Karlsruhe Institute of Technology

Revised review and revised proposal for best fit of wire-wrapped fuel bundle friction factor and pressure drop predictions using various existing correlations

by Evaldas Bubelis[1], Michael Schikorr[1]

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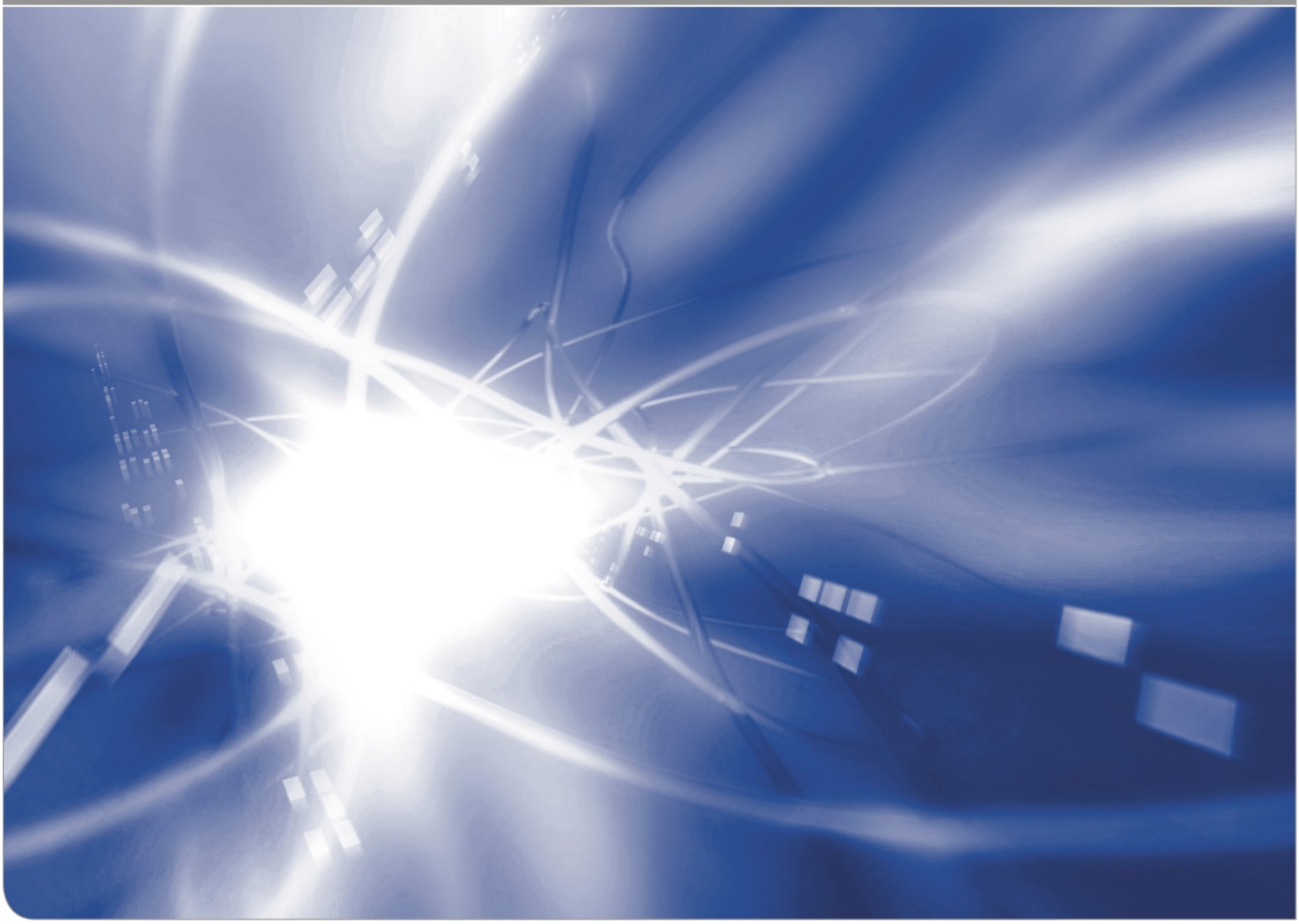

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Impressum

Karlsruher Institut für Technologie (KIT)
www.kit.edu

2016

ISSN: 2194-1629

KIT Scientific Working Papers
ISSN 2194-1629
www.kit.edu

Abstract

The aim of this report is to provide a recently revised review and overview of wire-wrapped fuel bundle friction factor/pressure drop correlations and to quantitatively re-evaluate which of the existing friction factor correlations is the best in retracing the results of a randomly selected set of experimental data sets (namely 22) available in the open literature on wire-wrapped fuel assemblies under different coolant conditions and different wire-wrapped bundle configurations.

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Nomenclature

A – axial average (total) flow area, (m^2)

A_i – flow area of i-th sub-channel, (m^2)

BWR – boiling water reactor

D_r – rod diameter, (m)

D_w – wire (spacer) diameter, (m)

D_e – bundle equivalent hydraulic diameter, (m)

DHRS – decay heat removal system

ETDR – Experimental Technology Demonstration Reactor

f – friction factor

FA – fuel assembly

FM – flow meter

GCFR – Gas Cooled Fast Reactor

H – wire lead length (pitch), (m)

HX – heat exchanger

K – friction coefficient

L – axial length of FA, (m)

LBE – lead-bismuth eutectic

LWR – light water reactor

N_i – number of i-th sub-channels

N_r – number of fuel pins

p – pressure, (Pa)

P – rod pitch, (m)

$P_t = D_r + 1.0444 * D_w$ – rod pitch for wire-wrap configuration, (m)

P_w – wetted perimeter, (m)

PFBR – (Indian) Prototype Fast Breeder Reactor

PWR – pressurized water reactor

Re – Reynolds number (for hot SA and wire-wrap configuration)

RMS - root-mean-square error

SFR – sodium fast reactor

STD - standard deviation of the absolute error

S_t – total wetted perimeter, (m)

T_w – wall temperature, (K)

T_B – coolant bulk temperature, (K)

v – bundle average flow velocity, (m/s)

X – flow split parameter

ρ - density, (kg/m^3)

μ – dynamic viscosity, (Pa·s)

ψ – intermittency factor

Subscripts

1, 2, 3 – denote center, side and corner sub-channels, respectively

i – index of sub-channel type

l, L – laminar

t, T – turbulent

1 Introduction

A recent re-evaluation of the wire spacer correlations by Cheng-Todreas (Chen S.K. et al, 2014) has demonstrated that by an appropriate pre-selection of data sets (out of a total of ~140 data sets) the most applicable set of correlations for the prediction of wire spacer pressure drops for typical SFR fuel bundles is the one proposed by Cheng and Todreas themselves (Cheng S. K. and Todreas N. E., 1986). However, the authors of this report, in their prior publication of 2008 (Bubelis E. and Schikorr M., 2008), recommended Rehme correlation as the most applicable general-purpose correlation for the prediction of pressure drops of fast reactor sub-assemblies. On account of a not quite appropriate usage of the Cheng-Todreas correlation in our previous publication of 2008 (Bubelis E. and Schikorr M., 2008), as was made aware by Cheng and Todreas in their 2014 publication (Chen S.K. et al, 2014), we are reviewing in this current report our recommendation made in 2008, to be in conformance with the correct usage of the Cheng-Todreas correlation using the same unbiased data sets (22) as in our previous 2008 publication in order not to bias the conclusion by pre-selection of the data sets a priori. As a result of that, our 2008 ranking of the different pressure drop correlations needed some revision as discussed in detail in this report.

Different authors provide us with friction factor correlations for wire-wrapped fuel bundles generally based on a particular set of experimental data. These correlations usually are very good for friction factors prediction for a wire-wrapped fuel bundle within the parameter range for which they were derived based on certain fluid and fuel bundle parameters. But, when applying these friction factor correlations to another fluid (coolant) or different fuel bundle parameters, one often obtains friction factor predictions that are not always in satisfactory agreement with the experimental data. So an important question arises, which friction factor correlation should one use in system codes such as RELAP, TRACE, CATHARE, SIM-codes family, ASTEC, etc., in order to obtain reliable prediction of the friction factor for any coolant and any set of physically available fuel bundle parameters. This report tries to re-address this issue, based on the qualitative, as well as quantitative evaluation of the most commonly used friction factor correlations provided to us by different authors, while re-analyzing the same 22 experimental data sets available in the open literature. These experiments were conducted using different coolants (water, sodium, air), different fuel bundle configurations, by different scientists in different countries and organizations.

2 Fuel assembly pressure drop correlations

The total pressure drop in a fuel assembly is usually calculated using the following formula:

$$\Delta p_{FA} = \Delta p_{inlet} + \Delta p_{outlet} + \Delta p_{orf} + \Delta p_{fric} + \Delta p_{spacer} . \quad (1)$$

Fuel assembly inlet, outlet and orificing pressure losses are determined by:

$$\Delta p_{inlet} + \Delta p_{outlet} + \Delta p_{orf} = 0.5 * \rho * v^2 * (K_{inlet} + K_{outlet} + K_{orf}), \quad (2)$$

with ρ being the density and v the velocity of the coolant and K as the associated pressure loss coefficients. Pressure loss due to the flow friction along a smooth pipe is calculated as:

$$\Delta p_{fric} = f_{fric} * (L / D_e) * 0.5 * \rho * v^2, \quad (3)$$

where L is the tube length, D_e the hydraulic diameter of the flow channel, and f_{fric} stands for the turbulent single phase flow and can be estimated using the Blasius formula, namely

$$f_{fric} = 0.316 / Re^{0.25} ,$$

where Re represents the Reynolds number of the flow channel. In a similar manner, the pressure loss due to the spacer (in this case due to the wire-wrap) is calculated as:

$$\Delta p_{spacer} = f_{ww} * (L / D_e) * 0.5 * \rho * v^2, \quad (4)$$

where f_{ww} (friction factor) correlations for the wire-wrap spacer configuration will be discussed in more detail in section 3 of this report.

3 Friction factor correlations for wire-wrapped fuel assemblies

The various friction factor correlations for the wire-wrapped fuel bundles that are available today are summarized in this section. Application ranges for each of the below mentioned correlations are presented in Table 9-1.

In the following, all the various symbols used in the correlations are defined in the nomenclature section of this report.

The main changes in the use of the below correlations, that were undertaken by us in comparison to our previous paper of 2008 (Bubelis E. and Schikorr M., 2008), are as follows:

- (P_t/D_r) ratio in all the below correlations, except for Rehme and Engel, was replaced with the (P/D_r) ratio;
- $(H/(D_r+D_w))$ ratio in all the below correlations, except for Rehme and Engel, was replaced with the (H/D_r) ratio;
- In the case of Baxi and Dalle-Donne correlation (standard and modified), certain change (change of a coefficient) was made in the calculation of K factor.

3.1 Novendstern Model

Friction factor for the wire-wrapped fuel bundle in the Novendstern model (Novendstern E. H., 1972) is calculated based on the following correlations:

$$f = f_1 \cdot X_1^2 \cdot \frac{D_e}{D_{e1}}, \qquad (5)$$

where: $f_1 = f_s \cdot M$; $f_s = \frac{0.316}{\mathrm{Re}_s^{0.25}}$,

Re_s – average Reynolds number for non-wire-wrap configuration of the fuel bundle;

$$M = \left\{ \frac{1.034}{(P/D_r)^{0.124}} + \frac{29.7 \cdot (P/D_r)^{6.94} \cdot \mathrm{Re}_1^{0.086}}{(H/D_r)^{2.239}} \right\}^{0.885}, \qquad (6)$$

Re_1 - Reynolds number for the center sub-channel of the hot SA in the wire-wrap configuration with

$$Re_1 = \frac{\rho \cdot v_1 \cdot D_{e1}}{\mu} = Re \cdot X_1 \cdot \frac{D_{e1}}{D_e} \;,\; Re = \frac{\rho \cdot v \cdot D_e}{\mu} \;,\; v_1 = X_1 \cdot v \;,$$

$$X_1 = \frac{A}{N_1 \cdot A_1 + N_2 \cdot A_2 \cdot \left(\frac{D_{e2}}{D_{e1}}\right)^{0.714} + N_3 \cdot A_3 \cdot \left(\frac{D_{e3}}{D_{e1}}\right)^{0.714}} \;,\quad A = N_1 \cdot A_1 + N_2 \cdot A_2 + N_3 \cdot A_3 \;.$$

3.2 Rehme Model

Friction factor for the wire-wrapped fuel bundle in the Rehme model (Rehme, K., 1973) is calculated based on the following correlations:

$$f = \left(\frac{64}{Re} \cdot F^{0.5} + \frac{0.0816}{Re^{0.133}} \cdot F^{0.9335}\right) \cdot \frac{N_r \cdot \pi \cdot (D_r + D_w)}{S_t} \;, \tag{7}$$

where: $$F = \left(\frac{P_t}{D_r}\right)^{0.5} + \left[7.6 \cdot \frac{(D_r + D_w)}{H} \cdot \left(\frac{P_t}{D_r}\right)^2\right]^{2.16} \;. \tag{8}$$

3.3 Engel, Markley and Bishop Model

Friction factors for the wire-wrapped fuel bundle in the Engel, Markley and Bishop model (Engel F. C. et al, 1979) is calculated based on the following correlations:

Laminar flow: $f = \frac{110}{Re}$ for Re < 400 , (9)

Turbulent flow: $f = \frac{0.55}{Re^{0.25}}$ for Re > 5000 , (10) *Transition flow*: $f = \frac{110}{\text{Re}} \cdot (1-\psi)^{0.5} + \frac{0.55}{\text{Re}^{0.25}} \cdot \psi^{0.5}$ for $400 \le \text{Re} \le 5000$, (11)

where: $\psi = \frac{(\text{Re} - 400)}{4600}$.

3.4 Cheng and Todreas Models – simplified and detailed

Friction factor for the wire-wrapped fuel bundle in the simplified Cheng and Todreas model (Cheng S. K. and Todreas N. E., 1986) is calculated based on the following correlations:

Laminar flow: $f = \frac{C_{fL}}{\text{Re}}$ for $\text{Re} \le \text{Re}_L$, (12)

Turbulent flow: $f = \frac{C_{fT}}{\text{Re}^{0.18}}$ for $\text{Re}_T \le \text{Re}$, (13)

Transition flow: $f = \frac{C_{fL}}{\text{Re}} \cdot (1-\psi)^{1/3} + \frac{C_{fT}}{\text{Re}^{0.18}} \cdot \psi^{1/3}$ for $\text{Re}_L < \text{Re} < \text{Re}_T$, (14)

where: $\log\left(\frac{\text{Re}_L}{300}\right) = 1.7 \cdot \left(\frac{P}{D_r} - 1.0\right)$, $\log\left(\frac{\text{Re}_T}{10000}\right) = 0.7 \cdot \left(\frac{P}{D_r} - 1.0\right)$,

$$\psi = \left(\log(\text{Re}) - \left(1.7 \cdot \frac{P}{D_r} + 0.78\right)\right) \Big/ \left(2.52 - \frac{P}{D_r}\right) ,$$

$$C_{fL} = \left(-974.6 + 1612.0 \cdot \left(\frac{P}{D_r}\right) - 598.5 \cdot \left(\frac{P}{D_r}\right)^2\right) \cdot \left(\frac{H}{D_r}\right)^{0.06 - 0.085 \cdot (P/D_r)} ,$$

$$C_{fT} = \left(0.8063 - 0.9022 \cdot \log\left(\frac{H}{D_r}\right) + 0.3526 \cdot \left(\log\left(\frac{H}{D_r}\right)\right)^2\right) \cdot \left(\frac{P}{D_r}\right)^{9.7} \cdot \left(\frac{H}{D_r}\right)^{1.78 - 2 \cdot (P/D_r)} .$$

Friction factors for the wire-wrapped fuel bundle in the detailed Cheng and Todreas model is calculated based on the center, side and corner sub-channels equations that are described in more detail in Ref. (Cheng S. K. and Todreas N. E., 1986) as well.

The most useful form of coding of the Cheng-Todreas set of correlations can be downloaded from Ref. (Pramuditya S., 2014, link valid on 2 February 2015), made available by Mr. Syeilendra Pramuditya.

3.5 Baxi and Dalle-Donne Model

Friction factor for the wire-wrapped fuel bundle in the Baxi and Dalle-Donne model (Pergamon Press, 1981) is calculated based on the following correlations:

Laminar flow: $Re \le 400$

$$f = \left(\frac{K}{Re}\right) \cdot \left(\frac{T_W}{T_B}\right), \; K = \frac{320}{\sqrt{H}} \cdot \left(\frac{P}{D_r}\right)^{1.5} \text{; where H in (cm).} \tag{15}$$

Turbulent flow: $Re \ge 5000$

$f_t = f_s \cdot M$, where f_s = smooth friction factor in a tube (Blasius) = $0.316/Re^{0.25}$,

$$M = \left[\frac{1.034}{(P/D_r)^{0.124}} + \frac{29.6 \cdot (P/D_r)^{6.94} \cdot Re^{0.086}}{(H/D_r)^{2.239}}\right]^{0.885} . \tag{16}$$

Transition flow: $400 < Re < 5000$

$$f = f_l \cdot (1-\psi)^{1/2} + f_t \cdot \sqrt{\psi} \; , \tag{17}$$

f_l = laminar friction factor, f_t = turbulent friction factor, $\psi = (Re - 400)/4600$.

3.6 Sobolev Model

Friction factor for the wire-wrapped fuel bundle in the Sobolev model (Sobolev V., 2006) is calculated based on the following equation:

$$f = \left(1 + 600 \cdot \left(\frac{D_r}{H}\right)^2 \cdot \left(\frac{P}{D_r} - 1\right)\right) \cdot \left(\frac{0.210}{\mathrm{Re}^{0.25}} \cdot \left(1 + \left(\frac{P}{D_r} - 1\right)^{0.32}\right)\right) . \tag{18}$$

4 Modified friction factor correlations for wire-wrapped fuel assemblies

Several of the above presented friction factor correlations for the wire-wrapped fuel bundles were slightly modified in order to obtain an improved agreement with the available experimental data sets, as explained in (Bubelis E. and Schikorr M., 2008) publication. The modified friction factor correlations for the wire wrapped fuel bundles are presented below in this section.

In the following, all the various symbols used in the correlations are defined in the nomenclature section of this report.

4.1 Modified Engel, Markley and Bishop model

Friction factors for the wire-wrapped fuel bundle in the modified Engel, Markley and Bishop model are calculated based on the following modified correlations:

Laminar flow: $f = \frac{110}{\text{Re}}$ for Re < 400 ,

Turbulent flow: $f = \frac{0.37}{\text{Re}^{0.25}}$ for Re > 5000 , (19)

Transition flow: $f = \frac{110}{\text{Re}} \cdot (1-\psi)^{0.5} + \frac{0.37}{\text{Re}^{0.25}} \cdot \psi^{0.5}$ for 400 ≤ Re ≤ 5000 , (20)

where: $\psi = \frac{(\text{Re}-400)}{4600}$.

4.2 Modified Baxi and Dalle-Donne Model

Friction factors for the wire-wrapped fuel bundle in the modified Baxi and Dalle-Donne model is calculated based on the following correlations:

Laminar flow: Re ≤ 400

$$f = \left(\frac{K}{\mathrm{Re}}\right)\cdot\left(\frac{T_W}{T_B}\right), \quad K = \frac{320}{\sqrt{H}}\cdot\left(\frac{P}{D_r}\right)^{1.5} \text{ ; where H in (cm).} \tag{21}$$

Turbulent flow: Re ≥ 5000

$f_t = f_s \cdot M$, where f_s = smooth friction factor in a tube (Blasius) = $0.316/\mathrm{Re}^{0.25}$,

$$M = \left[\frac{1.034}{(P/D_r)^{0.124}} + \frac{29.6\cdot(P/D_r)^{6.94}\cdot \mathrm{Re}^{0.086}}{(H/D_r)^{2.239}}\right]^{0.885}.$$

Transition flow: 400 < Re < 5000

$$f = f_l \cdot (1-\psi)^{1/2} + f_t \cdot \sqrt{\psi}\ , \tag{22}$$

f_l = laminar friction factor, f_t = turbulent friction factor, and modified $\psi = (\mathrm{Re}-400)/5000$.

5 Correlation evaluation and scoring methodology

The quality of the friction factor predictions was first estimated calculating the absolute error for each data point:

$$\varepsilon_i = \left[\left(f_i^m - f_i^c\right)/ f_i^m\right]*100 \text{, in [\%]} \qquad (23)$$

where f_i^m is friction factor evaluated in an experiment and f_i^c is friction factor calculated by a correlation corresponding to f_i^m.

Then, the mean absolute error $\bar{\varepsilon}$, the standard deviation (STD) of the absolute error σ, and the root-mean-square (RMS) error r, defined in the following manner, were evaluated as measures of the overall quality of a correlation:

$$\bar{\varepsilon} = \sum_{i=1}^{N} \varepsilon_i / N \text{, in [\%]} \qquad (24)$$

$$\sigma = \sqrt{\sum_{i=1}^{N} \left(\varepsilon_i - \bar{\varepsilon}\right)^2 /(N-1)} \text{, in [\%]} \qquad (25)$$

$$r = \sqrt{\sum_{i=1}^{N} \varepsilon_i^{\,2} / N} \text{, in [\%],} \qquad (26)$$

where N is the number of experimental data points.

We have also plotted the calculated friction factors versus the experimental friction factors for each of the analyzed friction factor correlations separately, in order to see graphically how well experimental data are predicted by each correlation.

The summary of all the statistical analysis carried out is presented in the 'Summary and Conclusions' section of this report.

6 Analysis of the experimental data based on water experiments

In all below subsections, based on the data provided in the specific reference from the open literature, corresponding calculations were always performed with the SIM-ADS system code (Schikorr W. M., 2001) and the calculation results were then compared to the available experimental data from the reference. A subsequent development of the original SIM-ADS code lead to the SIM-codes family, that allow the transient assessment of gas-cooled, Pb-cooled, Pb-Bi-cooled, or Na-cooled fast reactor concepts. The calculations for this publication were performed using the SIM-ADS code, belonging to the SIM-codes family (SIM-ADS, SIM-GFR, SIM-LFR, SIM-SFR, etc.), which incorporates all the various pressure drop correlations as model options.

6.1 Choi et al., 2003 (Choi et al, 2003) water experiments

A detailed description of the experimental facility used by Choi et al (Choi et al, 2003) can be found in section 6.1 of the Ref. (Bubelis E. and Schikorr M., 2008). Choi et al (Choi et al, 2003) measured the pressure drop in a 271-pin wire-wrapped fuel assembly. The diameter of the fuel rod used in these experiments is 7.4 mm and the diameter of the wire is 1.4 mm. The rod pitch to rod diameter ratio is 1.2 and the wire lead length to rod diameter ratio is 24.84. The experimental range of flow rate is 2.2-60 l/s and the experimental range of Reynolds number based on the hydraulic diameter of the fuel assembly is 1100-78000.

Figure 6-1 shows the comparison of the calculational results for the wire-wrapped FA pressure drop (in the fuel region) as calculated using different friction factor correlations (see above sections 3 and 4) with the experimental data. As can be seen from Figure 6-1, all considered friction factor correlations provide quite satisfactory agreement to the experimental data in the flow rate range above 7 kg/s. Below this flow rate differences between the correlations become quite observable. Over the entire flow range, Rehme, detailed Cheng-Todreas (CTD), simplified Cheng-Todreas (CTS), and Engel (modified) correlations yield almost identical results, all underpredicting slightly the experimental data for flow rates of less than 6 kg/s. In general, the ranking of the investigated correlations is as follows: Rehme, Cheng-Todreas (CTD), Cheng-Todreas (CTS) and Engel (modified) are very good, followed by Sobolev and Novendstern (both of them under-predicting in the low flow rate range), and Baxi-Dalle-Donne (modified) over-predicting slightly in the low flow rate regime.

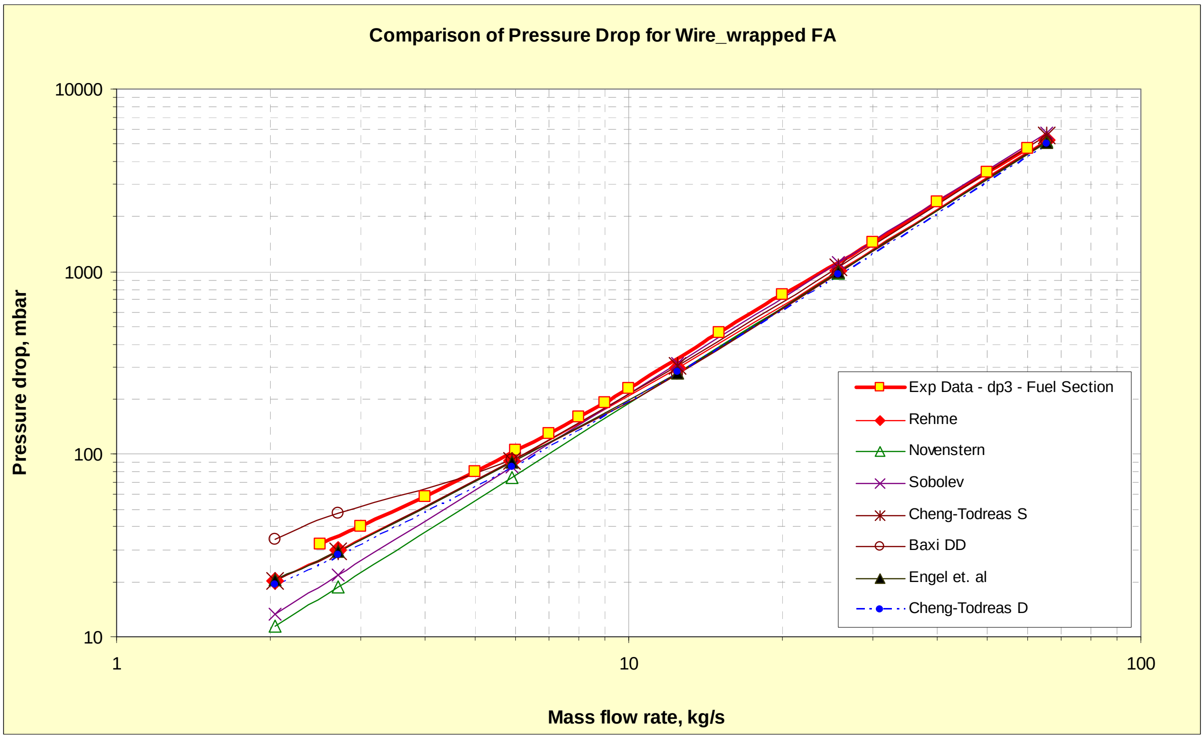


Figure 6-1: Comparison of calculated pressure drops (SIM-ADS calculated) using different friction factor correlations to experimental pressure drops in the wire-wrapped fuel assembly: (water, Choi et al., 2003)

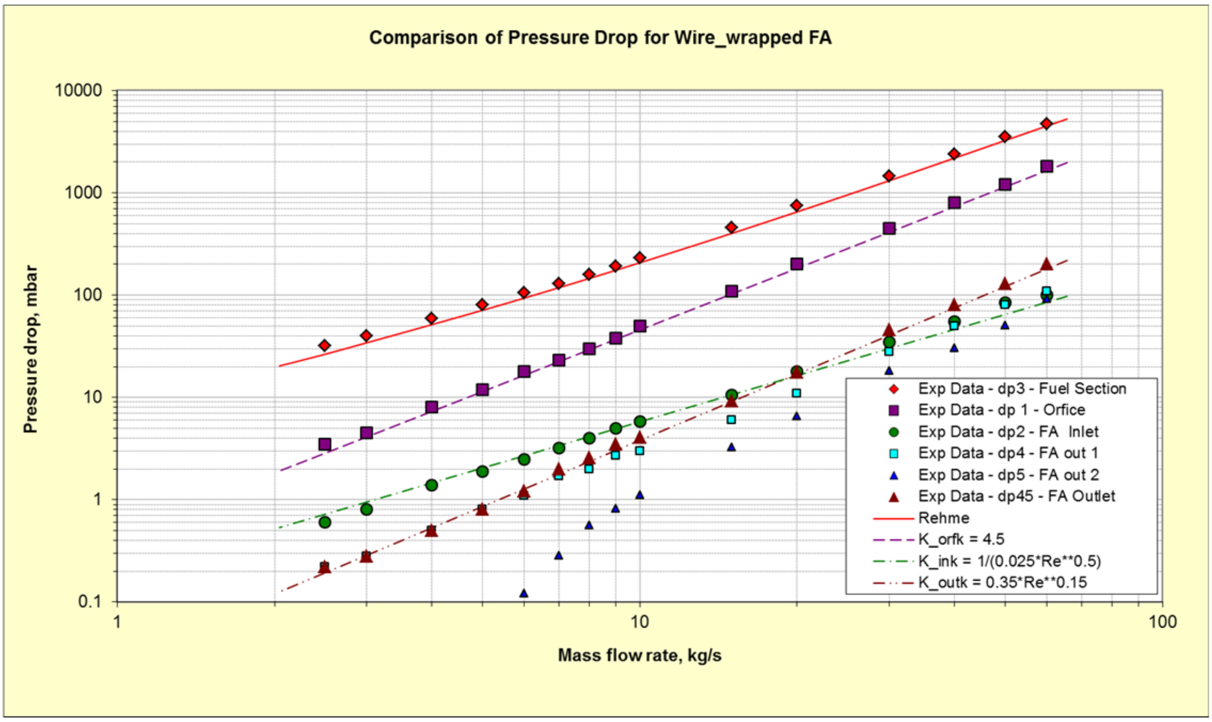


Figure 6-2: Comparison of experimental and SIM-ADS calculated pressure drops in the different regions (inlet, outlet, fuel section, etc) of the wire-wrapped fuel assembly: (water, Choi et al., 2003) using the above FA inlet and FA outlet friction coefficient correlations and Rehme for the fuel section

Figure 6-2 shows the comparison for the calculated corresponding pressure drops in different parts of the wire-wrapped FA applying the SIM-ADS code, using Rehme friction factor correlation in the core region, and the experimental data.

The following formulations of the friction coefficients were obtained for FA inlet and outlet regions in order to obtain excellent agreement with the experimental data:

FA inlet friction coefficient - $K_{inlet} = 1/(0.025 * Re^{0.5})$;

FA outlet friction coefficient - $K_{outlet} = 0.35 * Re^{0.15}$.

As can be observed, excellent agreement with the experimental data was obtained in most regions of the FA using the Rehme correlation (inlet orifice and wire-wrapped fuel assembly) and the corresponding inlet and outlet friction coefficients.

Figure 6-3 shows the comparison of the friction factor values for the wire-wrapped FA as calculated using the different friction factor correlations with the experimental data as a function of the Reynolds number. Above Re > 8000 all correlations provide reasonably good agreement drifting slightly towards under-prediction at Re > 50000. Significant deviation is observed at lower Re (<4000) numbers. As can be observed from Figure 6-3, friction factor correlations best fitting experimental data overall are in order (based on RMS values): both Rehme, Cheng-Todreas simplified (CTS) followed closely by Engel (modified) and Cheng-Todreas detailed (CTD), retracing CTD very closely. Based on the information observed in Figure 6-3, Sobolev, Novendstern and Baxi-DD (modified) correlations are only applicable for the turbulent region (Re > 5000).

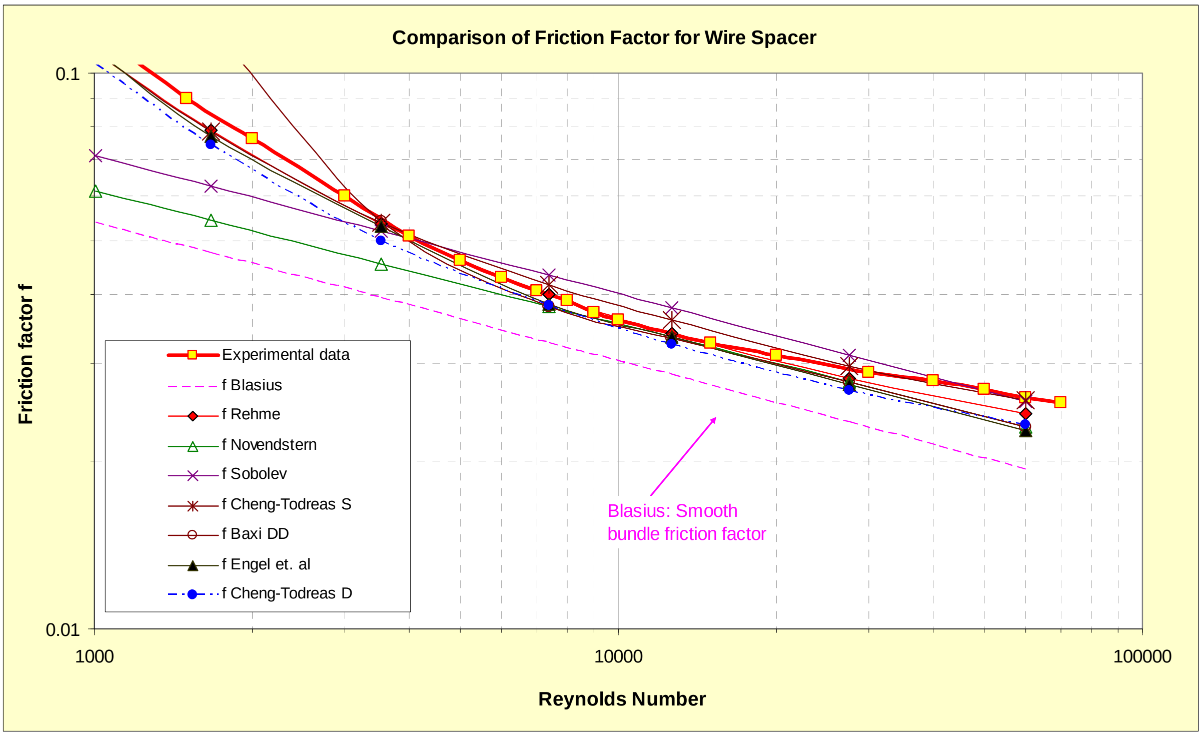


Figure 6-3: Comparison of different friction factor correlations (SIM-ADS calculated) and experimental friction factor values for the wire-wrapped fuel assembly: (water, Choi et al., 2003)

6.2 Chun et al., 2001 (Chun M.H. and Seo K.W., 2001) water experiments

A detailed description of the water test loop used by Chun et. al. (Chun M.H. and Seo K.W., 2001) can be found in section 6.2 of the Ref. (Bubelis E. and Schikorr M., 2008). Chun et al (Chun M.H. and Seo K.W., 2001) measured the pressure drop in a 19-pin wire wrapped fuel assembly with the following characteristics: wire lead to diameter ratio is 25.0, pitch to diameter ratio is 1.256, bundle equivalent hydraulic diameter is 4.75 mm, pin outer diameter is 8.0 mm, pin pitch is 10.04 mm, FA length is 1.3 m, wire diameter is 2.0 mm, wire lead length is 20 cm.

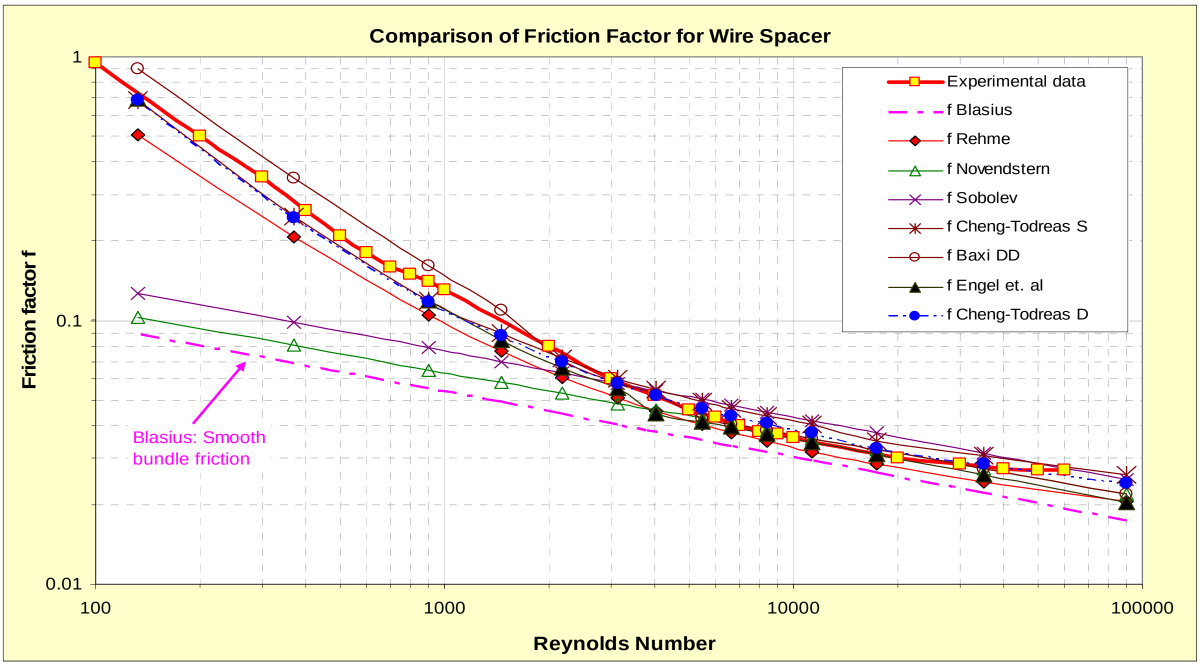


Figure 6-4: Comparison of different friction factor correlations (SIM-ADS calculated) and experimental friction factor values for the wire-wrapped fuel assembly (Chun M.H. and Seo K.W., 2001): (water, Chun et al., 2001)

Figure 6-4 shows the comparison of the friction factor values for the wire-wrapped FA as calculated using different friction factor correlations with the experimental data. As can be observed from Figure 6-4, friction factor correlations best fitting experimental data are in order (based on RMS values): in the turbulent regime (Re~>3000) all correlations yield satisfactory agreement to the experimental data (the best being Cheng-Todreas detailed (CTD)) with the exception at very high Re (>50000) numbers, whereas in the laminar regime (Re ~< 3000) both Cheng-

Todreas simplified (CTS), Cheng-Todreas detailed (CTD), and Engel (modified) yield very good agreement, followed by Baxi-DalleDonne (modified) (slight over-prediction) and Rehme (slight under-prediction). As it was already observed earlier, Sobolev and Novendstern correlations can be used only in the turbulent region (Re ~> 3000).

6.3 Arwikar et al., 1979 (Arwikar K. and Fenech H, 1979) water experiments

A detailed description of the closed loop water circulation system used by Arwikar et. al. (Arwikar K. and Fenech H, 1979) for their experiments can be found in section 6.3 of the Ref. (Bubelis E. and Schikorr M., 2008). The experimental bundle consists of 61 stainless steel tubes arranged in a triangular pitch layout with a pitch to diameter ratio of 1.05. The tubes have a 21.1 mm outside diameter and are ~76.2 cm long. Each tube is tightly wrapped with a 1.067 mm diameter stainless steel wire at a helical pitch of 30.48 cm and the starting points of the wire between adjacent rods are at 120 degree phase shift. The tube bundle is placed in a hexagonal Plexiglas box with 25.4 mm thick walls. The inner sides of the box are each 10.287 cm wide.

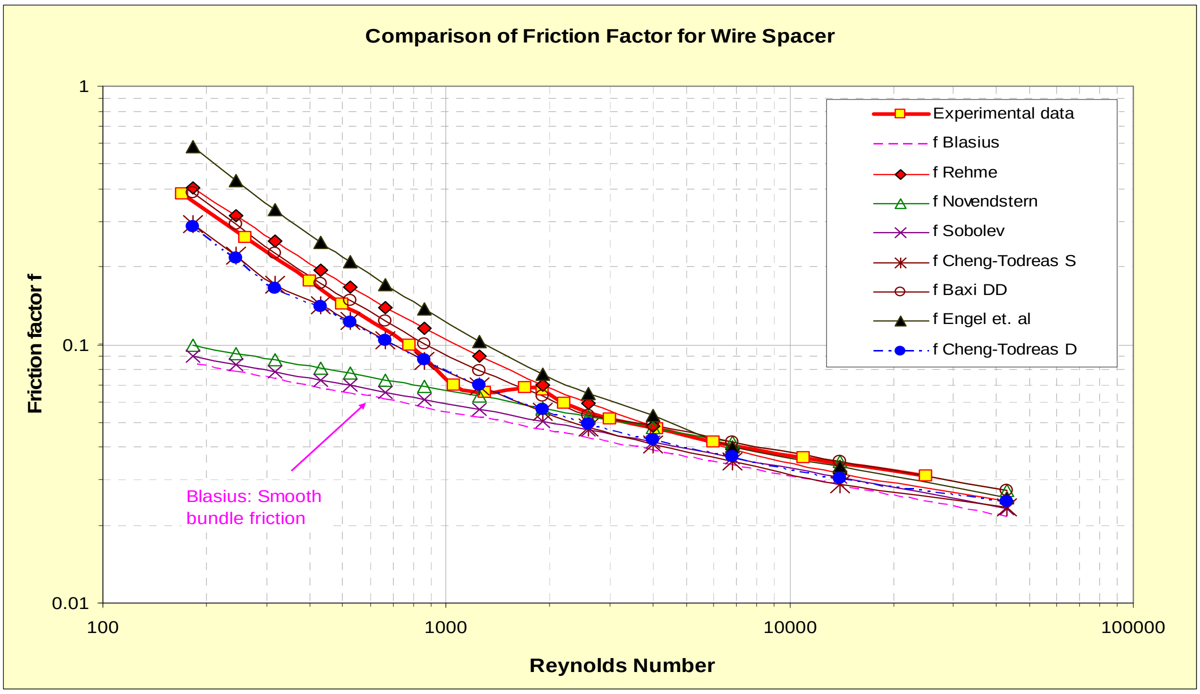


Figure 6-5: Comparison of different friction factor correlations (SIM-ADS calculated) and experimental friction factor values for the wire-wrapped fuel assembly: (water, Arwikar et al., 1979)

Figure 6-5 shows the comparison of the friction factor values for the wire-wrapped FA as calculated using different friction factor correlations with the experimental data. As can be seen from Figure 6-5, in the turbulent regime (Re >3000), all correlation yield fairly good results tending towards under-prediction at Re > 20000, whereas in the laminar regime, results diverge noticeably. Excellent agreement in the laminar regime (based on RMS values) is observed for Baxi-DalleDonne (modified), followed by both Cheng-Todreas simplified (CTS) and Cheng-Todreas detailed (CTD) with slight under-predictions, and then Rehme (slight over-prediction), followed by noticeable over-predition of Engel (modified). As it was already mentioned earlier, Sobolev and Novendstern correlations can be used only in turbulent region (Re > 3000) where they yield good agreement with experimental data.

6.4 Chiu et al., 1979 (Chiu C. et al, 1979) water experiments

A detailed description of the wire wrapped fuel bundle as used by Chiu et. al. (Chiu C. et al, 1979) can be found in section 6.4 of the Ref. (Bubelis E. and Schikorr M., 2008). Rod bundle parameters for the Chiu et al (Chiu C. et al, 1979) experimental setup are: number of pins/rods is 61, pitch to diameter ratio is 1.063, wire lead length to diameter ratio is 8.0 and pin/rod diameter is 12.73 mm.

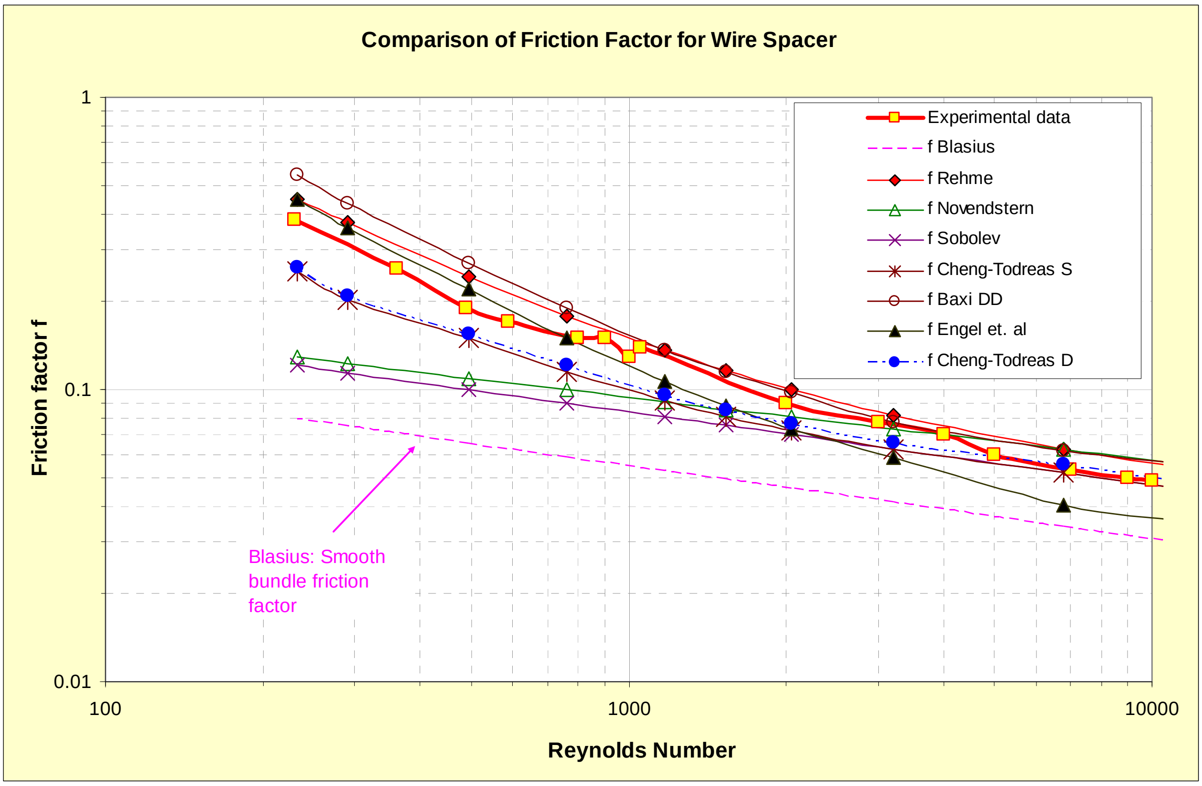


Figure 6-6: Comparison of different friction factor correlations (SIM-ADS calculated) and the experimental friction factor values for the wire-wrapped fuel assembly: (water, Chiu et al., 1979)

Figure 6-6 shows the comparison of the friction factor values for the wire-wrapped FA as calculated using different friction factor correlations with the experimental data. As can be seen from Figure 6-6 and based also on RMS values, friction factor correlations best fitting the turbulent flow regime (Re > 3000) experimental data are in order: Cheng-Todreas detailed (CTD), Sobolev, Cheng-Todreas simplified (CTS), followed by Rehme and Baxi-DalleDonne (modified). In the laminar flow regime (Re < 3000), Engel (modified) provides the closest fit followed by Rehme (over-predicting), Cheng-Todreas detailed (CTD) and Cheng-Todreas simplified (CTS) (both under-predicting), and then Baxi-DalleDonne (modified) over-predicting the experimental data. Again, as it was mentioned earlier, Sobolev and Novendstern correlations are not applicable in the laminar regime (Re < 3000).

6.5 Tong/Bishop, 1968 (Tong L.S., 1968) water experiments

A detailed description of the wire wrapped fuel bundle as used by Tong/Bishop (Tong L.S., 1968) can be found in section 6.5 of the Ref. (Bubelis E. and Schikorr M., 2008). Rod bundles parameters for the Tong/Bishop experimental setup are: number of pins/rods is 19, pitch to diameter ratio is 1.205, wire lead length to diameter ratios are 8 and 16; pin/rod diameter is assumed to be 12.73 mm and the center pin of these bundles is not wire wrapped.

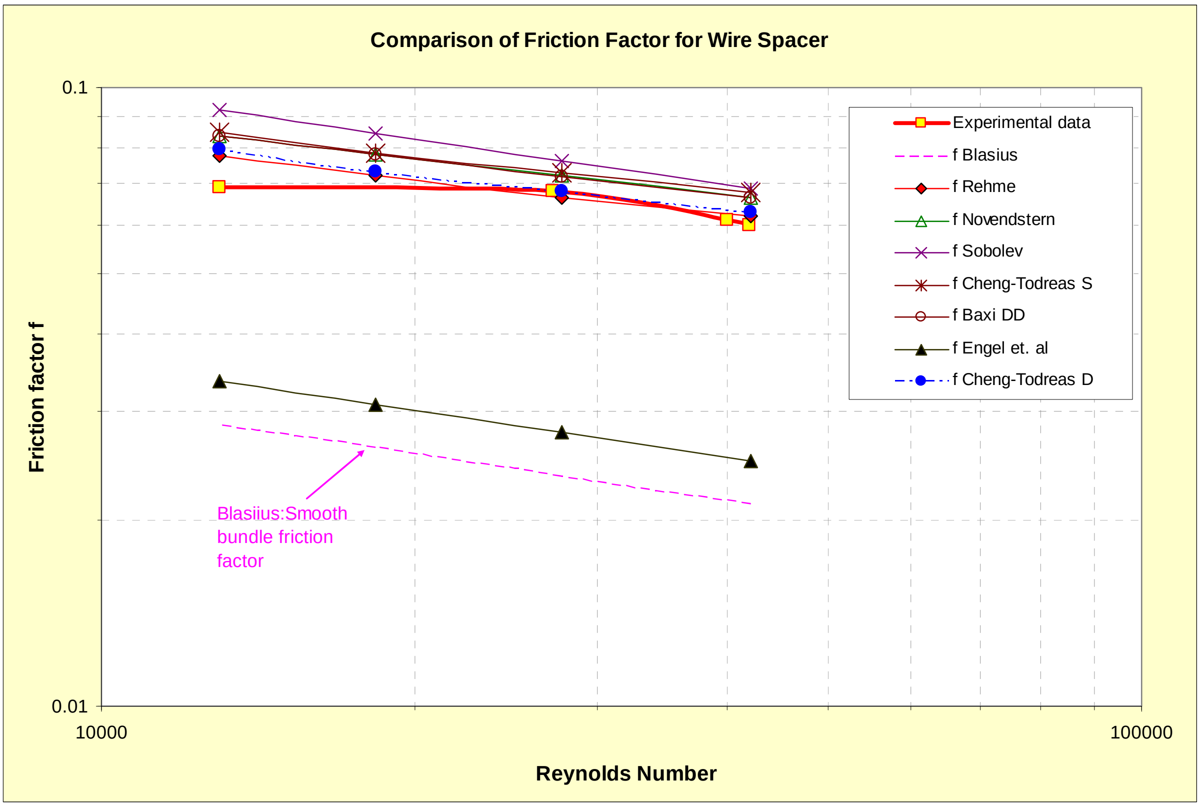


Figure 6-7: Comparison of different friction factor correlations (SIM-ADS calculated) and experimental friction factor values for the wire-wrapped fuel assembly (case H/D=8): (water, Tong/Bishop, 1968)

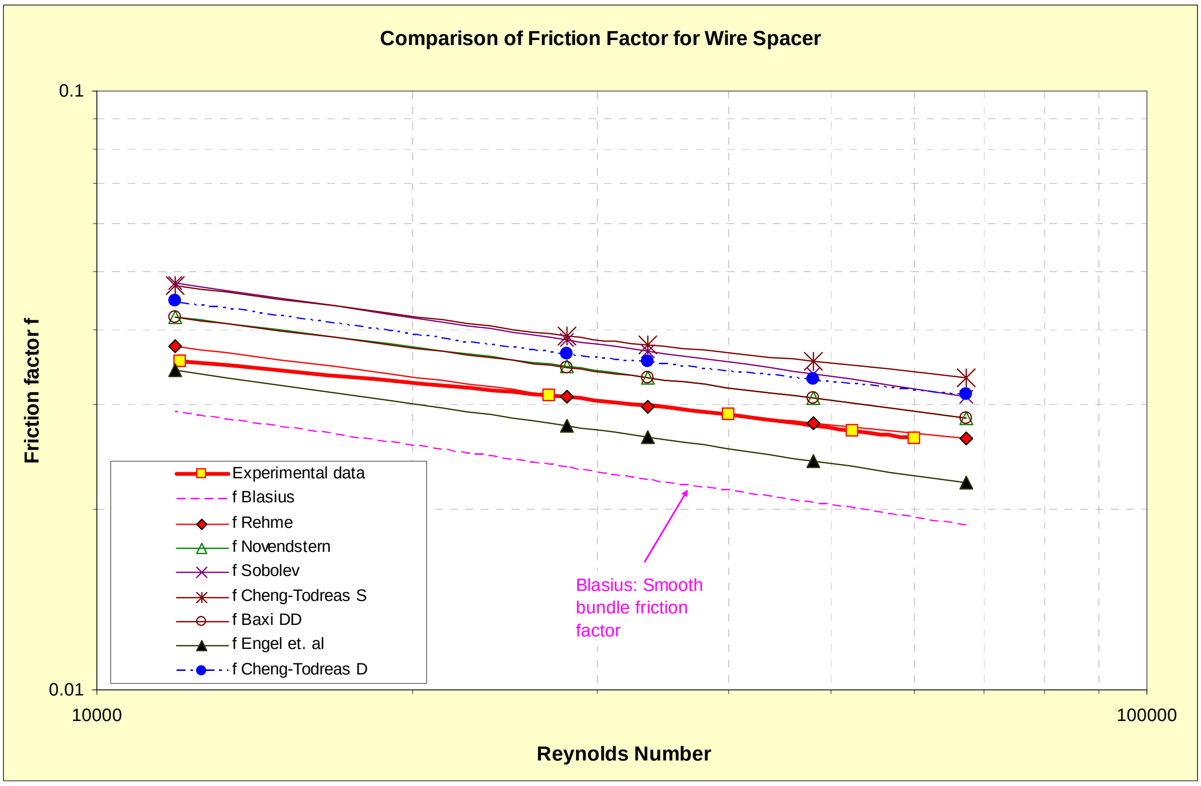


Figure 6-8: Comparison of different friction factor correlations (SIM-ADS calculated) and the experimental friction factor values for the wire-wrapped fuel assembly (case H/D=16): (water, Tong/Bishop, 1968)

Figure 6-7 (H/D=8) and Figure 6-8 (H/D=16), show the comparison of the friction factor values for the wire-wrapped FA as calculated using different friction factor correlations with the experimental data. Having Re > 10000, the flow regime is turbulent. As can be seen from Figure 6-7 and based also on RMS values, not all friction factor correlations exhibit satisfactory response, with Engel (modified) being not applicable. The closest correspondence to experimental data is observed to be provided by Rehme and Cheng-Todreas detailed (CTD). Baxi-DalleDonne (modified), Novendstern, Cheng-Todreas simplified (CTS) and Sobolev are over-predicting the experimental data. As can be seen from Figure 6-8 (H/D=16) and based also on RMS values, friction factor correlation best fitting experimental data is Rehme. Engel (modified) is under-predicting, whereas all other remaining correlations are over-predicting the experimental data, just as expected since the center pin is not wire wrapped.

6.6 Marten et al., 1982 (Marten K., Yonekawa S. and Hoffmann H, 1982) water experiments

A detailed description of the wire wrapped fuel bundle as used by Marten et. al. (Marten K., Yonekawa S. and Hoffmann H, 1982) can be found in section 6.6 of the Ref. (Bubelis E. and Schikorr M., 2008). Rod bundle parameters for the experimental setup are: number of pins/rods is 37, pitch to diameter ratios are 1.041 and 1.101, wire lead length to diameter ratios are 17.01 and 12.31, correspondingly; pin/rod diameter is assumed to be 12.0 mm.

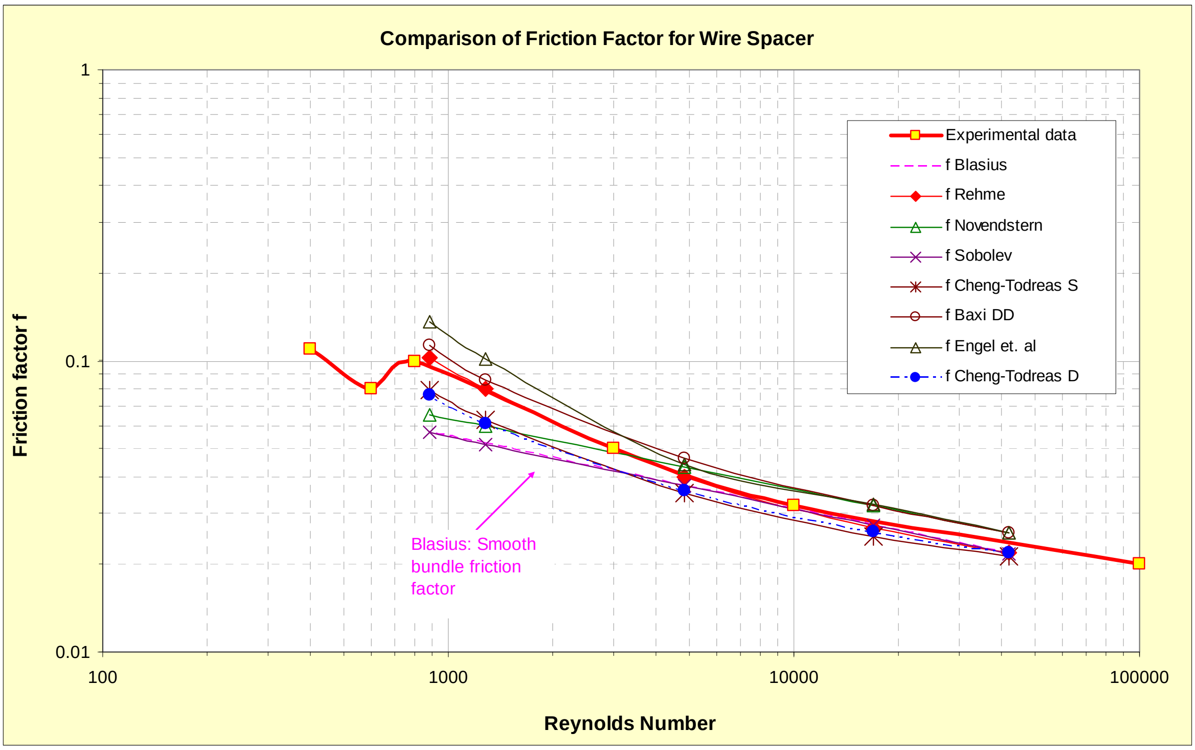


Figure 6-9: Comparison of different friction factor correlations (SIM-ADS calculated) and experimental friction factor values for the wire-wrapped fuel assembly (case P/D=1.041; H/D=17.01): (water, Marten et al., 1982)

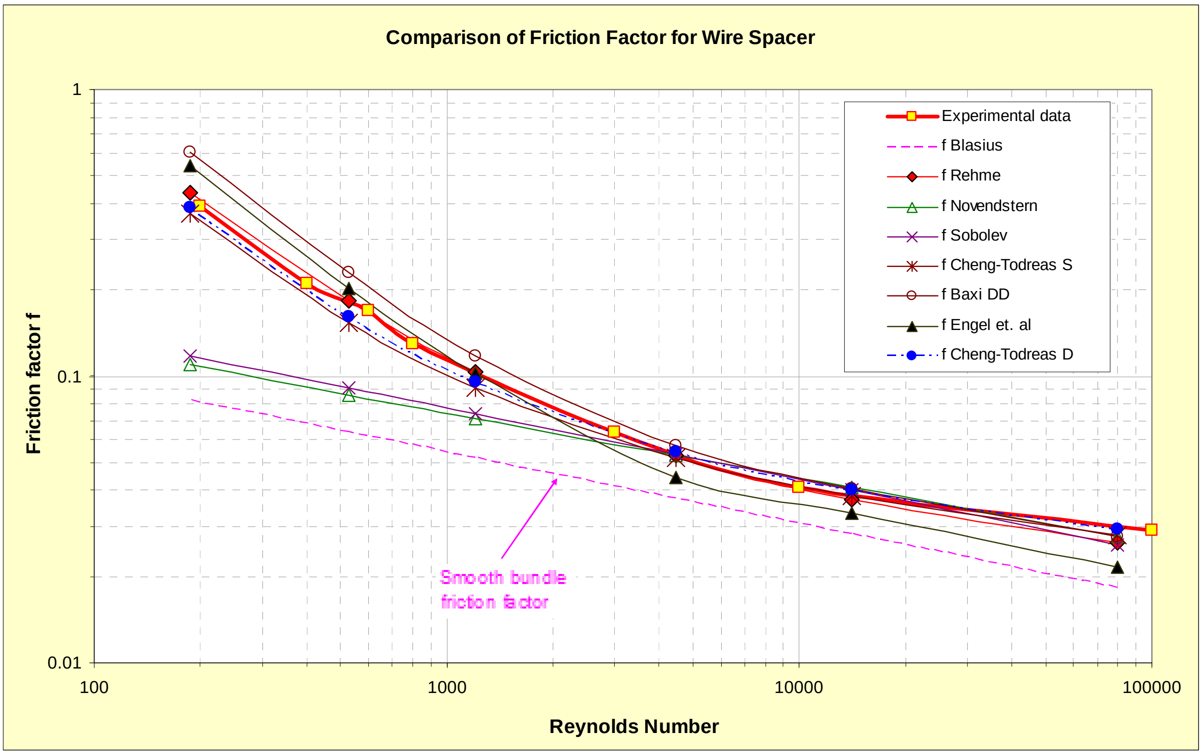


Figure 6-10: Comparison of different friction factor correlations (SIM-ADS calculated) and experimental friction factor values for the wire-wrapped fuel assembly (case P/D=1.101; H/D=12.31): (water, Marten et al., 1982)

Figure 6-9 (P/D=1.041; H/D=17.01) and Figure 6-10 (P/D=1.101; H/D=12.31) show the comparison of the friction factor values for the wire-wrapped FA as calculated using different friction factor correlations with the experimental data. As can be seen from Figure 6-9 (P/D=1.041; H/D=17.01) and based also on RMS values, in the turbulent range Rehme yields an excellent fit to the experimental data followed by Sobolev, Cheng-Todreas detailed (CTD), Novendsten, Engel (modified), Cheng-Todreas simplified (CTS) and Baxi-DalleDonne (modified). In the laminar range, none of the correlations replicate the data, the best fit is provided however by Cheng-Todreas simplified (CTS) and Cheng-Todreas detailed (CTD). All remaining models are actually too far off to be considered applicable. In Figure 6-10 (P/D=1.101; H/D=12.31) and based also on RMS values, it is Cheng-Todreas detailed (CTD) that correlates closest to the experimental data in the turbulent range, followed very closely by Cheng-Todreas simplified (CTS), Novendstern, Baxi-DalleDonne (modified), Rehme and Sobolev. Engel (modified) drifts significantly to the lower side of the data. In the laminar range, in this particular case, it is Rehme that yields the closest fit, followed by Cheng-Todreas detailed (CTD) and Cheng-Todreas simplified (CTS), and then Engel (modified) and Baxi-DalleDonne (modified), both the latter somewhat on the high side. Both Novendstern and Sobolev correlations are not adequate for laminar range as noted previously (Re < 3000).

6.7 Itch, 1981 (Cheng S.K., 1984) water experiments

A detailed description of the wire wrapped fuel bundle as used by Itch (Cheng S.K., 1984) can be found in section 6.7 of the Ref. (Bubelis E. and Schikorr M., 2008). The experimental setup is: number of pins/rods are 127 and 169, pitch to diameter ratios are 1.176 and 1.214, wire lead length to diameter ratios are 38.0 and 47.39, correspondingly; pin/rod diameter is assumed to be 12.0 mm.

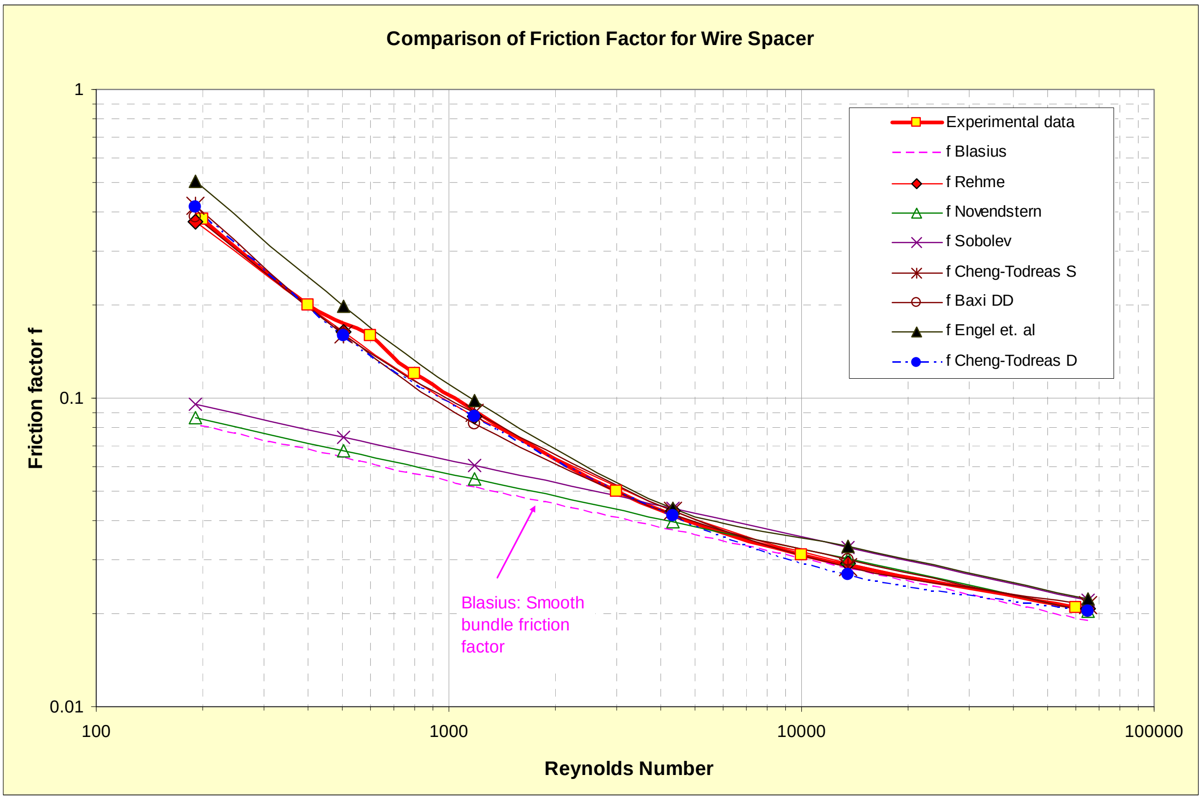


Figure 6-11: Comparison of different friction factor correlations (SIM-ADS calculated) and experimental friction factor values for the wire-wrapped fuel assembly (case 127-pin, P/D=1.176; H/D=38.0): (water, Itch, 1981)

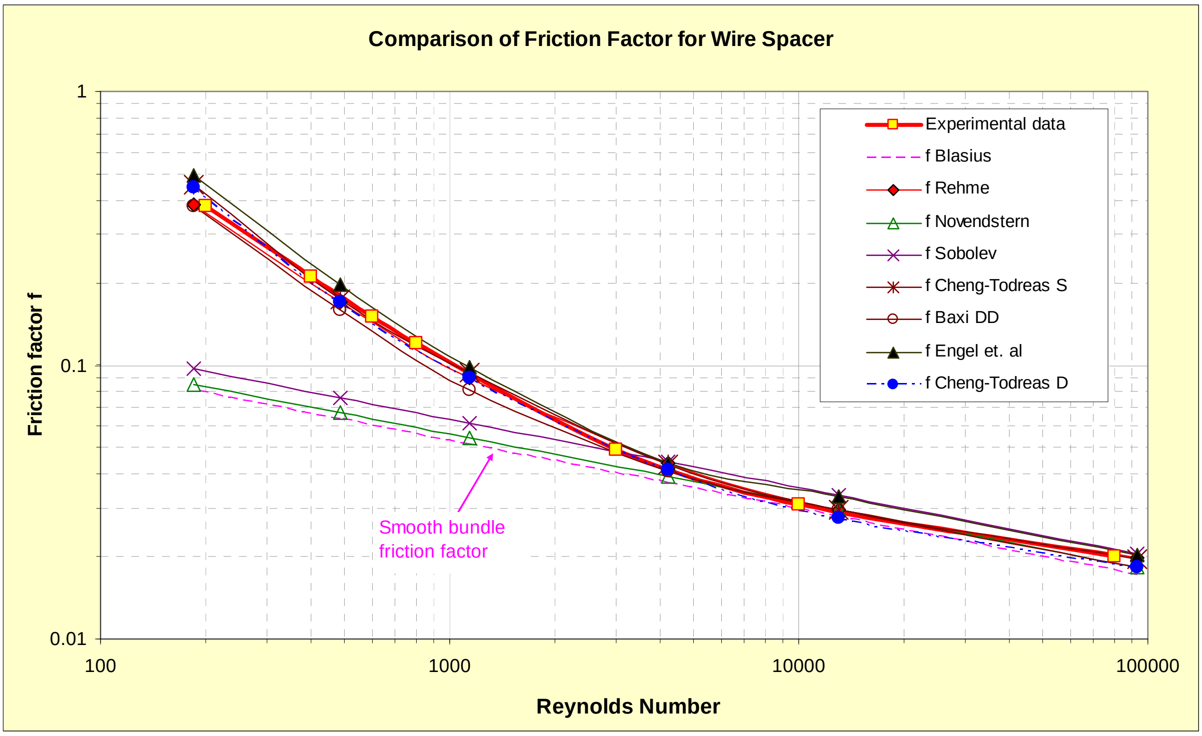


Figure 6-12: Comparison of different friction factor correlations (SIM-ADS calculated) and experimental friction factor values for the wire-wrapped fuel assembly (case 169-pin, P/D=1.214; H/D=47.39): (water, Itch, 1981)

Figures 6-11 and 6-12 show the comparison of the friction factor values for the wire-wrapped FA as calculated using different friction factor correlations with the experimental data. As can be seen from Figure 6-11 (127-pin, P/D=1.176; H/D=38.0) and Figure 6-12 (169-pin, P/D=1.214; H/D=47.39) and based also on RMS values, friction factor correlations best fitting experimental data are in order: all correlations – excellent fit, except Engel (modified) – good fit. As mentioned above, Sobolev and Novendstern correlations can be considered only in the turbulent region (Re > 3000).

6.8 Spencer, 1980 (Cheng S.K., 1984) water experiments

A detailed description of the wire wrapped fuel bundle as used by Spencer (Cheng S.K., 1984) can be found in section 6.8 of the Ref. (Bubelis E. and Schikorr M., 2008). Rod bundle parameters for the experimental setup are: number of pins/rods is 217, pitch to diameter ratio is 1.252, wire lead length to diameter ratio is 51.74; pin/rod diameter is assumed to be 12.0 mm.

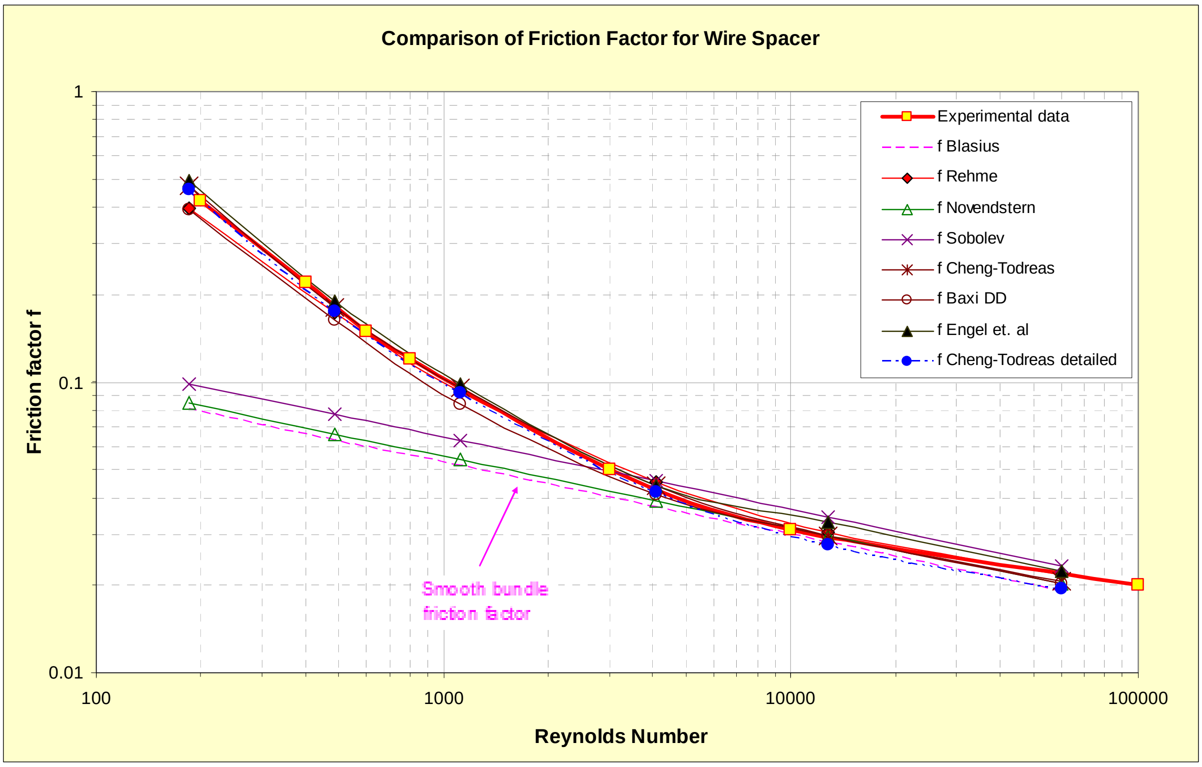


Figure 6-13: Comparison of different friction factor correlations (SIM-ADS calculated) and experimental friction factor values for the wire-wrapped fuel assembly (case 217-pin, P/D=1.252; H/D=51.74): (water, Spencer, 1980)

Figure 6-13 (217-pin, P/D=1.252; H/D=51.74) shows the comparison of the friction factor values for the wire-wrapped FA as calculated using different friction factor correlations with the experimental data. According to Figure 6-13 (217-pin, P/D=1.252; H/D=51.74) and based also on RMS values, friction factor correlations best fitting experimental data in the turbulent range are Cheng-Todreas simplified (CTS), Rehme, Baxi-DalleDonne (modified), Novendstern, Cheng-Todreas detailed (CTD) and Engel (modified), all of them basically replicating the experimental data very well. Sobolev does not follow the experimental data well. In the laminar flow range, friction factor correlations best fitting experimental data are Cheng-Todreas detailed (CTD), Cheng-Todreas simplified (CTS), Engel (modified), Rehme and Baxi-DalleDonne (modified), with the exception of Novendstern and Sobolev that are not applicable in this range.

6.9 Rehme, 1973 (Rehme K., 1973) water experiments

A detailed description of the wire wrapped fuel bundles as used by Rehme (Rehme K., 1973) can be found in section 6.9 of the Ref. (Bubelis E. and Schikorr M., 2008). The length of the test section was 1500 mm. Stainless steel rods of a diameter 12 mm and length 940 mm were inserted into a hexagonal channel. The polished surface of the cores resulted in a perfectly smooth surface of the channel. The important parameters varied in that study are the pitch-to-diameter ratio of the rods by using different wire diameters with the same rod diameter, the lead of the wire wraps and the number of rods in the rod bundles. The pitch-to-diameter ratio studied ranged between 1.125 and 1.417, the lead of the wire wraps between 100 and 600 mm, and the number of rods between 7 and 19 rods.

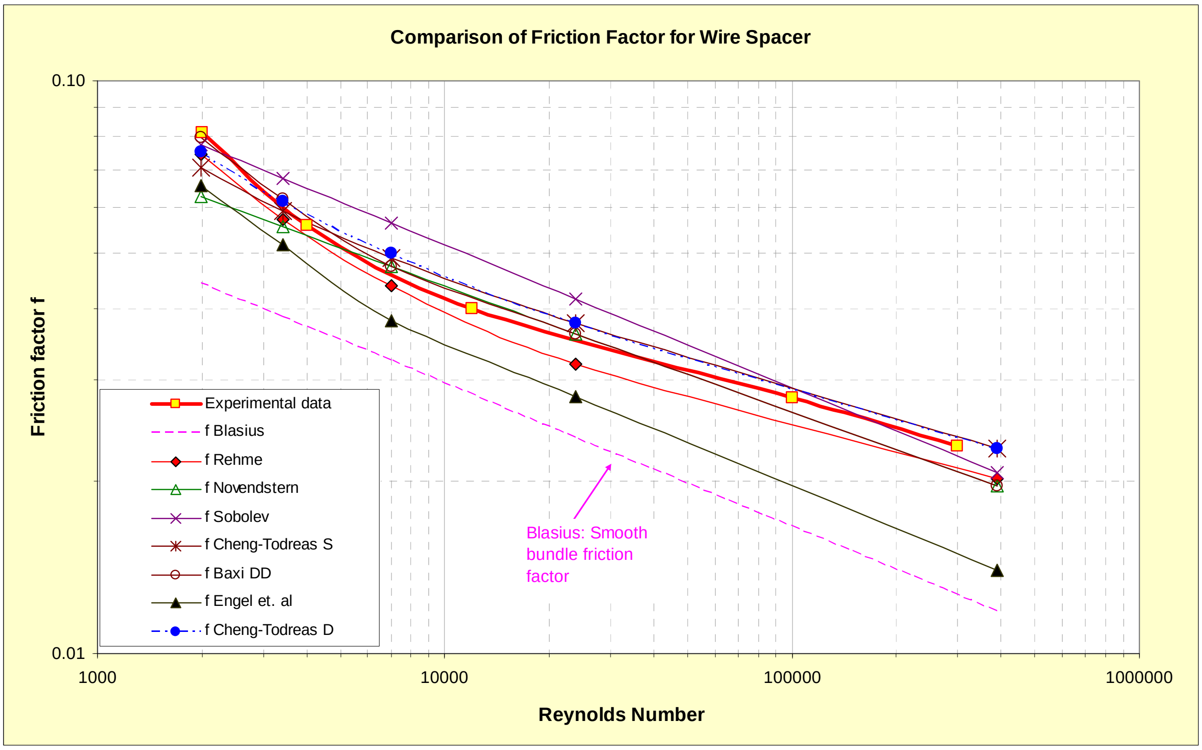


Figure 6-14: Comparison of different friction factor correlations (SIM-ADS calculated) and experimental friction factor values for the wire-wrapped fuel assembly (case 19-rods, P/D=1.417; wire lead length 300 mm): (water, Rehme, 1973)

The first set of the Rehme experimental data analyzed (refer to Figure 25 in Ref. (Bubelis E. and Schikorr M., 2008)) demonstrates the effect of different leads of wire wraps on the friction factor for 19 rods and the highest pitch-to-diameter ratio tested - 1.417. It is obvious that the friction factor increases with decreasing wire wraps pitch. One can notice a strong increase in the friction factor with a high pitch-to-diameter ratio of the rods.

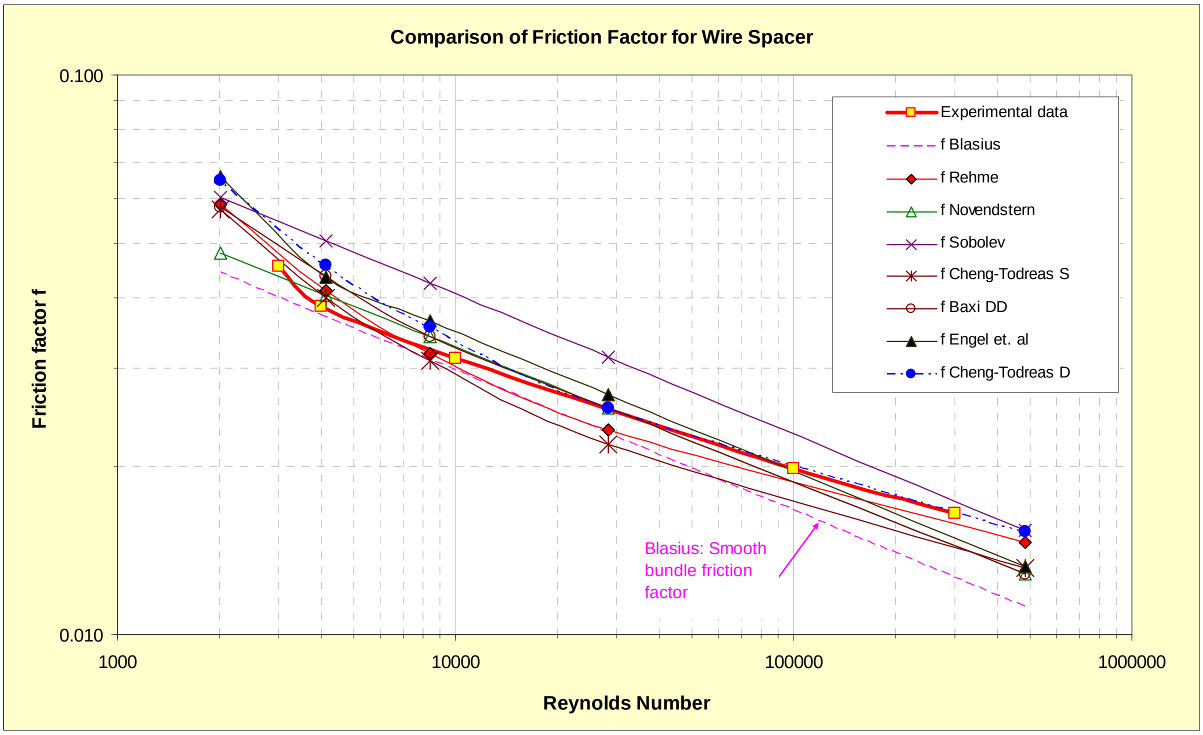


Figure 6-15: Comparison of different friction factor correlations (SIM-ADS calculated) and experimental friction factor values for the wire-wrapped fuel assembly (case 19-rods, P/D=1.417; wire lead length 600 mm): (water, Rehme, 1973)

Figure 6-14 (19-rods, P/D=1.417; wire lead length 300 mm) and Figure 6-15 (19-rods, P/D=1.417; wire lead length 600 mm) illustrate the influence of the wire lead length at a P/D of 1.417 and show the comparison of the friction factor values for the wire-wrapped FA as calculated using different friction factor correlations with the experimental data. As it can be seen from Figure 6-14 (wire lead length 300 mm) and Figure 6-15 (wire lead length 600 mm) and based also on RMS values, friction factor correlations best fitting experimental data are Baxi-DalleDonne (modified), Cheng-Todreas detailed (CTD), Rehme and Cheng-Todreas simplified (CTS). Engel (modified) is close to the data for the 600 mm case (Figure 6-15), but deviates quite significantly for the 300 mm case (Figure 6-14).

The second set of the Rehme experimental data analyzed (refer to Figure 28 in Ref. (Bubelis E. and Schikorr M., 2008)) demonstrates again the effect of different leads of wire wraps on the friction factor for 19 rods and the lowest P/D ratio of 1.125. It is obvious that the friction factor increase with decreasing wire wraps pitch is smaller with a smaller pitch-to-diameter ratio of the rods. This fact can be explained by the decreasing blockage of the flow area caused by the wire wraps with decreasing pitch-to-diameter ratio of the rods.

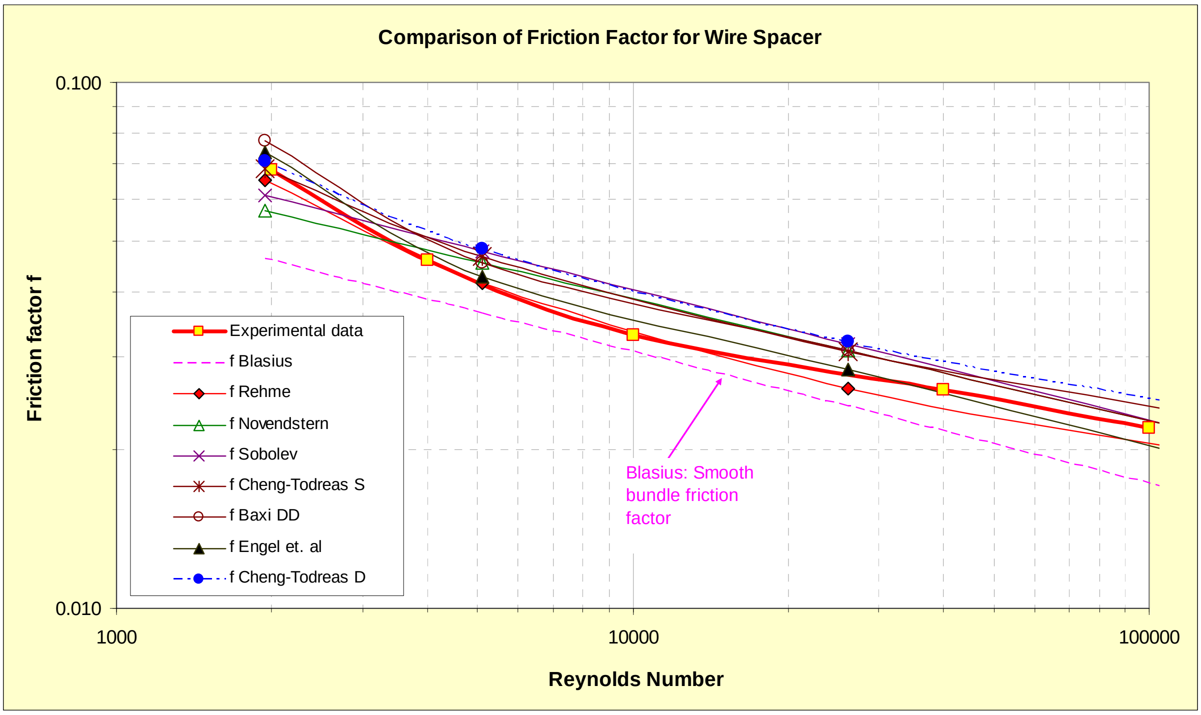


Figure 6-16: Comparison of different friction factor correlations (SIM-ADS calculated) and experimental friction factor values for the wire-wrapped fuel assembly (case 19-rods, P/D=1.125; wire lead length 200 mm): (water, Rehme, 1973)

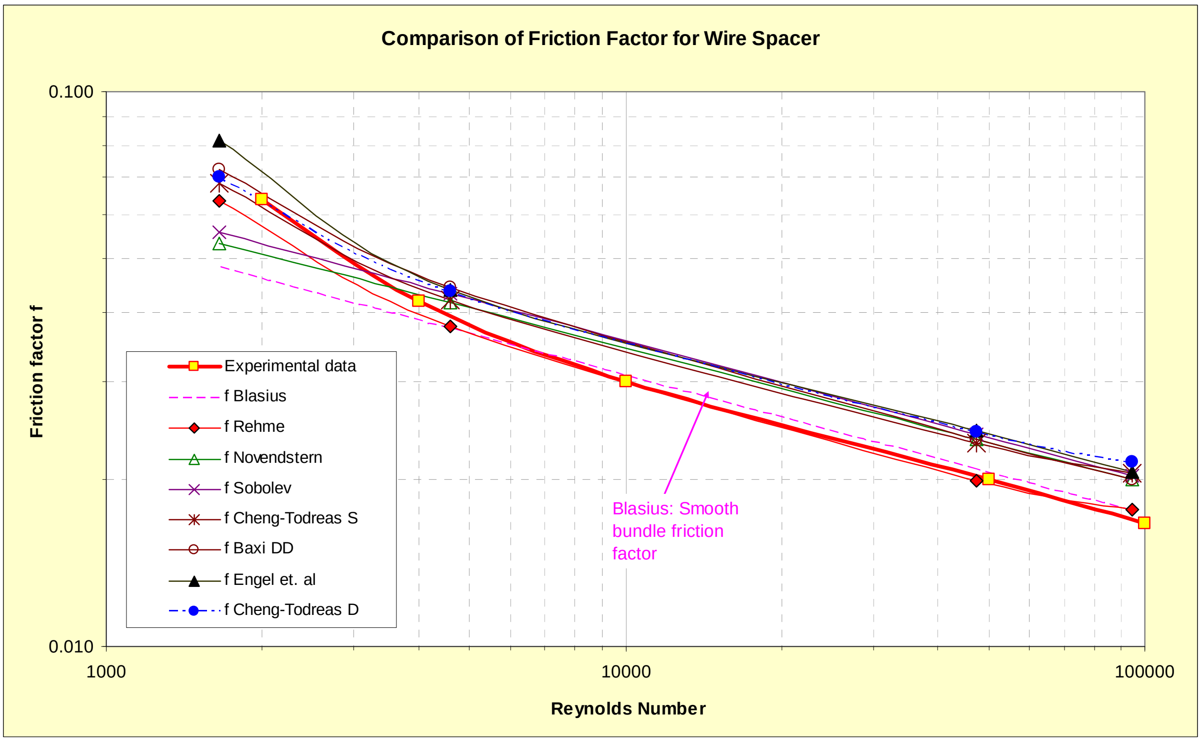


Figure 6-17: Comparison of different friction factor correlations (SIM-ADS calculated) and experimental friction factor values for the wire-wrapped fuel assembly (case 19-rods, P/D=1.125; wire lead length 300 mm): (water, Rehme, 1973)

Figure 6-16 (19-rods, P/D=1.125; wire lead length 200 mm) and Figure 6-17 (19-rods, P/D=1.125; wire lead length 300 mm) show the comparison of the friction factor values for the wire-wrapped FA as calculated using different friction factor correlations with the experimental data. As can be seen from Figures 6-16 and 6-17 and based also on RMS values, friction factor correlations best fitting experimental data are in order: Rehme – excellent fit, others – good fit.

The third set of the Rehme experimental data analyzed (refer to Figure 31 in Ref. (Bubelis E. and Schikorr M., 2008)) demonstrates more clearly the effect of different pitch-to-diameter ratio on the friction factor for 7 rods and the smallest pitch of wire wraps (100 mm) configuration as a function of Reynolds number. The dependence of pitch-to-diameter ratio on the friction factor is much stronger for smaller pitch of wire wraps value (100 mm) than for higher pitch of wire wraps value (e.g. 600 mm).

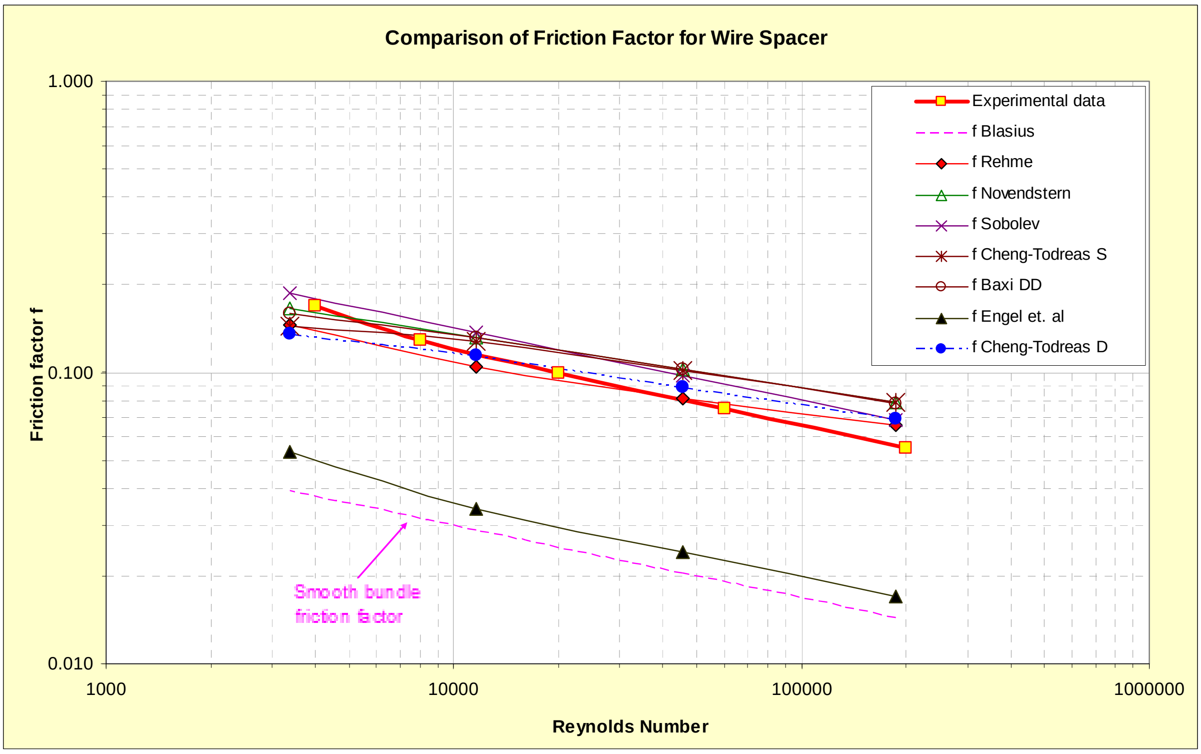


Figure 6-18: Comparison of different friction factor correlations (SIM-ADS calculated) and experimental friction factor values for the wire-wrapped fuel assembly (case 7-rods, P/D=1.343; wire lead length 100 mm): (water, Rehme, 1973)

Figure 6-18 (7-rods, P/D=1.343; wire lead length 100 mm) and Figure 6-19 (7-rods, P/D=1.275; wire lead length 100 mm) shows the comparison of the friction factor values for the wire-wrapped FA as calculated using different friction factor correlations with the experimental data. As it can be seen from Figures 6-18 and 6-19 and based also on RMS values, friction factor correlations best fitting experimental data are in order: Rehme followed by Cheng-Todreas detailed (CTD), Baxi-DalleDonne (modified), Novendstern, Sobolev, Cheng-Todreas simplified (CTS) and Engel (modified).

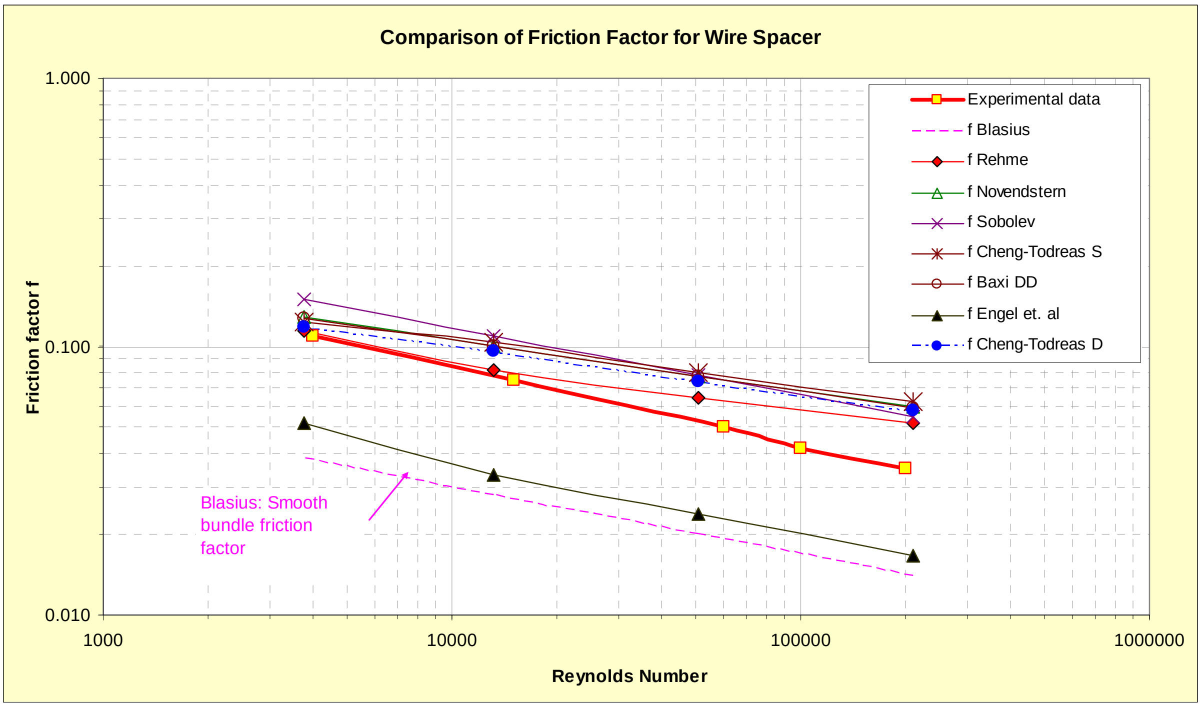


Figure 6-19: Comparison of different friction factor correlations (SIM-ADS calculated) and experimental friction factor values for the wire-wrapped fuel assembly (case 7-rods, P/D=1.275; wire lead length 100 mm): (water, Rehme, 1973)

The fourth set of the Rehme experimental data analyzed (refer to Figure 34 in Ref. (Bubelis E. and Schikorr M., 2008)) demonstrates how the friction factor depends on the lead wire length as well as on the number of rods in a rod bundle. The friction factor increases with increasing number of rods. This effect can be explained by the fact that the influence of the smooth channel wall results in a lower pressure loss. Since rod bundles with only a few rods include a relatively higher part of channel wall with respect to the total wetted perimeter, the total pressure drop is lower.

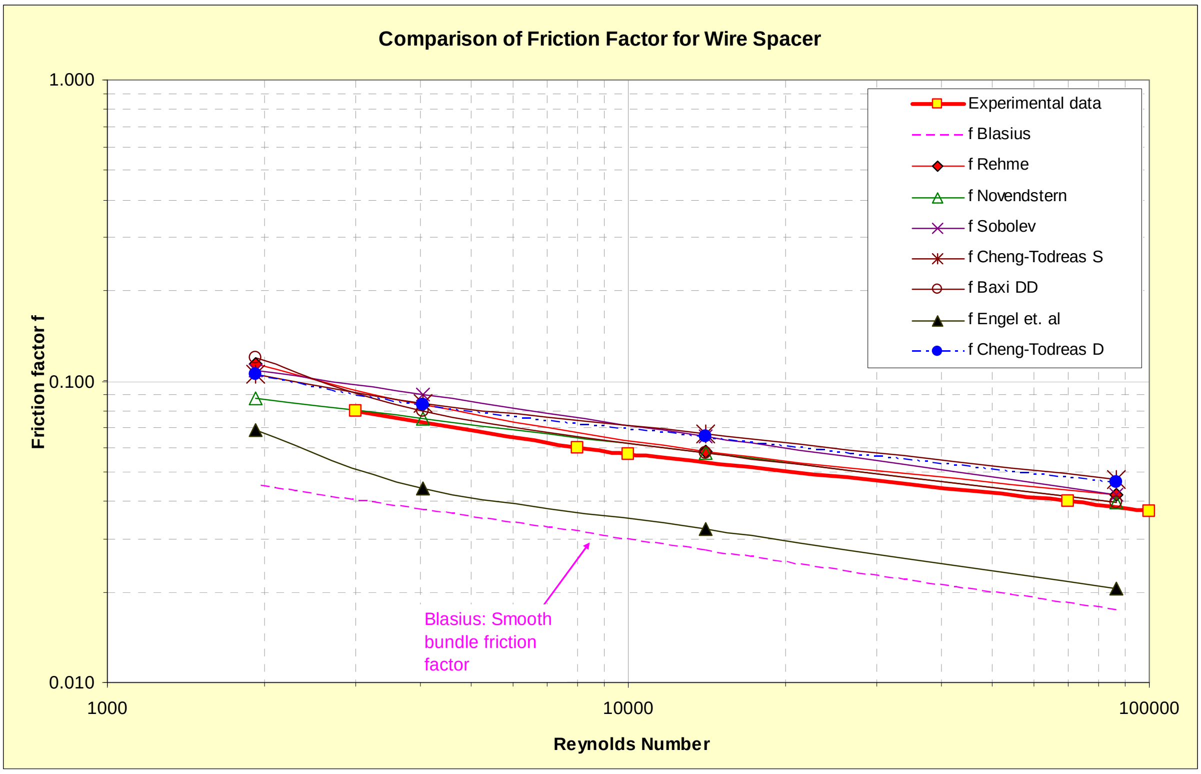


Figure 6-20: Comparison of different friction factor correlations (SIM-ADS calculated) and experimental friction factor values for the wire-wrapped fuel assembly (case 19-rods, P/D=1.275; wire lead length 150 mm): (water, Rehme, 1973)

Figure 6-20 (19-rods, P/D=1.275; wire lead length 150 mm) and Figure 6-21 (19-rods, P/D=1.275; wire lead length 600 mm) illustrate again the effect of the wire lead length and it shows the comparison of the friction factor values for the wire-wrapped FA as calculated using different friction factor correlations with the experimental data. According to Figures 6-20 and 6- 21 and based also on RMS values, friction factor correlations best fitting experimental data are in order: Rehme, Novendstern, Baxi-DalleDonne (modified), Cheng-Todreas simplified (CTS), Cheng-Todreas detailed (CTD), Engel (modified) and Sobolev.

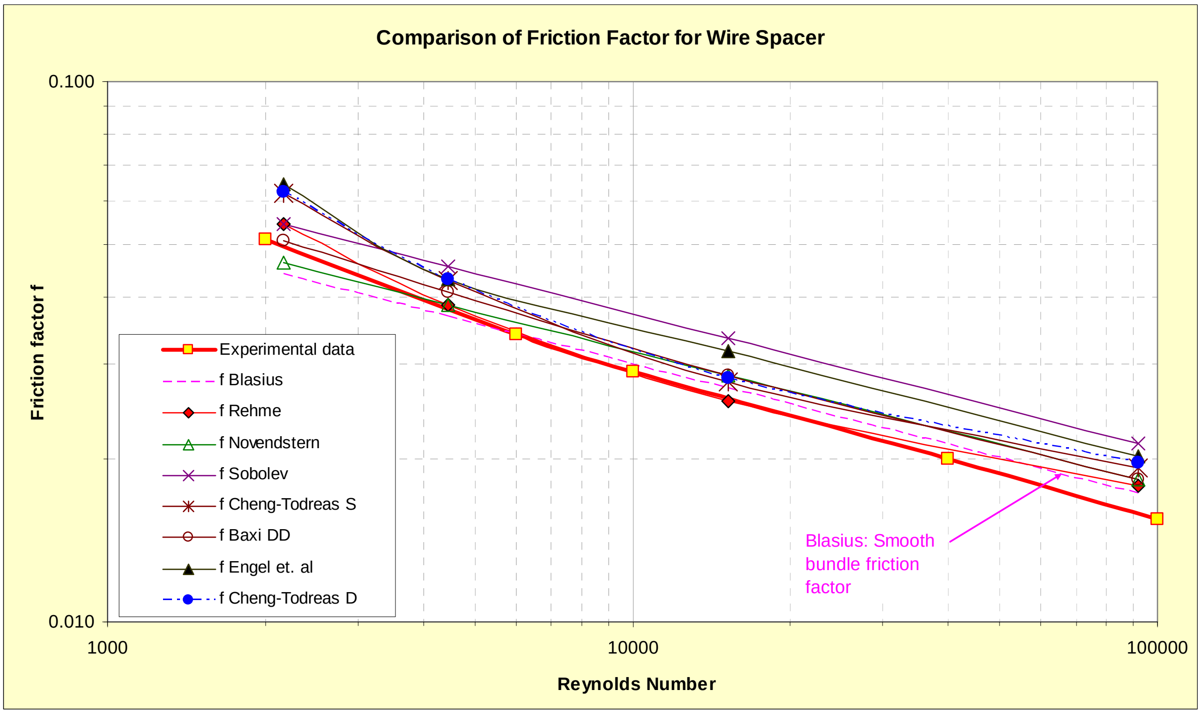


Figure 6-21: Comparison of different friction factor correlations (SIM-ADS calculated) and experimental friction factor values for the wire-wrapped fuel assembly (case 19-rods, P/D=1.275; wire lead length 600 mm): (water, Rehme, 1973)

6.10 Vijayan et al., 1999 (Vijayan P.K. et al, 1999) water experiments

A detailed description of the two different test facilities as used by Vijayan (Vijayan P.K. et al, 1999) can be found in section 6.10 of the Ref. (Bubelis E. and Schikorr M., 2008). A low pressure flow test facility was used (for generating low and medium Reynolds number data (up to ~50,000) whereas a high pressure facility was used to generate high Reynolds number (10,000 to 550,000)) to measure the pressure drop in a 19-rod wire wrapped circular fuel bundle. Prototype fuel channel with 12 fuel bundles were stacked one after another. The geometric details of the fuel channel and the bundles used are the following: channel inside diameter 0.08255 m, flow area 0.0018851 m^2, hydraulic diameter 5.88 mm, total wetted perimeter 1.28226 m, number of bundles per channel 12, clad outside diameter 15.21 mm, center-to-center spacing of elements 16.43 mm, length of one bundle 0.4953 m, lead of the wire wrap 0.231775 m, wire diameter ~1.22 mm, wire length 0.4877 m, number of wires per bundle 24, pitch to diameter ratio 1.0802, wire lead to diameter ratio 15.24. The water flow rate ranged from 0.017 to 18.3 kg/s.

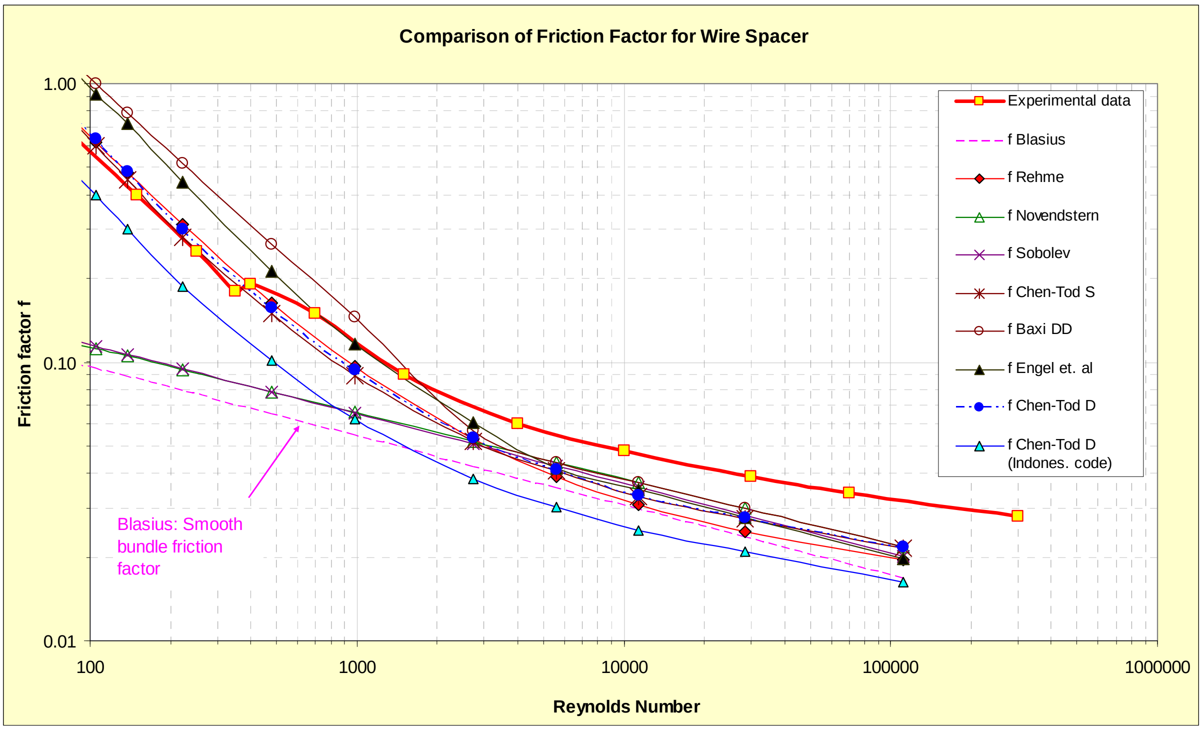


Figure 6-22: Comparison of different friction factor correlations (SIM-ADS calculated) and experimental friction factor values for the wire-wrapped fuel assembly: (water, Vijayan et al., 1999)

Figure 6-22 shows the comparison of the friction factor values for the wire-wrapped FA as calculated using different friction factor correlations with the experimental data. As can be observed from Figure 6-22 and based also on RMS values, none of the friction factor correlations provide a good fit in this regime. Most of the correlations yield results in a very narrow band significantly below the experimental data. In the laminar range, only Rehme, Cheng-Todreas simplified (CTS) and Cheng-Todreas detailed (CTD) provide reasonably good fits. It appears that there may be an experimental bias in this particular data set in the turbulent flow regime as all other data sets analyzed so far showed at least one-two correlations yielding very good or acceptable retracement of the experimental data.

The results of the code recommended by Cheng and Todreas (see link in section 3.4 of this report) to be used for calculating the friction factors using their current model(s) – both detailed and simplified, is also plotted in Figure 6-22. Here we observe, that the results of the code (marked in Figure 6-22 as “CTD Indones. code”) deviate in this particular case quite significantly from the actual, detailed Cheng-Todreas detailed (CTD) results. The authors of this report checked the coding of the Indones. code and found some deviations from the Cheng-Todreas model description as documented in Ref. (Cheng S. K. and Todreas N. E., 1986). Upon modifying the Indonesian code, the “revised Indonesian code” now replicates exactly the detailed Cheng-Todreas detailed (CTD) results as plotted in Figure 6-22. The authors thus recommend that the revised version of the code should be formalized by Cheng and Todreas and subsequently made available for further distribution.

7 Analysis of the CFD modeling results based on Gajapathy et. al., 2007 (Gajapathy R. et al., 2007) sodium cooled PFBR fuel bundle investigation

A detailed description of the sodium cooled fuel bundle investigated by Gajapathy et. al. (Gajapathy R. et al., 2007) can be found in section 7 of the Ref. (Bubelis E. and Schikorr M., 2008). The sodium cooled fuel bundle, investigated with a CFD code, consists of seven fuel pins of diameter 6.6 mm arranged in a triangular pitch of 8.28 mm which is that of the Indian Prototype Fast Breeder Reactor (PFBR) at Kalpakkam. The width across flat of the hex-can is 24.52 mm. The helical wire diameter is 1.65 mm with a lead of 150 mm. Only one pitch height of the helical wire-wrapped pin bundle is considered. The hydraulic diameter of the bundle with spacer wire is 4.0 mm and the same for the bundle without spacer wire is 4.9 mm. Reynolds number in this study is varied from 1000 up to 100,000.

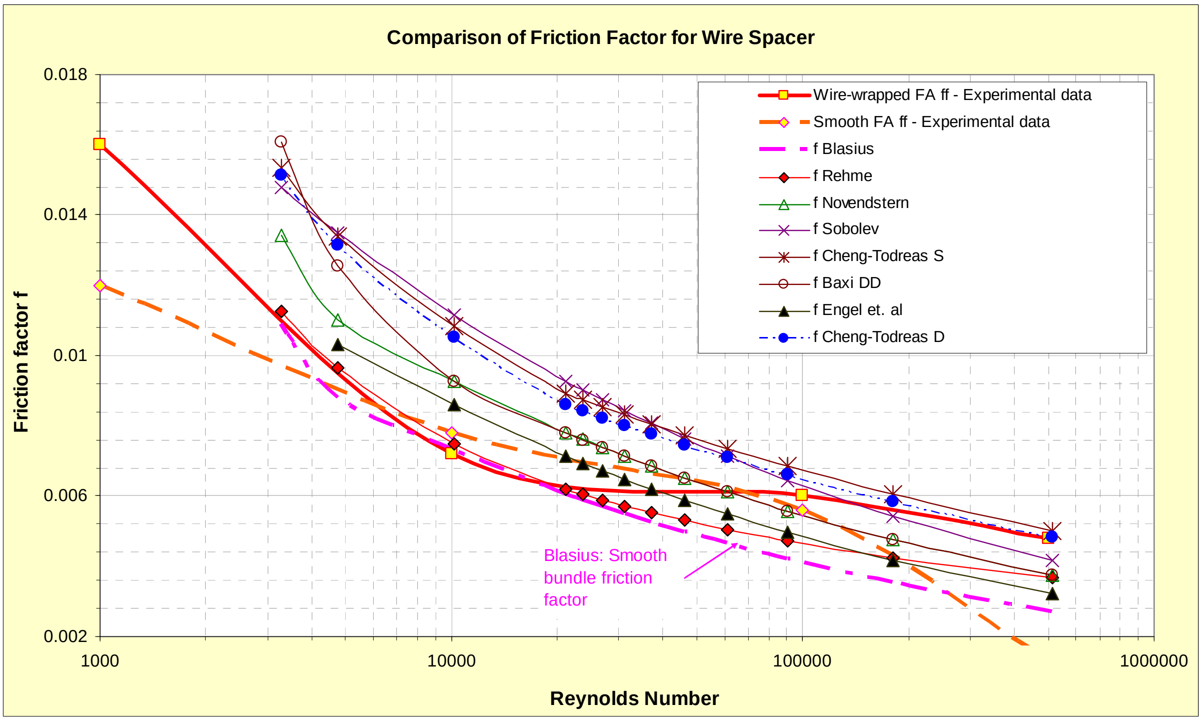


Figure 7-1: Comparison of different friction factor correlations (SIM-ADS calculated) and experimental friction factor values for the wire-wrapped fuel assembly, as well as for the case without a wire-wrap: (sodium, Gajapathy et al., 2007)

Based on the data provided in Ref. (Gajapathy R. et al., 2007), corresponding calculations were performed with SIM-ADS code (Schikorr W. M., 2001) and the calculational results compared to the CFD study data. Figure 7-1 shows the comparison of the friction factor values for the wire-wrapped FA, as well as for the case without a wire-wrap, as calculated using different friction factor correlations with the CFD study data. As can be seen from Figure 7-1 and based also on RMS values, friction factor correlations best fitting CFD study data are: Rehme – excellent fit below Re ~ 20000, under-predicting at Re > 20 000; Engel (modified) – good fit, followed by Novendstern and Baxi-DalleDonne (modified).

8 Analysis of the experimental data by Geffraye, 2008 (Geffraye G., 2008) based on ESTHAIR air experiments

A detailed description of the ESTHAIR test facility, as well as the fuel assembly, used by Geffraye et. al. (Geffraye G., 2008) can be found in section 8 of the Ref. (Bubelis E. and Schikorr M., 2008). The fuel assembly used to measure the pressure drop in a 19-pin wire wrapped fuel assembly was cooled by air. Main characteristics of the 19-pin bundle are: scale 2.44, rod diameter 16 mm, heating length 1.65 m, wire lead 350 mm, pins pitch 19.84 mm, pitch to diameter ratio is 1.24, wire diameter is 3.84 mm.

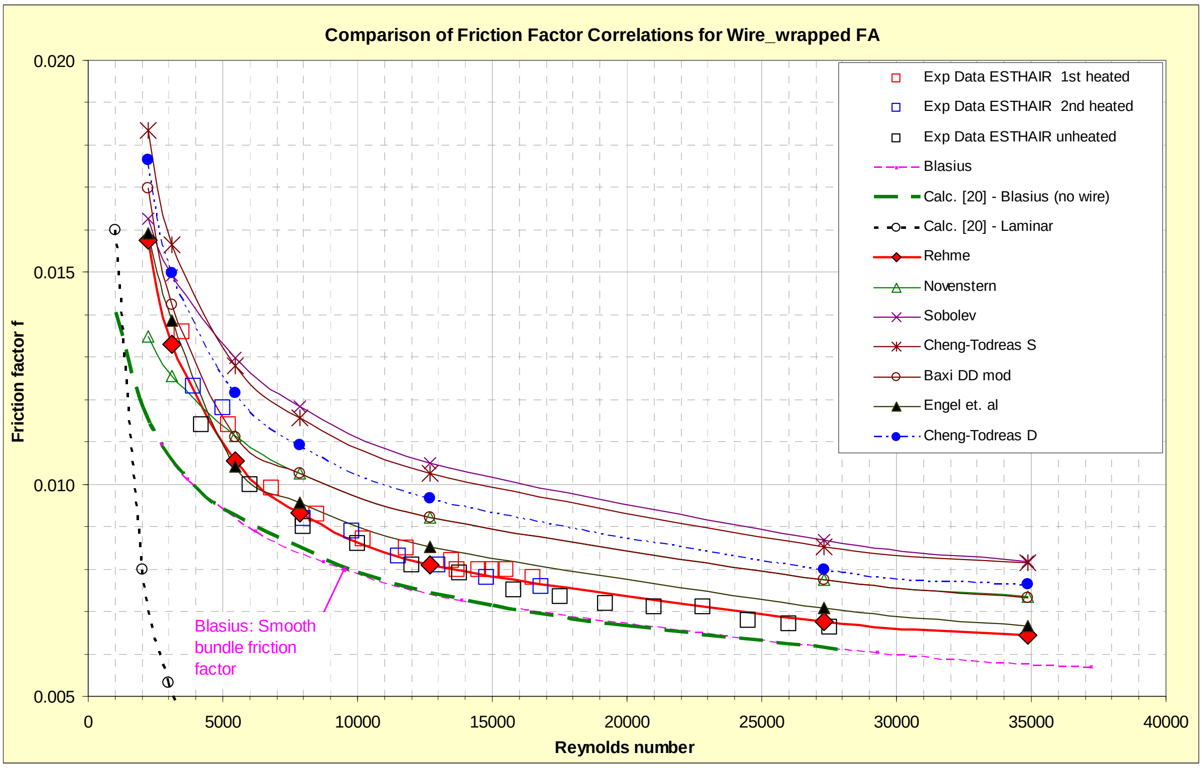


Figure 8-1: Comparison of different friction factor correlations (SIM-ADS calculated) and experimental friction factor values for the wire-wrapped fuel assembly: (air, Geffraye et al., 2008, ESTHAIR exp.)

Based on the data provided in Ref. (Geffraye G., 2008), corresponding calculations were performed with SIM-ADS code (Schikorr W. M., 2001) and the calculational results compared to the experimental data. Figure 8-1 shows the comparison of the friction factor values for the wire-wrapped FA as calculated using different friction factor correlations with the experimental data.

As can be seen from Figure 8-1 and based also on RMS values, friction factor correlations best fitting experimental data are in order: Rehme – excellent fit, Engel (modified) – good fit.

When looking at the friction factor curve in Figure 8-1 and the experimental data from Ref. (Geffraye G., 2008), one can see some difference between the two predictions. The difference here is due to the Re value used when calculating friction factor as proposed by Rehme. In Figure 8-1 the Rehme friction factor was calculated using Re value for the hot SA in wire-wrap configuration, while in the experimental data from Ref. (Geffraye G., 2008) the Rehme friction factor was calculated using average Re value for the smooth pin configuration not taking into account the existing wire-wrap.

The latest information on the experimental data for the 19-pin assembly friction factor values obtained on ESTHAIR test facility can be found in Ref. (Berthoux M. and Carenza A., 2008) and should be compared to the experimental data presented in Ref. (Geffraye G., 2008). Again, along with the experimental data one can see some predictions of the friction factors obtained by the authors of Ref. (Berthoux M. and Carenza A., 2008) using several different friction factor correlations for smooth, as well as wire-wrapped FAs. The only difference between the two data sets is that now authors of Ref. (Berthoux M. and Carenza A., 2008) used the correct Re value (Re value for the hot SA in wire-wrap configuration) when calculating friction factor as proposed by Rehme. This now nicely corresponds also to our predictions as shown in Figure 8-1 (friction factor values obtained using the Rehme correlation).

Once again it should be noted here that in all friction factor correlations presented in sections 3 and 4 of this report, all FA parameters should be taken for the wire-wrap configuration and Re should be taken for the hot SA in wire-wrap configuration as well. Only under these conditions good agreement could be obtained between calculated friction factor values and the existing experimental data.

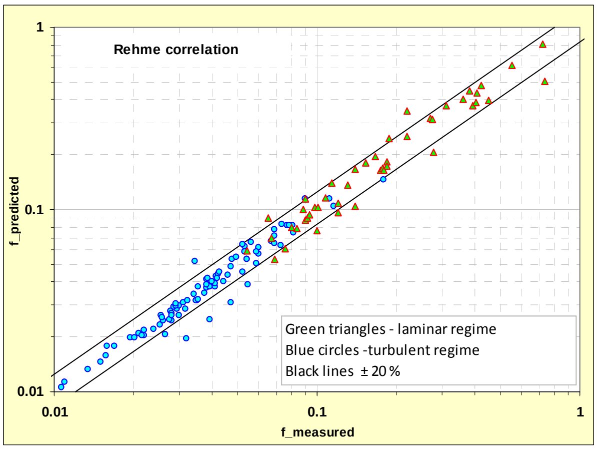
9 Analyses for best fit correlation

A total of 22 data sets were used to investigate the applicability of the various correlations (see Table 9-4), of which only 10 data sets include both laminar and turbulent flow regime data, namely those listed in Table 9-1 (see Figures 6-3, 6-4, 6-5, 6-6, 6-9, 6-10, 6-11, 6-12, 6-13, and 6-22 for more details). This implies that only turbulent flow regime data is available for the remaining 12 data sets (see Figures 6-7, 6-8, 6-14, 6-15, 6-16, 6-17, 6-18, 6-19, 6-20, 6-21, 7-1, and 8-1). In the quantitative analysis differentiation of the underlying data set ("22", or "10") can be made in the turbulent regime analysis, all "22" (or the "10") data sets can be used, whereas looking at the laminar regime, only the "10" data sets are applicable. When looking for an overall, or "combined" quantification (extending over both laminar and turbulent flow regimes), the issue arises if the underlying data is limited to the "10" data sets exclusively (for which both laminar and turbulent flow regime data is available), or extension to the "22" data sets is allowed thereby overweighting the turbulent flow regime. Both procedures are analyzed and documented (i.e. using the "10" as well as the "22" data sets) in order to allow differentiation.

Table 9-1: Evaluation of RMS for "laminar" flow regime of different friction factor correlations against 10 experimental data sets

RMS Laminar flow regime															
					Correlation:	**Rehme**	**Novendst.**	**Sobolev**	**BDD (m)**	**Engel (m)**	**CTD**	**CTS**	RMS Ranking		
Experiment	fluid	Figure	Validation range of correlation (N, P/D, H/D)			7-217, 1.1-1.42, 8-50	19-217, 1.06-1.42, 8-96		19-217, 1.06-1.42, 8-96	19-61, 1.06-1.42, 8-96	7-217, 1.0-1.42, 4-52	19-217, 1.025-1.42, 8-50	(First)	(Second)	(Third)
			N	P/D	H/D	RMS [%]									
Choi et al., 2003	w	6-3	271	1.2	24.84	7.8	NA	NA	47.6	8.5	12.7	8.0	Rehme	CTS	Engel (m)
Chun et al., 2001	w	6-4	19	1.256	25	25.3	NA	NA	17.3	12.9	11.7	10.2	CTS	CTD	Engel (m)
Arwikar et al., 1979	w	6-5	61	1.05	14.45	20.3	NA	NA	9.5	49.2	15.1	14.6	BDD (m)	CTS	CTD
Chiu et al., 1979	w	6-6	61	1.063	8	17.5	NA	NA	29.4	16.3	24.2	27.3	Engel (m)	Rehme	CTD
Marten et al., 1982	w	6-9	37	1.041	17.01	3.5	NA	NA	12.3	33.3	23.0	20.6	Rehme	BDD (m)	CTS
Marten et al., 1982	w	6-10	37	1.101	12.31	4.4	NA	NA	33.0	20.2	8.1	12.5	Rehme	CTD	CTS
Itch, 1981	w	6-11	127	1.176	38	4.9	NA	NA	6.7	19.5	6.7	6.5	Rehme	CTS	CTD
Itch, 1981	w	6-12	169	1.214	47.39	3.8	NA	NA	9.4	15.2	6.7	7.8	Rehme	CTD	CTS
Spencer, 1980	w	6-13	217	1.252	51.74	8.1	NA	NA	11.7	6.2	3.5	3.5	CTD	CTS	Engel (m)
Vijayan et al., 1999	w	6-22	19	1.08	15.24	15.4	NA	NA	66.6	51.6	16.8	15.9	Rehme	CTS	CTD
Averaged over 10 analysed experiments: Mean						11.1	NA	NA	24.4	23.3	12.9	12.7	Rehme	CTS	CTD

Re number range - Rehme: Re=1000-300000; Novendstern, Sobolev: Re=2600-100000; Engel: Re=50-100000; CTD, CTS: Re=50-1000000.


Rehme correlation
f_predicted
f_measured
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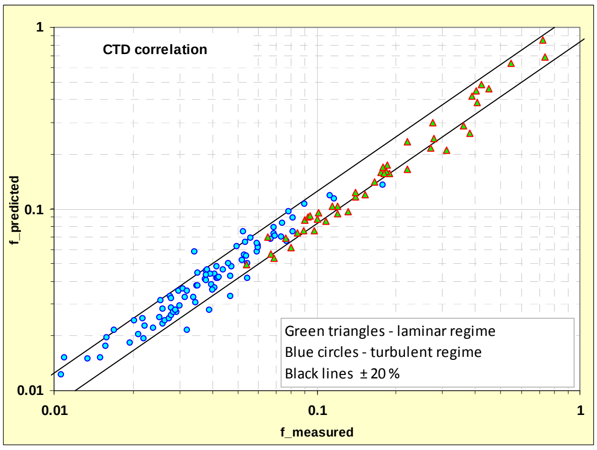
0.1
0.01
0.01
0.1
1
Green triangles - laminar regime
Blue circles -turbulent regime
Black lines ± 20 %


CTD correlation
f_predicted
f_measured
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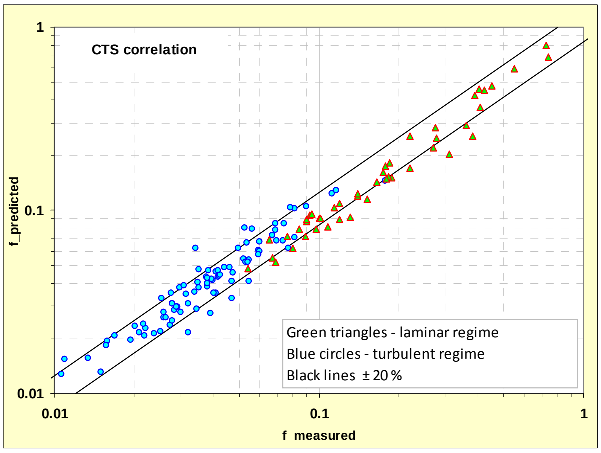
0.1
0.01
0.01
0.1
1
Green triangles - laminar regime
Blue circles - turbulent regime
Black lines ± 20 %


CTS correlation
f_predicted
f_measured
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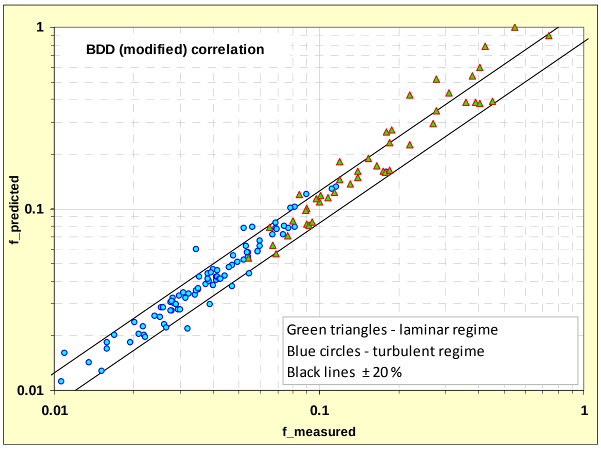
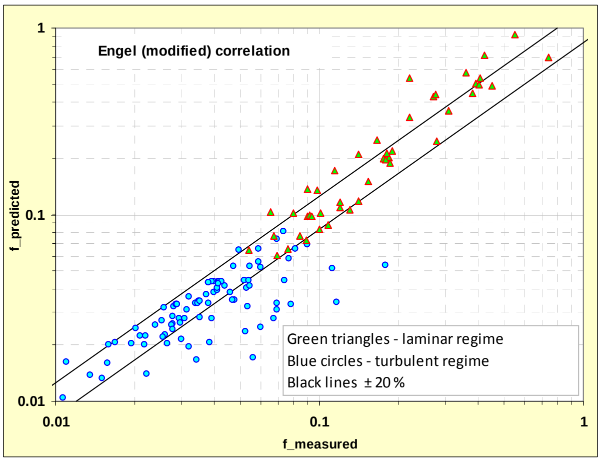
0.1
0.01
0.01
0.1
1
Green triangles - laminar regime
Blue circles - turbulent regime
Black lines ± 20 %


BDD (modified) correlation
f_predicted
f_measured
1
0.1
0.01
0.01
0.1
1
Green triangles - laminar regime
Blue circles - turbulent regime
Black lines ± 20 %


Engel (modified) correlation
f_predicted
f_measured
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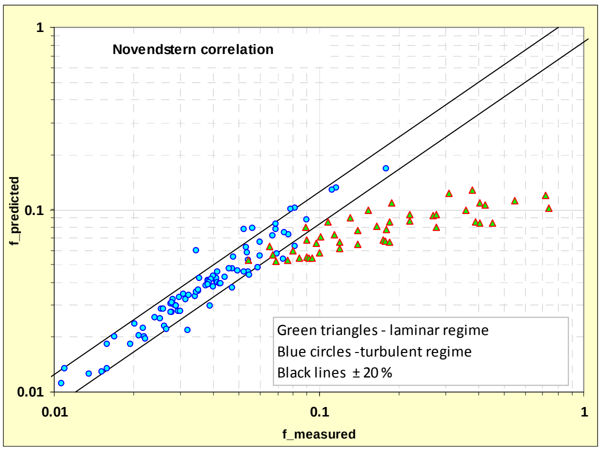
0.1
0.01
0.01
0.1
1
Green triangles - laminar regime
Blue circles - turbulent regime
Black lines ± 20 %


Novendstern correlation
f_predicted
f_measured
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0.1
0.01
0.01
0.1
1
Green triangles - laminar regime
Blue circles -turbulent regime
Black lines ± 20 %

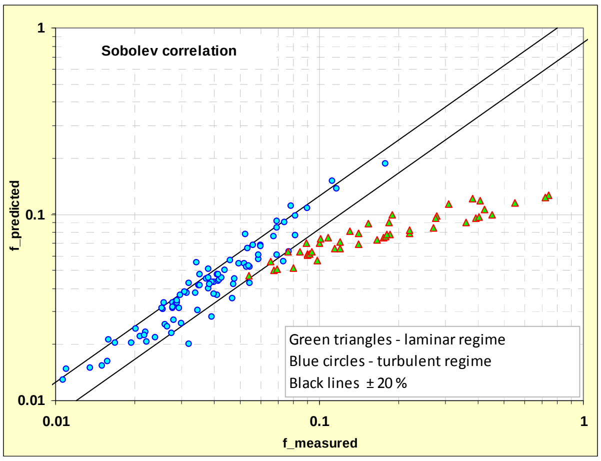

Figure 9-1: Comparison of predicted and the measured friction factors using different investigated correlations of 22 data sets in both turbulent and laminar flow regimes

Figure 9-1 shows the plots of the predicted friction factor versus the measured friction factor distributions for the Rehme, CTD, CTS, Baxi-DalleDonne (modified), Engel (modified), Novendstern and Sobolev correlations for all 22 data sets. As can be clearly observed from these plots, not all correlations are applicable in the laminar regime (friction factor ~ > 0.1), in particular Novendstern and Sobolev. All other correlations indicated reasonable or good fits also in the laminar flow regime, in particular CTD, CTS and Rehme.

To allow the comparison of the goodness of the various correlations, the quantitative analysis uses the root mean square (RMS) and the standard deviation (STD) as the merit of measure. The RMS and the STD in the laminar and the turbulent flow regime of each data set of the “10” or “22” data sets was calculated and listed in Tables 9-1 to 9-11 along with a ranking scheme based on the RMS or STD reflecting the fidelity of the particular correlation to the specific data set.

Laminar Flow Regime:

Tables 9-1 and 9-2 list the calculated RMS and STD in the laminar flow regime of each data set of the “10” data sets. Columns 14, 15, and 16 provide a ranking of the first three ranked correlations. In line 16 of Tables 9-1 and 9-2, the averaged RMS and STD values of all “10” data sets are calculated and compared. As can be observed for both RMS and STD, the ranking of correlations in the laminar flow regime yields the following sequential order, namely: Rehme, CTS and then CTD.

Table 9-2: Evaluation of STD for "laminar" flow regime of different friction factor correlations against 10 experimental data sets

STD Laminar flow regime															
					Correlation:	**Rehme**	**Novendst.**	**Sobolev**	**BDD (m)**	**Engel (m)**	**CTD**	**CTS**	STD Ranking		
Experiment	fluid	Figure	Validation range of correlation (N, P/D, H/D)			7-217, 1.1-1.42, 8-50	19-217, 1.06-1.42, 8-96		19-217, 1.06-1.42, 8-96	19-61, 1.06-1.42, 8-96	7-217, 1.0-1.42, 4-52	19-217, 1.025-1.42, 8-50	(First)	(Second)	(Third)
			N	P/D	H/D	STD [%]									
Choi et al., 2003	w	6-3	271	1.2	24.84	2.4	NA	NA	5.6	0.2	1.3	2.1	Engel (m)	CTD	CTS
Chun et al., 2001	w	6-4	19	1.256	25	4.1	NA	NA	12.7	4.3	3.5	3.8	CTD	CTS	Rehme
Arwikar et al., 1979	w	6-5	61	1.05	14.45	9.8	NA	NA	7.5	16.1	9.4	8.4	BDD (m)	CTS	CTD
Chiu et al., 1979	w	6-6	61	1.063	8	8.5	NA	NA	17.6	17.6	6.8	6.2	CTS	CTD	Rehme
Marten et al., 1982	w	6-9	37	1.041	17.01	3.7	NA	NA	5.5	8.5	1.2	2.0	CTD	CTS	Rehme
Marten et al., 1982	w	6-10	37	1.101	12.31	3.8	NA	NA	16.3	16.5	4.1	3.9	Rehme	CTS	CTD
Itch, 1981	w	6-11	127	1.176	38	1.5	NA	NA	4.2	10.4	7.9	8.0	Rehme	BDD (m)	CTD
Itch, 1981	w	6-12	169	1.214	47.39	1.4	NA	NA	3.3	8.0	8.0	8.0	Rehme	BDD (m)	Engel (m)
Spencer, 1980	w	6-13	217	1.252	51.74	5.6	NA	NA	1.3	3.4	3.7	3.8	BDD (m)	Engel (m)	CTD
Vijayan et al., 1999	w	6-22	19	1.08	15.24	16.7	NA	NA	40.6	36.7	18.2	16.1	CTS	Rehme	CTD
Averaged over 10 analysed experiments: Mean						5.8	NA	NA	11.5	12.2	6.4	6.2	Rehme	CTS	CTD

Re number range - Rehme: Re=1000-300000; Novendstern, Sobolev: Re=2600-100000; Engel: Re=50-100000; CTD, CTS: Re=50-1000000.

Table 9-3: Ranking summary of the laminar flow regime RMS of different friction factor correlations against 10 experimental data sets for which laminar data is provided (see Table 9-1)

RMS Laminar Flow Regime 10 experiments			
	water only		
Ranking	**RMS** ranking	RMS [%]	RMS rel. merit fr
1	**Rehme**	11.1	1.00
2	CTS	12.7	0.88
3	CTD	12.9	0.86
4	Engel	23.3	0.48
5	BDD	24.4	0.46
6	Sobolev	51.4	0.22
7	Novendstern	52.8	0.21

Table 9-3 provides the RMS ranking for all correlations in the laminar flow regime, along with a factor called 'RMS relative merit' based on the ratio of the lower ranking RMS values relative to the top ranked. This factor allows a quantitative inter-comparison of the relative goodness of various correlations to each other. As an example, in the laminar flow regime, based on 10 data sets, Rehme attains the top ranking with the lowest RMS value of 11.1% yielding a "RMS relative merit" of 1.0 (see Table 9-3), closely followed by CTS with a RMS value of 12.7% and 0.88 for RMS relative merit, and by CTD with 12.9% for RMS and 0.86 of relative merit. This indicates that first, CTD and CTS essentially provide about the same fidelity in the laminar flow regime, and second, both are about 12-14% away from the top ranked Rehme.

Turbulent Flow Regime:

Tables 9-4 and 9-5 list the calculated RMS and STD in the turbulent flow regime of each data set of the "22" data set. Columns 14, 15, and 16 again provide a ranking of the first three ranked correlations for each data set. In lines 28 to 32 of Tables 9-4 and 9-5, various "averaged" and differently weighted RMS and STD values of all "22" data sets are calculated and compared. For example, line 28 lists the mean, or averaged RMS in Table 9-4 (or STD in Table 9-5) over all 22 turbulent flow regime data sets. As can be observed, the top three RMS ranking of correlations in the turbulent flow regime yields the following sequential order, namely: Rehme, BDD(m) and then Novendstern, and the top three STD ranking of correlations yields: Rehme, Engel(m) and then CTD.

Lines 29 to 32 in Table 9-4 are used to assess the sensitivity to different weighting schemes on the RMS as summarized in Table 9-6. 20\1\1 indicates that each of the 22 data sets is allowed equal weight thereby representing the 'mean RMS' value, whereas 3\1\1 indicates, that the average of the 20 water data sets is weighted by a factor three relative to the single air and Na data sets. 1\1\1 indicates equal weighting of the averaged 20 water data sets with the single Na and air data sets. As can be observed from Table 9-6, for all cases considered, the Rehme correlation always yields the lowest RMS value (ranging from 9.4 to 8.1%) relative to all other correlations. The second placed correlations are relatively "far away" from the Rehme RMS value as indicated in their relatively low RMS relative merit numbers ranging from 0.74 to 0.56.

Table 9-4: Evaluation of RMS for "turbulent" flow regime of different friction factor correlations against 22 experimental data sets

RMS of the Turbulent flow regime															
					Correlation:	**Rehme**	**Novendst.**	**Sobolev**	**BDD (m)**	**Engel (m)**	**CTD**	**CTS**	RMS Ranking		
Experiment	fluid	Figure	Validation range of correlation (N, P/D, H/D)			7-217, 1.1-1.42, 8-50	19-217, 1.06-1.42, 8-96		19-217, 1.06-1.42, 8-96	19-61, 1.06-1.42, 8-96	7-217, 1.0-1.42, 4-52	19-217, 1.025-1.42, 8-50	(First)	(Second)	(Third)
			N	P/D	H/D	RMS [%]									
Choi et al., 2003	w	6-3	271	1.2	24.84	3.4	9.5	7.0	6.1	6.6	7.6	3.3	CTS	Rehme	BDD (m)
Chun et al., 2001	w	6-4	19	1.256	25	10.5	8.0	15.0	2.1	6.7	5.4	11.2	BDD (m)	CTD	Engel (m)
Arwikar et al., 1979	w	6-5	61	1.05	14.45	7.0	1.9	12.6	2.5	7.4	10.3	14.9	Novendst.	BDD (m)	Rehme
Chiu et al., 1979	w	6-6	61	1.063	8	12.6	13.8	11.2	13.3	25.0	8.6	11.2	CTD	Sobolev	CTS
Tong/Bishop, 1968	w	6-7	19	1.205	8	6.7	14.1	22.5	13.9	56.1	8.6	15.5	Rehme	CTD	BDD (m)
Tong/Bishop, 1968	w	6-8	19	1.205	16	3.0	13.2	25.6	13.1	10.9	21.1	29.0	Rehme	Engel (m)	BDD (m)
Marten et al., 1982	w	6-9	37	1.041	17.01	5.4	10.4	7.2	12.7	11.1	9.0	11.4	Rehme	Sobolev	CTD
Marten et al., 1982	w	6-10	37	1.101	12.31	7.3	6.4	8.6	7.1	20.5	3.7	4.5	CTD	CTS	Novendst.
Itch, 1981	w	6-11	127	1.176	38	2.4	4.2	9.9	3.5	10.5	3.8	2.7	Rehme	CTS	BDD (m)
Itch, 1981	w	6-12	169	1.214	47.39	3.0	5.4	9.8	4.1	8.9	4.8	2.4	CTS	Rehme	BDD (m)
Spencer, 1980	w	6-13	217	1.252	51.74	5.1	6.6	11.9	5.3	8.6	7.3	4.1	CTS	Rehme	BDD (m)
Rehme, 1973	w	6-14	19	1.417	25	7.4	12.0	14.6	5.8	22.9	6.4	7.5	BDD (m)	CTD	Rehme
Rehme, 1973	w	6-15	19	1.417	50	5.4	11.3	23.1	9.9	11.9	11.0	8.9	Rehme	CTS	BDD (m)
Rehme, 1973	w	6-16	19	1.125	16.67	5.2	11.5	11.9	9.4	5.4	13.2	9.5	Rehme	Engel (m)	BDD (m)
Rehme, 1973	w	6-17	19	1.125	25	7.3	18.6	19.0	14.0	17.5	18.2	14.1	Rehme	BDD (m)	CTS
Rehme, 1973	w	6-18	7	1.343	8.33	13.9	25.4	17.8	25.5	70.1	17.8	26.7	Rehme	Sobolev	CTD
Rehme, 1973	w	6-19	7	1.275	8.33	28.5	46.9	47.3	46.6	54.4	42.1	51.8	Rehme	CTD	BDD (m)
Rehme, 1973	w	6-20	19	1.275	12.5	16.2	4.6	19.5	17.7	38.4	18.7	20.0	Novendst.	Rehme	BDD (m)
Rehme, 1973	w	6-21	19	1.275	50	8.1	9.9	25.2	10.0	24.3	19.4	18.2	Rehme	Novendst.	BDD (m)
Vijayan et al., 1999	w	6-22	19	1.08	15.24	34.9	24.6	28.5	24.6	29.8	29.0	29.5	Novendst.	BDD (m)	Sobolev
Gajapathy et al., 2007	Na	7-1	7	1.255	22.73	13.3	18.1	34.5	22.7	20.3	29.4	33.1	Rehme	Novendst.	Engel (m)
Geffraye, 2008	air	8-1	19	1.24	21.88	1.3	12.6	23.8	11.5	4.1	16.7	23.3	Rehme	Engel (m)	BDD (m)
Averaged over all 22 analysed experiments: Mean						9.4	13.1	18.5	12.8	21.4	14.2	16.0	Rehme	BDD (m)	Novendst.
Averaged over 20 water experiments:						9.7	12.9	17.4	12.4	22.4	13.3	14.8	Rehme	BDD (m)	Novendst.
Averaged over 1 Na experiments:						13.3	18.1	34.5	22.7	20.3	29.4	33.1	Rehme	Novendst.	Engel (m)
Averaged over 1 Air experiments:						1.3	12.6	23.8	11.5	4.1	16.7	23.3	Rehme	Engel (m)	BDD (m)
Assuming equal weight of water/air/Na						8.1	14.5	25.3	15.5	15.6	19.8	23.8	Rehme	Novendst.	BDD (m)

Re number range - Rehme: Re=1000-300000; Novendstern, Sobolev: Re=2600-100000; Engel: Re=50-100000; CTD, CTS: Re=50-1000000.

Table 9-5: Evaluation of STD for the “turbulent” flow regime of different friction factor correlations against 22 experimental data sets

STD Turbulent flow regime															
					Correlation:	Rehme	Novendst.	Sobolev	BDD (m)	Engel (m)	CTD	CTS	STD Ranking		
Experiment	fluid	Figure	Validation range of correlation (N, P/D, H/D)			7-217, 1.1-1.42, 8-50	19-217, 1.06-1.42, 8-96		19-217, 1.06-1.42, 8-96	19-61, 1.06-1.42, 8-96	7-217, 1.0-1.42, 4-52	19-217, 1.025-1.42, 8-50	(First)	(Second)	(Third)
			N	P/D	H/D	STD [%]									
Choi et al., 2003	w	6-3	271	1.2	24.84	2.8	5.9	6.6	4.3	4.5	2.7	3.0	CTD	Rehme	CTS
Chun et al., 2001	w	6-4	19	1.256	25	2.4	7.6	8.1	2.3	4.3	3.8	4.6	BDD (m)	Rehme	CTD
Arwikar et al., 1979	w	6-5	61	1.05	14.45	5.5	1.6	2.3	1.8	8.5	1.2	1.6	CTD	Novendst.	CTS
Chiu et al., 1979	w	6-6	61	1.063	8	5.7	12.5	8.8	9.0	1.4	10.0	9.3	Engel (m)	Rehme	Sobolev
Tong/Bishop, 1968	w	6-7	19	1.205	8	5.4	5.8	9.2	5.8	3.4	5.8	6.0	Engel (m)	Rehme	CTD
Tong/Bishop, 1968	w	6-8	19	1.205	16	2.7	3.2	5.6	3.2	4.0	3.3	3.3	Rehme	Novendst.	BDD (m)
Marten et al., 1982	w	6-9	37	1.041	17.01	4.1	3.7	3.4	4.3	4.0	1.7	0.7	CTS	CTD	Sobolev
Marten et al., 1982	w	6-10	37	1.101	12.31	6.0	7.8	9.6	8.4	8.0	3.9	3.7	CTS	CTD	Rehme
Itch, 1981	w	6-11	127	1.176	38	2.4	5.1	5.6	4.0	5.6	3.0	2.5	Rehme	CTS	CTD
Itch, 1981	w	6-12	169	1.214	47.39	1.7	5.1	5.8	4.3	5.8	2.5	1.9	Rehme	CTS	CTD
Spencer, 1980	w	6-13	217	1.252	51.74	4.3	5.8	6.8	5.1	6.6	5.3	5.0	Rehme	CTS	BDD (m)
Rehme, 1973	w	6-14	19	1.417	25	2.4	10.9	13.4	6.4	9.0	6.5	8.4	Rehme	BDD (m)	CTD
Rehme, 1973	w	6-15	19	1.417	50	5.9	11.7	15.4	11.0	11.1	8.0	7.7	Rehme	CTS	CTD
Rehme, 1973	w	6-16	19	1.125	16.67	3.0	13.2	12.5	3.9	6.1	6.6	6.0	Rehme	BDD (m)	CTS
Rehme, 1973	w	6-17	19	1.125	25	7.4	21.1	20.6	8.8	5.8	13.6	12.1	Engel (m)	Rehme	BDD (m)
Rehme, 1973	w	6-18	7	1.343	8.33	15.8	20.1	8.1	21.7	0.4	20.5	25.8	Engel (m)	Sobolev	Rehme
Rehme, 1973	w	6-19	7	1.275	8.33	22.7	25.5	11.4	25.5	2.5	26.7	30.8	Engel (m)	Sobolev	Rehme
Rehme, 1973	w	6-20	19	1.275	12.5	8.4	4.5	6.5	13.7	9.9	3.7	4.8	CTD	Novendst.	CTS
Rehme, 1973	w	6-21	19	1.275	50	6.6	9.7	10.6	5.4	7.5	8.1	8.3	BDD (m)	Rehme	Engel (m)
Vijayan et al., 1999	w	6-22	19	1.08	15.24	4.5	5.5	6.7	5.5	6.5	3.4	3.1	CTS	CTD	Rehme
Gajapathy et al., 2007	Na	7-1	7	1.255	22.73	10.1	16.1	20.8	19.6	21.0	14.4	14.4	Rehme	CTD	CTS
Geffraye, 2008	air	8-1	19	1.24	21.88	1.4	12.1	10.8	5.0	3.0	4.1	5.5	Rehme	Engel (m)	CTD
Averaged over all 22 analysed experiments: Mean						6.0	9.8	9.5	8.1	6.3	7.2	7.7	Rehme	Engel (m)	CTD
Averaged over 20 water experiments:						6.0	9.3	8.9	7.7	5.7	7.0	7.4	Engel (m)	Rehme	CTD
Averaged over 1 Na experiments:						10.1	16.1	20.8	19.6	21.0	14.4	14.4	Rehme	CTD	CTS
Averaged over 1 Air experiments:						1.4	12.1	10.8	5.0	3.0	4.1	5.5	Rehme	Engel (m)	CTD
Assuming equal weight of water/air/Na						5.8	12.5	13.5	10.8	9.9	8.5	9.1	Rehme	CTD	CTS

Re number range - Rehme: Re=1000-300000; Novendstern, Sobolev: Re=2600-100000; Engel: Re=50-100000; CTD, CTS: Re=50-1000000.

Table 9-6: Ranking summary of the turbulent flow regime RMS of different friction factor correlations against 22 experimental data set using different weighting schemes of the various (water/Na/air) data sets

RMS Turbulent: 22 experiments									
weight dist. (water\Na\air):	**[20** \ 1 \ 1]			**[3** \ 1 \ 1]			**[1** \ 1 \ 1]		
Ranking	**RMS** ranking	RMS [%]	RMS rel. merit fr	**RMS** ranking	RMS [%]	RMS rel. merit fr	**RMS** ranking	RMS [%]	RMS rel. merit fr
1	**Rehme**	9.4	1.00	**Rehme**	8.7	1.00	**Rehme**	8.1	1.00
2	BDD	12.8	0.74	Novendstern	13.9	0.63	Novendstern	14.5	0.56
3	Novendstern	13.1	0.72	BDD	14.2	0.61	BDD	15.5	0.52
4	CTD	14.2	0.67	CTD	17.2	0.51	Engel	15.6	0.52
5	CTS	16.0	0.59	Engel	18.3	0.48	CTD	19.8	0.41
6	Sobolev	18.5	0.51	CTS	20.2	0.43	CTS	23.8	0.34
7	Engel	21.4	0.44	Sobolev	22.1	0.39	Sobolev	25.3	0.32

Total of 22 experiments yielded turbulent data: 20 water, one Na, one air.
[20 \ 1 \ 1] corresponds to equal weighting of 22 experiments;
[3 \ 1 \ 1] corresponds to weighting of 3 times averaged weight of 20 water experiments, 1 times weighting of each single Na and Air experiments;
[1 \ 1 \ 1] corresponds to equal weighting of 1 times averaged weight of 20 water experiments, 1 times weight of single Na and Air experiments.

In summary, in the turbulent flow regime the Rehme correlation clearly displays superior behavior compared to all other correlations, followed either by BDD or Novendstern, depending on the selected weighting scheme.

Combined laminar and turbulent Flow Regime:

The RMS assessment based on the combined flow regions (both laminar and turbulent) is at first based on “10” data set as for only these 10 data sets both laminar and turbulent flow regime experimental data is provided . This “combined” assessment presumes that the applied correlation yields useable results in predicting the friction factor in both the turbulent as well as in the laminar flow regime.

The 10 data sets providing experimental data for both regimes are listed in Table 9-1 for the laminar regime and the corresponding data sets for the turbulent regime are extracted from the “22” data set, Table 9-4.

In the laminar flow regime, we know from Tables 9-1 and 9-3 that the RMS ranking yields Rehme, CTS, CTD as the top three correlations (11.1, 12.7, and 12.9%, see Table 9-3) with RMS relative merit fractions of 1.00, 0.88 and 0.86, respectively.

Table 9-7: Ranking summary of the turbulent flow regime RMS of different friction factor correlations against 10 and 9 (excluding data from Figure 6-22) experimental water data sets for which laminar flow regime data is provided (see Tables 9-1 and 9-4)

RMS Turbulent Flow Regime 10 experiments				**RMS 9 experiments (excluding Fig 6-22)**		
	water only			**water only**		
Ranking	**RMS** ranking	RMS [%]	RMS rel. merit fr	**RMS** ranking	RMS [%]	RMS rel. merit fr
1	**BDD**	8.1	1.00	**Rehme**	6.3	1.00
2	CTD	8.9	0.91	BDD	6.3	1.00
3	Novendstern	9.1	0.90	CTD	6.7	0.94
4	Rehme	9.2	0.89	CTS	7.3	0.86
5	CTS	9.5	0.85	Novendstern	7.4	0.85
6	Sobolev	12.2	0.67	Sobolev	10.4	0.61
7	Engel	13.5	0.60	Engel	11.7	0.54

The corresponding RMS ranking of the correlation in the turbulent flow regime for these 10 experiments (as extracted from Table 9-4) is provided in Table 9-7 yielding the following ranking BDD, CTD, Novendstern and Rehme with RMS values of 8.1, 8.9, 9.1 and 9.2%, and RMS relative merit fractions of 1.00, 0.91, 0.90, and 0.89 are calculated respectively. Excluding the turbulent data from Figure 6-22 from these calculations as this data appears to be experimentally biased (see discussion in section 6.10), we obtain a different ranking sequence as displayed in Table 9-7, namely now we have Rehme followed by BDD, CTD and CTS with averaged RMS values of 6.3, 6.3, 6.7, and 7.3% respectively, or RMS relative merit fractions of 1.00, 1.00, 0.94 and 0.86.

For the "combined" assessment we retain the "10" data sets as basis in order to refrain from biasing, or filtering our re-evaluation by pre-selection.

Table 9-8: Evaluation of RMS of the "combined turbulent and laminar" flow regime of different friction factor correlations against 10 experimental water data sets

RMS of the Combined Laminar and Turbulent flow regimes (turbulent/laminar weight distribution: 1/1): 10 experiments															
					Correlation:	**Rehme**	**Novendst.**	**Sobolev**	**BDD (m)**	**Engel (m)**	**CTD**	**CTS**	RMS Ranking		
Experiment	fluid	Figure	Validation range of correlation (N, P/D, H/D)			7-217, 1.1-1.42, 8-50	19-217, 1.06-1.42, 8-96		19-217, 1.06-1.42, 8-96	19-61, 1.06-1.42, 8-96	7-217, 1.0-1.42, 4-52	19-217, 1.025-1.42, 8-50	(First)	(Second)	(Third)
			N	P/D	H/D	RMS [%]									
Choi et al., 2003	w	6-3	271	1.2	24.84	5.6	26.1	20.5	26.8	7.6	10.1	5.6	Rehme	CTS	Engel (m)
Chun et al., 2001	w	6-4	19	1.256	25	17.9	34.0	34.1	9.7	9.8	8.5	10.7	CTD	BDD (m)	Engel (m)
Arwikar et al., 1979	w	6-5	61	1.05	14.45	13.7	23.3	30.8	6.0	28.3	12.7	14.7	BDD (m)	CTD	Rehme
Chiu et al., 1979	w	6-6	61	1.063	8	15.0	28.0	29.0	21.3	20.7	16.4	19.3	Rehme	CTD	CTS
Marten et al., 1982	w	6-9	37	1.041	17.01	4.4	20.1	23.0	12.5	22.2	16.0	16.0	Rehme	BDD (m)	CTD
Marten et al., 1982	w	6-10	37	1.101	12.31	5.9	30.6	30.6	20.1	20.3	5.9	8.5	Rehme	CTD	CTS
Itch, 1981	w	6-11	127	1.176	38	3.7	32.8	33.9	5.1	15.0	5.2	4.6	Rehme	CTS	BDD (m)
Itch, 1981	w	6-12	169	1.214	47.39	3.4	34.1	34.0	6.8	12.0	5.7	5.1	Rehme	CTS	CTD
Spencer, 1980	w	6-13	217	1.252	51.74	6.6	35.6	35.6	8.5	7.4	5.4	3.8	CTS	CTD	Rehme
Vijayan et al., 1999	w	6-22	19	1.08	15.24	25.2	44.5	46.4	45.6	40.7	22.9	22.7	CTS	CTD	Rehme
Analysed 10 water experiments: Mean															
Equal weight of laminar and turbulent regime:						10.1	30.9	31.8	16.2	18.4	10.9	11.1	Rehme	CTD	CTS
Flow regime weight distribution (turbulent/laminar: 5/1)						9.5	16.4	18.7	10.1	10.8	15.1	9.6	Rehme	CTS	BDD (m)

Re number range - Rehme: Re=1000-300000; Novendstern, Sobolev: Re=2600-100000; Engel: Re=50-100000; CTD, CTS: Re=50-1000000.

Table 9-9: Evaluation of STD for the "combined turbulent and laminar" flow regime of different friction factor correlations against 10 experimental water data sets

STD of the Combined Laminar and Turbulent flow regimes (turbulent/laminar weight distribution: 1/1): 10 experiments															
					Correlation:	**Rehme**	**Novendst.**	**Sobolev**	**BDD (m)**	**Engel (m)**	**CTD**	**CTS**	STD Ranking		
Experiment	fluid	Figure	Validation range of correlation (N, P/D, H/D)			7-217, 1.1-1.42, 8-50	19-217, 1.06-1.42, 8-96		19-217, 1.06-1.42, 8-96	19-61, 1.06-1.42, 8-96	7-217, 1.0-1.42, 4-52	19-217, 1.025-1.42, 8-50	(First)	(Second)	(Third)
			N	P/D	H/D	STD [%]									
Choi et al., 2003	w	6-3	271	1.2	24.84	2.6	7.7	8.7	4.9	2.3	2.0	2.6	CTD	Engel (m)	CTS
Chun et al., 2001	w	6-4	19	1.256	25	3.3	14.9	17.2	7.5	4.3	3.7	4.2	Rehme	CTD	CTS
Arwikar et al., 1979	w	6-5	61	1.05	14.45	7.6	13.5	12.3	4.7	12.3	5.3	5.0	BDD (m)	CTS	CTD
Chiu et al., 1979	w	6-6	61	1.063	8	7.1	16.4	12.9	13.3	9.5	8.4	7.7	Rehme	CTS	CTD
Marten et al., 1982	w	6-9	37	1.041	17.01	3.9	4.7	4.0	4.9	6.3	1.4	1.3	CTS	CTD	Rehme
Marten et al., 1982	w	6-10	37	1.101	12.31	4.9	14.8	15.9	12.4	12.3	4.0	3.8	CTS	CTD	Rehme
Itch, 1981	w	6-11	127	1.176	38	2.0	12.3	13.5	4.1	8.0	5.5	5.2	Rehme	BDD (m)	CTS
Itch, 1981	w	6-12	169	1.214	47.39	1.6	12.0	13.7	3.8	6.9	5.3	4.9	Rehme	BDD (m)	CTS
Spencer, 1980	w	6-13	217	1.252	51.74	5.0	12.6	14.7	3.2	5.0	4.5	4.4	BDD (m)	CTS	CTD
Vijayan et al., 1999	w	6-22	19	1.08	15.24	10.6	13.3	13.5	23.1	21.6	10.8	9.6	CTS	Rehme	CTD
Analysed 10 water experiments: Mean															
Equal weight of laminar and turbulent regime:						4.8	12.2	12.6	8.2	8.8	5.1	4.9	Rehme	CTS	CTD
Flow regime weight distribution (turbulent/laminar: 5/1)						4.2	8.1	8.5	4.0	6.0	6.6	4.2	BDD (m)	CTS	Rehme

Re number range - Rehme: Re=1000-300000; Novendstern, Sobolev: Re=2600-100000; Engel: Re=50-100000; CTD, CTS: Re=50-1000000.

The results of RMS and the STD evaluation of the "combined" data sets are listed in Tables 9-8 and 9-9, respectively. In line 16, the mean RMS and STD values are listed and ranked. We observe that Rehme, CTD, and CTS are ranked in sequential order, as summarized in Table 9-10, with RMS values of 10.1, 10.9, and 11.1% and RMS relative merit fractions of 1.00, 0.93, and 0.91, respectively. The STD ranking in Table 9-9 is Rehme, CTS, and CTD with STD values of 4.8, 4.9, and 5.1% respectively.

Table 9-10: Ranking summary of the RMS of the combined turbulent and laminar flow regimes of different friction factor correlations against 10 experimental water data sets for which both laminar and turbulent flow regime data is provided using different weighting schemes regarding the relative importance of the two flow regimes (see Tables 9-1 and 9-4)

RMS Combined (turbulent + laminar) 10 experiments									
weight dist. (turb/lam):	[**1** \ 1]			[**2** \ 1]			[**5** \ 1]		
Ranking	**RMS** ranking	RMS [%]	RMS rel. merit fr	**RMS** ranking	RMS [%]	RMS rel. merit fr	**RMS** ranking	RMS [%]	RMS rel. merit fr
1	**Rehme**	10.1	1.00	**Rehme**	9.8	1.00	**Rehme**	9.5	1.00
2	CTD	10.9	0.93	CTD	10.2	0.96	CTD	9.6	0.99
3	CTS	11.1	0.91	CTS	10.6	0.93	CTS	10.1	0.94
4	BDD	16.2	0.62	BDD	13.5	0.72	BDD	10.8	0.87
5	Engel	18.4	0.55	Engel	16.8	0.58	Engel	15.1	0.63
6	Novendstern	30.9	0.33	Novendstern	23.6	0.41	Novendstern	16.4	0.58
7	Sobolev	31.8	0.32	Sobolev	25.3	0.39	Sobolev	18.7	0.51

Total of 10 experiments (all water) for which both turbulent and laminar flow regime data is provided (see Tables 9-1 and 9-4).
[1 \ 1] corresponds to equal weighting of turbulent and laminar flow regime;
[2 \ 1] corresponds to weighting turbulent regime by factor 2 and laminar regime by one;
[5 \ 1] corresponds to weighting turbulent regime by factor 5 and laminar regime by one.

Table 9-10 also summarizes RMS sensitivity results assuming different weighting schemes of the turbulent data sets relative to the laminar data information. This presumes that for system codes a more precise description of the friction factor in the turbulent regime may be of higher interest as the flow rates usually remain within the turbulent flow regime in most plant accident transients analyzed. Three different weighting schemes have been analyzed by presuming relative turbulent\laminar weightings of [1\1], [2\1], and [5\1]. As can be observed, for all cases, a relative RMS ranking of Rehme, closely followed by CTD, CTS is calculated. For the [2\1] turbulent\laminar weighting, RMS values of 9.8, 10.2, and 10.6%, and RMS relative merit fractions of 1.00, 0.96, and 0.93 have been calculated. Putting more weight on the turbulent flow regime by assuming [5\1], the RMS ranking of the correlation does not change from the [1\1] weighting scheme, the only difference being that the RMS relative merit fractions become now 1.00, 0.99, and 0.94, essentially yielding all three correlations (Rehme, CTD, CTS) to provide essentially equally good results within 5% of each other.

Table 9-11: Summary of the RMS and STD ranking of the turbulent, laminar and combined flow regimes of different friction factor correlations against 22 (for turbulent regime analysis) and 10 experimental data sets (for laminar and combined) using “meaned” weighting schemes regarding the water\Na\air data sets (20\1\1) and “meaned” relative importance of the two flow regimes (1\1)

Correlation:	**Rehme**	**Novendst.**	**Sobolev**	**BDD (m)**	**Engel (m)**	**CTD**	**CTS**	**Ranking** (First)	(Second)	(Third)
Turbulent flow regime: 22 data sets					water: **20**		Na: 1		air: 1	
Mean RMS [%]	9.4	13.1	18.5	12.8	21.4	14.2	16.0	Rehme	BDD (m)	Novendst.
Mean STD [%]	6.0	9.8	9.5	8.1	6.3	7.2	7.7	Rehme	Engel (m)	CTD
22 experiments yielded turbulent data: 20 water, one Na, one air										
Laminar flow regime: 10 data sets										
Mean RMS [%]	11.1	52.8	51.4	24.4	23.3	12.9	12.7	Rehme	CTS	CTD
Mean STD [%]	5.8	18.4	18.9	11.5	12.2	6.4	6.2	Rehme	CTS	CTD
10 experiments (all water) yielded laminar flow regime data (see Tables 1 and 2)										
Combined (turbulent + laminar): 10 data sets							turb: 1		lam: 1	
Mean RMS [%]	10.1	30.9	31.8	16.2	18.4	10.9	11.1	Rehme	CTD	CTS
Mean STD [%]	4.8	12.2	12.6	8.2	8.8	5.1	4.9	Rehme	CTS	CTD

10 Summary and Conclusions

This report presents an overview of existing wire-wrapped fuel bundle friction factor/pressure drop correlations and provides a qualitative and quantitative re-evaluation, which of the existing friction factor correlations is the best general-purpose correlation in retracing satisfactorily the results of a set of randomly selected experimental data sets (available in the open literature) on wire-wrapped fuel assemblies using different coolants and different fuel assembly geometries, not always similar to those used specifically for SFRs (as it was analyzed by Cheng and Todreas in (Chen S.K. et al, 2014)).

The assessment is based on the identical data sets (namely 22) as used in the original 2008 publication (Bubelis E. and Schikorr M., 2008) in order to allow an objective re-assessment of the 2008 conclusions using the correct formulation of the Cheng-Todreas correlations. In the meantime it is known that actually more than 22 bundle experimental data sets are available (namely ~140, however most of them not available in the open literature), and a more comprehensive analysis should include some further subsets of these other data sets as well.

In the prior publication of 2008 the authors applied a somewhat arbitrary ranking scheme based on engineering judgment (i.e. visual inspection), foregoing, at that time, a more scientific approach as both methodologies were judged to yield similar results. Both approaches were applied in this publication by calculating and comparing the RMS (root mean square error) and STD (standard deviation) values. Only the results of the rigorous methodology are reported in this report, as both approaches (judgmental and scientific) yielded almost identical results, thereby reconfirming the "judgmental" procedure as used in 2008. All 22 data sets were re-evaluated by calculating their RMS and STD values. These results are summarized in Tables 9-1 to 9-11 for the laminar and the turbulent flow regimes, as well as for the "combined" flow regime (based on 10 data sets). An analysis of the relative merits of the various friction factor correlations by comparing their RMS values in the laminar and the turbulent regimes is presented in Tables 9-3, 9-6, 9-7, and 9-10, where Table 9-11 provides a summary of the overall-ranking of the various correlations.

A RMS ranking scheme was introduced, so-called "RMS relative merit fraction", based on the ratio of the lower ranking RMS values relative to the top ranked. This factor allows a quantitative inter-comparison of the relative goodness of the various correlations to each other. If differences between the correlations are five percentage points or less, then the correlations should be judged essentially as being of “equal” merit, - in our opinion.

Based on the above methodology, we came up with the following conclusions:

(1) In the laminar flow regime, only 10 water based data sets yielded data as summarized in Tables 9-1 and 9-2.

(2) Analyzing the laminar data sets, the Rehme correlation yielded the lowest mean RMS value of 11.1%, followed by the simplified (CTS) and then the detailed (CTD) Cheng-Todreas sets of correlations (see Table 9-3). The RMS relative merit fractions were 1.00, 0.88, and 0.86, respectively, indicating that both CTD and CTS are about of equal merit at least 10% away from the top ranked Rehme correlation.

(3) In the turbulent flow regime all 22 data sets were used for the RMS and STD analyses. Rehme clearly ranked first followed by BDD and Novendstern (see Table 9-6). This ranking remains essentially unchanged using different weighting schemes. For the “mean” (20\1\1) weighting scheme, the calculated mean RMS was 9.4% for Rehme, followed by Baxi Dalle Donne (BDD) and Novendstern with RMS values of 12.8 and 13.1% respectively, or RMS relative merits fractions of 1.00, 0.74, and 0.72, respectively. The second ranked BDD correlation is thus 26% apart from Rehme, considered quite a large difference in relative merit.

(4) In the turbulent regime for air, we analyzed only a single, most recent experiment from CEA (Geffraye G., 2008), yielding the highest ranking for Rehme (see Table 9-4, last line for the listed experiments, or Figure 8-1) with a very low RMS value of only 1.3%, followed by Engel with 4.1% and BDD with 11.5%. CTD and CTS yield RMS values of 16.7 and 23.3% respectively for this particular case of experimental data.

(5) In the turbulent regime for sodium, also based only on a single CFD study data set, Rehme yielded the lowest RMS of 13.3%, followed by Novendstern (18.1%) and BDD (22.7%). We like to note however, that this particular CFD study should not be considered as being representative of typical sodium experiments. As this particular CFD data set was part of the original 2008 paper, we nonetheless retained it in our current study in order not to bias conclusions by filtering, or pre-selection of data sets.

(6) Using the 10 data sets for which both laminar and turbulent flow regime data was available (see Tables 9-1 and 9-4) we came to the conclusion that only three correlations can be recommended when only a single correlation should be used to cover the entire flow regime range (turbulent and laminar), namely Rehme, followed by CTD and CTS. Based on this data Rehme ranked highest with and RMS of 10.1%, followed by CTD with 10.9%, and CTS with 11.1% (see Table 9-10). All other correlations yield RMS values higher than 16%.

In summary, using the same randomly selected experimental data sets (22) as analyzed in our previous publication in 2008 (Bubelis E. and Schikorr M., 2008), we re-iterate upon detailed reanalysis that the friction factor correlation, providing generally the best fit to all the analyzed experimental data sets for wire-wrapped rod/fuel bundles of different configurations and different coolants, is the Rehme friction factor correlation for wire-wraps, followed closely by the Cheng-Todreas correlation(s), that also yield very good results.

Comparing the ranking of the correlations of the re-evaluated data sets (this publication) to the previous 2008 ranking results we do observe significant changes, as now the Cheng-Todreas correlations CTD and CTD have moved up to second and third place in the list of the recommended correlations.

For SFR fuel bundle design analyses, the Cheng-Todreas correlation(s) yield better results as has been noted in the most recent publication of Cheng and Todreas (Chen S.K. et al, 2014).

A general conclusion as to which is the most general-purpose friction factor correlation that covers the entire flow regime range (both laminar and turbulent) and that can be recommended for use in system code packages (either for scoping analysis of different core designs, or assessment of the transient behavior of different core/primary system configurations) is clearly the Rehme correlation, followed by either the detailed Cheng-Todreas (CTD), or the simplified Cheng-Todreas (CTS), then Baxi-Dalle-Donne (modified), and Engel (modified), as summarized in Tables 9-10 and 9-11.

We thus again repeat our previous recommendation that the user friendly Rehme friction factor correlation can be used quite reliably and efficiently for the estimation of the pressure drops in wire-wrapped rod/fuel bundles for all fast reactor types using different coolants (i.e., water, gas, liquid metals).

Acknowledgement

The authors of this report would like to acknowledge the fruitful discussions with Prof. N. E. Todreas and Dr. S. K. Cheng that made it possible to resolve various noticeable inconsistencies in our previous paper, in particular as related to the implementation of Cheng-Todreas detailed and simplified (CTD and CTS) friction factor correlations in SIM-codes family.

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KIT Scientific Working Papers
ISSN 2194-1629