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Investigation of Helical Oval-Twisted Tube HX/SG Dynamic Performance Using RELAP5-3D

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Innovating Current HX/SG for SMR Applications

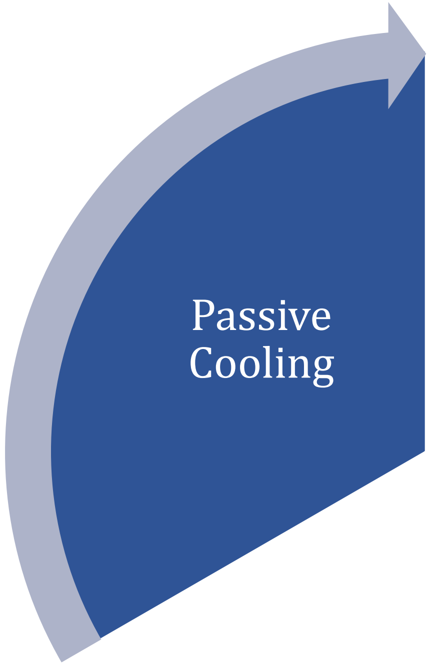
How to design a better HX?

Positives

- Potentially eliminates external driving mechanisms (cost reduction)
- Enhances safety features

Negatives

- Slower thermal response to power fluctuations and flow instabilities
- Situation-dependent reliability



Positives

- Plenty of enhancement options available (active and passive) methods
- Can greatly improve thermal efficiency
- Can reduce fouling buildup

Negatives

- May require additional fabrication costs
- Enhancement technique may increase equipment fallibility and shorten lifespan

Positives

- Larger surface area per unit volume
- Lower capital cost and footprint
- Relatively higher thermal performance

Negatives

- Small flow passages (increased ΔP)
- Higher chance of fouling buildup

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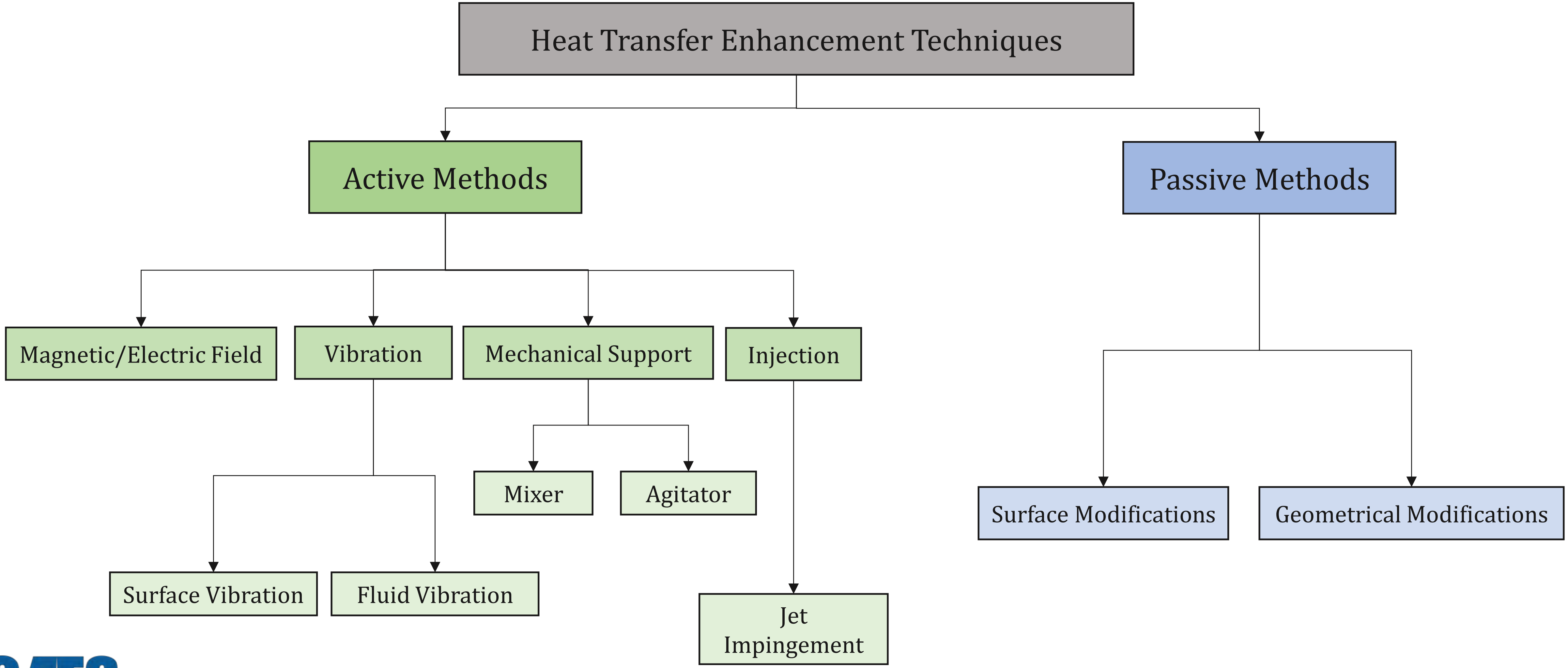

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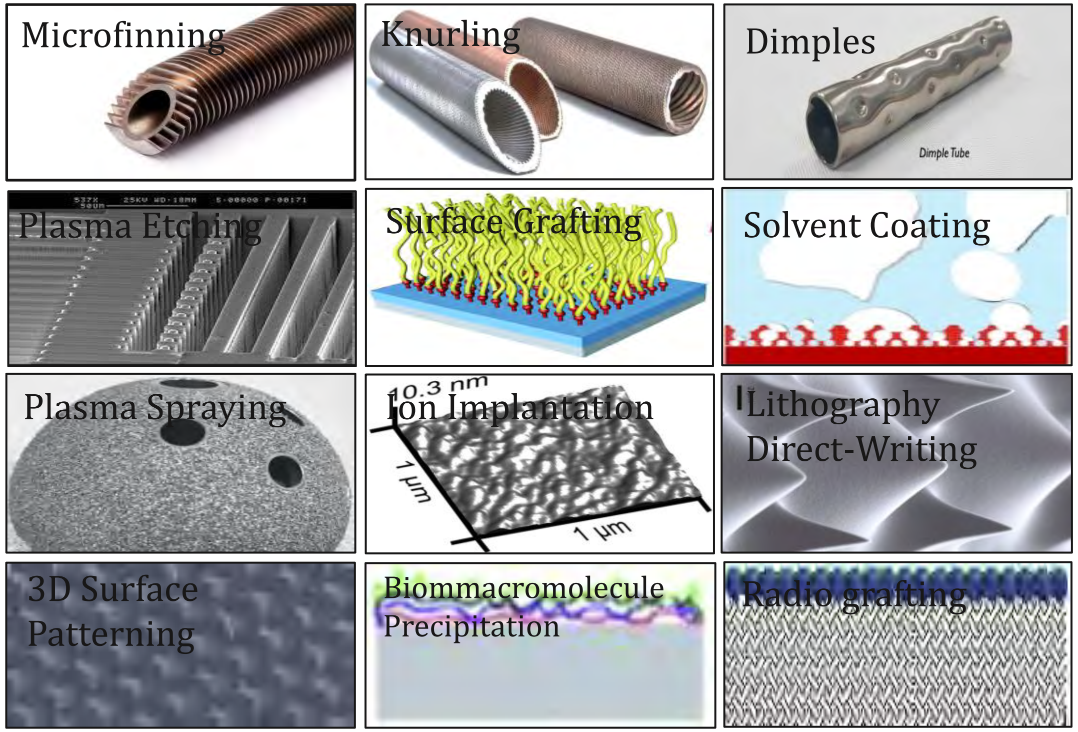
SURFACE MODIFICATIONS:



GEOMETRICAL MODIFICATIONS:

Surface Modifications:

- Seek to improve conduction between wall and fluid.

Geometrical Modifications:

- Seek to improve convection and localized turbulence.

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*References for all figures provided at end of presentation

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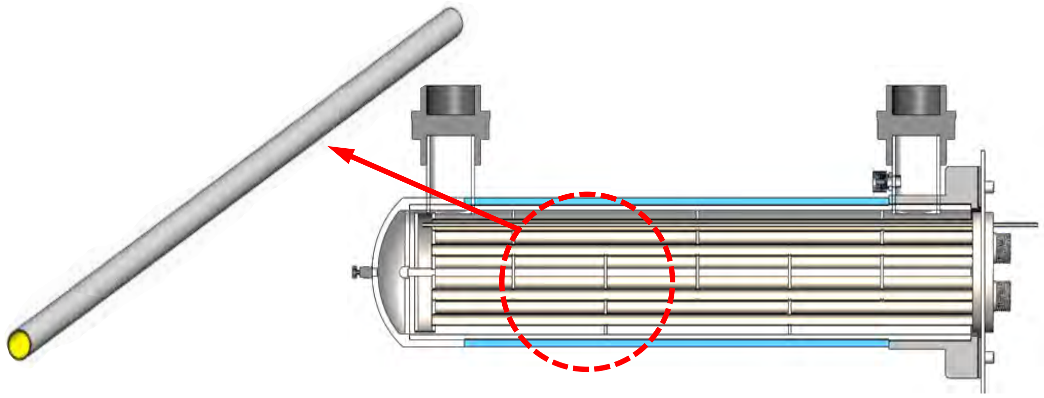
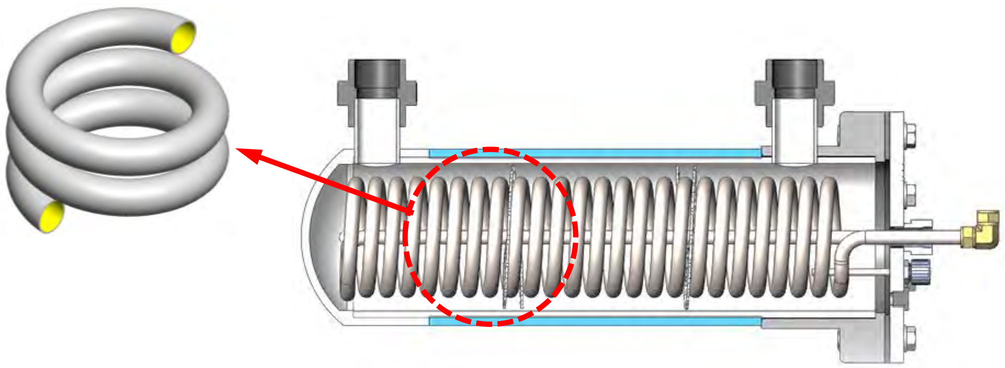
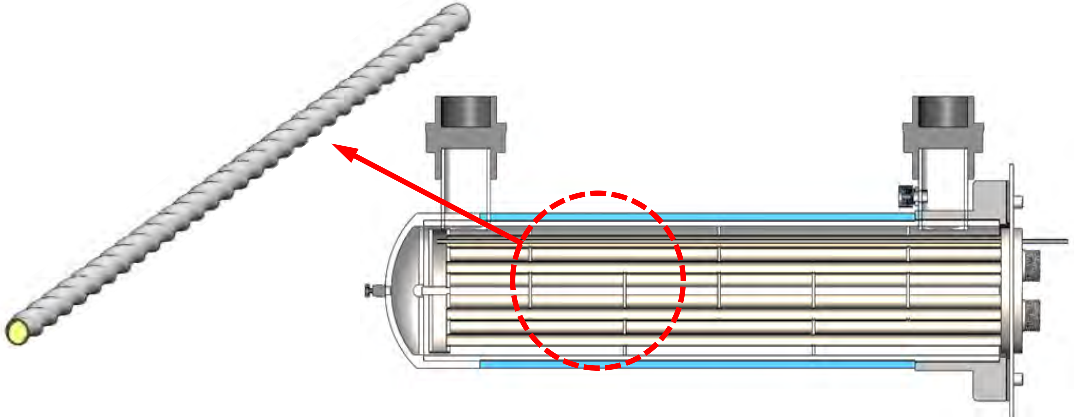


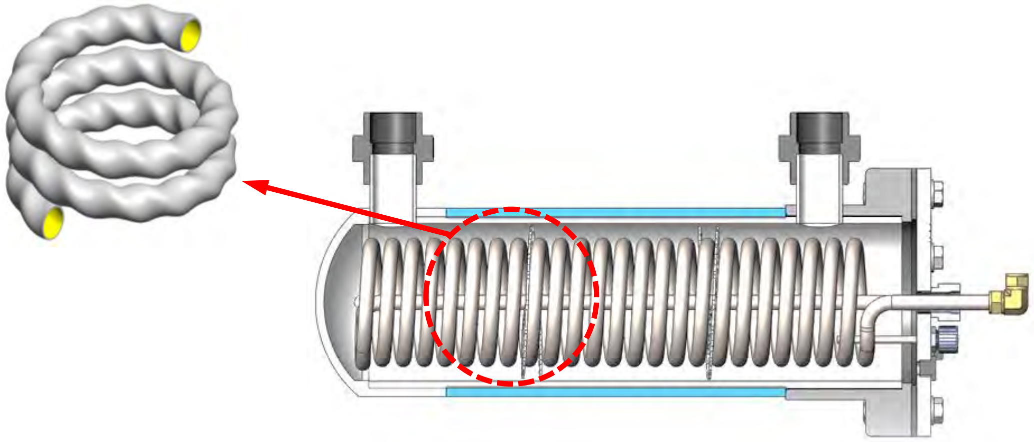
Straight circular tube – Shell and Tube HXs
- Standard steam generator unit



Helical tube – Helical Coiled HXs
- Enhanced heat transfer from secondary flow
- Increased compactness



Oval twisted tube – Twisted tube HXs
- Enhanced heat transfer from swirling vortices induction



Oval twisted-helical tube – Twisted-Helical HXs
- Enhanced heat transfer from combination of secondary flow and swirling vortices induction
- Increased compactness

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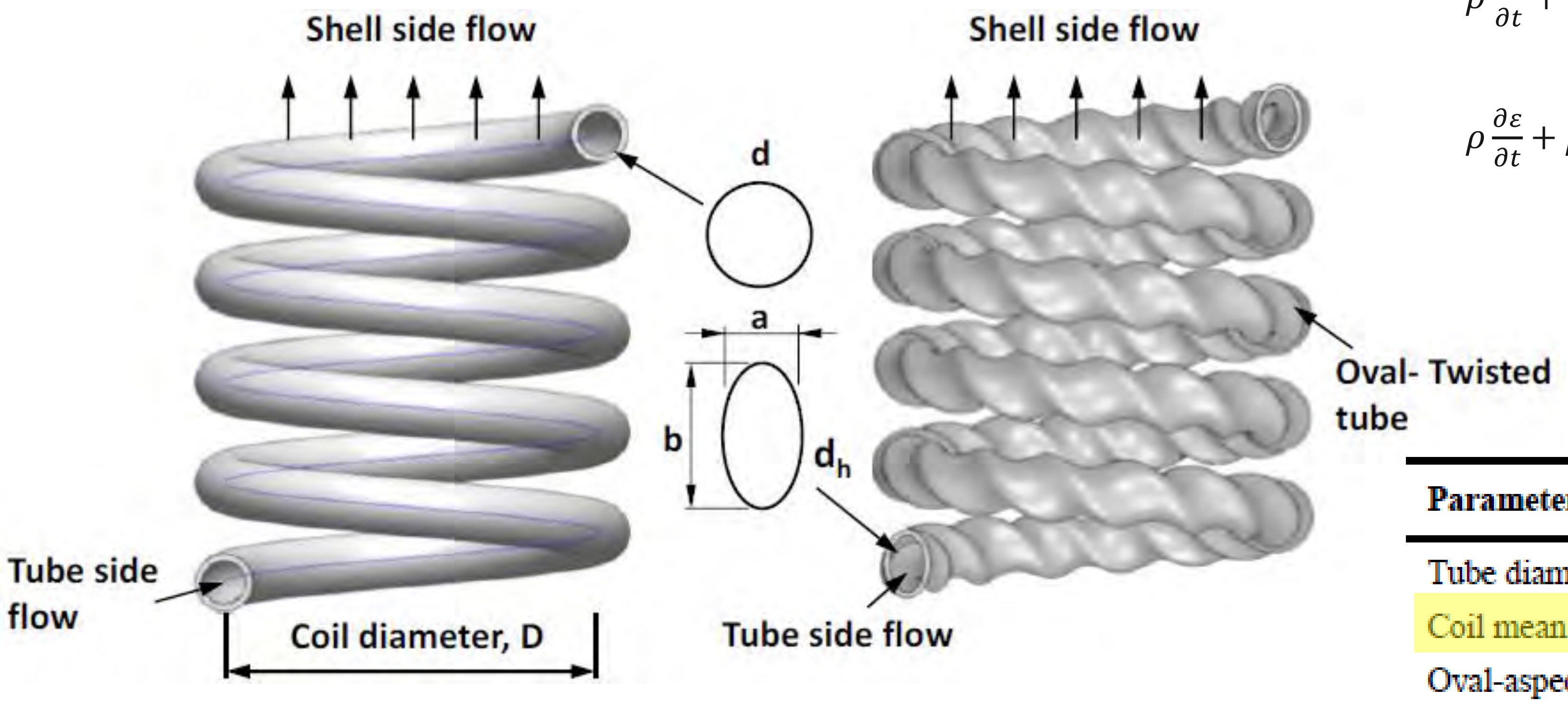
CFD Analysis Comparison of H-OTSG and OTHCHX

H-OTSG: Helical Once-Through Steam Generator

OTHCHX: Oval-Twisted Helical Coil Heat Exchanger



Turbulence Model – Low *Re* k-ε Model:

The Low *Re* k-ε model best matches experimentally derived correlations in the literature for H-OTSG

$$\rho\frac{\partial k}{\partial t} + \rho\,\boldsymbol{u}\cdot\nabla k = \nabla\cdot\left(\left(\mu + \frac{\mu_T}{\sigma_k}\right)\nabla k\right) + P_k - \rho\varepsilon$$

$$\rho\frac{\partial \varepsilon}{\partial t} + \rho\,\boldsymbol{u}\cdot\nabla \varepsilon = \nabla\cdot\left(\left(\mu + \frac{\mu_T}{\sigma_\varepsilon}\right)\nabla \varepsilon\right) + C_{\varepsilon 1}\frac{\varepsilon}{k}P_k - f_\varepsilon C_{\varepsilon 2}\rho\frac{\varepsilon^2}{k}$$

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Parameter	Value	Units
Tube diameter or hydraulic diameter, d or d_h	17.44	mm
Coil mean diameter, D	75-225	mm
Oval-aspect ratio, a/b	2	
Coil pitch, P	40	mm
Coil height, H	113-336	mm
Coil length, L	2000	mm

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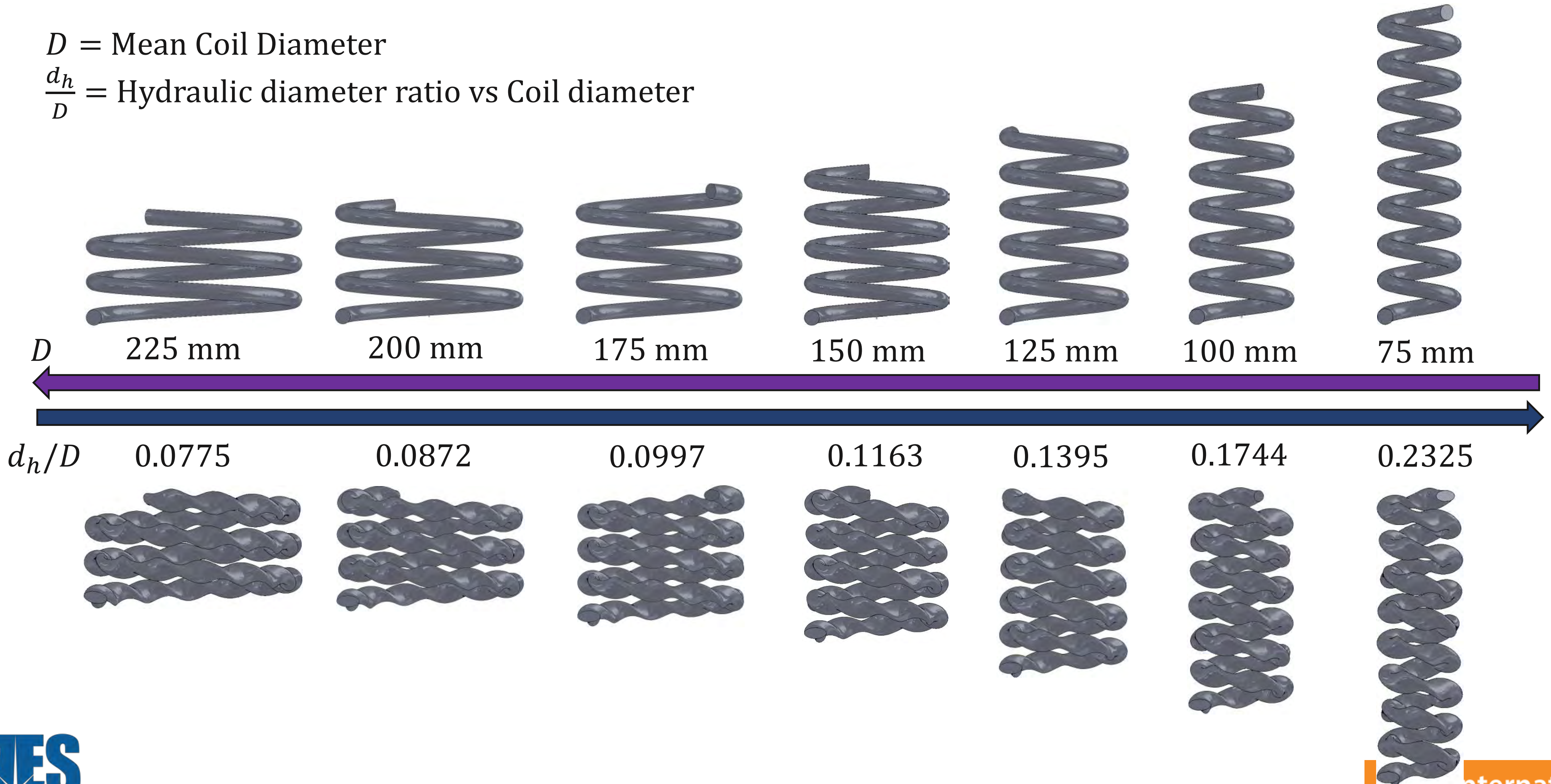
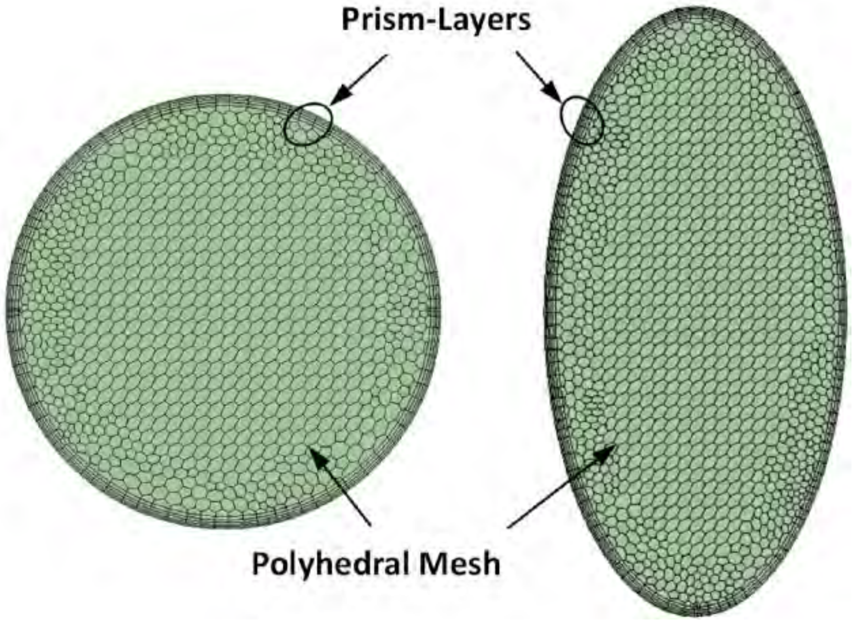
D = Mean Coil Diameter

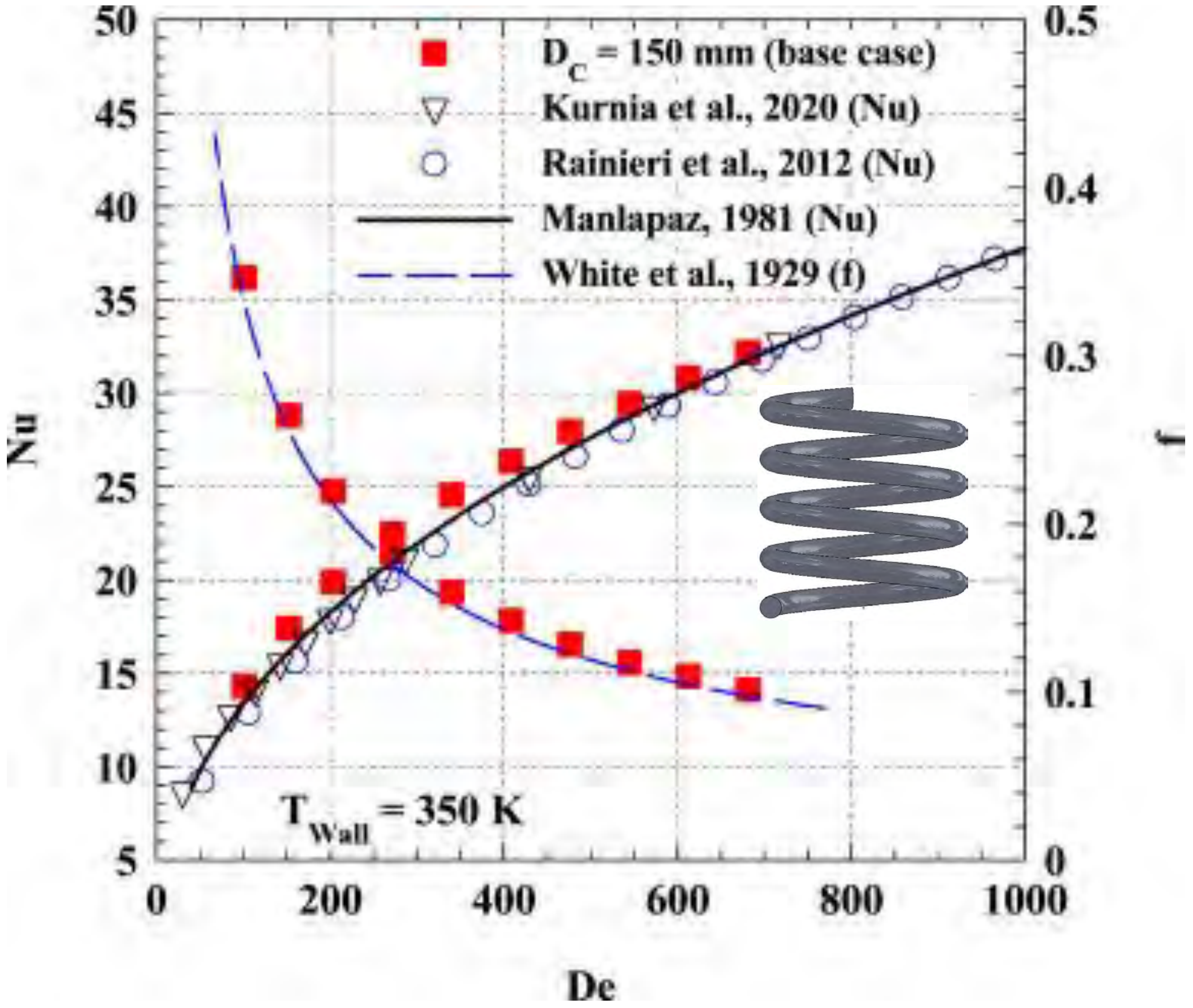
$\frac{d_h}{D}$ = Hydraulic diameter ratio vs Coil diameter



CFD Analysis Comparison of H-OTSG and OTHCHX



	Normal, h_3	Finer, h_2	Extra-fine, h_1
Number of Cells	1471090	2955594	5911299
Nu	28.62	27.87	27.95
GCI_{fine}^{21}	0.05%		
ΔP (Pa)	53.77	54.26	55.64
GCI_{fine}^{21}	1.59%		



1. Wahlquist et al.., 2022, "Laminar Flow Heat Transfer In Helical Oval-Twisted Tube For Heat Exchanger Applications," Front. Heat Mass Transf., 18.
2. Wahlquist et al., 2025, "Development of novel oval-twisted helical tube once-through steam generator: Part I: Single-phase laminar flow," Prog. Nucl. Eng.,183, 105667.

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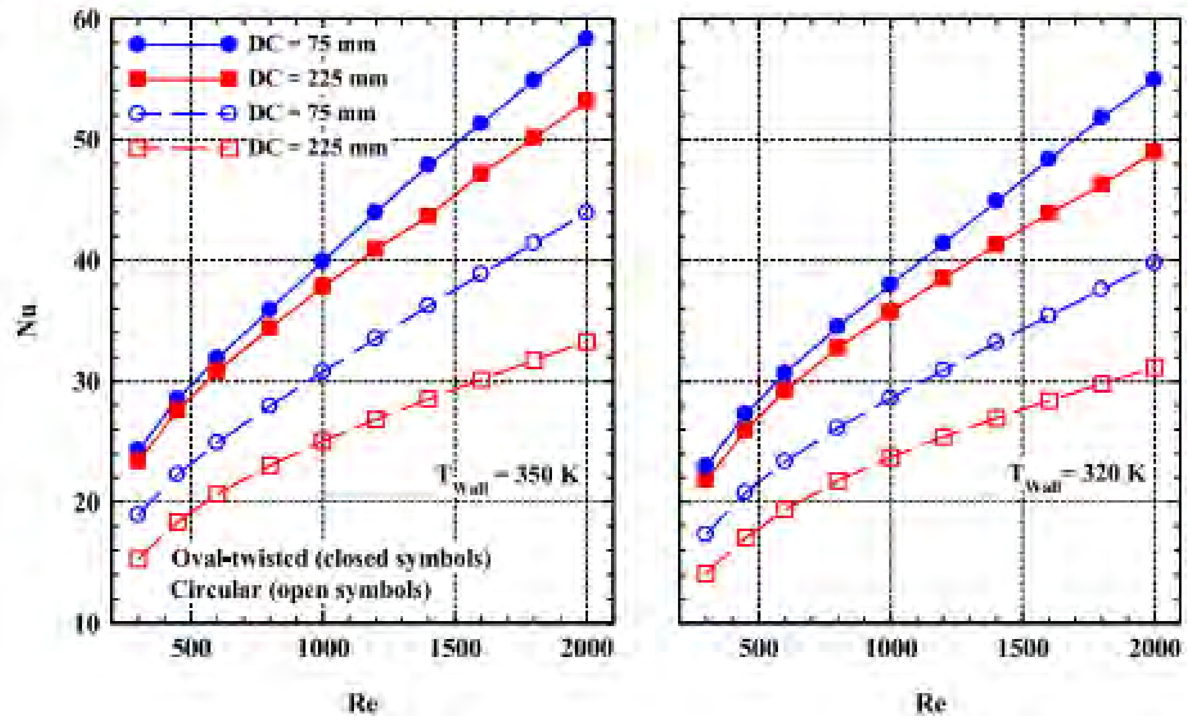
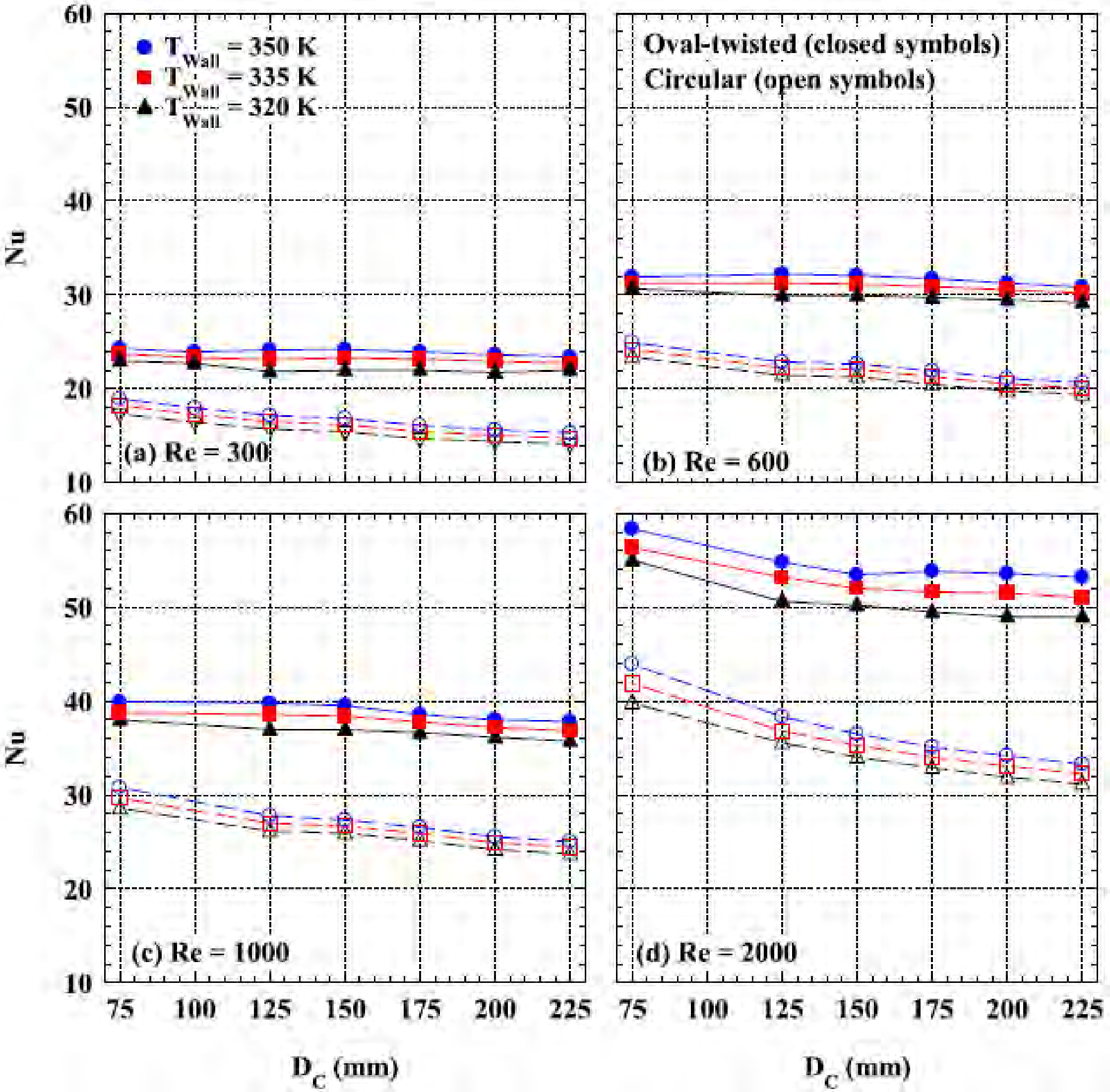
CFD Analysis Comparison of H-OTSG and OTHCHX





T_{Wall} (K)	D_c (mm)	*Re*	$\frac{Nu_o}{Nu_c}$ (%)	$\frac{q_o}{q_c}$ (%)	$\frac{f_o}{f_c}$ (%)
320	75	300	32.61	19.74	15.07
		2000	38.18	29.31	26.48
	225	300	54.41	21.43	31.48
		2000	57.16	39.06	37.80
350	75	300	28.29	19.14	15.98
		2000	32.82	24.95	34.31
	225	300	52.83	20.24	33.92
		2000	59.78	36.50	41.84

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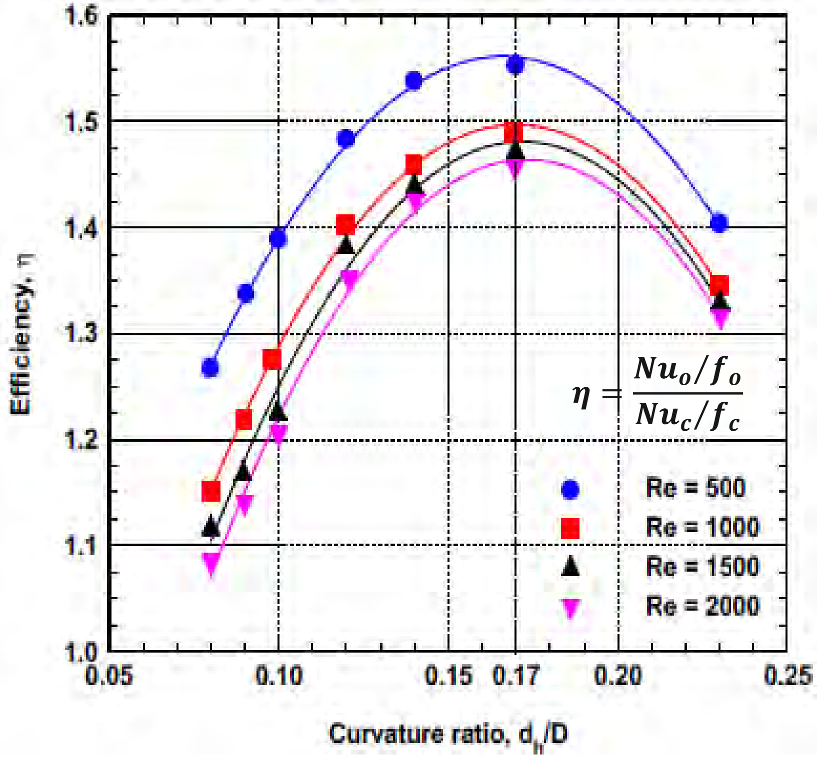
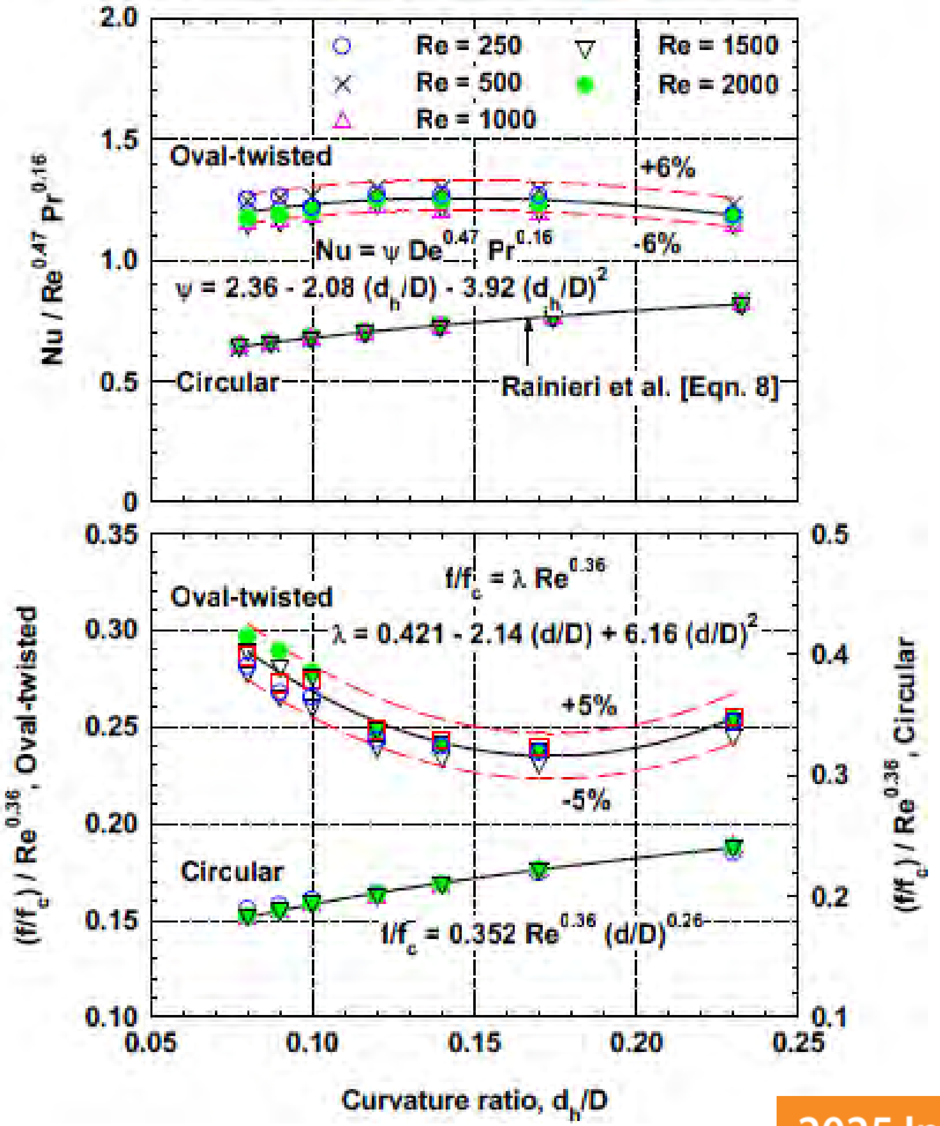
1. Wahlquist et al.., 2022, "Laminar Flow Heat Transfer In Helical Oval-Twisted Tube For Heat Exchanger Applications," Front. Heat Mass Transf., 18.
2. Wahlquist et al., 2025, "Development of novel oval-twisted helical tube once-through steam generator: Part I: Single-phase laminar flow," Prog. Nucl. Eng.,183, 105667.

CFD Analysis Comparison of H-OTSG and OTHCHX





The convective performance of the OTHCHX performed roughly 10-55% better, with a peak HT performance increase at d_h/D being around 0.15 and 0.17.

Nu and f correlations based on the numerical results were developed for the laminar flow regime, which are within ±6% and ±5%, respectively.

1. Wahlquist et al.., 2022, "Laminar Flow Heat Transfer In Helical Oval-Twisted Tube For Heat Exchanger Applications," Front. Heat Mass Transf., 18.
2. Wahlquist et al., 2025, "Development of novel oval-twisted helical tube once-through steam generator: Part I: Single-phase laminar flow," Prog. Nucl. Eng.,183, 105667.

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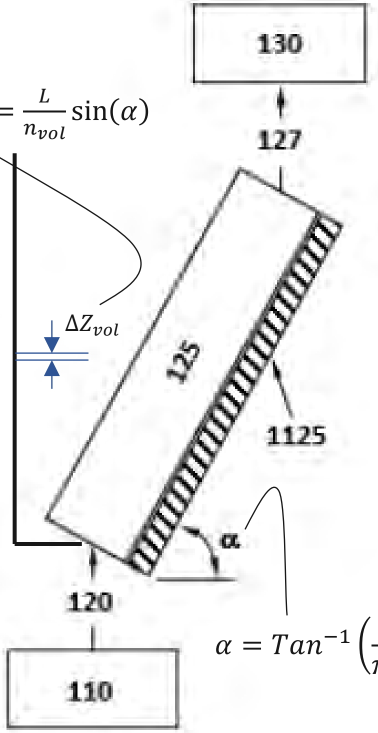
H-OTSG and OTHCHX RELAP5-3D Model

$$\Delta Z_{vol} = \frac{L}{n_{vol}} \sin(\alpha)$$



$$\alpha = Tan^{-1}\left(\frac{P}{\pi D}\right)$$

The single tube helical coil can be simplified[1,2] in RELAP5-3D by
1. Unwrapping the coil tube and make an inclined straight pipe component of the same length.
2. Add a vertical change in elevation corresponding to the bundle height.
3. Applying corresponding HTC and friction factor correlations to heat structure(s)

Comp.	Description
110	TMDPVL
120	TMDJUN
125	PIPE
1125	PIPE HEAT STRUCTURE
127	SNGLJUN
130	TMDPVL

<u>H-OTSG: Manlapaz and Churchill, 1987</u>

$$Nu = \left[\left(3.657 + \frac{4.343}{X_1}\right)^3 + 1.158\left(\frac{De}{X_2}\right)^{\frac{3}{2}}\right]^{\frac{1}{3}}$$

$$X_1 = 1 + \frac{957}{(De^2 Pr)^2}, X_2 = 1 + \frac{0.477}{Pr}$$

<u>OTHCHX: Wahlquist et al., 2021</u>

$$Nu = \psi De^{0.47} Pr^{0.16}$$

$$\psi = 2.36 - 2.08\left(\frac{d_h}{D}\right) - 3.92\left(\frac{d_h}{D}\right)^2$$

<u>Location of prescribed B.Cs:</u>
110 – Apply water inlet temperature and pressure
120 – Apply calculated mass flowrate corresponding to chosen Re
125 – Horizontal pipe component with prescribed elevation gain per volume (ΔZ_{vol}) and vertical angle change (α). Pipe contains 99 vols.
1125 – Apply HTC correlation corresponding with developed models from literature

<u>(1) BOUNDARY CONDITIONS:</u>
Oscillating Wall Temperature
(Triangle, Sinusoidal, Square f)

Wall Conditions:
- $T_s = 320, 335, 350$ K
- $f = 20, 50, 100$ mHz

Inlet Conditions:
- $T_{in} = 300$ K
- $Re = 600 - 2000$

External Conditions
- Gravity present, opposing vertical flow.

<u>(2) BOUNDARY CONDITIONS:</u>
Pulsating Flowrate
(Square $f_{\dot{m}}$)

Wall Conditions:
- $T_s = 350$ K

Inlet Conditions:
- $T_{in} = 300$ K
- $Re = 600 - 2000$
- $f_{\dot{m}} = 20, 50, 100$ mHz

External Conditions
- Gravity present, opposing vertical flow.

<u>(3) BOUNDARY CONDITIONS:</u>
Combined conditions
(Square f and Square $f_{\dot{m}}$)

Wall Conditions:
- $T_s = 350$ K
- $f = 20, 50, 100$ mHz

Inlet Conditions:
- $T_{in} = 300$ K
- $Re = 600 - 2000$
- $f_{\dot{m}} = 20, 50, 100$ mHz

External Conditions
- Gravity present, opposing vertical flow.

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1. Hoffer, N.V., Sabharwall, P., Anderson, N.A., 2011 “Modeling a Helical-coil Steam Generator in RELAP5-3D for the Next Generation Nuclear Plant,” INL Report INL/EXT-10-19621.
2. Xu, Z., Liu, M. Xiao, Y., Gu, H., 2021 “Development of a RELAP5 model for the thermo-hydraulic characteristics simulation of the helically coiled tubes,” Ann. Nucl. Energ., 153, 108032.

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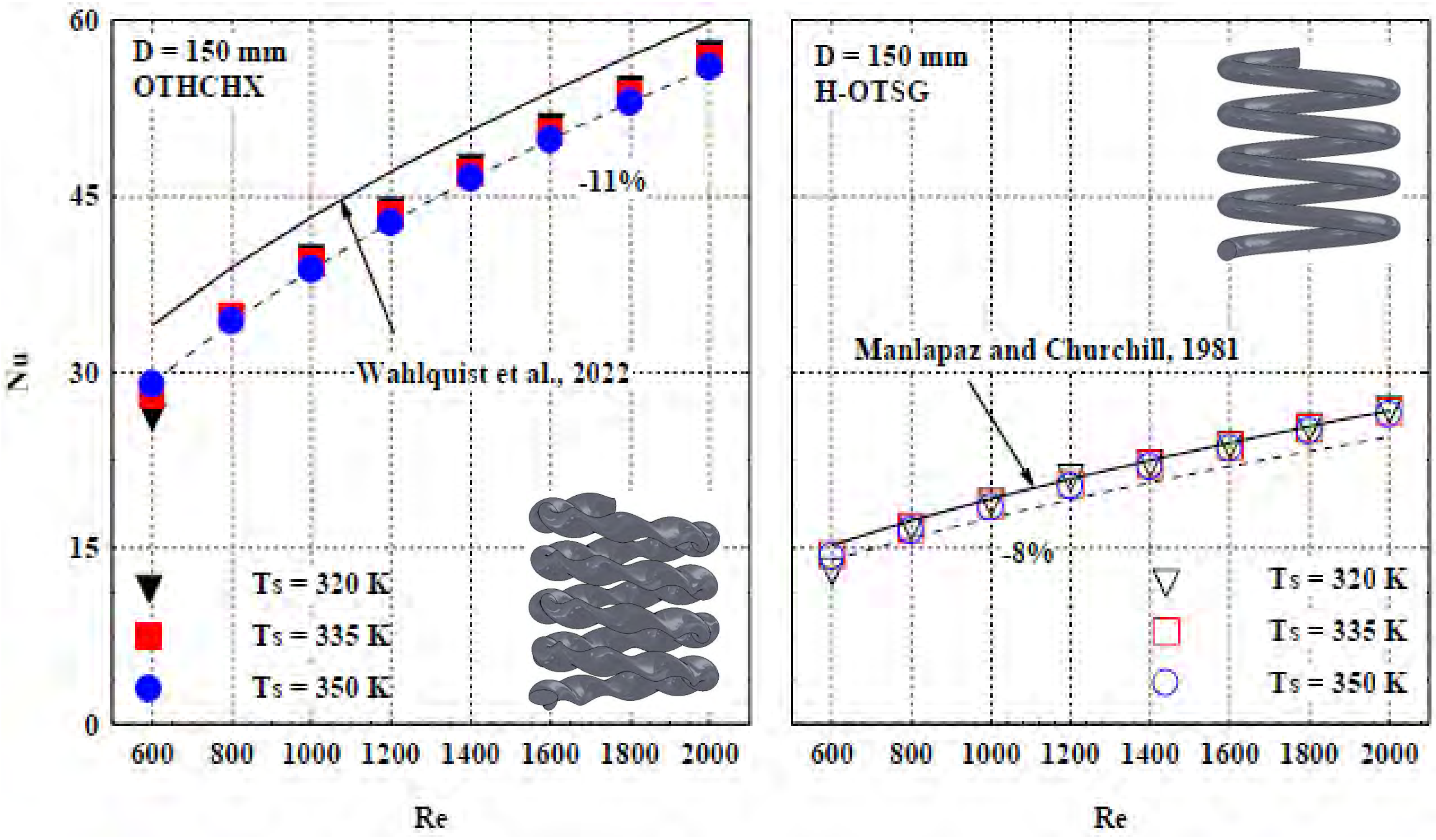
H-OTSG and OTHCHX RELAP5-3D Model



The developed RELAP5-3D models for the OTHCHX and H-OTSG match their respective Nusselt number correlations within 11% and 8%, respectively. The friction factor behavior also matches the data and is not be presented here.

Disclaimer: The H-OTSG *Nu* correlation is experimentally validated, however the OTHCHX correlation based on RANS CFD analyses has yet to be experimentally evaluated.

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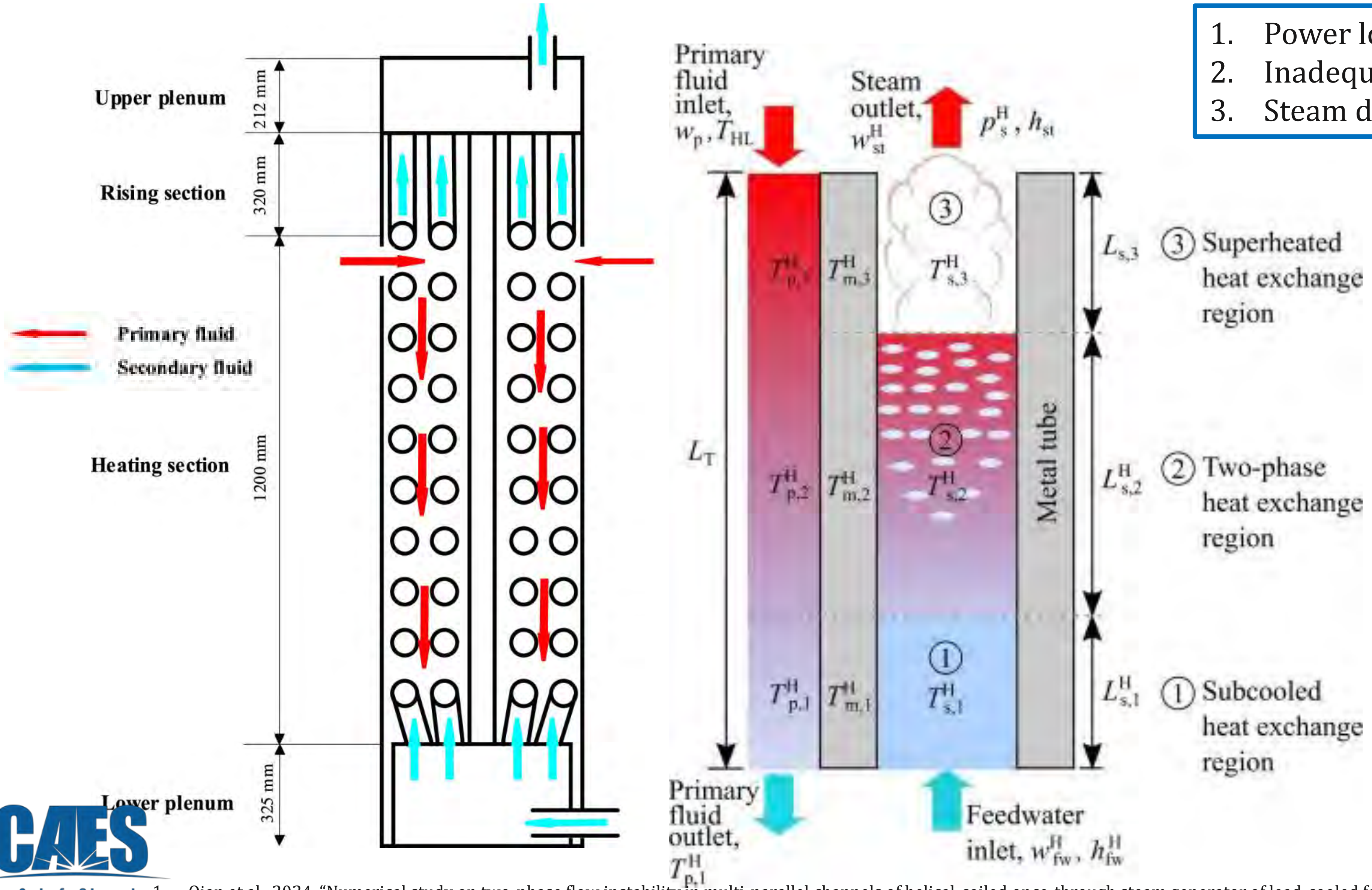
Temperature Instability Instigators



1. Power load variations
2. Inadequate control systems
3. Steam demand fluctuations

No effect from geometric flow path

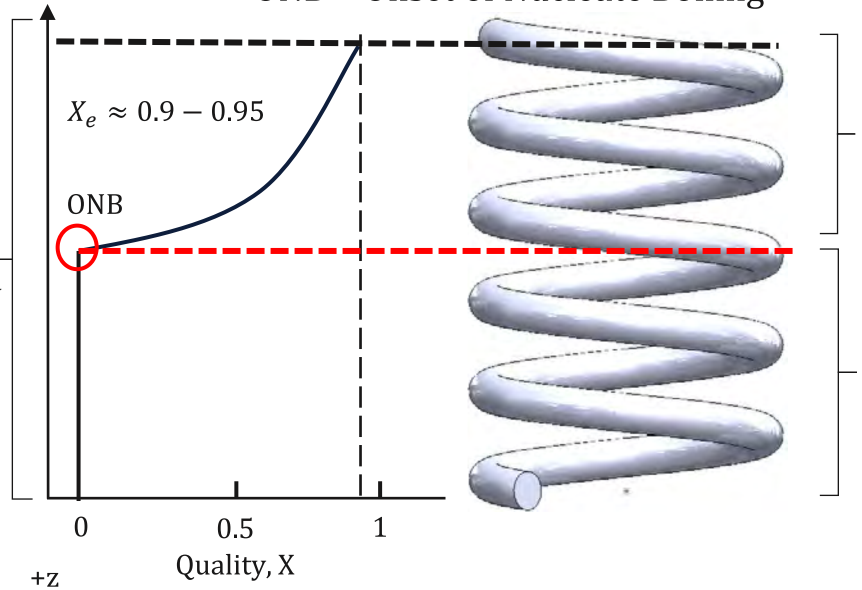
Depreciating effects of geometric flow path

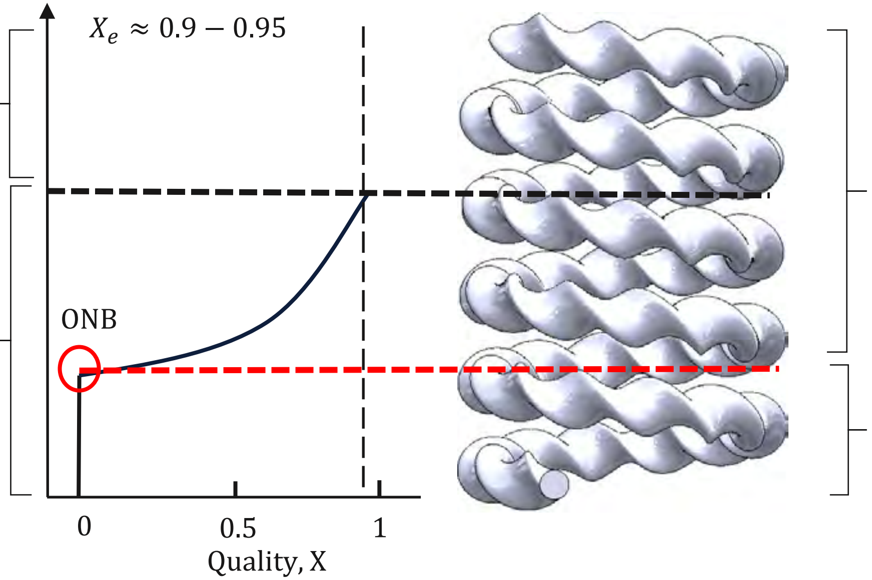
Maximum effect of geometric flow path

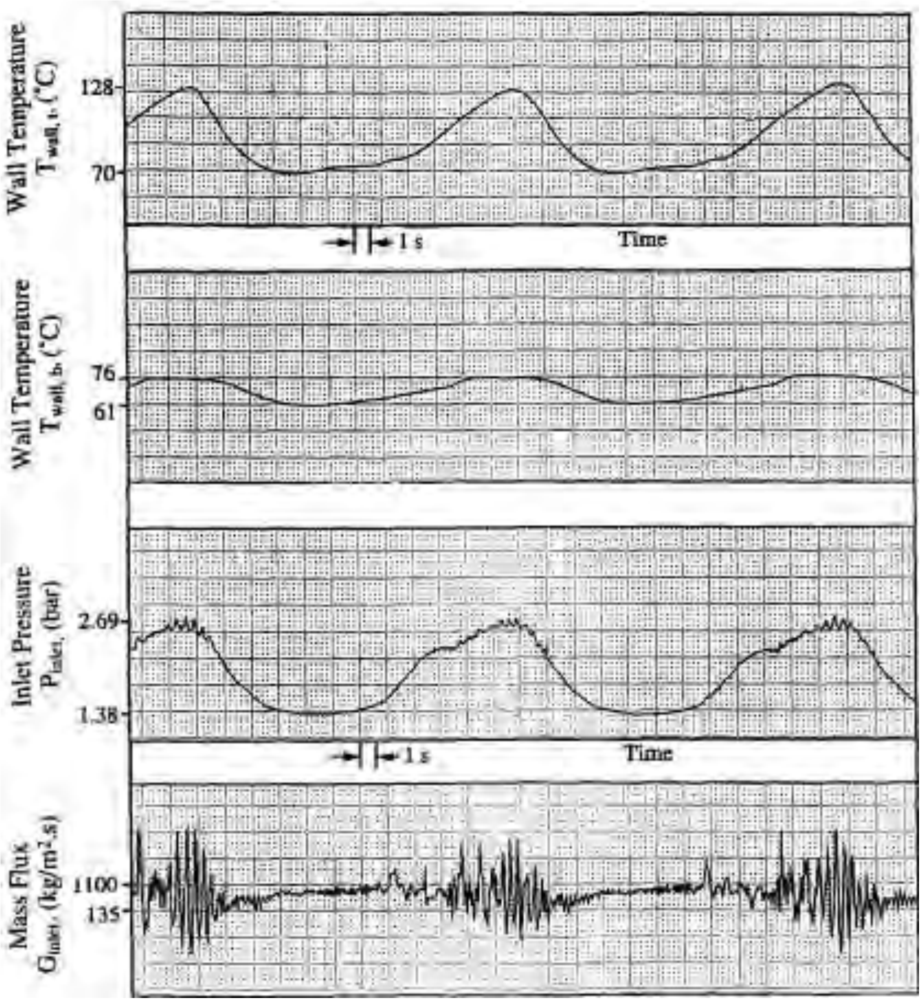
1. Qian et al., 2024, "Numerical study on two-phase flow instability in multi-parallel channels of helical-coiled once-through steam generator of lead-cooled fast reactor," Nucl. Eng. Tech., 56, 4895-4904.
2. Sabir and Jiang, 2022, Comparing the dynamic response of U-tube and helical coil steam generators in small modular reactor flexible operation," Nucl. Eng. Des., 388, 111610.

Temperature Instability Instigators

ONB = Onset of Nucleate Boiling







1. Din et al., 1995, "Dynamic instabilities of boiling two-phase flow in a single horizontal channel," Exp. Therm. Fluid Sci., 11, 327-342.

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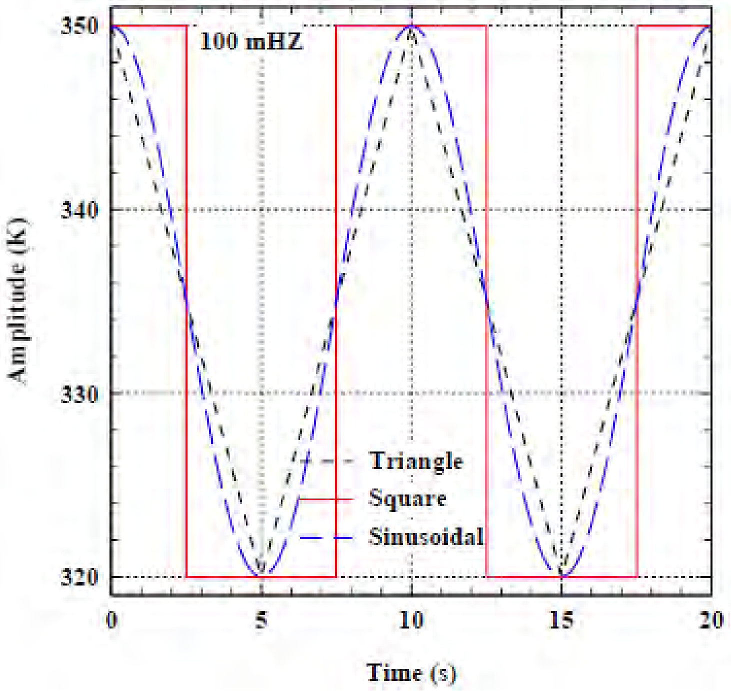
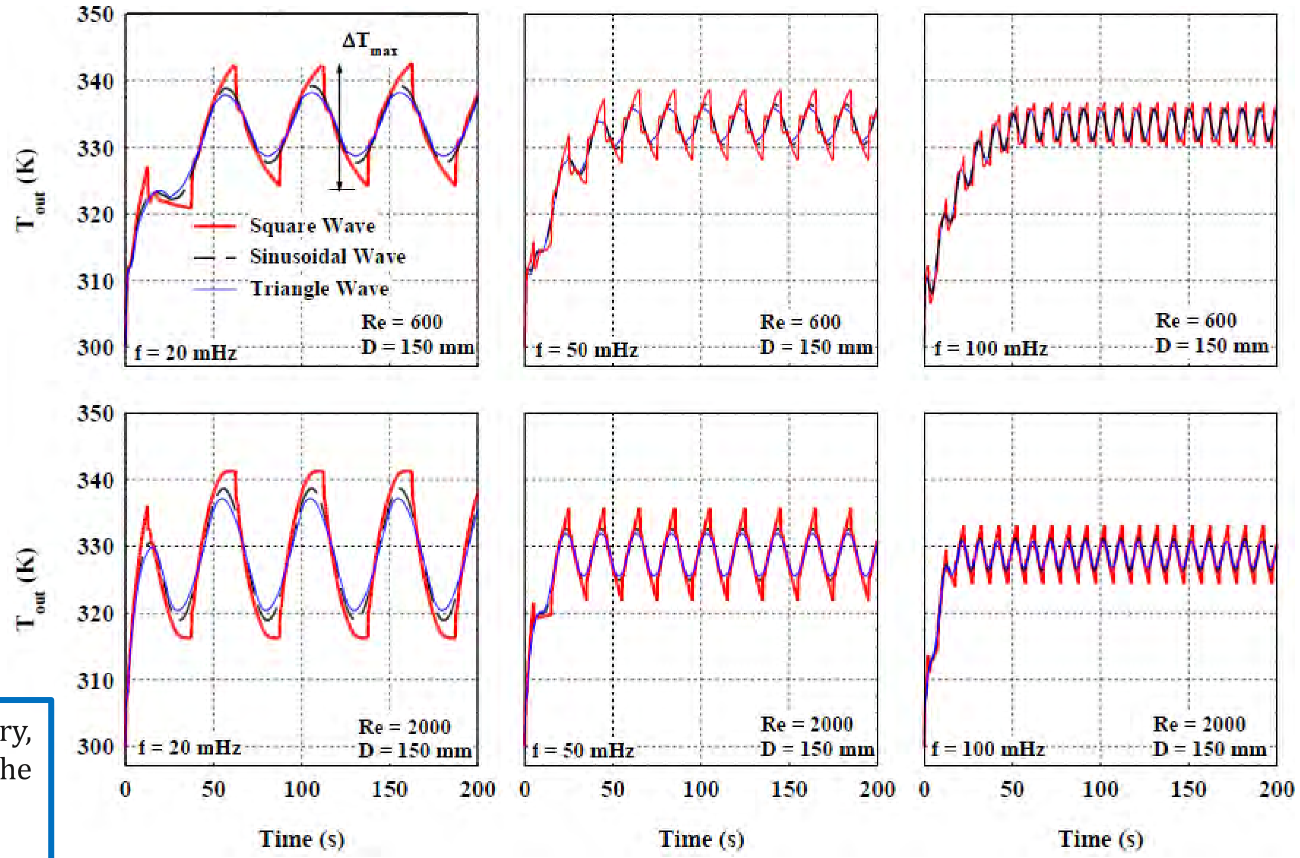
Results – Oscillating Wall Temperature





For two-phase and saturated environments on the outer pipe wall boundary, such as in steam generators, constant temperatures better represent the thermal boundary condition.

Triangle – Represents idealized gradual power variations
Square – Represents rapid power load spikes
Sinusoidal – Represents real gradual power variations

Oscillatory steady-state behavior observed after about $t = 100$ s for all investigated Re and f.

Lower frequencies produce larger ΔT_{max} in outlet temperatures.

Oscillating wall temperature are known to induce thermal stress and fatigue which could lead to pipe rupture and mixing of primary and secondary fluids[1].

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1. Paffumi, E., Nilsson, K.-F., Taylor, N.G., 2010, "Thermal frequency response studies of a hollow cylinder subject to loads of different amplitude and shape," Nucl. Eng. Des., 240, 1355-1362.

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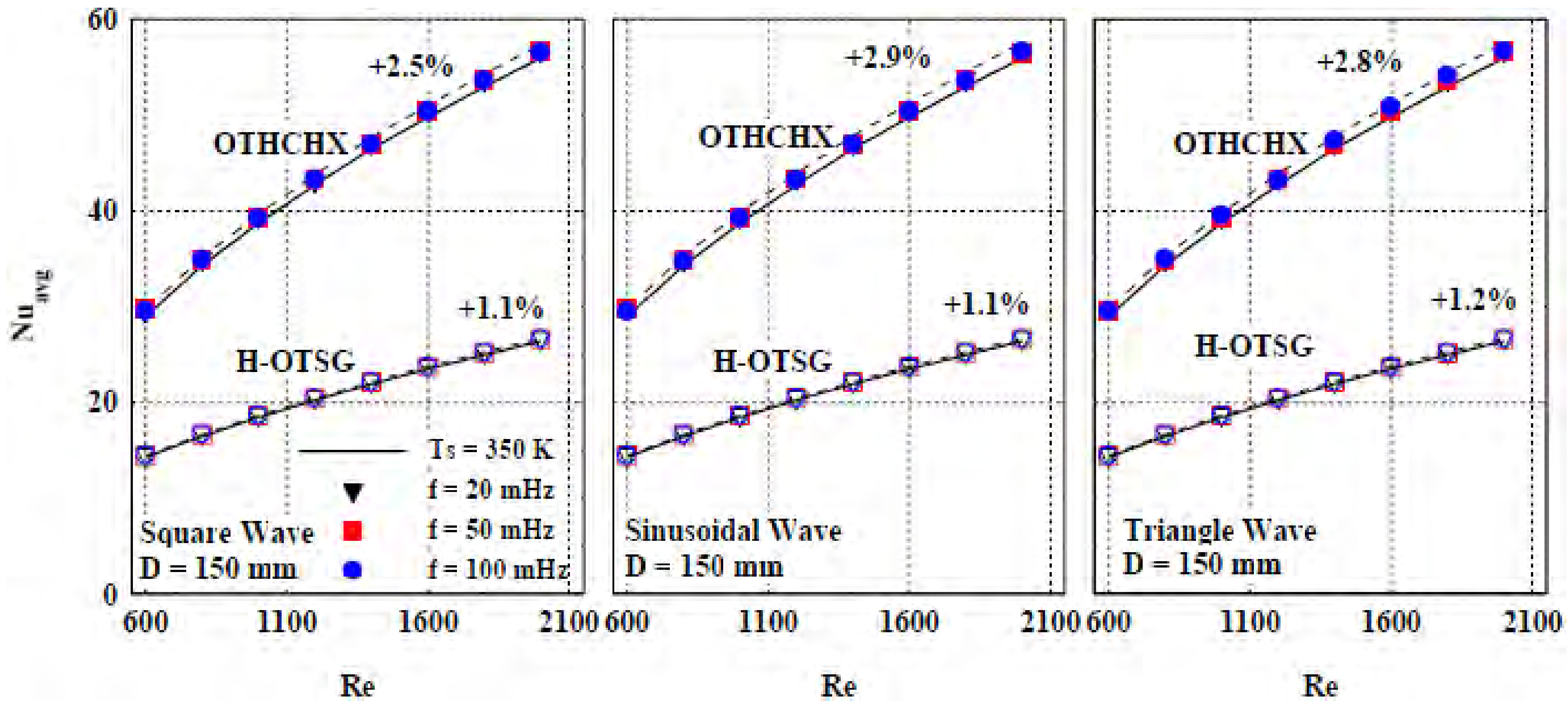
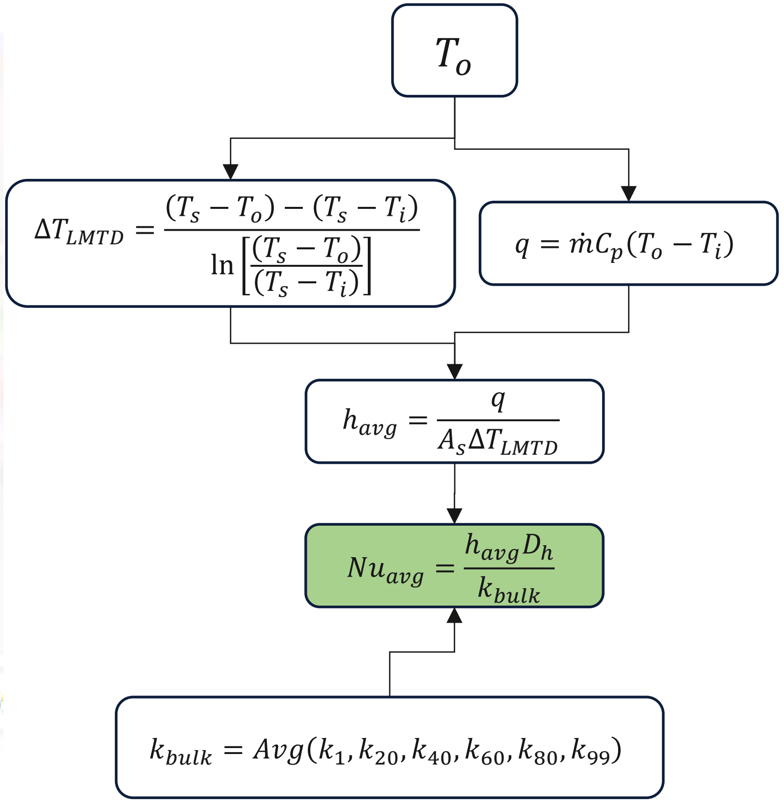
Results – Oscillating Wall Temperature





By averaging the transient temperature values between $t = 100$s and 500s, an average outlet temperature can be obtained, which can be used to determine Nu_{avg}.

The introduction of fluctuating wall temperature boundary conditions leads to a slight increase in Nu_{avg} for the OTHCHX and there is negligible change for the equivalent H-OTSG geometry.

There is a slight difference in Nu_{avg} increase between the square wave loading and the triangle/sinusoidal wave loading, however the difference is very small.

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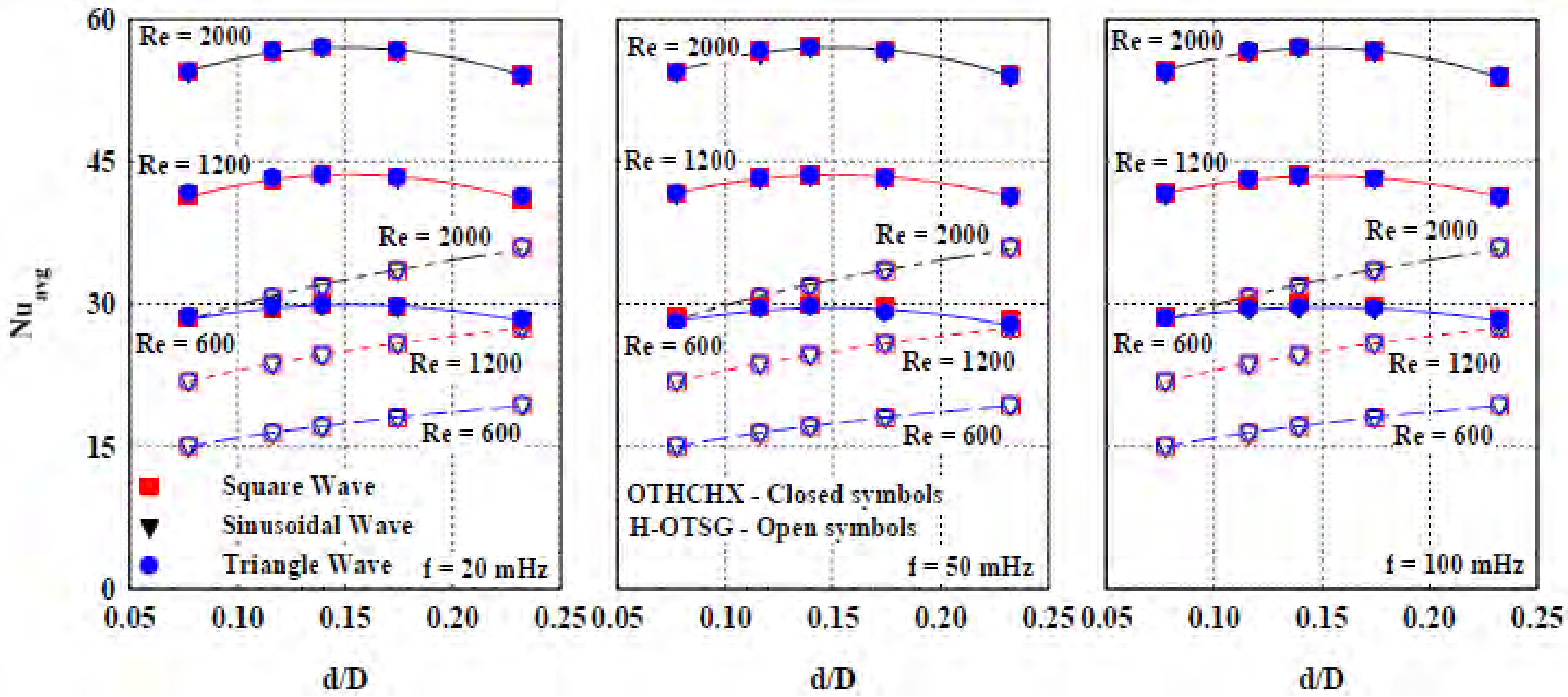
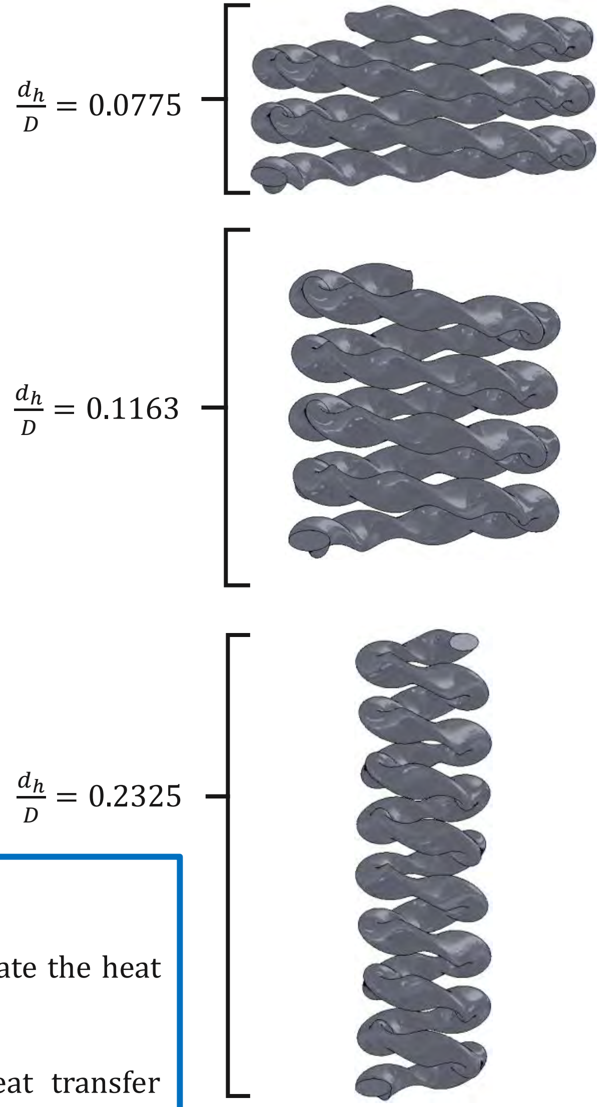
Results – Oscillating Wall Temperature





For H-OTSG, generally increasing d_h/D leads to higher Nu_{avg}. This cannot be said for OTHCHX.

For $d_h/D < 0.15$, the secondary centrifugal forces generated from the large diameter helical configuration dominate the heat transfer performance enhancement but reduces the enhancement provided by the swirling vortices.

For $d_h/D > 0.17$, the extended helical configuration allows for more swirling vortices to dominate the heat transfer performance but reduces the enhancement provided by the small diameter helical configuration (secondary centrifugal forces).

Very little Nu_{avg} enhancement is provided by oscillating wall temperatures.

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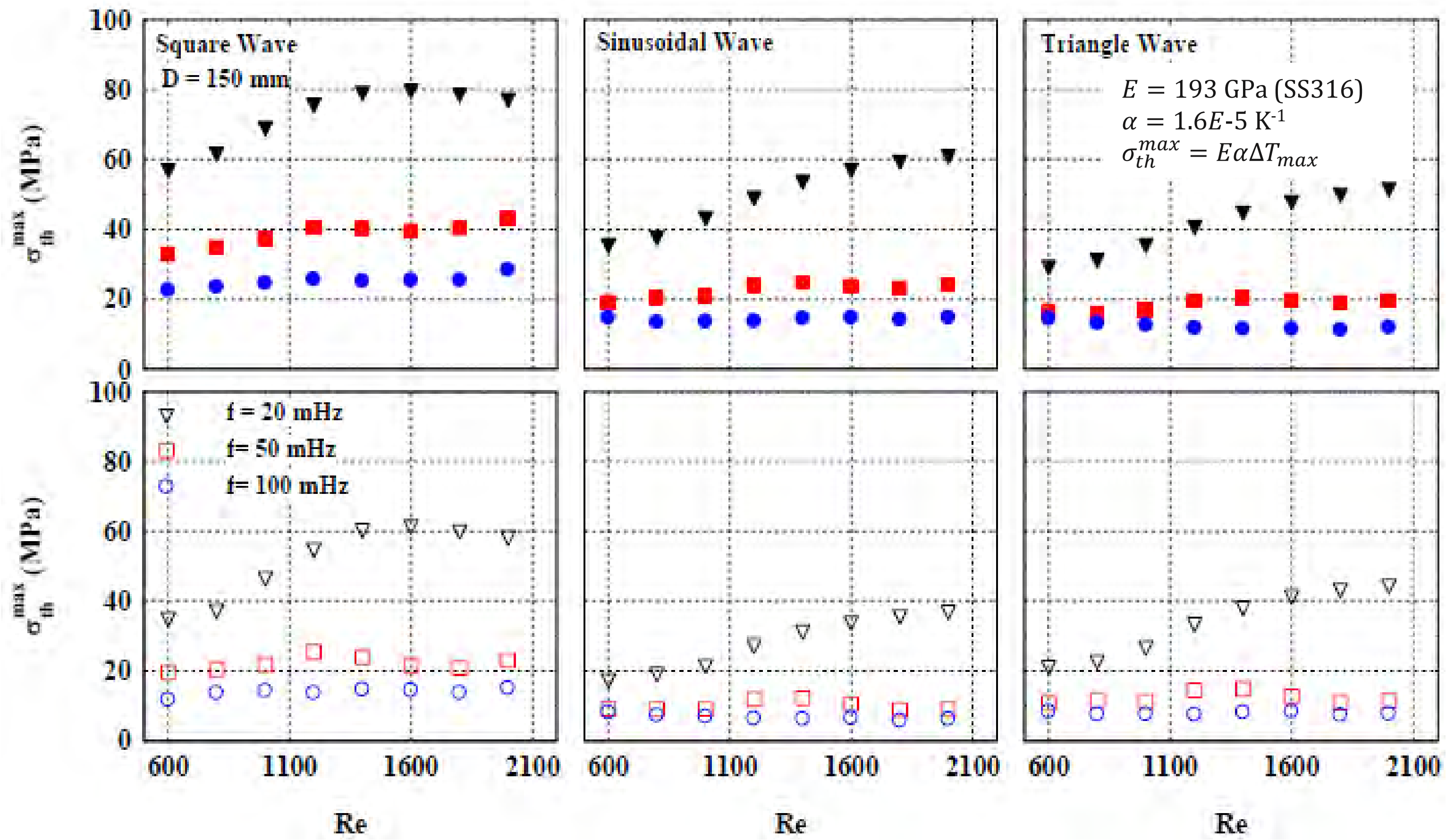
Results – Oscillating Wall Temperature



The steep temperature change in the square wave type attributes to the highest σ_{th}^{max}.

σ_{th}^{max} increases as wave frequency goes down (slower wave). At lower frequencies, the bulk fluid temperature has a more extended periodic time to heat up and cool down, which allows for higher oscillation peaks and troughs.

Comparison of σ_{th}^{max} between the H-OTSG and OTHCHX shows that the OTHCHX geometry contributes higher σ_{th}^{max}, which could indicate a potential negative trait of the OTHCHX geometry.

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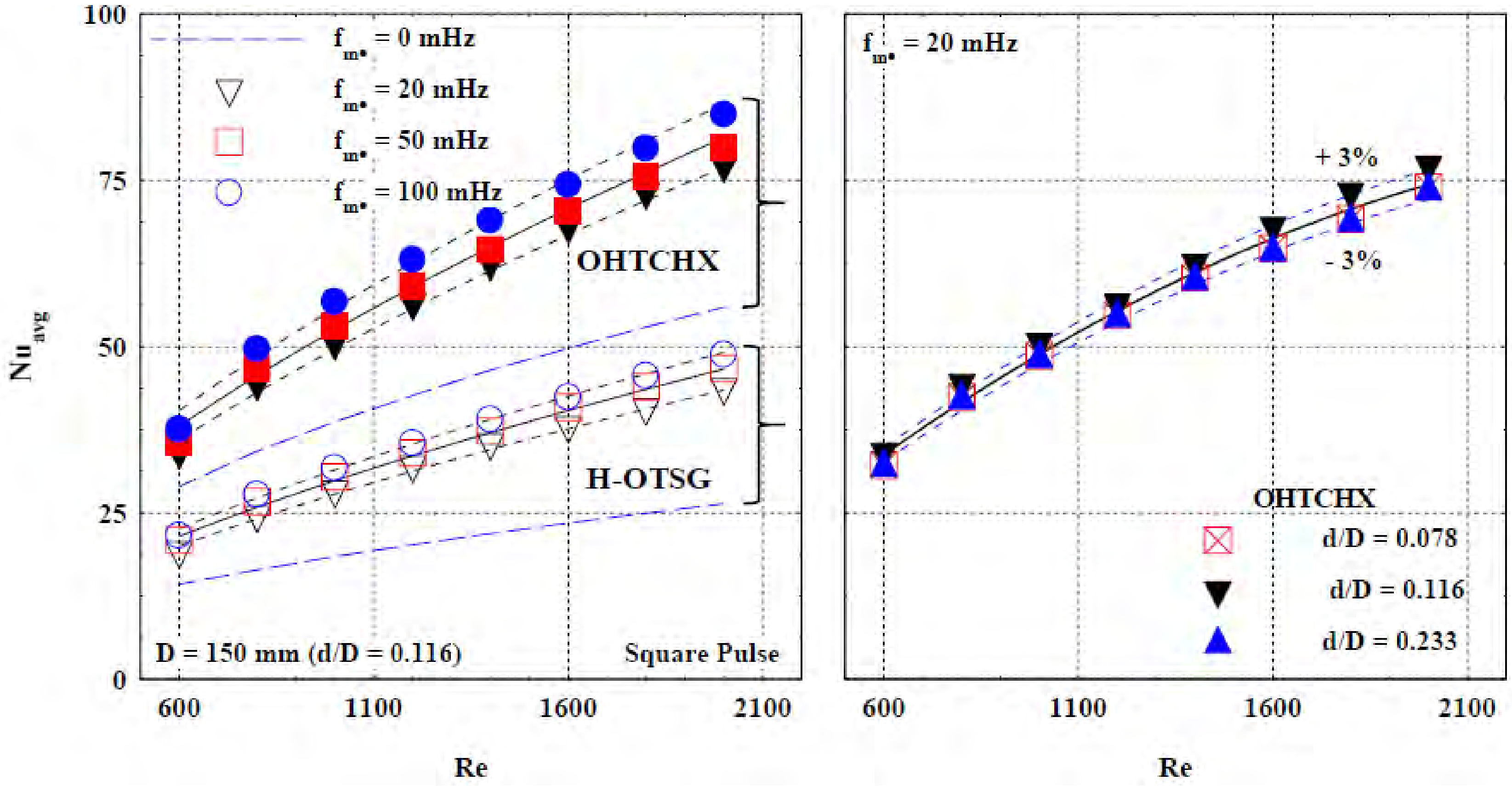
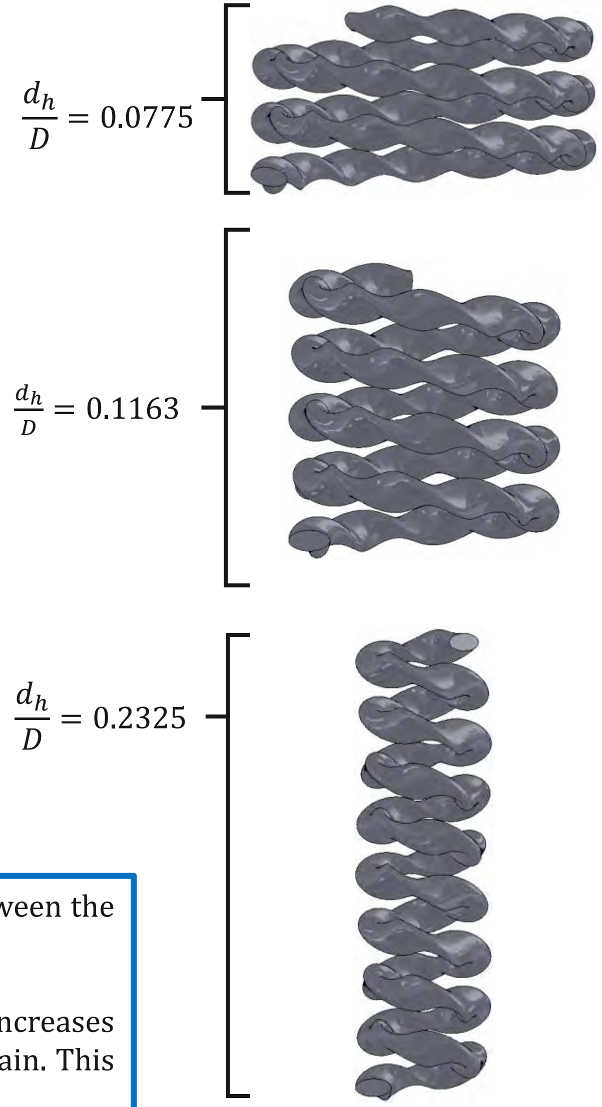
Results – Pulsating Flowrate





Pulsating flow is known disrupts the thermal boundary layer, promotes mixing, and increases the interaction between the wall and fluid.

In the absence of fluid flow in the pipe during pulsating flow conditions, the bulk fluid temperature naturally increases towards T_{wall}. Once the flow rate resumes, the fluid temperature rapidly decreases and slowly begins to climb again. This process repeats until the fluid outlet temperature oscillates between T_{wall} and a quasi-steady state T_{out} value.

The OTHCHX Nu_{avg} performed roughly 75% higher than the H-OTSG and adds roughly 45-56% increase over constant flow conditions.

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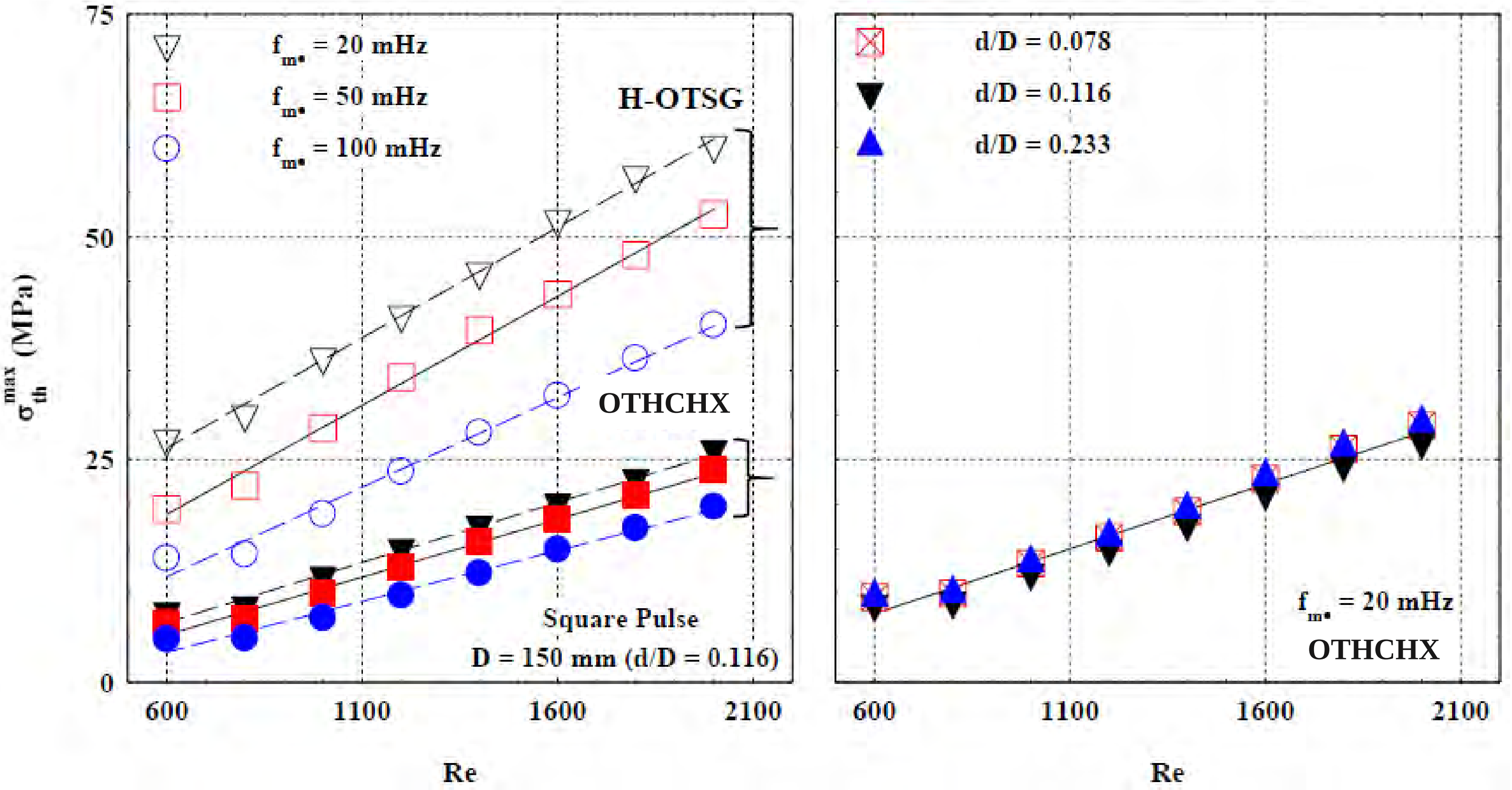
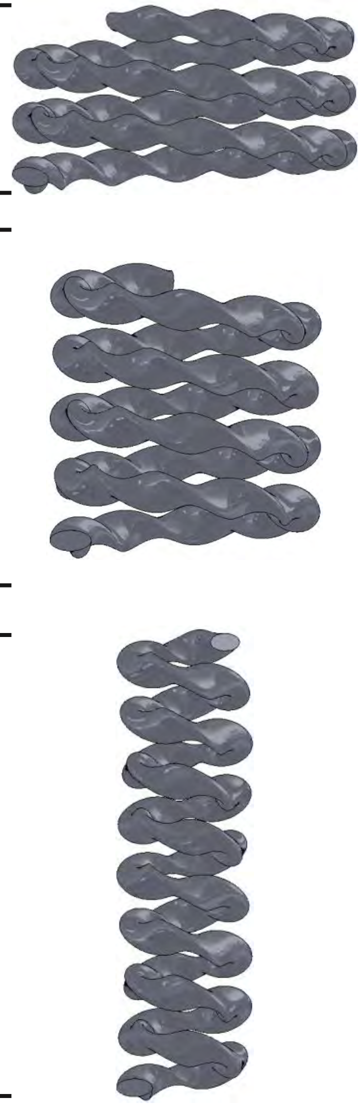
Results – Pulsating Flowrate



$\frac{d_h}{D} = 0.0775$

$\frac{d_h}{D} = 0.1163$

$\frac{d_h}{D} = 0.2325$



The OTHCHX geometry provided lower ΔT_{max} compared to the H-OTSG under pulsating flow conditions.

The increased turbulence added from the oval-twisted geometry of the OTHCHX increased the time-averaged quasi-steady state trough outlet temperature which made ΔT_{max} smaller, leading to lower σ_{th}^{max}.

d_h/D shows insignificant impact on the calculated σ_{th}^{max} for OTHCHX under pulsating flow conditions.

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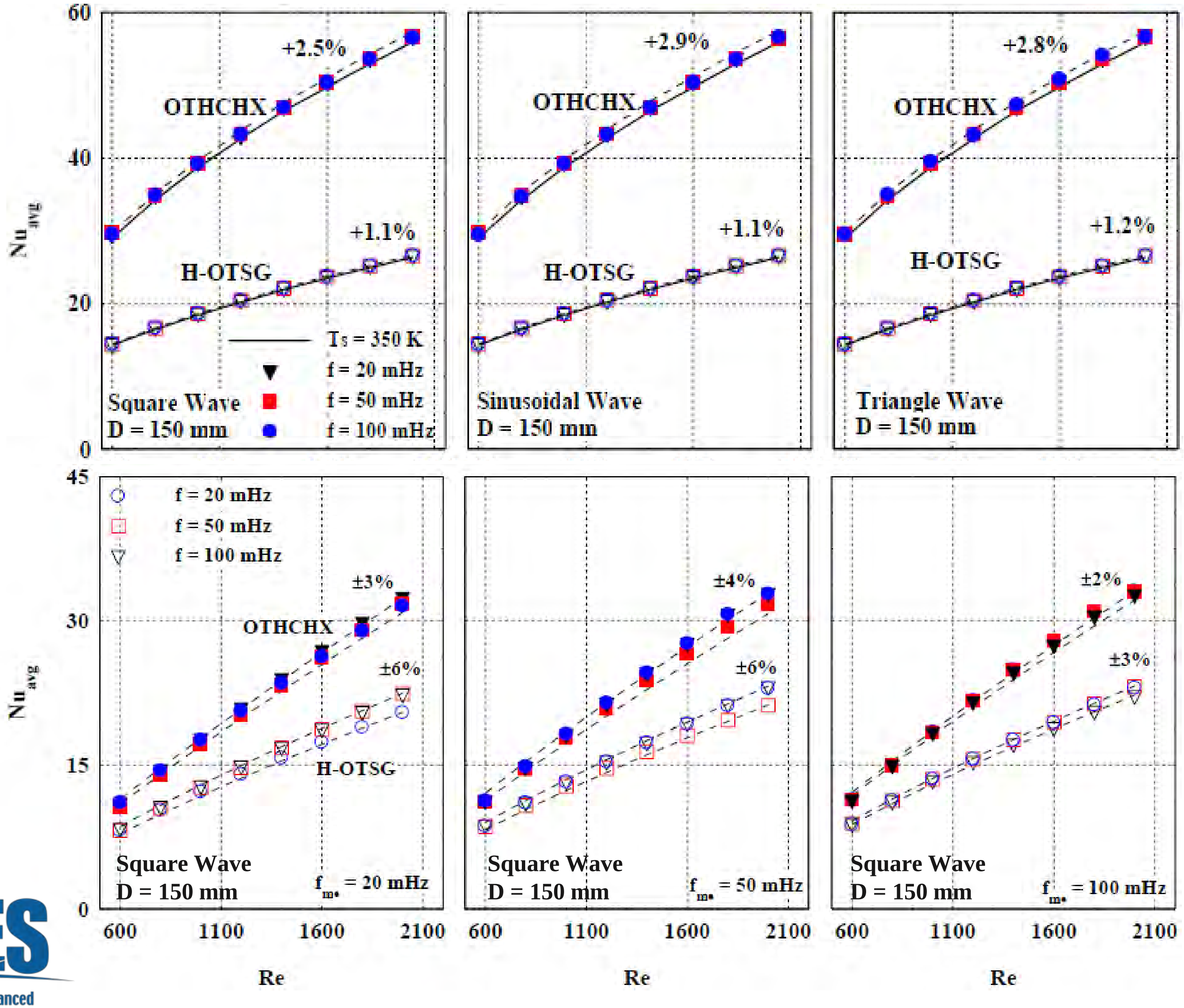
Results – Combined Effects

Fluctuating Wall Temp. Only

Combined Loading



(3) BOUNDARY CONDITIONS:
Combined conditions
(Square f and Square $f_{\dot{m}}$)

Wall Conditions:
- $T_s = 350$ K
- $f = 20, 50, 100$ mHz

Inlet Conditions:
- $T_{in} = 300$ K
- $Re = 600 - 2000$
- $f_{\dot{m}} = 20, 50, 100$ mHz

External Conditions
- Gravity present, opposing vertical flow.

Although both the fluctuating wall temperature and pulsating flow conditions separately increase Nu_{avg}, the effects of combined fluctuating wall temperature and pulsating flow conditions do not increase Nu_{avg}.

For all investigated $f_{\dot{m}}$ and f, the OTHCHX performed better than the H-OTSG under combined conditions, similar to each individual condition (fluctuating wall temperature and pulsating flowrate) being applied. However, the Nu_{avg} is lower in general compared to its constant wall temperature and constant flowrate conditions.

This indicates that the two conditions are opposing each other in the convective heat transfer enhancement.

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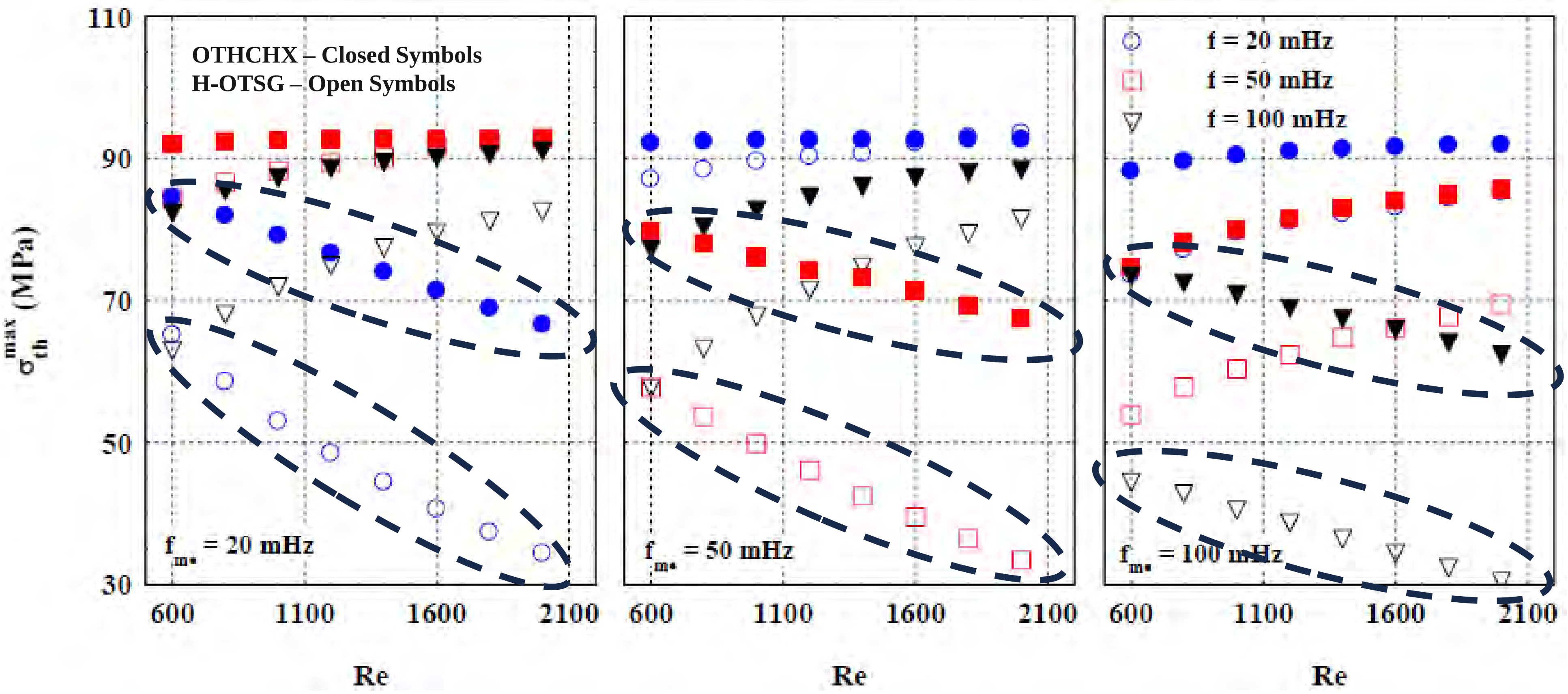
Results – Combined Effects



Under combined conditions, σ_{th}^{max} decreases when $f_{\dot{m}}$ matches f for both H-OTSG and OTHCHX, leading to a resonance behavior that decreases ΔT_{max}.

When $f_{\dot{m}}$ differs from f, σ_{th}^{max} increases with increasing Re.

The highest σ_{th}^{max} observed for a given boundary condition was around 93 MPa and is deemed to be the highest obtainable σ_{th}^{max} for the given boundary conditions.

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Conclusions and Future Work

Conclusions:

	f_{in} (mHz)	f (mHz)	OTHCHX		H-OTSG	
			Nu_{avg}	σ_{th}^{max} (MPa)	Nu_{avg}	σ_{th}^{max} (MPa)
Pulsating Flowrate	20-100	0 ($T_s = 350$ K)	77.1-84.9	19.7-26.1	43.1-48.8	40.1-60.1
Fluctuating Wall Temp.	0	20-100	56.5-56.7	28.4-77.5	26.4-26.6	15.1-59
Combined	20-100	20-100	31.5-33.2	66.6-92.7	20.4-23.1	30.7-93.6

Future Work:

- The presented work is a preliminary study/exercise under mock conditions to assess idealized dynamic boundary conditions for the H-OTSG and novel OTHCHX geometries.
- Further numerical analyses are to be conducted to investigate higher dynamic temperatures closer to primary/secondary loop temperatures of standard LWR systems for the H-OTSG and OTHCHX. The following are also future analyses:
    - Single-phase turbulent flow regime comparison between CFD and RELAP5-3D under dynamic conditions for H-OTSG and OTHCHX.
    - Two-phase flow CFD and RELAP5-3D comparison for H-OTSG and OTHCHX.
    - Single-phase & two-phase experiment testing with thermal stress fiber optic sensors using ISU/CAES IHX Test Facility.

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Thanks!
Any Questions?

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