Improvements to the Cheng-Todreas Wire-Wrapped Rod Bundle Friction Factor Correlation in Response to Pin Number and in the Transition Flow Region

by

Vincent John Kindfuller

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Author ............................................................

Department of Nuclear Science and Engineering

May 23, 2016

Certified by ..........................................................

Neil Todreas

KEPCO Professor of Nuclear Science and Engineering, Emeritus

Professor of Mechanical Engineering, Emeritus

Thesis Supervisor

Accepted by ..........................................................

Michael Short

Assistant Professor of Nuclear Science and Engineering

Chair, NSE Committee for Undergraduate Students
Abstract

The Cheng-Todreas Detailed (CTD) Pressure Drop Correlation (1986) is the most accurate correlation for measuring the pressure drop of sodium coolant through a Sodium-Cooled Fast Reactor (SFR). Although CTD is the most accurate correlation, there is room for improvement with new data and modern ways to visualize data and check the accuracy of changes easily. This thesis attempts to offer a method for altering the CTD correlation to better account for changing pin numbers in SFR assemblies, and a better fit for the correlation to the data in the transition flow region between turbulent and laminar flow.

Although CTD is more accurate than other correlations, it shows an inverse response to changing pin number in some geometries of bundle assemblies. In this thesis, a method is laid out to attempt to correct for that inverse response. Although no successful conclusion was reached, the thesis also offers a method for future attempts at improvement. In addition, a set of Matlab codes are offered that allow changes to be easily attempted and checked for validity.

In addition, examining the data points of bundles in the transition flow regime shows possibilities for improving the accuracy of the correlation in that flow region. Two changes are implemented in this thesis: a change to the equation for the boundary between laminar and transition flow, and a change to the transition region friction factor equation. Both changes, when implemented, offer slight improvements to the overall accuracy and precision of the Cheng-Todreas Pressure Drop Correlation.

Thesis Supervisor: Neil Todreas
Title: KEPCO Professor of Nuclear Science and Engineering, Emeritus
Professor of Mechanical Engineering, Emeritus
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Chapter 1

Introduction

One of the potential designs for a next generation reactor is to use liquid sodium coolant in Sodium-cooled Fast Reactors (SFRs), a concept which offers better economic viability and safety. The Cheng-Todreas Correlation (CTD) [1], is the most commonly used correlation for calculating the pressure drop of sodium coolant through a Sodium Fast Reactor (SFR). CTD is the most accurate correlation across a large range of geometrical parameters and flow conditions. CTD is used in hydrodynamic calculations by many reactor designers and researchers working on SFRs.

With new data and new tools for making and evaluating changes to the correlation, it has become possible to improve and increase the accuracy of CTD. This thesis attempts to improvements to acheive CTD’s predictions in two areas: the pin number effect and the transition flow region. Although the bundle friction factor should increase with pin number, for a certain range of geometrical parameters, CTD predicts a decrease in friction factor. This thesis attempts to make a correction to that trend. In addition, this thesis attempts to make changes to CTD at the transition flow region between laminar and turbulent, to increase the accuracy there.
Chapter 2

Background

2.1 Sodium Fast Reactors

Generation IV reactors are a set of new reactor designs using advanced fuel types, intended to replace the currently dominant Light Water Reactor technology in use around the world. One such Gen IV reactor is the Sodium Fast Reactor (SFR), which is a fast spectrum reactor that uses liquid sodium as a reactor coolant.

The liquid sodium coolant allows a low-pressure system with low volume fraction in the core but with high power density. In addition, the large thermal inertia of sodium accommodates transients and combined with the high boiling point offers significant safety advantages. One large potential disadvantage of the SFR is that sodium reacts chemically with water and air, and therefore needs to be fully segregated from water and air in all operating scenarios to safely operate [2].

SFRs are capable of management of high-level wastes as well, through implementation of a partially or fully closed fuel cycle [3]. There are several SFRs in various stages of construction in multiple countries, including Japan, China, Korea Russia, India and, to a limited degree under design evaluation in the United States [4]. Potential plant sizes for SFRs range from small modular 50-300 MWe plants to full sized plants up to 1500 MWe.

SFRs use fuel and control rods packed into tight hexagonal rod arrays, referred to as bundles, with wires round around the rods for spacing. The spacing wires,
which follow a helical pattern, also increase coolant mixing between subchannels. Figure 2-1 shows an assembly with 37 pins, as well as the geometrical parameters P, W and H. In most bundles, P/D and H/D are the most important geometrical parameters. Although there are alternate potential configurations for the bundles, such as multiple wires or wires going in alternating directions, these are not considered in the Cheng-Todreas Pressure Drop Correlation. Most SFR reactor designs currently being developed have a P/D between 1.08 and 1.41 and H/D values vary significantly from as low as 8 to as high as 50 [5].

2.2 Pressure Drop Correlations

To insure confidence in thermal/hydraulic calculations under both steady-state and transient pressure conditions, it is important to understand the pressure characteristics of the coolant as it flows through the reactor. Pressure loss calculations can show the design limits for cladding as well as the heat transfer coefficients of the coolant at different points in the core [6].

The pressure drop of fluid is $\Delta P_{total} = \Delta P_{acceleration} + \Delta P_{friction} + \Delta P_{gravity} +$
\[ \Delta P_{\text{friction}} \] is generally the pressure drop from friction, \( \Delta P_{\text{friction}} \), in the steady state coolant flow situation for the wire-wrapped bundle assembly. The equation for \( \Delta P_{\text{friction}} \) is laid out in equation 2.1.

\[ \Delta P_{\text{friction}} = f \frac{L}{D_e} \rho V^2 \frac{2}{2} \] \hspace{1cm} (2.1)

The Darcy friction factor, \( f \), is a function of Reynolds number (Re) and dimensionless bundle parameters such as H/D and P/D. In different geometries of coolant flow, \( f \) varies. It therefore needs to be determined for specific reactor designs, in order to determine the total pressure drop.

There are several correlations for determining the friction factor for a reactor with a similar geometry to an SFR, with wire-wrapped fuel rods in the core. These correlations take specific values for the geometry of the bundle – rod diameter, pitch and wire diameter, for example, and plug them into a formula to determine the friction factor. The Cheng-Todreas Detailed (CTD) correlation is the best fit correlation to the experimental data from wire-wrapped bundles. In addition, it has the largest range of applicability for both P/D and H/D changes[7].

2.3 The Cheng-Todreas Correlation

Drs. Chen and Todreas developed the Detailed Cheng-Todreas Correlation as part of Dr. Chen’s PhD thesis in 1986 [1]. The Cheng-Todreas correlation takes empirical data for bare rod friction factor and adds in wire effects based on hydrodynamical theoretical results calibrated to actual data to produce a correlation for bundle pressure drop for a broad range of bundle dimensions. CTD uses three subchannels, interior, edge and corner, to represent the different friction drop behaviour in different parts of the assembly.

The interior subchannel pressure drop is mainly caused by surface friction and wire drag, while the edge and corner subchannels mainly lose pressure due to skin friction from the swirl velocity following the wire. When wire diameter is set to zero,
the models reduce to bare rod correlations. The empirical constants were calibrated by the significant amount of then available data for the turbulent region. Constants for the laminar region were obtained using the much fewer laminar data then available, assumed to be fractions of the values for turbulent flow[5]. The Cheng-Todreas correlation is depicted in Appendix A.

In the laminar and turbulent flow regions, $f$ varies consistently with Re. Therefore, the product of CTD is a bundle friction factor constant ($C_{fb}$) for turbulent and laminar respectively. Equations 2.2 and 2.3 show how $f$ varies with Re and the friction factor constants in the laminar and turbulent zones respectively.

$$f = \frac{C_{fbL}}{Re} \quad (2.2)$$

$$f = \frac{C_{fbT}}{Re^{0.18}} \quad (2.3)$$

Syeilendra Pramuditya from Indonesia published a code written in Fortran which can easily take inputs of geometrical parameters and run them through the CTD code to find subchannel and bundle average friction factors. The code can be found at http://wp.me/p61TQ-tI.

As more data has become available and computational codes have increased in ease of use, it has become possible to make improvements to the Cheng-Todreas correlation. The two improvements discussed in this thesis are adjusting for the effect of pin number on the friction factor of bundles and changing the correlation to better represent the transition flow regime between laminar and turbulent flow. These improvements are presented in Chapters 3 through 5 for pin number and Chapter 6 for the transition flow region.

### 2.4 Correlation Data Set

Appendix B shows the experimental data used for the correlation and this thesis. The main data set used in evaluating the correlation is a set of 80 bundles, shown in Table B.4. 24 of these bundles are bundles evaluated by Rehme, out of his total of
74 bundles evaluated with combinations of different geometrical parameters and pin numbers. As discussed in [7] and [5], the remaining Rehme bundles were omitted to prevent possible systematic error in bundle comparisons from using too many bundles from the same source. The 54 Rehme bundles with pin numbers higher than 7 are shown in Table B.3.

Table B.1 shows the set of 13 experimental bundles in which the flows through different subchannels were measured. These bundles, called flow split bundles, show the flow through the interior, edge and corner subchannels. Finally, 33 experiments with bare rod bundles have been conducted, as shown in Table B.2.
Chapter 3

Correlation Behavior for Varying Bundle Pin Number

SFR bundles can vary significantly in the number of pins within the assembly. As shown in Figure 2-1, the hexagonal pattern means that the number of pins will be those which create hexagons – 7, 19, 37, 61, 91 and so on. The majority of bundles that have been used to test pressure drop and are used as data for this correlation are 37 pins, though there are a number with fewer or more pins. However, typical fuel bundles in SFRs have more pins, such as the Prototype Generation-IV SFR (PGSFR) being planned for construction in Korea in the 2020s, with 271 fuel pins [6].

It is important to understand how the number of pins in an assembly affects the pressure drop, as that will be a key design parameter for the design of future SFRs for actual operation.

3.1 Empirical Pin Number Trend

3.1.1 Bare Rod Trends

Bare rod bundles are bundles without wires wrapping around them. They are not being considered for use in power production SFRs, but the Cheng-Todreas correlations uses bare rod data to find the $Cf_1$, $Cf_2$ and $Cf_3$, the bare rod subchannel friction
factor constants which are used to calculate the wire-wrapped subchannel constants.

CfbT is a constant that is related to $f$ by $Re^{0.18}$ in the turbulent region, as shown in Equation 2.3. Therefore, CfbT can show how the friction factor changes with different parameters independent of Reynolds number. Figure 3-1 shows the CfbT for bare rod bundles compared to P/D, for a range of pin numbers.

As can be seen, the pin number effect isn’t clear, and it’s difficult to see how the friction factor for bare rod bundles changes with pin number. However, there is a slight increase of friction factor with pin number.

### 3.1.2 Wire-Wrapped Trends

Most of the experimental bundle data available varies geometrical factors, but does not vary the pin number, so it’s difficult to isolate pin number effects from the effects
of varying other parameters. However, the Rehme experimental bundles [8] tested the same geometries with different pin number, and were therefore able to show a trend with respect to pin number.

Based on the empirical data, especially the 54 bundles tested by Rehme, shown in Table B.2, as pin number increases, the friction factor of the bundle increases as well when P/D and H/D are held constant. The Rehme bundles show an increased CfbT by an average of 4.15% with pin number increasing from 19 to 37, with one outlier which decreased by -27.36%. With that outlier excepted, the average increase is 5.52%. Going from 37 to 61 pins, CfbT increases by 1.57%. The increase from 61 to 91 and higher is harder to judge, since Rehme only had experiments with pin numbers of 61 and below. However, based on results from other experimental bundles, increasing pin number above 61 also shows increases the CfbT, though at that point it falls well within scattering of data.

Figure 3-2 shows the CfbT values of a set of 3 bundles in the Rehme13 bundle set. The bundles in the set have a P/D of 1.125 and H/D of 16.67. As can be seen, with increase in pin number, the bundle friction factor constant increases as well.

3.2 Cheng-Todreas Correlation Trend

The Cheng-Todreas correlation does not directly account for pin numbers in the friction factor calculations. However, due to the use of subchannel friction factors it still shows a different friction factor at different pin numbers.

Although increasing the pin number should increase friction factor, for CTD in the range of \( P/D \) from approximately 1.1 to 1.35, CTD predicts a decrease. Figure 3-3 shows this difference for \( H/D = 25 \), comparing the CTD predictions to the predictions of the Rehme correlation [9], which show the correct trend. However, the Rehme correlation consistently shows a lower predicted friction factor than the empirical data shows.
3.2.1 Wire Sweeping Effect

The total bundle average friction factor constant, $C_{fbT}$, is found by combining the subchannel friction factors in equation 3.1,

$$C_{fbT} = Deb \left( \sum_{i=1}^{3} \left( \frac{N_i A_i}{A_b} \right) \left( \frac{De_i}{De_b} \right)^{0.0989} \left( \frac{De_i}{C_{f iT}} \right)^{0.54945} \right)^{1.82}$$

(3.1)

where $i$ is 1 for interior, 2 for edge and 3 for corner.

The effect of pin number on $C_{fbT}$, therefore, depends on $N_i$, as the number of interior subchannels increase more than do edge subchannels as the number of bundle pins increase. If $f2$ is enough higher than $f1$, increasing pin number will decrease total friction factor. Therefore, this means that in order to help correct the pin number trend effect of the CTD correlation explained in chapter 3, the interior subchannel friction factor should be increased to be above that of the edge subchannel.

The subchannel friction factors are calculated by Equations 3.2, 3.3 and 3.4, where $f1$ is the interior subchannel friction factor, $f2$ is the edge and $f3$ is the corner.
Figure 3-3: Predicted effect of Pin Number on $Cfb_T$ as a function of $P/D$ at $H/D = 25$ for CTD and Rehme correlations

\[ f_1 = \frac{1}{Re_1^{m}}[Cf'_1\left(\frac{P'w_1}{Pw_1}\right) + Wd\left(\frac{3Ai}{A'1}\right)\left(\frac{De_1}{H}\right)\left(\frac{De_1}{Dw}\right)^m] \]  \hspace{1cm} (3.2)

\[ f_2 = \frac{Cf'_2}{Re_1^{m}}[1 + Ws\left(\frac{As_2}{A'2}\right)^{3-m/2} \tan^2 \theta]^{3-m/2} \]  \hspace{1cm} (3.3)

\[ f_3 = \frac{Cf'_3}{Re_1^{m}}[1 + Ws\left(\frac{As_3}{A'3}\right)^{3-m/2} \tan^2 \theta]^{3-m/2} \]  \hspace{1cm} (3.4)

To increase the interior subchannel factor above the edge subchannel friction factor, the $Wd$ factor needs to be increased to be larger than $Ws$ in the turbulent region. In the original correlation, $WdT$ is calculated by Equation 3.5, and $WsT$ is calculated by Equation 3.6,

\[ WdT = [29.5 - 140(Dw/D) + 401(Dw/D)^2](H/D)^{-0.85} \]  \hspace{1cm} (3.5)

\[ WsT = 20.0 \log(H/D) - 7.0 \]  \hspace{1cm} (3.6)

The first attempt to do so will be to try and see if new data and the use of a Matlab code to analyze the data give different $WdT$ and $WsT$ predictive equations than the ones used to develop the initial CTD correlation from 1986.
Chapter 4

Methodology for Changing WdT and WsT Factors

4.1 Process

To arrive at the equations used in [1], Cheng and Todreas used the process laid out in Figure 4-1. Because we have the CTD correlation to work from, the initial WsT guess will be the equation from Equation 3.6, rather than a total guess as was necessary in the attempt to make the original CTD equation.

The process for changing the WdT and WsT factors, therefore is:

1. Calculate WdT for each bundle using Cf2 and Cf3 as calculated from Equations 3.3 and 3.4 with the initial WsT equation, 3.6.
2. Fit a WdT equation to the parameters $D_w/D$ and $H/D$.
3. Use new WdT equation to find CfbT for flow split bundles and calculate friction factor.
4. Use the flow split data to calculate WsT.
5. Fit a WsT equation to $H/D$.
6. Use the new WsT equation to calculate new WdT for bundles.
7. Fit a new WdT equation.
8. Check fit of modified CTD to empirical friction factors.
9. Attempt further adjustments to the WdT and WsT factors as necessary.
Figure 4-1: Calibration Procedure for Empirical Constants $W_d$ and $W_s$ in the turbulent region

4.2 Calculate Bundle $W_d T$

To calculate $W_d T$ for each bundle, the calculated $C_{fbT}$ for each bundle is found. $C_{fbT}$, or bundle average friction factor constant, is a constant for turbulent conditions.

\[ C_{fbT} = f \times Re^{0.18} \]  

Equation 3.1 can be rearranged to form Equations 4.2 and 4.3 to find the interior subchannel friction factor, $C_f T_1$.

\[ \text{flow}1 = \left( \frac{C_{fbT}}{De_b} \right)^{e_1} - \sum_{i=2}^{3} \left( \frac{(NiAi/Ab)(Dei/Deb)0.0989(Dei/C_{fiT})0.54945}{Dei/C_{fiT}} \right)^{-1.82} \]  

where $C_f T_2$ and $C_f T_3$ are calculated by equations 3.3 and 3.4, using the original $W_s T$ equation 3.6.
CfT1 = \frac{(flow1/(n(1))A_1}{A_b}(\frac{De_1}{De_b})^{(1/e1)}*De(1); \quad (4.3)

Equation 3.2 can then be rearranged to form Equation 4.4 to find the WdT value for each bundle.

WdT = \left(CfT1 - CfT1\left(\frac{Pwo1}{Pw1}\right)\right)\left(\frac{3 * Ar1}{Ao1}\right)(\frac{De1}{h})(\frac{De1}{dw})^{0.18} \quad (4.4)

All of the variables entering into these equations are geometric, so with CfT calculated for each bundle from the average friction factors, the only unknown is WdT. Using these equations, a WdT can be calculated for each individual bundle.

4.3 Fit WDT Equation

Once WdT is calculated for each bundle using the CfT, the next step is to fit a new equation to the calculated WdT values. Assuming that the WdT equation will take the same form as the original equation, Equation 3.5, gives an equation with four constants, with the form in Equation 4.5,

WdT = \left[C_1 - C_2(Dw/D) + C_3(Dw/D)^2\right](H/D)^{C_4} \quad (4.5)

Excel’s solver optimization tool can be used to optimize a solution for these four constants using the 79 data points of WdTs for bundles with their geometrical constants.

4.4 Use Flow Split Data to Calculate WsT

There have been several experimental bundles where the flow in the interior, edge and corner subchannels have been measured independently. These bundles, shown in Table B.1, will allow us to determine the subchannel friction factors based on the bundle average friction factor. The factors $X_1$, $X_2$, and $X_3$ of these flow split bundles are ways to compare the flow in each of the subchannels. Equation 4.6, shows the
Table 4.1: Flow Split Bundles and $X_2$ values

<table>
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<tr>
<th>ID</th>
<th>Pin Number</th>
<th>P/D</th>
<th>W/D</th>
<th>H/D</th>
<th>D</th>
<th>Dw</th>
<th>$Re_b$</th>
<th>$X_2$</th>
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<td>ANLCT91</td>
<td>91</td>
<td>1.24</td>
<td>1.24</td>
<td>48</td>
<td>12.7</td>
<td>3.05</td>
<td>20000</td>
<td>0.99</td>
</tr>
<tr>
<td>ANLRAS91</td>
<td>91</td>
<td>1.21</td>
<td>1.21</td>
<td>48</td>
<td>6.35</td>
<td>1.27</td>
<td>20000</td>
<td>1.03</td>
</tr>
<tr>
<td>ANLCT7</td>
<td>7</td>
<td>1.2</td>
<td>1.22</td>
<td>48</td>
<td>12.7</td>
<td>2.7</td>
<td>25000</td>
<td>1.012</td>
</tr>
<tr>
<td>CHEN2</td>
<td>61</td>
<td>1.25</td>
<td>1.25</td>
<td>48</td>
<td>6.35</td>
<td>1.59</td>
<td>4500</td>
<td>1.04</td>
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<td>48</td>
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<td>PNC37a</td>
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<td>1.19</td>
<td>1.19</td>
<td>34.8</td>
<td>31.6</td>
<td>6</td>
<td>14000</td>
<td>1.048</td>
</tr>
<tr>
<td>CHEN1</td>
<td>61</td>
<td>1.25</td>
<td>1.25</td>
<td>24</td>
<td>6</td>
<td>1.5</td>
<td>4500</td>
<td>1.02</td>
</tr>
<tr>
<td>UK1</td>
<td>37</td>
<td>1.25</td>
<td>1.25</td>
<td>14.8</td>
<td>10</td>
<td>2.5</td>
<td>20000</td>
<td>0.999</td>
</tr>
<tr>
<td>CHENG</td>
<td>37</td>
<td>1.154</td>
<td>1.164</td>
<td>13.4</td>
<td>6.35</td>
<td>1.59</td>
<td>26300</td>
<td>1.042</td>
</tr>
<tr>
<td>CHIU2</td>
<td>61</td>
<td>1.067</td>
<td>1.069</td>
<td>8</td>
<td>12.73</td>
<td>0.8</td>
<td>14680</td>
<td>1.21</td>
</tr>
<tr>
<td>CHANG</td>
<td>37</td>
<td>1.13</td>
<td>1.13</td>
<td>27.65</td>
<td>8</td>
<td>1</td>
<td>37100</td>
<td>1.018</td>
</tr>
</tbody>
</table>

relationship between $f_b$, $X_2$ and $f_2$, as well as that of the other subchannels.

$$\frac{f_b}{De_b} = \frac{f_1}{De_1} X_1^2 = \frac{f_2}{De_2} X_2^2 = \frac{f_3}{De_3} X_3^2$$  \hspace{1cm} (4.6)

Only the Cheng, Chang and Chiu2 bundles have friction factor data included in the data set. With WdT calculated above, $f_b$ can be determined for the ten flow split bundles that didn’t have friction factor data using the CTD correlation. Therefore, since we know Deb and De2 from the geometry of the flow split bundles, with $X_2$ from table B.1, the edge subchannel friction factor can be determined.

Equation 3.3 can be rearranged to

$$WsT = ((\frac{f_2 \cdot Re_b^{0.18}}{Cf\bar{t}_2})^{(1/1.41)} - 1) \cdot \frac{A_0}{Ar \cdot \tan^2 \theta}$$  \hspace{1cm} (4.7)

Since the ANLCT7 and UK1 bundles have an $X_2$ under 1.0, they will not be useful for our purposes because they show the wrong behaviour and will only increase the scattering of the data. For the other eleven bundles, with a WsT value found for each bundle, we can fit a new equation for WsT to $H/D$ to find the WsT values for other bundles of different geometries. Just as with the WdT equation, we will maintain the same form for the equation for WsT as in Equation 3.6. Therefore, the new WsT
equation will have two unknown constants,

\[ WsT = C1\log(H/D) - C2 \]  

(4.8)

With these constants found by fitting an equation to the data, we will have a new equation for WsT based on the flow split data, which is usable to find WsT for bundles with other geometries.

Using this new WsT equation, we can then find new WdT values for each bundle as done above with Equation 4.4 and fit a new WdT equation to the data.

### 4.5 Check New Correlation Fit and Attempt Further Adjustments to WdT and WsT as necessary

Finally, using the new WdT and WsT equations, we check the modified CTD correlation to see if it increased the accuracy of the correlation. If not, we can continue the cycle of fitting new WsT and WdT values. We also see if the new equations result in an interior friction factor higher than edge friction factor. If so, the trend of the correlation with respect to pin number should be correct.

If the trend is not correct, we will try to decrease WsT with respect to WsT and see how that changes the trend. With new WsT equations, we can calculate new WdT equations to try and maintain the accuracy of the correlation. Finally, with new WdT and WsT equations, we try again to ensure that the accuracy of the correlation has improved or at least has not decreased its overall accuracy as a result of the changes we made.
Chapter 5

Results and Discussion

5.1 Calculate Bundle WdT

Following the process outlined in Chapter 4, the first step is to find WdT values for all of the bundles in the dataset. The new WdT values are shown, compared to the old values vs. H/D in Figure 5-1 and Dw/D in Figure 5-2 from Equation 3.5. As can be seen, the bundle calculated WdTs are consistently higher than the original WdT equation, particularly at high and low H/D values.

Figure 5-1: WdT values calculated by Individual Bundles and original Equation versus H/D

Therefore, when a new equation is fit to the bundle WdT values, it will result in
Figure 5-2: WdT values calculated by Individual Bundles and original Equation versus Dw/D

![Graph of WdT values](image)

a new equation producing higher values.

### 5.2 Fit WdT Equation

Using the solver function in Excel with the calculated WdT values produces the new set of constants in Table 5.1.

<table>
<thead>
<tr>
<th>Constant</th>
<th>Original Value</th>
<th>New Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>29.5</td>
<td>13.20</td>
</tr>
<tr>
<td>C2</td>
<td>-140</td>
<td>-60.30</td>
</tr>
<tr>
<td>C3</td>
<td>401</td>
<td>167.8</td>
</tr>
<tr>
<td>C4</td>
<td>-0.85</td>
<td>-0.527</td>
</tr>
</tbody>
</table>

Therefore, the new WdT equation is shown in equation 5.1,

\[
WdT = [13.20 - 60.30(Dw/D) + 167.8(Dw/D)^2](H/D)^{-0.527} \tag{5.1}
\]

Figure 5-3 and 5-4 show the new WdT equation compared to the empirical WdTs calculated for each bundle in Section 5.1. The new WdT equation has a slightly better fit to the WdT values calculated by each bundle, particularly in the low H/D and high Dw/D region, where friction factors are high.
5.3 Use Flow Split Data to calculate WsT

Using CTD with the new WdT equation created above, CfbT values can be calculated for all of the flow split bundles. These CfbT values can be plugged into the equations in section 4.4, to find WsT values. Figure 5-5 shows the WsT values calculated using the flow split data according to the process laid out in section 4.4.

Fitting a new equation to the data gives Equation 5.2,

\[ WsT = 33.78 \log(H/D)35.694 \]  

(5.2)
5.4 Use WsT Equation to Calculate new WdT

Using the same process as above, the new Wst equation can be plugged into CTD to find WdT values for all of the bundles. From there, the WdT equations can be fit into a new equation, with the resulting constants shown in Table 5.2 compared to the original ones and the ones calculated in Section 5.2.

<table>
<thead>
<tr>
<th>Constant</th>
<th>Original Value</th>
<th>First Calculated Value</th>
<th>Value Calculated with WsT from 5.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>29.5</td>
<td>13.20</td>
<td>21.3</td>
</tr>
<tr>
<td>C2</td>
<td>-140</td>
<td>-60.30</td>
<td>-136.9</td>
</tr>
<tr>
<td>C3</td>
<td>401</td>
<td>167.8</td>
<td>402.9</td>
</tr>
<tr>
<td>C4</td>
<td>-0.85</td>
<td>-0.527</td>
<td>-0.999</td>
</tr>
</tbody>
</table>

Equation 5.3 shows the new WdT equation with these new constants.

\[
WdT = \left[21.23 - 136.9(Dw/D) + 402.9(Dw/D)^2\right](H/D)^{-0.999} \tag{5.3}
\]

5.5 Check New Correlation Fit

Unfortunately, as Figure 5-6 shows, these changes to the WdT and WsT equations significantly decrease the accuracy of the CTD correlation. In particular, the high
Figure 5-6: Predicted vs. Actual Friction Factors with changed WdT and Wst Equations

Friction factor bundles are significantly over-predicted by the correlation when Equations 5.2 and 5.3 are used to replace Equations 3.6 and 3.5. Table 5.3 shows the mean error and standard deviation with the original CTD and the new WdT and WsT equations.

Table 5.3: Mean Error and Standard Deviation for Original and CTD With Altered WsT and WdT Equations

<table>
<thead>
<tr>
<th>WdT and WsT Equations</th>
<th>Original</th>
<th>Modified</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Error</td>
<td>-0.30%</td>
<td>8.7%</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>9.60%</td>
<td>13.2%</td>
</tr>
</tbody>
</table>

5.6 Further Attempts to Fit Data

This decrease in accuracy is likely due to the uncertainty in the flow split data. Due to data scattering, the WsT values found by using the CfbTs for the flow split bundles
varies significantly. In addition, the CfbT values themselves were generated using the CTD equation, introducing significant error into the calculation. If the flow split data is too uncertain to be able to find a useful WsT equation, one option is to change the WsT equation by guessing, and see how that affects the accuracy of the correlation. Unfortunately there was not enough time for this to be fully carried out in the course of this thesis, but one example is how the accuracy changes if WsT is reduced to 80% of its original value, as shown in Equation 5.4.

\[
WsT = 16\log(H/D) - 5.6
\]  

(5.4)

This new equation, when plugged into the optimizer, gives a new WdT equation as well, with the new constants shown in Table 5.4.

<table>
<thead>
<tr>
<th>Constant</th>
<th>Original Value</th>
<th>New Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>29.5</td>
<td>26.84</td>
</tr>
<tr>
<td>C2</td>
<td>-140</td>
<td>-125.9</td>
</tr>
<tr>
<td>C3</td>
<td>401</td>
<td>399.5</td>
</tr>
<tr>
<td>C4</td>
<td>-0.85</td>
<td>-0.767</td>
</tr>
</tbody>
</table>

Therefore, this newly adjusted WdT equation is shown in equation 5.5,

\[
WdT = [26.84 - 125.9(Dw/D) + 399.5(Dw/D)^2](H/D)^{-0.767}
\]  

(5.5)

When used in the correlation, Figure 5-7 shows the predicted vs. actual friction factors for bundles in the turbulent region.

Table 5.5 shows the mean error and standard deviation of the CTD correlation with the WsT equation equal to 80% of its original value and the WdT equation calculated based on that. Although the mean error shows that this modified correlation over-predicts bundles, the reduced standard deviation shows that the calculated values scatter less compared to empirical data. This means that given more time, new values can be found which do increase the accuracy and decrease the standard deviation of the correlation.
The pin number trend of this changed correlation shows a significant dependence on H/D, as does that of the original correlation. At H/D of 25 and below, the trend is correct, while above 25 the trend shows that friction factor stays the same with pin number, and at $H/D - 48$ the trend is reversed for the pin numbers between 1.04 and 1.15.
Chapter 6

Flow-Region Boundary Behavior

6.1 Transition Region Original Correlation

In CTD, in wire-wrapped rod bundles, the transitions from laminar flow conditions and to turbulent conditions occur at varying Reynolds numbers depending on P/D of the bundle. The change from laminar to transition flow occurs with as low Reynolds numbers as 400 to 1000, and the transition to turbulent conditions occurs between 12000 and 20000, leaving a large zone with flow conditions between laminar and turbulent. In the laminar zone, the bundle average friction factor shows typical $1/Re$ behavior. For Reynolds number over the turbulent region boundary, the data follows a $1/Re^{0.18}$ behavior.

The transition regime behavior is expressed from [1] by the equation:

$$f_{br} = f_{bL}(1 - \Psi_b)^{1/3} + f_{bT}\Psi_b^{1/3}$$  \hspace{1cm} (6.1)

where $\Psi_b = \text{intermittency factor} = \log\left(\frac{Re_b}{Re_L}\right)/\log\left(\frac{Re_T}{Re_L}\right)$ and $Re_L$ and $Re_T$ are determined by equations 6.2 and 6.3,

$$\log\left(\frac{Re_L}{300}\right) = 1.7\left(\frac{P}{D}\right) - 1.0$$  \hspace{1cm} (6.2)

$$\log\left(\frac{Re_T}{10,000}\right) = 0.7\left(\frac{P}{D}\right) - 1.0$$  \hspace{1cm} (6.3)
6.2 Modified Transition Region Friction Factor

A 2013 paper by Chen et al. [10] proposed a modified friction factor formula for the transition region, Equation 6.4, to smooth the correlation’s friction factor calculation at the transition to turbulent boundary region,

\[ f_{btr} = f_{bL}(1 - \Psi_b)^{1/3}(1 - \Psi_b^\lambda) + f_{bT}(\Psi_b^{1/3}) \]  

(6.4)

where \( \lambda = 13 \).

The original CTD, without this modification, shows a bump in the correlation around the turbulent-transition boundary, which is fixed by the addition of the \( \lambda \) factor. However, \( \lambda = 13 \) does not precisely meet the slope of the data. Using lower \( \lambda \) values makes a smoother transition between laminar and transition flow regimes. As shown in Figure 6-1, \( \lambda = 7 \) fits the slope closely, but more evaluation of the correct \( \lambda \) value can be continued.

Figure 6-1: Chun1 Bundle with original CTD and Modified \( \lambda = 7 \)
6.3 Modified Laminar Transition Regime Boundary Equation

Secondly, the slope of the laminar-transition boundary equation needs to be changed. Figure 6-2 shows the observed Reynolds number values of the laminar-transition boundary at different P/Ds, compared to the original CTD equation and a proposed change. The proposed change is to change Equation 6.2 to Equation 6.5,

\[
\log\left(\frac{ReL}{300}\right) = 0.7\left(\frac{P}{D} - 1.0\right)
\]

This changes the slope from 1.7 to 0.7, the same slope as for the Turbulent transition boundary equation, Equation 6.3.

![Figure 6-2: Laminar-Transition Boundary Data Fit](image)

As shown in Figure 6-2, this change fits better with the empirical data for the laminar transition boundary.

Figure 6-3 displays the predicted versus actual friction factor values for a set of 80 bundles using both the original Cheng-Todreas correlation and the modification discussed above which changes the slope of the laminar-transition boundary equation. As can be seen, the modification predicts a set of data points directly at the transition
Table 6.1: Mean Error and Standard Deviation for Original CTD and CTD with new Transition Behavior

<table>
<thead>
<tr>
<th></th>
<th>Original CTD</th>
<th>Changed Transition Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Error</td>
<td>-.30%</td>
<td>0.30%</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>9.60%</td>
<td>9.40%</td>
</tr>
</tbody>
</table>

boundaries which were under-predicted by the original correlation better.

As shown in Table 6.1, changing the laminar transition boundary equation to a slope of 0.7 changes the mean error from -0.3 to 0.3 percent, and slightly decreases the standard deviation of the prediction. Therefore, the change is effective and improves the accuracy of the correlation.
Figure 6-3: Predicted vs. Actual Friction Factor Values for the original CTD correlation the modification to the laminar-transition boundary equation.
Chapter 7

Conclusions and Future Work

7.1 Final Changes to CTD

The conclusion of this thesis is that two changes to the Cheng-Todreas Correlation need to be made, as shown in Chapter 6. First, the $\lambda$ value, as included into the correlation in [10], needs to be decreased from $\lambda = 13$, perhaps to $\lambda = 7$. Secondly, the slope of the laminar-transition boundary equation needs to be changed from 1.7 to 0.7. These two changes improve the accuracy of the CTD correlation in the transition flow region.

Unfortunately, no final conclusion for dealing with pin number trends was reached. Although it can be shown that CTD shows an inverse response to pin number, no solution was reached. However, this thesis showed a process for working on a better pin number trend response. Importantly, the Matlab codes developed for this thesis allow changes to the correlation to be made easily and quickly, and their affects evaluated. The Matlab codes used are shown in Appendix C.

7.2 Future Work

The next steps, which I will begin over the summer after graduation, will be to attempt to further refine the WdT and WsT equations to try and obtain the correct pin number response without decreasing the accuracy of the correlation as a whole.
As briefly shown in Section 5.6, there are potential future ways by which to modify the equations and correct the inverse trend.

However, if changing the WdT and WsT equations does not work sufficiently well, or causes adverse affects to the accuracy of the correlation as a whole, the option to add in a pin number correction factor is still present. An additional factor added to the correlation based on pin number could create a correction to the trend without adversely affecting the overall accuracy. In fact, it should increase the accuracy of the correlation as a whole. However, addition of such an empirical factor will detract from the existing character of the correlation, which is derived solely on physically based arguments.

7.3 Conclusion

Despite the inverse response to pin number, CTD is still the most accurate correlation for use in determining the pressure drop in SFRs, as shown in [7]. Although correcting this trend is desirable, it is not vital to the applicability of the correlation.
Chapter 8

Bibliography


Appendix A

CTD Correlation

A.1 The Detailed Cheng and Todreas (1986) correlation

For laminar region, $Re < Re_L$

$$f = \frac{Cf_L}{Re}$$  \hspace{1cm} (A.1)

For turbulent region, $Re > Re_T$

$$f = \frac{Cf_T}{Re^{0.18}}$$  \hspace{1cm} (A.2)

For transition region, $Re_L \leq Re \leq Re_T$

$$f = \left(\frac{Cf_L}{Re}\right)(1 - \Psi_b)^{1/3} + \left(\frac{Cf_T}{Re^{0.18}}\right)\Psi_b^{1/3}$$  \hspace{1cm} (A.3)

where

$$Re_L = 300(10^{1.7(P/D-1.0)})$$  \hspace{1cm} (A.4)

$$Re_T = 10,000(10^{0.7(P/D-1.0)})$$  \hspace{1cm} (A.5)

$$\Psi_b = \frac{log(Re/Re_L)}{log(Re_T/Re_L)}$$  \hspace{1cm} (A.6)
\[ CfL = Deb \left( \sum_{i=1}^{3} (NiAi/Ab)(Dei/Deb)(Dei/CfL) \right) \] (A.7)

\[ CfT = Deb \left( \sum_{i=1}^{3} (NiAi/Ab)(Dei/Deb)^{0.0989}(Dei/CfT)^{0.54945} \right)^{-1.82} \] (A.8)

In which

\[ Cf1T = Cf1T' \left( Pw1'/Pw1 \right) + WdT \left( 3Ar1/A1' \right) \left( De1/H \right) \left( De1/Dw \right)^{0.18} \] (A.9)

\[ WdT = (29.5 - 140(Dw/D) + 401(Dw/D)^2)(H/D)^{0.85} \] (A.10)

\[ Cf2T = Cf2T' \left( 1 + WsT(Ar2/A2')tan^2\theta \right)^{1.41} \] (A.11)

\[ Cf3T = Cf3T' \left( 1 + WsT(Ar3/A3')tan^2\theta \right)^{1.41} \] (A.12)

\[ WsT = 20.0log(H/D)7.0 \] (A.13)

\[ Cf1L = Cf1L' \left( Pw1'/Pw1 \right) + WdL \left( 3Ar1/A1' \right) \left( De1/H \right) \left( De1/Dw \right) \] (A.14)

\[ WdL = 1.4WdT = (41.3 - 196(Dw/D) + 561(Dw/D)^2)(H/D)^{0.85} \] (A.15)

\[ Cf2L = Cf2L' \left( 1 + WsL(Ar2/A2')tan^2\theta \right) \] (A.16)

\[ Cf3L = Cf3L' \left( 1 + WsL(Ar3/A3')tan^2\theta \right) \] (A.17)

\[ WsL = 0.3WsT = 6.0log(H/D) - 2.1 \] (A.18)

Bare rod subchannel friction factor constants, using table A.1

\[ Cf'i = a + b(P/D - 1) + c(P/D - 1)^2 \] (A.19)

For \( i = 1 \).

For \( i = 2, 3 \) replace \( P/D \) by \( W/D \)
Table A.1: Coefficients in Equation A.19 for bare rod subchannel friction factor constants in hexagonal array.

<table>
<thead>
<tr>
<th>Constant</th>
<th>$1.0 \leq P/D(W/D) \leq 1.1$</th>
<th>$1.1 \leq P/D(W/D) \leq 1.5$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>a</td>
<td>b</td>
</tr>
<tr>
<td>$C_{f1L}$</td>
<td>26.00</td>
<td>888.2</td>
</tr>
<tr>
<td>$C_{f2L}$</td>
<td>26.18</td>
<td>554.5</td>
</tr>
<tr>
<td>$C_{f3L}$</td>
<td>26.98</td>
<td>1636.0</td>
</tr>
<tr>
<td>$C_{f1T}$</td>
<td>0.09378</td>
<td>1.398</td>
</tr>
<tr>
<td>$C_{f2T}$</td>
<td>0.09377</td>
<td>0.8732</td>
</tr>
<tr>
<td>$C_{f3T}$</td>
<td>0.1004</td>
<td>1.625</td>
</tr>
</tbody>
</table>

A.2 Changes to the CTD Correlation

\[ ReL = 300\left(10^{1.7(P/D-1.0)}\right) \]  \hspace{1cm} (A.20)

and

\[ f = \left(\frac{CfL}{Re}\right)\left(1 - \Psi_b\right)^{1/3}\left(1 - \Psi_b^7\right) + \left(\frac{CfT}{Re^{0.18}}\right)\Psi_b^{1/3} \]  \hspace{1cm} (A.21)
## Appendix B

### Experimental Bundle Data

#### Table B.1: Flow Split Bundles and $X_2$ values

<table>
<thead>
<tr>
<th>ID</th>
<th>Pin Number</th>
<th>P/D</th>
<th>W/D</th>
<th>H/D</th>
<th>D</th>
<th>Dw</th>
<th>$Re_b$</th>
<th>$X_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Symolon</td>
<td>217</td>
<td>1.25</td>
<td>1.25</td>
<td>51.72</td>
<td>5.89</td>
<td>1.47</td>
<td>12720</td>
<td>1.041</td>
</tr>
<tr>
<td>Wardfs</td>
<td>217</td>
<td>1.257</td>
<td>1.257</td>
<td>51.68</td>
<td>63.6</td>
<td>15.88</td>
<td>73000</td>
<td>1.04</td>
</tr>
<tr>
<td>ANLCT91</td>
<td>91</td>
<td>1.24</td>
<td>1.24</td>
<td>48</td>
<td>12.7</td>
<td>3.05</td>
<td>20000</td>
<td>0.99</td>
</tr>
<tr>
<td>ANLRAS91</td>
<td>91</td>
<td>1.21</td>
<td>1.21</td>
<td>48</td>
<td>6.35</td>
<td>1.27</td>
<td>20000</td>
<td>1.03</td>
</tr>
<tr>
<td>ANLCT7</td>
<td>7</td>
<td>1.2</td>
<td>1.22</td>
<td>48</td>
<td>12.7</td>
<td>2.7</td>
<td>25000</td>
<td>1.012</td>
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Appendix C

Matlab Codes

C.1 WdT Calculator

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2  % Converted and updated by Tat Nghia Nguyen, MIT’14 (nghiant@mit.edu)
3  % Further updated by Vince Kindfuller, MIT’16 (vkindfuller@gmail.com)
4
5  addpath(’Data’);
6
7  NData=79; %Number of data files
8
9  WdT=zeros(NData,3);
10  Cf1=zeros(NData,1);
11  flow=zeros(NData,3);
12  %NOTE: Raw data files must be named in form "n.mat" where n is the order
13  %For example: If there are total 69 data files, they must be named:
14  %1.mat, 2.mat, ... , 69.mat
15  for indx=1:NData
16     load(num2str(indx))
17     nre=length(re);
18     F=zeros(12,nre);
19     rel=300*10^(0.7*(pdr-1));
20     ret=10000*10^(0.7*(pdr-1));
21     WsT=20*log10(hdr)-7;
```
\begin{verbatim}
22 \text{F(13,:)=}f;
23 \text{WdT indx,1=}indx;
24 \text{WdT indx,2=}hdr;
25 \text{WdT indx,3=}dw/d;
26 \text{\% IN:}
27 \text{\% wst – WsT Guess}
28 \text{\% nrod – Number of rods}
29 \text{\% d – Rod diameter}
30 \text{\% dw – Wire diameter}
31 \text{\% pdr – Rod pitch to rod diameter ratio, P/D}
32 \text{\% wdr – Edge pitch parameter to rod diameter ratio, W/D}
33 \text{\% hdr – Wire lead length to rod diameter ratio, H/D}
34 \text{\% re – Reynolds number}
35 \text{\% CfTb – bundle average friction factor constant}
36 \%
37 \text{\% OUT:}
38 \text{\% WdT}
39
40 \text{rel=324*10^(0.93*(pdr-1));}
41 \text{ret=10000*10^(0.7*(pdr-1));}
42
43 \text{\% GEOMETRICAL PARAMETERS}
44 \text{nring=(3+sqrt(12*nrod-3))/6-1;}
45 \text{n=zeros(3,1);}
46 \text{n(1)=6*nring^2;}
47 \text{n(2)=6*nring;}
48 \text{n(3)=6;}
49 \text{p=pdr*d;}
50 \text{w=wdr*d;}
51 \text{h=hdr*d;}
52
53 \text{\% Bare rod flow area and wetted perimeter}
54 \text{Ao=zeros(3,1);}
55 \text{Ao(1)=(sqrt(3)/4)*p^2-pi*d^2/8;}
56 \text{Ao(2)=p*(w-d/2)-pi*d^2/8;}
\end{verbatim}
58 \[ Ao(3) = (w-d/2)^2/\sqrt{3} - \pi \cdot d^2/24; \]
59 \[ Pwo = \text{zeros}(3,1); \]
60 \[ Pwo(1) = \pi \cdot d/2; \]
61 \[ Pwo(2) = p + \pi \cdot d/2; \]
62 \[ Pwo(3) = \pi \cdot d/6 + 2/\sqrt{3} \cdot (w-d/2); \]
63
64 \% Wire-wrapped flow area and wetted perimeter
65 \[ \text{sinth} = \pi \cdot (d+dw)/\sqrt{h^2 + (\pi \cdot (d+dw))^2}; \]
66 \[ \text{costh} = h/\sqrt{h^2 + (\pi \cdot (d+dw))^2}; \]
67 \[ \text{tanh} = \text{sinth}/\text{costh}; \]
68 \[ A = Ao - \pi \cdot dw^2/(8 \cdot \text{costh}) \cdot [1 1 1/3]'; \]
69 \[ Ab = \text{sum}(n.*A); \]
70 \[ Pw = Pwo + \pi \cdot dw/(2 \cdot \text{costh}) \cdot [1 1 1/3]'; \]
71 \[ Pwb = \text{sum}(n.*Pw); \]
72
73 \% Wire projected area
74 \[ Ar = \pi \cdot (d+dw) \cdot dw \cdot [1/6 1/4 1/6]'; \]
75
76 \% Hydraulic equivalent diameter
77 \[ De = 4 \cdot A./Pw; \]
78 \[ Deb = 4 \cdot Ab/Pwb; \]
79
80 \% Coefficients for bare rod subchannel friction factor constants
81 \% in hexagonal array
82 \textbf{if} pdr < 1.1
83 \[ \text{abc} = [26.00 \quad 888.2 \quad -3334.0 \]
84 \[ \quad 26.18 \quad 554.5 \quad -1480.0 \]
85 \[ \quad 26.98 \quad 1636.0 \quad -10050.0 \]
86 \[ \quad 0.09378 \quad 1.398 \quad -8.664 \]
87 \[ \quad 0.09377 \quad 0.8732 \quad -3.341 \]
88 \[ \quad 0.1004 \quad 1.625 \quad -11.85]; \]
89 \textbf{else}
90 \[ \text{abc} = [62.97 \quad 216.9 \quad -190.2 \]
91 \[ \quad 44.40 \quad 256.7 \quad -267.6 \]
92 \[ \quad 87.26 \quad 38.59 \quad -55.12 \]
93 \[ \quad 0.1458 \quad 0.03632 \quad -0.03333 \]
Cflo = abc (1:3, 1) + abc (1:3, 2) * (wdr − 1) + abc (1:3, 3) * (wdr − 1)^2;

Cflo (1) = abc (1, 1) + abc (1, 2) * (pdr − 1) + abc (1, 3) * (pdr − 1)^2;

Cfto = abc (4:6, 1) + abc (4:6, 2) * (wdr − 1) + abc (4:6, 3) * (wdr − 1)^2;

Cfto (1) = abc (4, 1) + abc (4, 2) * (pdr − 1) + abc (4, 3) * (pdr − 1)^2;

C1 = 29.5;
C2 = −140;
C3 = 401;
C4 = −0.85;

WdT (indx, 4) = (C1 + C2 * (dw/d) + C3 * (dw/d)^2) * hdr * (C4);

WdT (indx, 4) = (5.493 − 4.12 * dw/d + 23.7 * dw/d^2) * hdr * −0.4;

WdT (indx, 4) = (29.5 − 140 * (dw/d) + 401 * (dw/d)^2) * hdr * (−0.85);

WsT = 16 * log10 (hdr) − 5.6;

WsT = 11.35 * log (hdr) − 16.58;

WsT = 33.78 * log (hdr) − 35.69;

WdL = 1.4 * WdT;

WsL = 0.3 * WsT;

em = 0.18;
e1 = 1 / (em − 2);
e2 = em / (2 − em);

% CfL = Cflo * (1 + WsL * (Ar ./ Ao) * tanh^2);

% CfL (1) = Cflo (1) * (Pwo (1) / Pw (1)) + WdL * 3 * Ar (1) / Ao (1) * De (1) / h * De (1) / dw;

% CfT = Cfto * (1 + WsT * Ar ./ Ao * tanh^2) * 1.41;

% CfT (1) = Cfto (1) * Pwo (1) / Pw (1) + WdT (indx, 4) * 3 * Ar (1) / Ao (1) * De (1) / h * (De (1) / dw)

% CT = Deb * (sum (n. * A / Ab. * (De / Deb)).^e2 * (De ./ CfT).^e1) / (−1.82);

flow2 = n (2) * (A (2) / Ab) * (De (2) / Deb)^e2 * (CfT (2) / De (2))^e1;

flow3 = n (3) * (A (3) / Ab) * (De (3) / Deb)^e2 * (CfT (3) / De (3))^e1;

flow1 = (CfTb / Deb)^e1 − flow2 − flow3;
\%(\sum(n(2:3) \cdot A(2:3) / Ab \cdot (De(2:3) / Deb) \cdot e2 \cdot (De(2:3) / CfT(2:3)) \cdot e1))

flow(indx,1)=flow1;
flow(indx,2)=flow2;
flow(indx,3)=flow3;

CfT1=(flow1 / (n(1) \cdot (A(1) / Ab) \cdot (De(1) / Deb) \cdot e2)) ^ (1/e1) \cdot De(1);

%Cf1(indx,3)=CfT1;
Cf1(indx,4)=CfT(2);
Cf1(indx,5)=CfT(3);
Cf1(indx,3)=CfT(1);
Cf1(indx,1)=hdr;
Cf1(indx,2)=pdr;

WdT(indx,5)=CfT1 - Cfto(1) \cdot Pwo(1) / Pw(1) / (3 \cdot Ar(1) / Ao(1) \cdot De(1) / h \cdot (De(1) / dw) \cdot 0.18);

%WdT(indx,6)=CfTb - Cfto(1) \cdot Pwo(1) / Pw(1) / (3 \cdot Ar(1) / Ao(1) \cdot De(1) / h \cdot (De(1) / dw) \cdot 0.18);

%CL=Deb \cdot (\sum(n \cdot A / Ab \cdot De / Deb / CfL)) ^ (-1);

CT=Deb \cdot (\sum(n \cdot A / Ab \cdot De / Deb / CfL) \cdot e2 \cdot (CfT / De) \cdot e1) ^ (-1.82);

CfbT(indx,1)=nrod;
CfbT(indx,2)=pdr;
CfbT(indx,3)=hdr;
CfbT(indx,4)=CT;

end

xlswrite('WdT',WdT);
xlswrite('Cf1',Cf1);
xlswrite('Flow',flow);
xlswrite('CfbT',CfbT);
C.2 Masterfile

% This file is used to:
% STEP 1:  - Calculate the error statistics tables
%          - Plot the FF figures and histograms
% STEP 2:  - Calculate the RMS tables
%          - Convert the RMS values to CV values and B&S Agreement index
% IN:  Data files containing Reynolds number values and corresponding
%      friction factor values predicted by each correlation
% OUT:
%      - STEP 1: Set cal_step=1 to perform Step 1
%          - Figures and histograms are plotted automatically
%          - Error statistics table:
%             mea   - Mean values
%             stdv  - Standard deviation values
%             corrange  - Error values that cover 90% data
%      - STEP 2:
%             rms   - RMS values
%             cs    - Credit score values
%             BSAI  - B&S Agreement index values

% Created by Tat Nghia Nguyen, MIT’14 | nghiant@mit.edu
% Extensively edited by Vince Kindfuller, MIT’16 [vkindfuller@gmail.com]
clear all
close all
clc
cal_step=1;

% Set default plotting properties
pos=[60 60 957 910];
set(0, 'DefaultFigurePosition', pos);
set(0, 'DefaultAxesFontName', 'Helvetica')
set(0,'DefaultAxesFontSize', 12)

% GIVE MATLAB ACCESS TO NECESSARY DIRECTORIES IN THE COMPUTER

% 1. The directory containing the data files
addpath('AData');

% 2. The directory containing the plotting functions
addpath('Plotting_supp');

Corr_name={'
bfRehme correlation', '
bfBaxi and Dalle Donne correlation'

'bfDetailed Cheng and Todreas correlation', ....
'bfSimplified Cheng and Todreas correlation', ....
'bfModified Baxi and Dalle Donne correlation', ....
'bfKirillov correlation', '
bfZhukov correlation', ....
'bfModified Zhukov correlation', '
bfNovendstern correlation', ....
'bfZhukov turbulent correlation', '
bfCTD with 80% WsT Equation', '

→ bfCT_Modb'};

Corr_list=[
'1. Rehme correlation' char(12) '2. Baxi and Dalle Donne correlation'

'3. Detailed Cheng and Todreas correlation' char(12) ...
'4. Simplified Cheng and Todreas correlation' char(12) '5. Modified Baxi and Dalle Donne correlation' char(12) ...
'6. Kirillov correlation' char(12) '7. Zhukov correlation' char(12) ...

'8. Modified Zhukov correlation' char(12) '9. Novendstern correlation'

'10. Zhukov turbulent correlation' char(12) ...
'11. Cheng Todreas Mod A' char(12) '12. Cheng Todreas Mod B'];

classes={'
All bundles', 'Fuel bundles', 'Blanket & control bundles', ....

'Bundles with P/D>1.1', 'Bundles with P/D>1.06'};

class1 = []; % All bundles with TT data.
class2 = []; % Fuel bundles
class3 = []; % Blanket & control bundles
class4 = []; % Bundles with P/D>1.1
class5 = []; \% Bundles with P/D > 1.06
N_bundles=input('Please enter the number of data bundles: ');
Group_ID=zeros(1,N_bundles);
for i=1:N_bundles
    load(num2str(i))
    class1=[class1 i];
    if (1.10<=pdr && pdr<=1.3) && (20<=hdr && hdr<=54)
        Group_ID(i)=1;
        class2=[class2 i];
    end
    if (1.04<=pdr && pdr<=1.13) && (7<=hdr && hdr<=23)
        Group_ID(i)=2;
        class3=[class3 i];
    end
    if Group_ID(i)==0
        Group_ID(i)=3;
    end
    if pdr>1.06
        class5=[class5 i];
    end
    if pdr>1.1
        class4=[class4 i];
    end
end
class_list=['1. All bundles' char(10) '2. Fuel bundles' char(10) '3. Blanket & control bundles'...
            char(10) '4. Bundles with P/D>1.1' char(10) '5. Bundles with P/D > 1.06'];
display(class_list,'List of pre-created classes: ')
D=input('Please enter the ID of a pre-created class to proceed or enter 6 to create a new class: ');
if D==1
    corr_list=[3 11];
    Datain=class1;
elseif D==2
    corr_list=[1 2 3 4 5 6];
    Datain=class2;
elseif D==3
    corr_list=[1 2 3 4 5 6 7 8];
    Datain=class3;
elseif D==4
    corr_list=[1 2 3 4 5 6];
    Datain=class4;
elseif D==5
    corr_list=[1 2 3 4 5 6 9 10];
    Datain=class5;
elseif D==6
    Datain=input('Please enter the new class in form of a row vector (with components are bundle IDs) : ');
    classname=input('Please set a name for this class : ', 's');
    display(Corr_list,'List of available correlations');
    corr_list=input('Please enter a list of correlations in form of a row vector : ');
end
if D==6
    display(Corr_list,'List of available correlations ')
    display(corr_list,'Selected correlations ')
    corr_c=input('Enter 1 to re-select the correlations, 0 to keep it the same : ');
    if corr_c==1
        corr_list=input('Please enter a list of correlations in form of a row vector : ');
    else
        end
    end
Dr=input(['Please choose a data region (1 for Laminar, 2 for Transition, ' char(10) ...' ]);
'3 for Turbulent, 23 for Transition/Turbulent or 123 for all 3 flow
regimes');

%Choose save_fig=1 to save figures. After saving, MATLAB will automatically close every figure

answer=input('Do you want to save the figures (Y/N): ', 's')

if strcmp(answer, 'Y')
    save_fig=1;
else
    save_fig=0;
end

RM= []; RMid = []; 

for i=1:length(Datain)
    load(num2str(Datain(i)));
    if Dr==1 && min(re)>=rel
        RM=[RM i];
        RMid=[RMid Datain(i)];
    end
    if Dr==2
        if max(re)<rel || min(re)>ret
            RM=[RM i];
            RMid=[RMid Datain(i)];
        end
    end
    if Dr==3 && max(re)<ret
        RM=[RM i];
        RMid=[RMid Datain(i)];
    end
    if Dr==23 && max(re)<rel
        RM=[RM i];
        RMid=[RMid Datain(i)];
    end
end

nb=0;

for rm=RM
Datain (rm−nb) = [];  

nb=nb+1;  

end  

NData=length(Datain);  

position=zeros(length(Group.ID),1);  

if D==1  
  if Nbundles==88  
    classname=strcat('All (',num2str(NData−8),') bundles and 8 CFD results');  
  elseif Nbundles==22  
    classname=strcat('Bubelis and Schikorr (',num2str(NData),') bundles');  
  else  
    classname=strcat('All (',num2str(NData),') bundles');  
  end  
  elseif D==2  
    classname=strcat('Fuel (',num2str(NData),') bundles');  
  elseif D==3  
    classname=strcat('Blanket and control (',num2str(NData),') bundles');  
  elseif D==4  
    classname=strcat('All (',num2str(NData),') bundles with P/D > 1.1');  
  elseif D==5  
    classname=strcat('All (',num2str(NData),') bundles with P/D > 1.06');  
  else  
    classname=strcat(classname, ' (',num2str(NData),') bundles');  
  end  

%ncorr= %number of correlations  

nct=size(F,1);  

ncorr=length(corr_list);  

pO=0;  

FL1=[];
```matlab
while cal_step==1
    f_min =10;
    f_max=0;
    FF_plot=1;
    HIS_plot=1;
    n1=0;
    n2=0;
    n3=0;
    for i =1:NData
        tt = [];
        id=Datain(i);
        load(num2str(id));
        nre=length(re);
        if Dr==1
            nmin=1;
            tt=find(re>rel);
            if isempty(tt)
                nmax=length(re);
            else
                nmax=tt(1)-1;
            end
        else
            tt=find(re>rel);
            t=find(re>ret);
            if isempty(tt)
                ntt=nre;
            else
                ntt=tt(1);
            end
            if isempty(t)
                nt=nre;
            end
```
else
    nt=t(1);
end
nmin=nnt;
max=nre;
if Dr==2
    nmax=nt-1;
elseif Dr==3
    nmin=nt;
elseif Dr==123
    nmin=1;
    nmax=nre;
end
end
if f_min>min(F(nct,nmin:nmax))
    f_min=min(F(nct,nmin:nmax));
end
if f_max < max(F(nct,nmin:nmax))
    f_max=max(F(nct,nmin:nmax));
end
if i==1
    FT=F(:,nmin:nmax);
else
    FT=[FT F(:,nmin:nmax)];
end
if Group_ID(id)==1
    n1=n1+1;
    if Dr==1||Dr==123
        if isempty(FL1)
            FL1=F(:,nmin:nmax);
        else
            FL1=[FL1 F(:,nmin:nmax)];
        end
    end
    if Dr˜=1
        if isempty(FT1)
FTT1 = F(:, ntt : (nt - 1));
FT1 = F(:, nt : nre);
else
FTT1 = [FTT1 F(:, ntt : (nt - 1))];
FT1 = [FT1 F(:, nt : nre)];
end
end
elseif Group_ID(id) == 2
n2 = n2 + 1;
if Dr == 1 || Dr == 123
  if isempty(FL2)
    FL2 = F(:, nmin : nmax);
  else
    FL2 = [FL2 F(:, nmin : nmax)];
  end
endif
if Dr^= 1
  if isempty(FT2)
    FTT2 = F(:, ntt : (nt - 1));
    FT2 = F(:, nt : nre);
  else
    FTT2 = [FTT2 F(:, ntt : (nt - 1))];
    FT2 = [FT2 F(:, nt : nre)];
  end
end
else
n3 = n3 + 1;
if Dr == 1 || Dr == 123
  if isempty(FL3)
    FL3 = F(:, nmin : nmax);
  else
    FL3 = [FL3 F(:, nmin : nmax)];
  end
endif
if Dr^= 1
  if isempty(FT3)
  end
end
if Dr==1 || Dr==123
    a=[f_min f_max];
else
    a=[1e-2 0.3];
end
for corr=1:ncorr
    icorr=corr_list(corr);
    if FF_plot==1
        figure(corr)
        loglog(1e-3,1e-3,'wo', 'MarkerSize',1);
        hold on
        if (D==1||D==4||D==5||D==6)
            loglog(1e-3,1e-3,'k^', 'MarkerFaceColor', 'k');
            loglog(1e-3,1e-3,'kv', 'MarkerFaceColor', 'k');
            loglog(1e-3,1e-3,'ko', 'MarkerFaceColor', 'k');
        end
        sa=[1e-3 1e-5];
        loglog(sa,sa,'k-', 'LineWidth',2);
        if Dr==1
            regi='\fontsize{16}Laminar regime';
        elseif Dr==2
            regi='\fontsize{16}Transition regime';
        elseif Dr==3
            regi='\fontsize{16}Turbulent regime';
        elseif Dr==23
            regi='\fontsize{16}Transition/Turbulent regime';
        elseif Dr==123
            regi='\fontsize{16}Transition/Turbulent regime';
        end
    end
end
regi='\text{All flow regimes}';

else
    error('Incorrect data region id');
end

if Dr==23
    grpn='(Blue-turbulent, Pink-transition)';
elseif Dr==123
    grpn=['(Black-Laminar, ' char(10) 'Blue→ Turbulent, Pink-Transition)'];
else
    grpn='';
end

if D==2||D==3
    if Dr==123
        hL=legend([regi, grpn], . . .
        '\text{pm 20\% lines}', 'Location', 'SouthEast')
    else
        hL=legend([regi char(10) grpn], . . .
        '\text{pm 20\% lines}', 'Location', 'SouthEast')
    end
else
    if Dr==123
        hL=legend([regi grpn], . . .
        '\text{Group 1 – Fuel assembly}', . . .
        '\text{Group 2 – Blanket and control assembly}'
        . . .
        '\text{pm 20\% lines}', 'Location', 'SouthEast')
    else
        hL=legend([regi char(10) grpn], . . .
        '\text{Group 1 – Fuel assembly}', . . .
        '\text{pm 20\% lines}', 'Location', 'SouthEast')
    end
end
Group 3 – Others, ...

pm 20% lines, 'Location', 'SouthEast')

end

end

legend boxoff

if n1>0
    if Dr==1
        loglog(FL1(nct,:),FL1(icorr,:), 'k^', 'MarkerFaceColor 

    elseif Dr==2
        loglog(FTT1(nct,:),FTT1(icorr,:), 'm^', ' 

    elseif Dr==3
        loglog(FT1(nct,:),FT1(icorr,:), 'b^', 'MarkerFaceColor 

    elseif Dr==23
        loglog(FTT1(nct,:),FTT1(icorr,:), 'm^', ' 

    else 
        loglog(FL1(nct,:),FL1(icorr,:), 'k^', 'MarkerFaceColor 

end

if n2>0
    if Dr==1
        loglog(FL2(nct,:),FL2(icorr,:), 'kv', 'MarkerFaceColor 

    elseif Dr==2
loglog(F2(nct,:),F2(icorr,:),'bv','MarkerFaceColor'→'b','MarkerSize',5);

else if Dr==3
loglog(F2(nct,:),F2(icorr,:),mv,'MarkerFaceColor'→m,'MarkerSize',5);

elseif Dr==23
loglog(F2(nct,:),F2(icorr,:),mv,'MarkerFaceColor'→m,'MarkerSize',5);

else
loglog(FTT2(nct,:),FTT2(icorr,:),mv,'MarkerFaceColor'→m,'MarkerSize',5);

loglog(F2(nct,:),F2(icorr,:),bv,'MarkerFaceColor'→b,'MarkerSize',5);

end

if n3>0

if Dr==1
loglog(FL3(nct,:),FL3(icorr,:),ko,'MarkerFaceColor'→k,'MarkerSize',5);

else if Dr==2
loglog(FTT3(nct,:),FTT3(icorr,:),mo,'MarkerFaceColor'→m,'MarkerSize',5);

else if Dr==3
loglog(FT3(nct,:),FT3(icorr,:),bo,'MarkerFaceColor'→b,'MarkerSize',5);

else if Dr==23
loglog(FTT3(nct,:),FTT3(icorr,:),mo,'MarkerFaceColor'→m,'MarkerSize',5);

loglog(FT3(nct,:),FT3(icorr,:),bo,'MarkerFaceColor'→b,'MarkerSize',5);

else
\texttt{loglog}(FL3(nct,:,),FL3(icorr,:),'ko', 'MarkerFaceColor' → 'k', 'MarkerSize', 5);

\texttt{loglog}(FTT3(nct,:),FTT3(icorr,:),'mo', '
\rightarrow MarkerFaceColor', 'm', 'MarkerSize', 5);

\texttt{loglog}(FT3(nct,:),FT3(icorr,:),'bo', 'MarkerFaceColor' → 'b', 'MarkerSize', 5);

\texttt{end}

\texttt{xlabel}(\texttt{\textbackslash fontsize}\{21\} \texttt{f} \{\texttt{measured}\})

\texttt{ylabel}(\texttt{\textbackslash fontsize}\{21\} \texttt{f} \{\texttt{predicted}\})

\texttt{loglog}(a,1.2*a,'k-', 'LineWidth', 2)

\texttt{loglog}(a,0.8*a,'k-', 'LineWidth', 2)

\texttt{if} Dr==1 || Dr==123

\texttt{axis}([f_{min} f_{max} f_{min} f_{max}])

\texttt{text}(1.3*f_{min},0.85*f_{max}, Corr\_name(icorr),'FontSize', → 16)

\texttt{text}(1.3*f_{min},0.69*f_{max},[classname, ', ', regi],'
\rightarrow FontSize', 16)

\texttt{else}

\texttt{axis}([1e-2 0.3 1e-2 0.3])

\texttt{text}(0.011,0.26, Corr\_name(icorr),'FontSize', 16)

\texttt{text}(0.011,0.23,[classname, ', ', regi],'FontSize', 16)

\texttt{end}

\texttt{plotfixer\_paper}

\texttt{if} save\_fig==1

\texttt{export\_fig(num2str(corr),'-tif','-nocrop','-transparent'
\rightarrow ,'-r300')}

\texttt{\% Change '-tif' to set the desired output file format}

\texttt{\% Chan '-r300' to set the desired output image resolution}

\texttt{\%For more information, refer to the export\_fig file}

\texttt{end}

\texttt{end}

\texttt{\% % % HIS plot}

\texttt{N\_points=length(FT(1,:));}
err = zeros(ncorr, length(FT(1,:)));  
for corr = 1:ncorr  
    icorr = corr_list(corr);  
    err(corr,:) = 100*(FT(icorr,:) - FT(ncnt,:))/FT(ncnt,:);  
end  
mea = zeros(1,ncorr);  
stdv = zeros(1,ncorr);  

npoint = 0;  
corrange = mea;  
for corr = 1:ncorr  
    erange = 0;  
    npoint = 0;  
    while npoint < 0.9*N_points  
        npoint = 0;  
        erange = erange + 0.1;  
        for i = 1:N_points  
            if abs(err(corr,i)) < erange  
                npoint = npoint + 1;  
            end  
        end  
    end  
    corrange(corr) = erange;  
end  

for corr = 1:ncorr  
    mea(corr) = mean(err(corr,:));  
    stdv(corr) = std(err(corr,:));  
end  
con_level = zeros(1,ncorr);  
for corr = 1:ncorr  
    low_b = 0;  
    high_b = 2*1.65*stdv(corr);  
    flag_OK = 0;  
    while flag_OK == 0
\( \text{con}_{\text{lvl}} = (\text{low}_b + \text{high}_b) / 2; \)
\( \text{a1} = (\text{con}_{\text{lvl}} + \text{mea}(\text{corr})) / \text{stdv}(\text{corr}); \)
\( \text{a2} = (\text{con}_{\text{lvl}} - \text{mea}(\text{corr})) / \text{stdv}(\text{corr}); \)
\( \text{p1} = 1 - \text{normcdf}(\text{a1}, 0, 1); \)
\( \text{p2} = 1 - \text{normcdf}(\text{a2}, 0, 1); \)
\( \text{rerr} = (\text{p1} + \text{p2} - 0.1) / 0.1; \)
\( \text{if} \ \text{rerr} < -0.001 \)
\( \text{high}_b = \text{con}_{\text{lvl}}; \)
\( \text{elseif} \ \text{rerr} > 0.001 \)
\( \text{low}_b = \text{con}_{\text{lvl}}; \)
\( \text{else} \)
\( \text{con}_{\text{level}}(\text{corr}) = \text{con}_{\text{lvl}}; \)
\( \text{flag}_{\text{OK}} = 1; \)
\( \text{end} \)
\( \text{end} \)
\( \text{display}(\text{mea}, '\text{Mean values}'); \)
\( \text{display}(\text{stdv}, '\text{Standard deviation values}'); \)
\( \text{disp}(\text{corrname}, '\text{Error values that cover 90\% data points}'); \)
\( \text{disp}(\text{con}_{\text{level}}, '\text{90\% confidence level}'); \)
\( \text{x} = -100:2:100; \)
\( \text{if} \ \text{HIS}_{\text{plot}} = 1 \)
\( \text{for} \ \text{corr} = 1: \text{ncorr} \)
\( \text{icorr} = \text{corr}_{\text{list}}(\text{corr}); \)
\( \text{if} \ \text{icorr} = 1 \)
\( \text{corrname} = '\text{bfRehme correlation}'; \)
\( \text{elseif} \ \text{icorr} = 2 \)
\( \text{corrname} = '\text{bfBaxi and Dalle Donne correlation}'; \)
\( \text{elseif} \ \text{icorr} = 3 \)
\( \text{corrname} = '\text{bfDetailed Cheng and Todreas correlation}'; \)
\( \text{elseif} \ \text{icorr} = 4 \)
\( \text{corrname} = '\text{bfSimplified Cheng and Todreas correlation}'; \)
\( \text{elseif} \ \text{icorr} = 5 \)
\( \text{corrname} = '\text{bfModified Baxi and Dalle Donne correlation}'; \)
\( \text{elseif} \ \text{icorr} = 6 \)
\( \text{corrname} = '\text{bfKirillov correlation}'; \)
85
elseif icorr==7
corrname='\bfZhukov correlation';
elseif icorr==8
corrname='\bfModified Zhukov correlation';
elseif icorr==9
corrname='\bfNovendstern correlation';
elseif icorr==10
corrname='\bfZhukov turbulent correlation';
elseif icorr==11
corrname='\bfCT ModA';
else
corrname='\bfCT ModB';
end
for j=1:101
   Fx(j)=N_points*2*Normal.dis(x(j),mea(corr),stdv(corr));
end
figure(corr+ncorr)
plot(0,0,'w. ')
hold on
hist(err(corr,:),x)
h = findobj(gca,'Type','patch');
set(h,'FaceColor',[0.65 0.65 1])
plot(0,0,'w. ')
plot(x,Fx,'b−','LineWidth',2);
plot(0,0,'w. ')
hs=Corr.name(corr_list(corr));
ymaxv=10*round(NData/6);
hleg1=legend(corrname,regi,...
   ['(' ,classname ,')', num2str(N_points),', data points]
  .chomp] ,...
   'Normal distribution',strcat( '('Mean = ',...
   num2str(mea(corr),'%6.1f'),',% STD = ',num2str(stdv(corr
   -> '),',%6.1f'),',%)')));
legend boxoff
set(hleg1,'Location','NorthWest')
set(hleg1,'FontSize',16);
if Dr==1
    axis([-100 100 0 20])
else
    axis([-100 100 0 ymaxv])
end
plotfixer_paper
if save_fig==1
    export_fig(num2str(corr+ncorr),'-tif','-nocrop','-transparent','-r300')
end
end
if save_fig==1
    close all
end
cal_step=2;
end
while cal_step==2
    rms=zeros(NData,ncorr);
    for i=1:NData
        id=Datain(i);
        position(id,1)=1;
        load(num2str(id))
        nre=length(re);
        temp=zeros(ncorr,nre);
        if Dr==1
            nmin=1;
            tt=find(re>rel);
            if isempty(tt)
                nmax=length(re);
            else
                nmax=tt(1)-1;
            end
        else
            nmax=tt(1)-1;
        end
        end
    end
end

tt = find(re > rel);

r = find(re > ret);

if isempty(tt)
    ntt = nre;
else
    ntt = tt(1);
end

if isempty(r)
    nrr = nre;
else
    nrr = r(1);
end

nmin = ntt;
nmax = nre;

if Dr == 2
    nmax = nt - 1;
elseif Dr == 3
    nmin = nt;
elseif Dr == 123
    nmin = 1;
nmax = nre;
end

for corr = 1:ncorr
    icorr = corr_list(corr);
    temp(corr,:) = ((F(icorr,:) - F(nct,:)) ./ F(nct,:)) .^ 2;
    rms(i,corr) = mean(temp(corr,nmin:nmax)) .^ 0.5;
end

end

cs = 10 * (0.2 - rms);

for i = 1:NData
    for j = 1:ncorr
        if cs(i,j) > 1
            cs(i,j) = 1;
        elseif cs(i,j) < 0
            cs(i,j) = 0;
        end
    end
end
Meane=zeros(1,ncorr);
STDE=zeros(1,ncorr);
for i=1:ncorr
    Meane=mean(rms(:,i));
    STDE=mean(rms(:,i));
end
BSAI=zeros(NData,ncorr);
for i=1:NData
    for j=1:ncorr
        if rms(i,j)<=0.1
            BSAI(i,j)=3;
        elseif rms(i,j)<=0.2
            BSAI(i,j)=2;
        elseif rms(i,j)<=0.3
            BSAI(i,j)=1;
        else
            BSAI(i,j)=0;
        end
    end
end
BSAI(NData+1,:)=sum(BSAI);
cs(NData+1,:)=sum(cs);
rms(NData+1,:)=mean(rms);
cal_step=0;
end
display(rms,'RMS table ')
display(cs,'Credit score table ')
display(BSAI,'B & S AI table ')
display(RMid,'The following bundles have no data in the selected region: ')
end
C.3 Flow Split Analysis

```matlab
clear all
close all
clc

%Flow Split Data
% This file is used to create raw data files from geometric inputs

% IN:
% nrod – Number of rods
% d – Rod diameter
% dw – Wire diameter
% pdr – Rod pitch to rod diameter ratio, P/D
% wdr – Edge pitch parameter to rod diameter ratio, W/D
% hdr – Wire lead length to rod diameter ratio, H/D
% re – Reynolds numbers
% f – Experimental friction factor values
% CfT –

% OUT:
% Raw data files – to be loaded and used by the Calculation file

% Geometric parameters. Example:
geo= xlsread('flowsplit','B2:J10');

pin=geo(:,4);
di=geo(:,5);
dwr=geo(:,6);
pd=geo(:,2);
wd=geo(:,3);
hd=geo(:,1);
```
Reb=geo(:,7);
X2=geo(:,8);
Cfb=geo(:,9);

%experimental data: column 1 = Re, column 2 = f.
\%data=xlsread('flowsplit','H2;I13');

\%re=data(:,1)';
\%f=data(:,2)';

\%save('name'), where name= the bundle order

WsTex=zeros(9,3);

for indx=1:9
  nrod=pin(indx);
  d=di(indx);
  dw=dwr(indx);
  pdr=pd(indx);
  wdr=wd(indx);
  hdr=hd(indx);
  WsTex(indx,1)=hdr;

  \%CTD Correlation:
  \%rel=300*10^(1.7*(pdr-1)); \%original Correlation
  \%rel=324*10^(0.93*(pdr-1)); \%Mod A (fit to rel values)
  rel=350*10^(0.7*(pdr-1)); \%Mod B (same slope as turbulent transition)
  ret=10000*10^(0.7*(pdr-1));
%GEOMETRICAL PARAMETERS

nring=(3+sqrt(12*nrod-3))/6-1;

n=zeros(3,1);

n(1)=6*nring^2;
n(2)=6*nring;
n(3)=6;
p=pdr*d;
w=wdr*d;
h=hdr*d;

%Bare rod flow area and wetted perimeter

Ao=zeros(3,1);
Ao(1)=(sqrt(3)/4)*p^2-pi*d^2/8;
Ao(2)=p*(w-d/2)-pi*d^2/8;
Ao(3)=(w-d/2)^2/sqrt(3)-pi*d^2/24;
Pwo=zeros(3,1);
Pwo(1)=pi*d/2;
Pwo(2)=p+pi*d/2;
Pwo(3)=pi*d/6+2/sqrt(3)*(w-d/2);

%Wire-wrapped flow area and wetted perimeter

sinth=pi*(d+dw)/sqrt(h^2+(pi*(d+dw))^2);
costh=h/sqrt(h^2+(pi*(d+dw))^2);
tanth=sinth/costh;
A=Ao-pi*dw^2/(8*cosoth)*[1 1 1/3]';
Ab=sum(n*A);
Pw=Pwo+pi*dw/(2*cosoth)*[1 1 1/3]';
Pwb=sum(n*Pw);

%Wire projected area

Ar=pi*(d+dw)*dw*[1/6 1/4 1/6]';

%Hydraulic equivalent diameter

De=4*A./Pw;
Deb=4*Ab/Pwb;
Coefficients for bare rod subchannel friction factor constants

in hexagonal array

if \( \text{pdr} < 1.1 \)

\[
\begin{bmatrix}
26.00 & 888.2 & -3334.0 \\
26.18 & 554.5 & -1480.0 \\
26.98 & 1636.0 & -10050.0 \\
0.09378 & 1.398 & -8.664 \\
0.09377 & 0.8732 & -3.341 \\
0.1004 & 1.625 & -11.85
\end{bmatrix};
\]

else

\[
\begin{bmatrix}
62.97 & 216.9 & -190.2 \\
44.40 & 256.7 & -267.6 \\
87.26 & 38.59 & -55.12 \\
0.1458 & 0.03632 & -0.03333 \\
0.1430 & 0.04199 & -0.04428 \\
0.1499 & 0.006706 & -0.009567
\end{bmatrix};
\]

end

\[
\text{Cflo} = \text{abc}(:,1) + \text{abc}(:,2) \times (\text{wdr} - 1) + \text{abc}(:,3) \times (\text{wdr} - 1)^2;
\]

\[
\text{Cflo}(1) = \text{abc}(1,1) + \text{abc}(1,2) \times (\text{pdr} - 1) + \text{abc}(1,3) \times (\text{pdr} - 1)^2;
\]

\[
\text{Cfto} = \text{abc}(4:6,1) + \text{abc}(4:6,2) \times (\text{wdr} - 1) + \text{abc}(4:6,3) \times (\text{wdr} - 1)^2;
\]

\[
\text{Cfto}(1) = \text{abc}(4,1) + \text{abc}(4,2) \times (\text{pdr} - 1) + \text{abc}(4,3) \times (\text{pdr} - 1)^2;
\]

\%

\%

\%

\%

\%

\%

\%

\%

\%

\%

\%

\%

\%

\%

\%

\%
C.4 Cheng-Todreas Correlation with Modifications
This function gives the friction factor value predicted by the Detailed Cheng & Todreas correlation with modifications.

% IN:
% wst – WsT Guess
% nrod – Number of rods
% d – Rod diameter
% dw – Wire diameter
% pdr – Rod pitch to rod diameter ratio, P/D
% wdr – Edge pitch parameter to rod diameter ratio, W/D
% hdr – Wire lead length to rod diameter ratio, H/D
% re – Reynolds number

% OUT:
% fb – The bundle average friction factor predicted by the CTD correlation

%Enter any modifications

function f = CT_ModA(nrod,d,dw,pdr,wdr,hdr,re)

%For unmodified correlation:
%function f = Chen_Todreas_corr(nrod,d,dw,pdr,wdr,hdr,re)

rel=350*10^(0.7*(pdr-1));
ret=10000*10^(0.7*(pdr-1));

%GEOMETRICAL PARAMETERS
nring=(3+sqrt(12*nrod-3))/6-1;
n=zeros(3,1);
n(1)=6*nring^2;
n(2)=6*nring;
n(3)=6;
p=pdr*d;

w=wdr*d;

h=hdr*d;

%Bare rod flow area and wetted perimeter

Ao=zeros(3,1);

Ao(1)=(sqrt(3)/4)*p^2-pi*d^2/8;

Ao(2)=p*(w-d/2)-pi*d^2/8;

Ao(3)=(w-d/2)^2/sqrt(3)-pi*d^2/24;

Pwo=zeros(3,1);

Pwo(1)=pi*d/2;

Pwo(2)=pi+(pi*d/2);

Pwo(3)=pi*d/6+2/sqrt(3)*(w-d/2);

%Wire-wrapped flow area and wetted perimeter

sinth=pi*(d+dw)/sqrt(h^2+(pi*(d+dw))^2);

costh=h/sqrt(h^2+(pi*(d+dw))^2);

tanths=sinth/costh;

A=Ao-pi*d^2/(8*costh)*[1 1 1/3];

Ab=sum(n.*A);

Pw=Pwo+pi*d/(2*costh)*[1 1 1/3];

Pwb=sum(n.*Pw);

%Wire projected area

Ar=pi*(d+dw)*dw*[1/6 1/4 1/6];

%Hydraulic equivalent diameter

De=4*A./Pw;

Deb=4*Ab/Pwb;

%Coefficients for bare rod subchannel friction factor constants

%in hexagonal array

if pdr<1.1

    abc=[26.00 888.2 -3334.0

    26.18 554.5 -1480.0

    26.98 1636.0 -10050.0

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else
    abc = [62.97, 216.9, -190.2, 44.40, 256.7, -267.6, 87.26, 38.59, -55.12, 0.1458, 0.03632, -0.03333, 0.1430, 0.04199, -0.04428, 0.1499, 0.006706, -0.009567];
end

Cflo = abc(1:3, 1) + abc(1:3, 2) * (wdr - 1) + abc(1:3, 3) * (wdr - 1)^2;

Cflo(1) = abc(1, 1) + abc(1, 2) * (pdr - 1) + abc(1, 3) * (pdr - 1)^2;

Cfto = abc(4:6, 1) + abc(4:6, 2) * (wdr - 1) + abc(4:6, 3) * (wdr - 1)^2;

Cfto(1) = abc(4, 1) + abc(4, 2) * (pdr - 1) + abc(4, 3) * (pdr - 1)^2;

% WdT = (19.57 - 59.67 * (dw/d) + 171.9 * (dw/d)^2) * hdr^(-0.583);
% WdT = (-2.25 + 6970 * (dw/d) + 4245 * (dw/d)^2) * hdr^(-2.318);
% WdT = (26.8 - 125.9 * dw/d + 299.6 * (dw/d)^2) * hdr^(-0.7);

C1 = 26.84926629;
C2 = -125.9264784;
C3 = 399.5573199;
C4 = -0.767629165;

% WdT = (29.5 - 140 * (dw/d) + 401 * (dw/d)^2) * hdr^(-0.85);
% C1 = 29.5;
% C2 = -140;
% C3 = 401;
% C4 = -0.85;
% C1=13.20038689;
% C2=-60.30171949;
% C3=167.8224845;
% C4=-0.52758217;
%
C1=21.30296697;
C2=-136.9509983;
C3=402.9644532;
C4=-0.999;
%
% C1=26.84;
% C2=-125.9;
% C3=399.5;
% C4=-0.767;

WdT=(C1+C2*(dw/d)+C3*(dw/d)ˆ2)*hdrˆ(C4);

WsT=16*log10(hdr)-5.6;
WsT=20*log10(hdr)-7.0;
WsT = 33.78*log(hdr) - 35.69;

WdL=1.4*WdT;
WsL=0.3*WsT;

CfL=Cflo*(1+WsL*(Ar./Ao)*tanhˆ2);

CfL(1)=Cflo(1)*(Pwo(1)/Pw(1))+WdL*3*Ar(1)/Ao(1)*De(1)/h*De(1)/dw;

CfT=Cfto*(1+WsT*Ar./Ao*tanhˆ2)ˆ1.41;

CfT(1)=Cfto(1)*Pwo(1)/Pw(1)+WdT*3*Ar(1)/Ao(1)*De(1)/h*(De(1)/dw)ˆ0.18;
\[
\begin{align*}
\text{em} &= 0.18; \\
\text{e1} &= 1/(2-\text{em}); \\
\text{e2} &= \text{em}/(2-\text{em}); \\
\text{CL} &= \text{Deb} \times \left(\sum (n \times \text{A}/\text{Ab} \times \text{De}/\text{Deb} \times \text{CfL})\right)^{-1}; \\
\text{CT} &= \text{Deb} \times \left(\sum (n \times \text{A}/\text{Ab} \times (\text{De}/\text{Deb}) \times \text{e2} \times (\text{De}/\text{CfT}) \times \text{e1})\right)^{-1.82}; \\
\text{phi} &= \log_{10}(\text{re}/\text{rel})/\log_{10}(\text{re}t/\text{rel}); \\
\text{f1} &= \text{CL}/\text{re}; \\
\text{ft} &= \text{CT}/\text{re}^{-0.18}; \\
\text{if } \text{re}<\text{rel} \\
& \quad \text{f} = \text{f1}; \\
\text{elseif } \text{re}>\text{re}t \\
& \quad \text{f} = \text{ft}; \\
\text{else} \\
& \quad \text{f} = \text{f1} \times (1-\text{phi})^{-1/3} \times \text{ft} \times \text{phi}^{-1/3}; \\
\text{end} \\
\text{end}
\end{align*}
\]

C.5 Code to Compare Correlations to Friction Factor Data

```matlab
% This file calculates friction factor values predicted by chosen ff correlations

clear all
close all
clc

% GIVE MATLAB ACCESS TO NECESSARY DIRECTORIES IN THE COMPUTER
% 1. The directory containing the raw data files
addpath('Data');
% 2. The directory containing the correlation functions
```
addpath('Correlations');
NData=79; %Number of data files
%NOTE: Raw data files must be named in form "n.mat" where n is the order
%For example: If there are total 69 data files, they must be name: 1.mat    
%2.mat, ... , 69.mat
for indx=1:NData
  load(num2str(indx))
  nre=length(re);
  F=zeros(12,nre);
  rel=300*10^(1.7*(pdr-1));
  ret=10000*10^(0.7*(pdr-1));
  F(13,:)=f;
  for j=1:nre
    F(1,j)=Rehme_corr(nrod,d,dw,pdr,wdr,hdr,re(j));
    F(2,j)=Baxi_Dalle_Donne_corr(nrod,d,dw,pdr,wdr,hdr,re(j));
    F(3,j)=Chen_Todreas_corr(nrod,d,dw,pdr,wdr,hdr,re(j));
    F(4,j)=Simplified_Chen_Todreas_corr(nrod,d,dw,pdr,wdr,hdr,re(j))
    \rightarrow ;
    F(5,j)=Modified_Baxi_Dalle_Donne_corr(nrod,d,dw,pdr,wdr,hdr,re(j))
    \rightarrow ;
    F(6,j)=Kirillov_corr(nrod,d,dw,pdr,wdr,hdr,re(j));
    F(7,j)=Zhukov_corr(nrod,d,dw,pdr,wdr,hdr,re(j));
    F(8,j)=Zhukov_corr(nrod,d,dw,pdr,wdr,hdr,re(j));
    F(9,j)=Novendstern_corr(nrod,d,dw,pdr,wdr,hdr,re(j));
    F(10,j)=ZHUT_corr(nrod,d,dw,pdr,wdr,hdr,re(j));
    F(11,j)=CT_ModA(nrod,d,dw,pdr,wdr,hdr,re(j));
    F(12,j)=CT_MODB(nrod,d,dw,pdr,wdr,hdr,re(j));
  end
  % if nrod>=91
  cd 'AData'
C.6 Converting Excel Files to Matlab .m files

% This file is used to create raw data files from geometric inputs

% IN:
% 
% nrod – Number of rods
% d – Rod diameter
% dw – Wire diameter
% pdr – Rod pitch to rod diameter ratio, P/D
% wdr – Edge pitch parameter to rod diameter ratio, W/D
% hdr – Wire lead length to rod diameter ratio, H/D
% re – Reynolds numbers
% f – Exprimental friction factor values
% CfTb –

% OUT:
% Raw data files – to be loaded and used by the Calculation_file file

clear all
close all
clc
addpath('excel files');
numbundles=79;
for n=1:numbundles
%Geometric parameters. Example:
geo = xlsread(num2str(n), 'A2:K2');
nrod = geo(1); d = geo(2); dw = geo(3); pdr = geo(4); wdr = geo(5); hdr = geo(6); CfTb = geo(11);

%experimental data: column 1 = Re, column 2 = f.
data = xlsread(num2str(n), 'H2:I32');
re = data(:,1); f = data(:,2);
clear 'geo'
clear 'data'
clear 'numbundles'
if nrod == 61
    save ('name'), where name = the bundle order
    save(num2str(n))
end