdot \bar{c}_p}{k} \right) \)

\( \text{Re} \) Reynolds number; \( \left( \frac{G \cdot D}{\mu} \right) \)

\( \text{Ra} \) Raleigh number; \((\text{Gr} \cdot \text{Pr})\)

\( \text{St} \) Stanton number; \( \left( \frac{\text{Nu}}{\text{Re} \cdot \text{Pr}} \right) \)

Symbols with an overline at the top denote average or mean values (e.g., \( \overline{\text{Nu}} \) denotes average (mean) Nusselt number).

**Subscripts or superscripts**

\( \text{ac} \) acceleration
\( \text{amb} \) ambient
ave average
b bulk
cal calculated
cr critical
cr sect cross section
dht deteriorated heat transfer
el electrical
ext external
f fluid
fl flow
fm flowmeter
fr friction
g gravitational
h heated
HB Heat Balance
hor horizontal
hy hydraulic
in inlet
int internal
iso isothermal
ℓ liquid or local
m molar
max maximum
meas measured
min minimum
nom nominal or normal
0 constant properties, scale, reference, characteristic, initial, or axial value
out outlet or outside
OD outside diameter
pc pseudocritical
T value of turbulent flow
TS  test section
th  threshold value
tot total
v volumetric
vert vertical
w wall

Abbreviations and acronyms widely used in the text and list of references
AC  Alternating Current
A/D  Analog-to-Digital (conversion)
A/I  Analog Input
AECL  Atomic Energy of Canada Limited (Canada)
AERE  Atomic Energy Research Establishment (UK)
AGR  Advanced Gas-cooled Reactor
AIAA  American Institute of Aeronautics and Astronautics
AIChE  American Institute of Chemical Engineers
ANS  American Nuclear Society
ASME  American Society of Mechanical Engineers
ASHRAE  American Society of Heating, Refrigerating and Air-conditioning Engineers
AWG  American Wire Gauge
BWR  Boiling Water Reactor
CANDU  CANada Deuterium Uranium nuclear reactor
CFD  Computational Fluid Dynamics
CHF  Critical Heat Flux
CRL  Chalk River Laboratories, AECL (Canada)
DAS  Data Acquisition System
DC  Direct Current
DOE  Department Of Energy (USA)
DP  Differential Pressure
emf  electromagnetic force
ENS  European Nuclear Society
EU  European Union
EXT EXTernal
FA Fuel Assembly
FBR Fast Breeder Reactor
FM FlowMeter
F/M Ferritic-Martensitic (steel)
FR Fuel Rod
f.s. full scale
FT Flow Transducer
GIF Generation IV International Forum
HMT Heat Mass Transfer
HT Heat Transfer
HTC Heat Transfer Coefficient
HTD Heat Transfer Division
HTR High Temperature Reactor
HVAC & R Heating Ventilating Air-Conditioning and Refrigerating
IAEA International Atomic Energy Agency (Vienna, Austria)
ID Inside Diameter
INEEL Idaho National Engineering and Environmental Laboratory (USA)
IP Intermediate-Pressure turbine
IPPE Institute of Physics and Power Engineering (Obninsk, Russia)
JAERI Japan Atomic Energy Research Institute
JSME Japan Society of Mechanical Engineers
KAERI Korea Atomic Energy Research Institute (South Korea)
KPI Kiev Polytechnic Institute (nowadays National Technical University of Ukraine “KPI”) (Kiev, Ukraine)
KP-SKD Channel Reactor of Supercritical Pressure (in Russian abbreviations)
LP Low-Pressure turbine
LOCA Loss Of Coolant Accident
LOECC Loss Of Emergency Core Cooling
Ltd. Limited
LWR Light Water Reactor
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
</tr>
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<tbody>
<tr>
<td>MEI</td>
<td>Moscow Power Institute (Moscow, Russia) (In Russian abbreviations)</td>
</tr>
<tr>
<td>MIT</td>
<td>Massachusetts Institute of Technology (Cambridge, MA, USA)</td>
</tr>
<tr>
<td>MOX</td>
<td>Mixed Oxide (nuclear fuel)</td>
</tr>
<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration (USA)</td>
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<tr>
<td>NIST</td>
<td>National Institute of Standards and Technology (USA)</td>
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<tr>
<td>NPP</td>
<td>Nuclear Power Plant</td>
</tr>
<tr>
<td>OD</td>
<td>Outside Diameter</td>
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<tr>
<td>PC</td>
<td>Personal Computer</td>
</tr>
<tr>
<td>PDT</td>
<td>Pressure Differential Transducer</td>
</tr>
<tr>
<td>PH.D.</td>
<td>Philosophy Degree</td>
</tr>
<tr>
<td>PLC</td>
<td>Programmable Logic Controller</td>
</tr>
<tr>
<td>ppb</td>
<td>parts per billion</td>
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<tr>
<td>ppm</td>
<td>parts per million</td>
</tr>
<tr>
<td>PT</td>
<td>Pressure Tube or Pressure Transducer</td>
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<tr>
<td>PWAC</td>
<td>Pratt &amp; Whitney AirCraft</td>
</tr>
<tr>
<td>PWR</td>
<td>Pressurized Water Reactor</td>
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<tr>
<td>R</td>
<td>Refrigerant</td>
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<tr>
<td>RAS</td>
<td>Russian Academy of Sciences</td>
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<tr>
<td>RBMK</td>
<td>Reactor of Large Capacity Channel type (in Russian abbreviations)</td>
</tr>
<tr>
<td>RDIPE</td>
<td>Research and Development Institute of Power Engineering (Moscow, Russia) (NIKIE in Russian abbreviations)</td>
</tr>
<tr>
<td>R&amp;D</td>
<td>Research and Development</td>
</tr>
<tr>
<td>RMS</td>
<td>Root-Mean-Square (error or surface roughness)</td>
</tr>
<tr>
<td>RPV</td>
<td>Reactor Pressure Vessel</td>
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<tr>
<td>RSC</td>
<td>Russian Scientific Centre</td>
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<tr>
<td>RT</td>
<td>propulsion fuel (in Russian abbreviations)</td>
</tr>
<tr>
<td>RTD</td>
<td>Resistance Temperature Detector</td>
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<tr>
<td>SCP</td>
<td>SuperCritical Pressure</td>
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<tr>
<td>SCR</td>
<td>SuperCritical Reactor</td>
</tr>
<tr>
<td>SCW</td>
<td>SuperCritical Water</td>
</tr>
<tr>
<td>SCWO</td>
<td>SuperCritical Water Oxidation technology</td>
</tr>
</tbody>
</table>
**SCWR**  SuperCritical Water-cooled Reactor
**SFL**  Supercritical Fluid Leaching
**SFR**  Sodium Fast Reactor
**SKD**  SuperCritical Pressure (in Russian abbreviations)
**SMR**  Steam-Methane-Reforming process
**SS**  Stainless Steel
**T**  fuel (in Russian abbreviation)
**TC**  ThermoCouple
**TE**  TEmperature
**TECO**  TEmperature of CO$_2$
**TS**  Test Section
**TsKTI**  Central Boiler-Turbine Institute (St.-Petersburg, Russia) (in Russian abbreviations)
**UCG**  Uranium-Carbide Grit pored over with calcium (nuclear fuel)
**UK**  United Kingdom
**U.K.A.E.A.**  United Kingdom Atomic Energy Authority (UK)
**UNESCO**  United Nations Educational, Scientific and Cultural Organization (Paris, France)
**US or USA**  United States of America
**USSR**  Union of Soviet Socialist Republics
**VHTR**  Very High-Temperature Reactor
**VNIIAM**  All-Union Scientific-Research Institute of Atomic Machine Building (Russia) (in Russian abbreviations)
**VTI**  All-Union Heat Engineering Institute (Moscow, Russia) (in Russian abbreviations)
**wt**  weight
**WWPR**  Water-Water Power Reactor (“VVER” in Russian abbreviations)
REFERENCES


