INL/CON-19-55220-Revision-2

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Evaluation of Pressure Drop Correlations for the Wire-wrapped Rod Bundles

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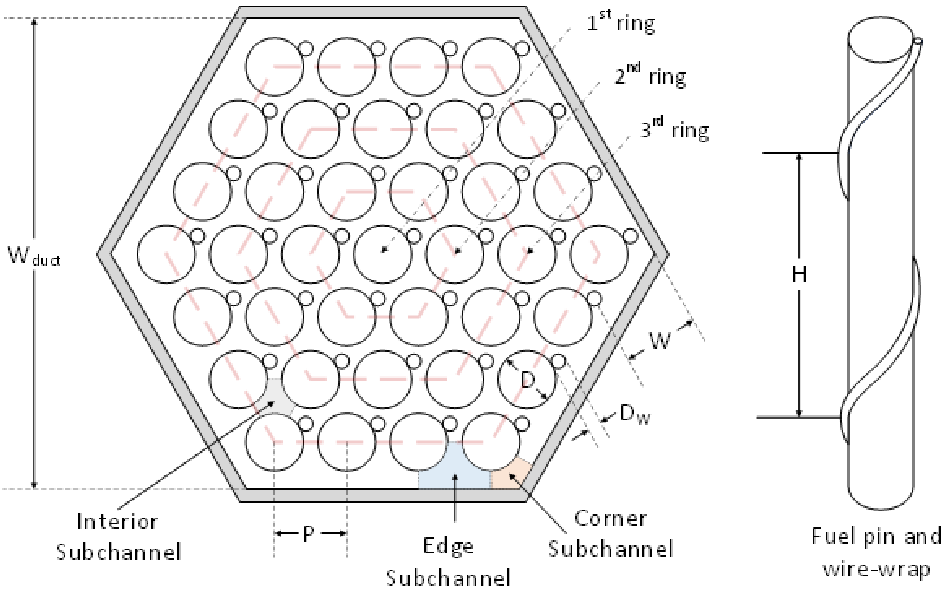
Objectives of Work

- Accurate prediction of pressure drop in the wire-wrapped fuel bundle of Sodium Fast Reactor (SFR) is of high importance as it directly affects the primary pump specifications, the flow distribution and the safety behavior of the core.

- The present work aims at evaluating the existing friction factor correlations for 217 pin wire-wrapped fuel rod bundle of SFR and the range of applicability of the correlations to identify the preferred correlation for the SFR analysis.



Parameter	Value
Assembly pitch (cm)	12
Fuel/Plenum length (cm)	80/80
Duct thickness (cm)	0.3
Duct inside flat-to-flat (cm)	11.1
Pins per assembly (#)	217
Pin diameter (cm)	0.625
Wire-wrap diameter (cm)	0.110
Wire-wrap axial pitch (cm)	26.67
P/D	1.18
H/D	42.67

Existing Friction Factor Correlations of Wire-wrapped Fuel Bundle

- There are several correlations for the wire-wrapped fuel rod bundle.
- In 2008, Bubelis and Schikorr have reviewed the existing friction factor correlation for the wire-wrapped fuel rod bundle to identify the best-fitting correlation. In this work, they concluded that the Rehme model generally provides the best fit for all the analyzed experimental data sets.
- In 2014, Cheng et al. pointed out that the Cheng-Todreas correlation described in Bubelis and Schikorr's work was not correct. In 2016, Bubelis and Schikorr responded this through the revision of 2008 work. Bubelis and Schikorr noted that the Cheng and Todreas correlations yields better prediction than the other correlation for the SFR, although the Rehme correlation would be recommended for the general application.
- In 2018, Cheng et al, released the Upgraded Cheng-Todreas correlation that improves the original correlation by revising wire-related empirical constant, the equation for calculating the transition regime, and the laminar-to-transition boundary criterion.

Existing Friction Factor Correlations of Wire-wrapped Fuel Bundle

- Rehme:

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

$$\text{where } F = \left(\frac{P_t}{D_r}\right)^{0.5} + \left[7.6\frac{(D_r+D_w)}{H}\left(\frac{P_t}{D_r}\right)^2\right]^{2.16}$$

- CTs (Detail):

Laminar flow: $f = \frac{C_{fL}}{Re}$ for $Re \le Re_L$

Turbulent flow: $f = \frac{C_{fT}}{Re^{0.18}}$ for $Re_T \le Re$.

Transition flow: $f = \frac{C_{fL}}{Re}(1-\Psi)^{1/3} + \frac{C_{fT}}{Re^{0.18}}\Psi^{1/3}$ for $Re_L \le Re \le Re_T$

- Novendstern

$$f = f_1 X_1^2 \frac{D_e}{D_{e1}},$$

where $f_1 = f_s M$, $f_s = \frac{0.316}{Re_1^{0.25}}$, and $M = \left\{\frac{1.034}{(\mathrm{P/D})^{0.124}} + \frac{29.7(\mathrm{P/D})^{6.94}Re_1^{0.086}}{(H/(\mathrm{D}))^{2.239}}\right\}^{0.885}$

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Upgraded Cheng and Todreas Correlation (2018)

Original CT

- Transition friction factor, $Re_L \leq Re \leq Re_T$

$$f = \frac{C_{fL}}{Re}(1-\Psi)^{1/3} + \frac{C_{fT}}{Re^{0.18}}\Psi^{1/3}$$

- $\log\left(\frac{Re_L}{300}\right) = 1.7\left(\frac{P_t}{D_r} - 1.0\right)$
- $W_{dT} = \left(29.5 - 140\left(\frac{D_w}{D}\right) + 401\left(\frac{D_w}{D}\right)^2\right)\left(\frac{H}{D}\right)^{-0.85}$
- $W_{sT} = 20.0\log\left(\frac{H}{D}\right) - 7.0$
- $W_{sL} = 0.3W_{sT} = 6.0\log\left(\frac{H}{D}\right) - 2.1$

Upgraded CT

- Transition friction factor, $Re_{bL} \leq Re \leq Re_{bT}$

$$f_i = \left(\frac{C_{fiL}}{Re_i}\right)(1-\psi_i)^{\frac{1}{3}}(1-\psi_i^7)\left(\frac{C_{fiT}}{Re_i^{0.18}}\right)\psi_i^{\frac{1}{3}}$$

where i = b, 1, 2, or 3 for bundle average, interior, edge and corner subchannel

- $Re_{bL} = 320\left(10^{\left(\frac{P}{D}-1.0\right)}\right)$
- $W_{dT} = \left(19.56 - 98.71\left(\frac{D_w}{D}\right) + 303.47\left(\frac{D_w}{D}\right)^2\right)\left(\frac{H}{D}\right)^{-0.541}$
- $W_{sT} = -11.0\log\left(\frac{H}{D}\right) + 19.0$
- $W_{sL} = 1.0W_{sT}$

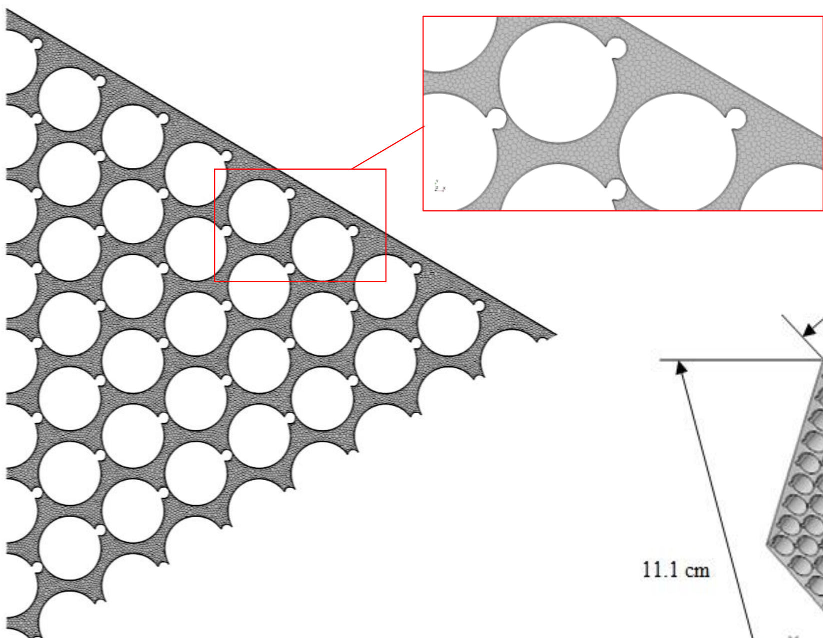
Applicable Ranges of the Existing Correlations

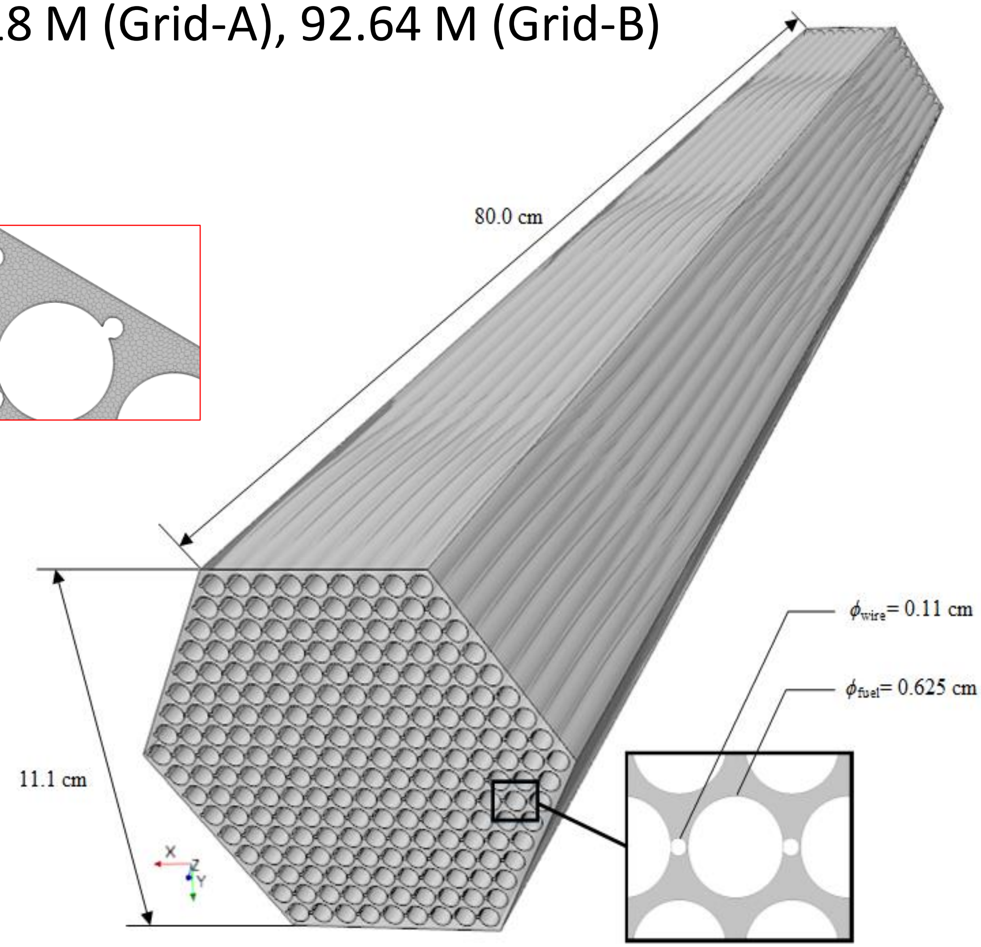
Model	Year	N_r	P/D	H/D	Reynolds number range	Uncertainty
NOV	1972	19-217	1.060-1.420	8.0-96.0	Transition & turbulent ($2600 - 10^5$)	±14%
REH	1973	7-217	1.100-1.420	8.0-50.0	Transition and turbulent ($1000 - 3\times10^5$)	±8%
EMB	1979	19-61	1.067-1.082	7.7-8.3	All regimes ($50 - 10^5$)	±15%
BDD	1981	19-217	1.060-1.420	8.0-96.0	All regimes ($50 - 10^5$)	NA
CTD	1986	19-217	1.000-1.420	4.0-52.0	All regimes ($50 - 10^6$)	±14%
CTS	1986	19-217	1.025-1.420	8.0-50.0	All regimes ($50 - 10^6$)	±15%
UCTD	2018	7-271	1.000-1.420	8.0-52.0	All regimes ($50 - 10^6$)	Not evaluated
UCTS	2018	19-217	1.025-1.420	8.0-50.0	All regimes ($50 - 10^6$)	Not evaluated

NOV: Novendstern, REH: Rehme, EMB: Engel, Markley and Bishop, BDD: Baxi and Dalle Donne, CTD: Cheng-Todreas Detailed, CTS: Cheng-Todreas Simplified, UCTD: Upgraded CTD, UCTS, Upgraded CTS

CFD Model of Wire-wrapped Fuel Rod Bundle

- Steady-state, incompressible, iso-thermal, RANS SST k-ω turbulence model with all y+ wall treatment
- Total number of mesh: 50.18 M (Grid-A), 92.64 M (Grid-B)



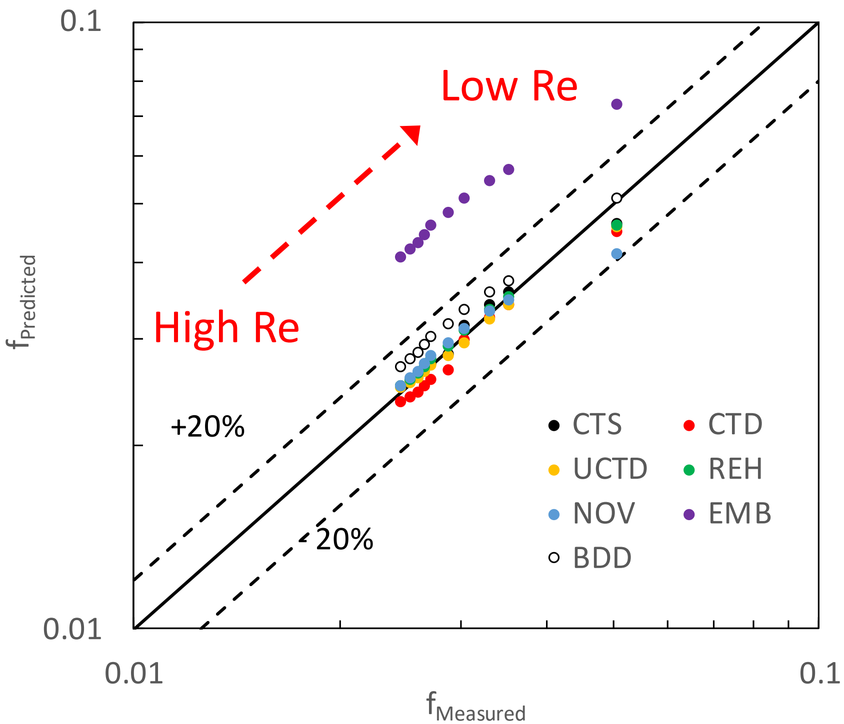


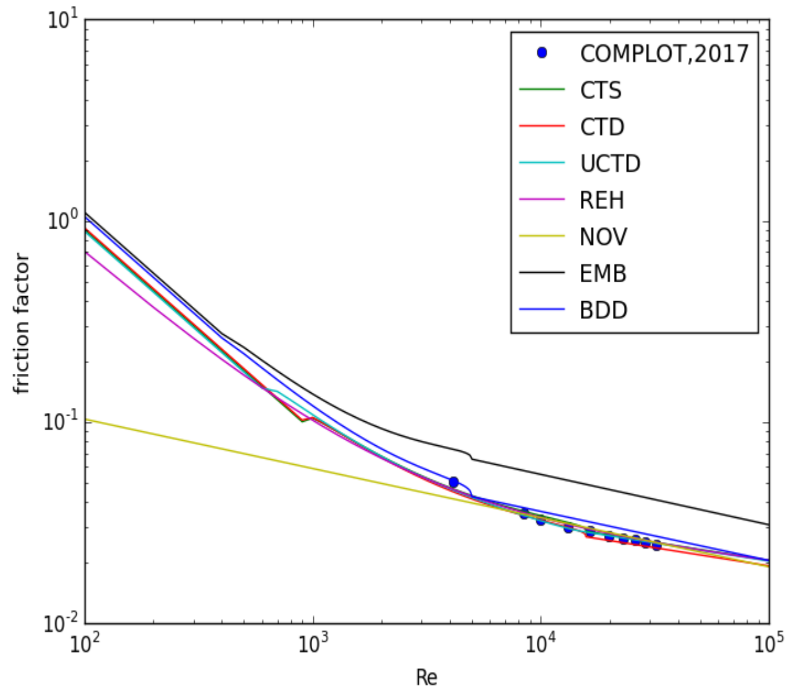
Experimental Dataset

ID	Year	Coolant	Pin no.	D (mm)	D_w (mm)	P/D	W/D	H/D
Reihman	1969	Water	217	6.35	0.762	1.135	1.143	48
Okamoto	1970	Water &Sodium	91	6.3	1.39	1.221	1.221	40.48
Davidson	1971	Water	217	6.39	1.808	1.283	1.283	48
Spencer	1981	Water	217	5.84	1.42	1.252	1.242	51.74
COMPLOT	2017	LBE	127	6.55	1.8	1.279	1.29	40
JSFR	2017	Water	127	5.5	0.9	1.176	1.176	38
Current Model			217	6.25	1.1	1.18	1.205	42.67

Evaluation of Existing Correlations

- CT correlations, Rehme, Novendstern and Baxi and Dalle Donna correlations agreed with COMPLOT data within the relative deviation of ± 20%.



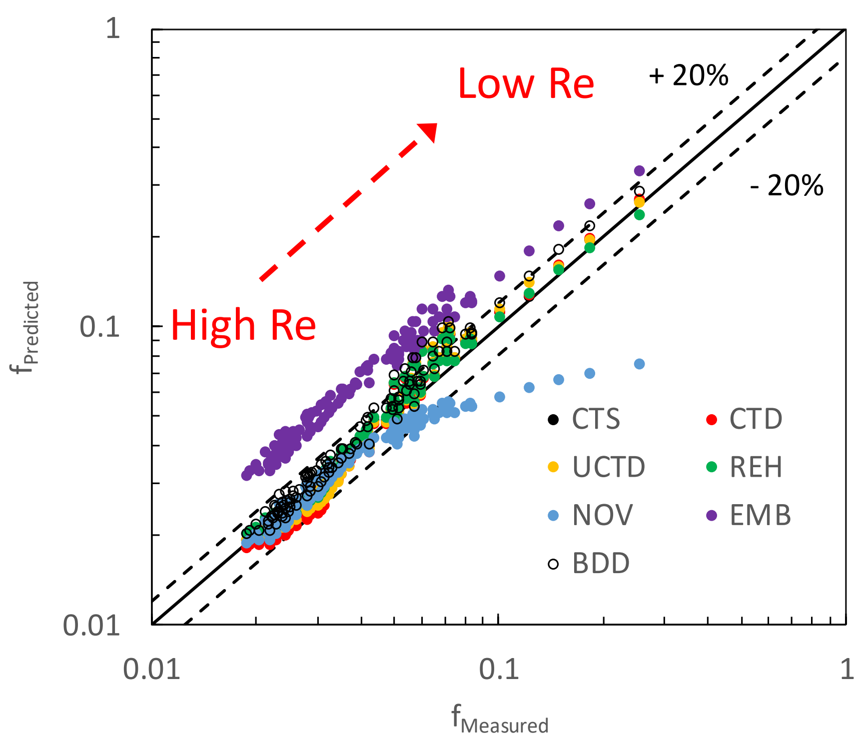


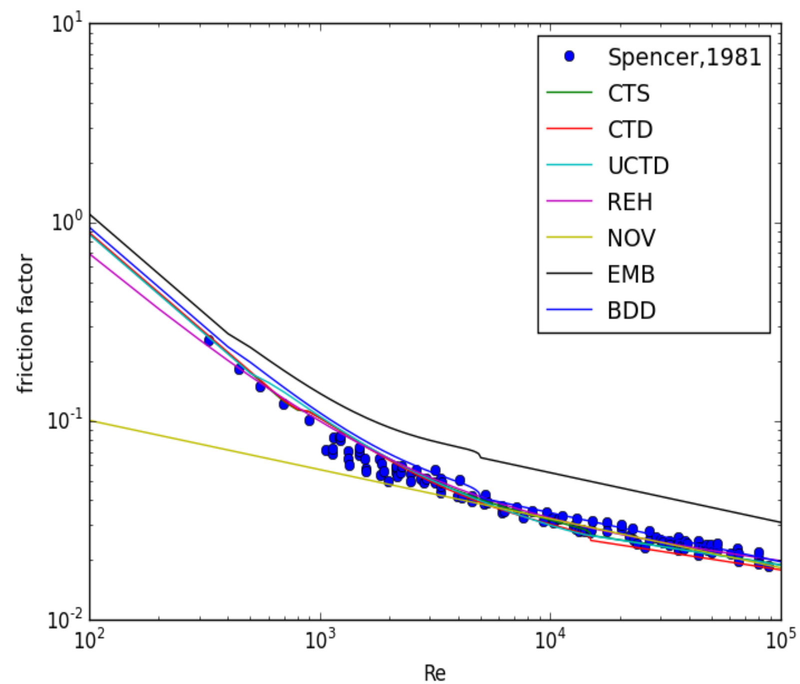
COMPLOT data (4000≤ Re ≤32000)†

※J. Pacio, K. Litfin, T. Wetzel, G. Kennedy and K. Van Tichelen, "Thermal-hydraulic Experiments Supporting the MYRRHA Fuel Assembly," IAEA-CN245-283, 2017.

Evaluation of Existing Correlations

- Cheng and Todreas correlations, Rehme and Baxi and Dalle Donna correlations agreed with experimental data within the relative deviation of ± 20%.





Spencer and Markley's data (330≤Re≤89000)†

† D. Spencer and R. Markley, "Friction Factor Correlation for 217 pin Wire-wrap Spaced LMFBR Fuel Assemblies," in ANS Winter meeting, San Francisco, CA, USA, Nov. 29 - Dec. 4, 1981.

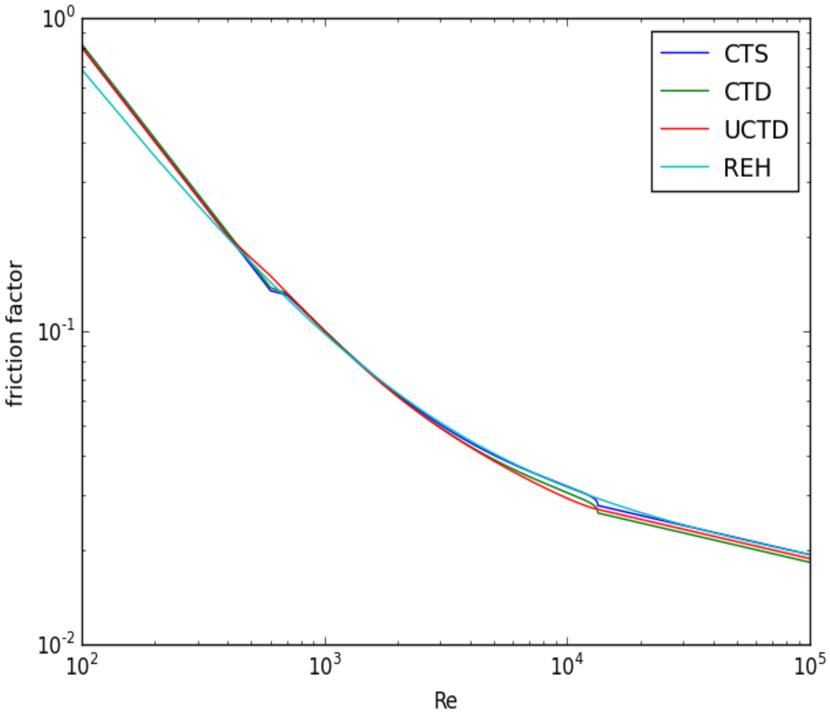
Mean, STD and RMS Errors of Existing Correlations

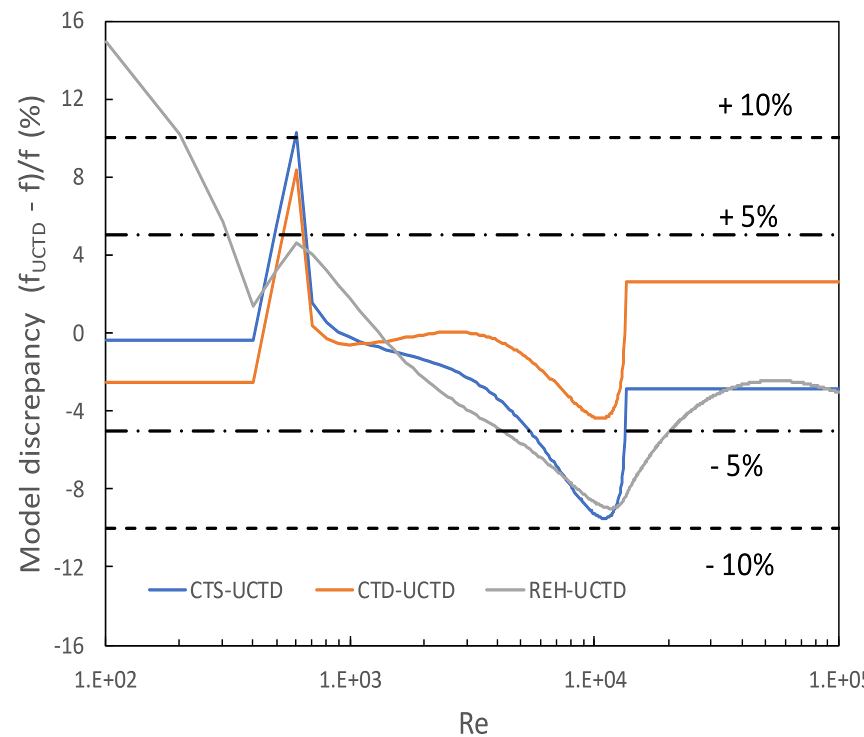
$$\varepsilon_i = \left(\frac{f_i^m - f_i^p}{f_i^m}\right) \qquad \bar{\varepsilon} = \sum_{i=1}^{N} \frac{\varepsilon_i}{N} \qquad \sigma = \sqrt{\sum_{i=1}^{N} \frac{(\varepsilon_i - \bar{\varepsilon})^2}{(N-1)}} \qquad \gamma = \sqrt{\sum_{i=1}^{N} \frac{{\varepsilon_i}^2}{N}}$$

Model	Spencer (300 ≤ Re < 90,000)			COMPLOT (4,000 ≤ Re ≤ 32,000)		
	Mean	STD	RMS	Mean	STD	RMS
CTS	-2.46	12.22	12.42	-1.10	3.58	3.56
CTD	1.12	13.59	13.58	4.42	2.94	5.22
UCTD	-1.55	12.97	13.01	1.21	3.25	3.31
REH	-4.47	10.16	11.05	-1.18	3.51	3.53
NOV	10.32	14.09	17.42	-0.53	6.66	6.34
EMB	-64.30	12.13	65.43	-65.52	7.58	65.91
BDD	-11.26	11.57	16.11	-9.38	3.24	9.87

Friction Factor of 217-pin Wire-wrapped Fuel Bundle

- UCTD showed a smooth prediction of friction factor at the laminar-to-transition flow regime.





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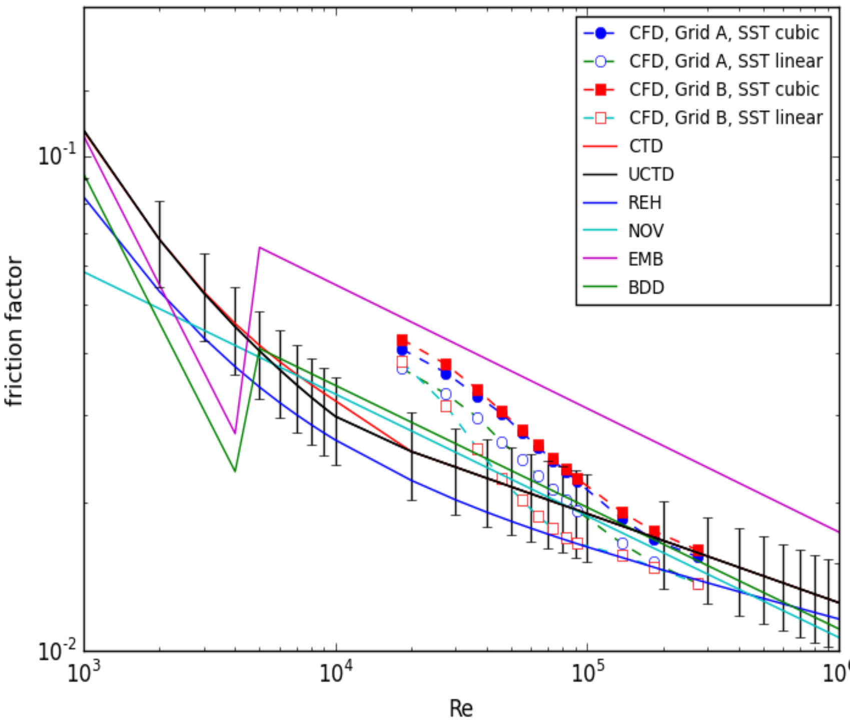
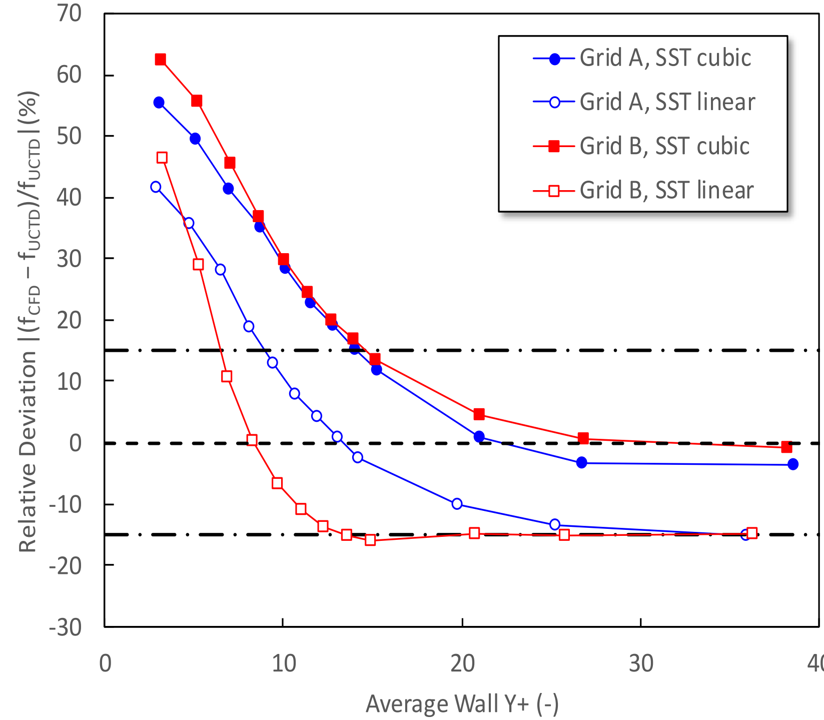
CFD Simulation Result

- Regardless of mesh density, non-linear SST model agreed with UCTD for high wall y+ value (> 20)



Evaluation of the Friction Factor Correlations and CFD Result for the SFR 217-pin Wire-wrapped Fuel Rod Bundle (Error bar: ±20% of UCTD).



Relative Deviation between the CFD and UCTD as a Function of Average Wall Y+ value of Fuel Rod Bundle

Concluding Remarks

- In present work, the existing friction factor correlations for wire-wrapped fuel rod bundles have been assessed to determine the preferred correlation for the thermal-hydraulic analysis of SFR core.
- The Engel, Markley and Bishop correlation, Novendstern correlation and Baxi and Dalle Donne correlation show the relatively inaccurate prediction of friction factor in some or all of the flow regimes.
- The relative differences among the Rehme correlation, Cheng and Todreas detailed correlations (original and upgraded) are around ±10% which is less than typical experimental measurement uncertainties.
- The CFD result showed the wall y^+ dependency of the friction factor prediction. For high y^+ value (>20), the CFD result agreed with the UCTD correlation and non-linear turbulence model showed better performance of prediction.

Thank you for your attention

(Q&A)

Appendix A. Novendstern Correlation (1972)

- $f = f_1 X_1^2 \frac{D_e}{D_{e1}}$

  where $f_1 = f_s M$

  $f_s = \frac{0.316}{Re_1^{0.25}}$

  $M = \left\{\frac{1.034}{(\mathrm{P/D})^{0.124}} + \frac{29.7(\mathrm{P/D})^{6.94} Re_1^{0.086}}{(H/(\mathrm{D}))^{2.239}}\right\}^{0.885}$

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

  $Re = \frac{\rho v D_e}{\mu}$

  $v_1 = X_1 v$

  $X_1 = \frac{A_b}{N_1 A_1 + N_2 A_2 \left(\frac{D_{e2}}{D_{e1}}\right)^{0.714} + N_3 A_3 \left(\frac{D_{e3}}{D_{e1}}\right)^{0.714}}$

  $A_b = N_1 A_1 + N_2 A_2 + N_3 A_3$

Appendix B. Rehme Correlation (1973)

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

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

  P_t: Rod pitch for wire-wrap configuration

  D_r : Rod diameter, (m)

  D_w : Wire (spacer) diameter, (m)

  H : Wire lead length (pitch), (m)

  N_r : Number of fuel pins

  S_t : Total wetted perimeter, (m)

Appendix C. Baxi and Dalle Donna Correlation (1981)

- Laminar flow: $f_L = \left(\frac{K}{Re}\right)\left(\frac{T_W}{T_B}\right)$ for *Re* ≤ 400

  where $K = \frac{80}{\sqrt{H}}\left(\frac{P}{\mathrm{D}}\right)^{1.5}$ *H in (cm) (original version)

  $K = \frac{320}{\sqrt{H}}\left(\frac{\mathrm{P}}{D}\right)^{1.5}$ *H in (cm) (modified by (Bubelis & Schikorr, 2008))

- Turbulent flow: $f_T = f_s M$ for *Re* ≥ 5,000

  where $f_s = \frac{0.316}{Re^{0.25}}$: smooth friction factor in a tube (Blasius)

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

- Transition flow: $f = f_L(1-\Psi)^{1/2} + f_T\Psi^{1/2}$ for 400 ≤ *Re* ≤ 5,000.

  where $\Psi = \frac{Re-400}{4{,}600}$.

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Appendix D. Cheng and Todreas Simplified Correlation (1986)

- Laminar flow: $f = \frac{C_{fL}}{Re}$ for $Re \le Re_L$.
- Turbulent flow: $f = \frac{C_{fT}}{Re^{0.18}}$ for $Re_T \le Re$.
- Transition flow: $f = \frac{C_{fL}}{Re}(1-\Psi)^{1/3} + \frac{C_{fT}}{Re^{0.18}}\Psi^{1/3}$ for $Re_L \le Re \le Re_T$.

where $\log\left(\frac{Re_L}{300}\right) = 1.7\left(\frac{P_t}{D_r} - 1.0\right)$

$$\log\left(\frac{Re_T}{10{,}000}\right) = 0.7\left(\frac{P_t}{D_r} - 1.0\right)$$

$$\Psi = \log\left({}^{Re}/_{Re_L}\right)/\log\left({}^{Re_T}/_{Re_L}\right)$$

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

$$C_{fT} = \left[0.8063 - 0.9022\log\left(\frac{H}{D}\right) + 0.3526\left(\log\left(\left(\frac{H}{D}\right)\right)\right)^2\right]\left(\frac{P}{D}\right)^{9.7}\left(\frac{H}{D}\right)^{1.78-2.0(P/D)}$$

Appendix E. Cheng and Todreas Detailed Correlation (1986)

- Laminar flow: $f = \frac{C_{fL}}{Re}$ for $Re \le Re_L$.
- Turbulent flow: $f = \frac{C_{fT}}{Re^{0.18}}$ for $Re_T \le Re$.
- Transition flow: $f = \frac{C_{fL}}{Re}(1-\Psi)^{1/3} + \frac{C_{fT}}{Re^{0.18}}\Psi^{1/3}$ for $Re_L \le Re \le Re_T$.

where

- $\log\left(\frac{Re_L}{300}\right) = 1.7\left(\frac{P_t}{D_r} - 1.0\right)$
- $\log\left(\frac{Re_T}{10{,}000}\right) = 0.7\left(\frac{P_t}{D_r} - 1.0\right)$
- $\Psi = \log\left({}^{Re}/_{Re_L}\right)/\log\left({}^{Re_T}/_{Re_L}\right)$
- $C_{fL} = D_{eb}\left(\sum_{i=1}^{3}\left(\frac{N_i A_i}{A_b}\right)\left(\frac{D_{ei}}{D_{eb}}\right)\left(\frac{D_{ei}}{C_{fiL}}\right)\right)^{-1}$
- $C_{fT} = D_{eb}\left(\sum_{i=1}^{3}\left(\frac{N_i A_i}{A_b}\right)\left(\frac{D_{ei}}{D_{eb}}\right)^{0.0989}\left(\frac{D_{ei}}{C_{fiT}}\right)^{0.54945}\right)^{-1.82}$
- $C_{f1T} = C'_{f1T}\left(\frac{P'_{w1}}{P_{w1}}\right) + W_{dT}\left(\frac{3A_{r1}}{A'_1}\right)\left(\frac{D_{e1}}{H}\right)\left(\frac{D_{e1}}{D_w}\right)^{0.18}$
- $W_{dT} = \left(29.5 - 140\left(\frac{D_w}{D}\right) + 401\left(\frac{D_w}{D}\right)^2\right)\left(\frac{H}{D}\right)^{-0.85}$
- $C_{f2T} = C'_{f2T}\left(1 + W_{sT}\left(\frac{A_{r2}}{A'_2}\right)\tan^2\theta\right)^{1.41}$
- $C_{f3T} = C'_{f3T}\left(1 + W_{sT}\left(\frac{A_{r3}}{A'_3}\right)\tan^2\theta\right)^{1.41}$
- $W_{sT} = 20.0\log\left(\frac{H}{D}\right) - 7.0$
- $C_{f1L} = C'_{f1L}\left(\frac{P'_{w1}}{P_{w1}}\right) + W_{dL}\left(\frac{3A_{r1}}{A'_1}\right)\left(\frac{D_{e1}}{H}\right)\left(\frac{D_{e1}}{D_w}\right)$
- $W_{dL} = 1.4W_{dT} = \left(41.3 - 196\left(\frac{D_w}{D}\right) + 561\left(\frac{D_w}{D}\right)^2\right)\left(\frac{H}{D}\right)^{-0.85}$
- $C_{f2L} = C'_{f2L}\left(1 + W_{sL}\left(\frac{A_{r2}}{A'_2}\right)\tan^2\theta\right)$
- $C_{f3L} = C'_{f3L}\left(1 + W_{sL}\left(\frac{A_{r3}}{A'_3}\right)\tan^2\theta\right)$
- $W_{sL} = 0.3W_{sT} = 6.0\log\left(\frac{H}{D}\right) - 2.1$

Appendix E. Cheng and Todreas Detailed Correlation (1986)

- Bare rod subchannel friction factor constants in Table A.1:
  - $C'_{fi} = a + b\left(\frac{P}{D} - 1\right) + c\left(\frac{P}{D} - 1\right)^2$

Constant	1.0 ≤ P/D (W/D) ≤ 1.1			1.1 ≤ P/D (W/D) ≤ 1.5		
	a	B	c	a	b	C
C'_{f1L}	26	888.2	−3334.0	62.97	216.9	−190.2
C'_{f2L}	26.18	554.5	−1480.0	44.4	256.7	−267.6
C'_{f3L}	26.98	1636	−10050.0	87.26	38.59	−55.12
C'_{f1T}	0.09378	1.398	−8.664	0.1458	0.03632	−0.03333
C'_{f2T}	0.09377	0.8732	−3.341	0.143	0.04199	−0.04428
C'_{f3T}	0.1004	1.625	−11.85	0.1499	0.006706	−0.009567

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Appendix F. Upgraded Cheng and Todreas (2018)

- Transition friction factor, $Re_{bL} \leq Re \leq Re_{bT}$

$$f_i = \left(\frac{C_{fiL}}{Re_i}\right)(1-\psi_i)^{\frac{1}{3}}(1-\psi_i^7)\left(\frac{C_{fiT}}{Re_i^{0.18}}\right)\psi_i^{\frac{1}{3}}$$

where i = b, 1, 2, or 3 for bundle average, interior, edge and corner subchannel

- $Re_{bL} = 320\left(10^{\left(\frac{P}{D}-1.0\right)}\right)$
- $W_{dT} = \left(19.56 - 98.71\left(\frac{D_w}{D}\right) + 303.47\left(\frac{D_w}{D}\right)^2\right)\left(\frac{H}{D}\right)^{-0.541}$
- $W_{sT} = -11.0\log\left(\frac{H}{D}\right) + 19.0$
- $W_{sL} = 1.0W_{sT}$