Supercritical CO_2 Power Cycle Symposium, Pittsburgh, USA, 2014

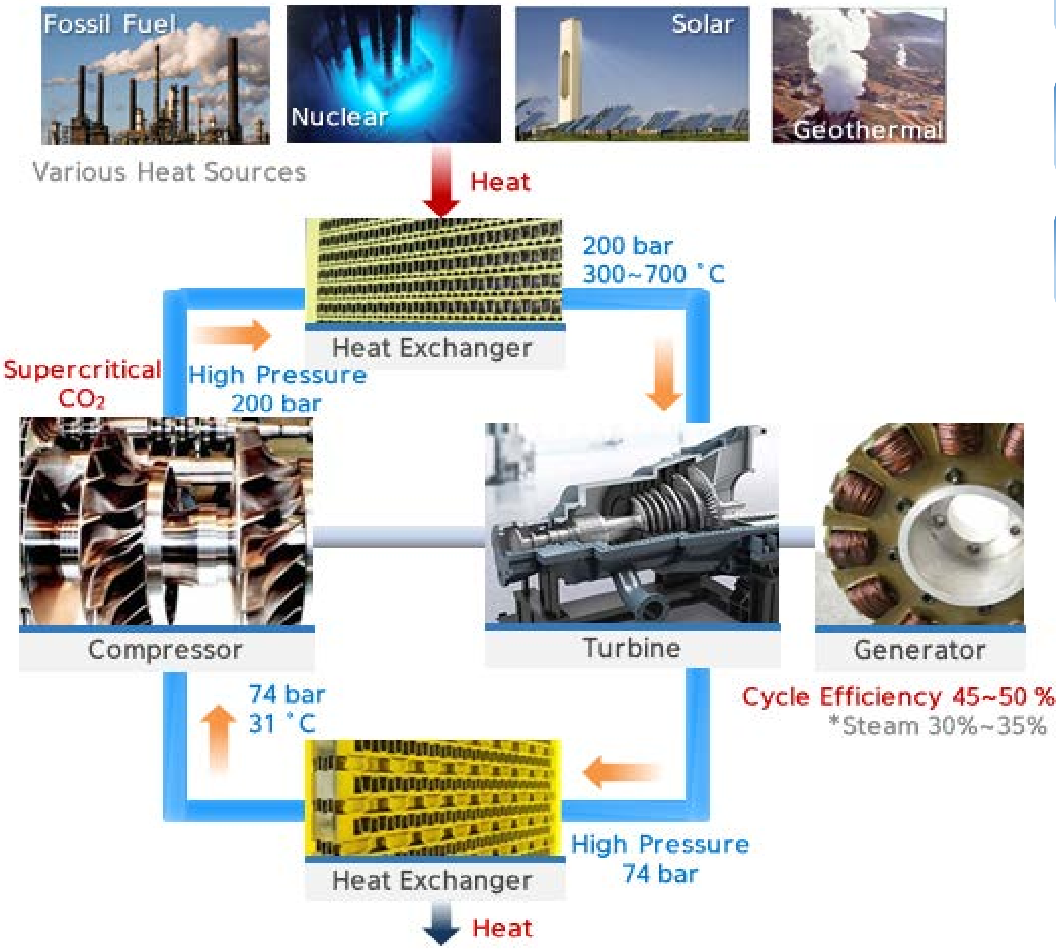
Numerical Analysis of a Fin Arrangement for an Optimal Design of Airfoil Fin PCHE

Jin Gyu Kwon, Tae Ho Kim, Hyun Sun Park**, Moo Hwan Kim

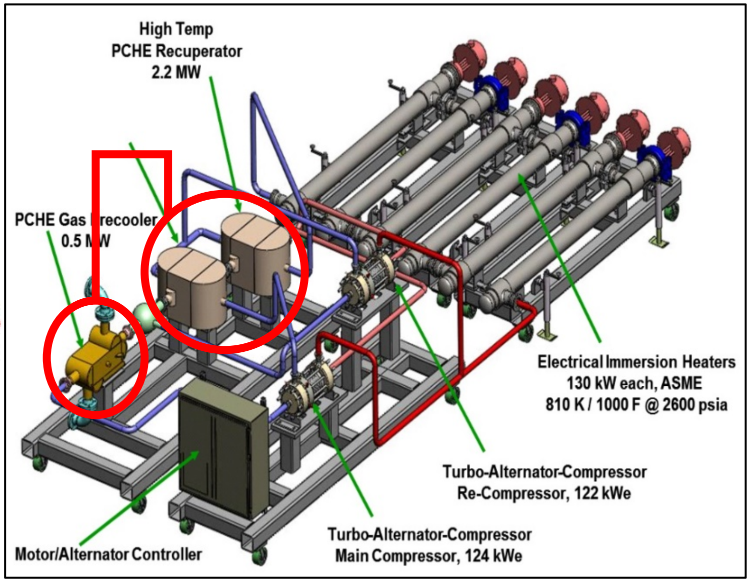
Division of Advanced Nuclear Engineering
POSTECH, KOREA

Contents

S-CO_2 Brayton Cycle



- Low compressible work
- High heat capacity
- High heat transfer



Supercritical **C**arbon dioxide **I**ntegral **E**xperimental **L**oop (2012~2015)

The SCIEL Facility in Korea (Compressor test loop)

Goal: 100 kWe (20 MPa - 500°C)

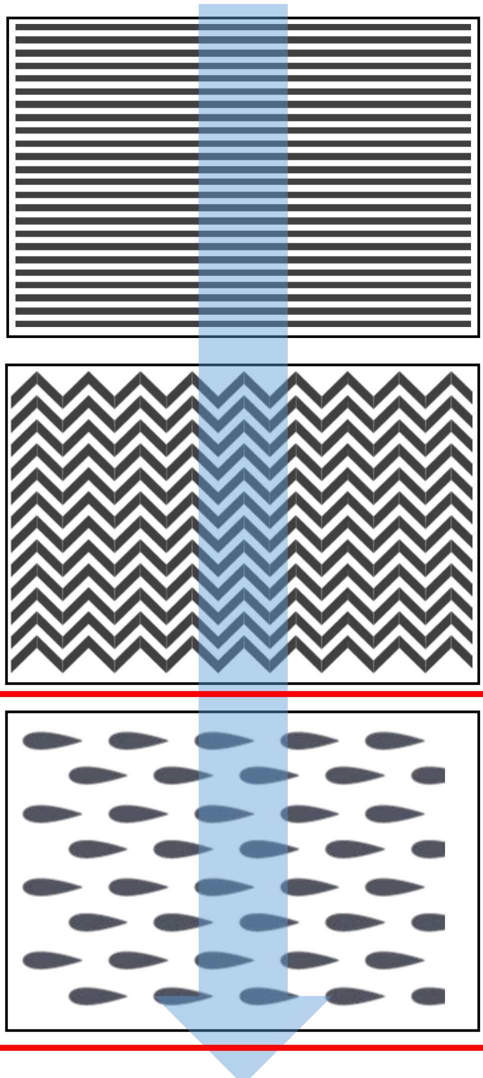
I. Development of Cycle construction & Operation Techniques(KAERI)

II. Verification of Turbine & Compressor Performance Verification (KAIST)

III. Development of Compact Heat Exchanger (POSTECH)

Collaborated work with KAERI, KAIST and POSTECH sponsored by NRF

Research Objectives



Low heat transfer

Low pressure loss

High heat transfer

High pressure loss

⇒ Many optimization researches have been reported.

High heat transfer

Low pressure loss

Optimization of fin configuration with cost analysis

SCO2 Research in POSTECH

Kim, D.E., et al. (2008)
- ✓ 3D numerical study about zigzag bending angle (4 cases)
- ✓ 3D numerical study about comparing zigzag and airfoil shape PCHE

Kim, D.E., et al. (2008, 2010)
- ✓ 3D numerical study about comparing zigzag and airfoil PCHE
- ✓ An Experimental study about comparing zigzag and airfoil PCHE

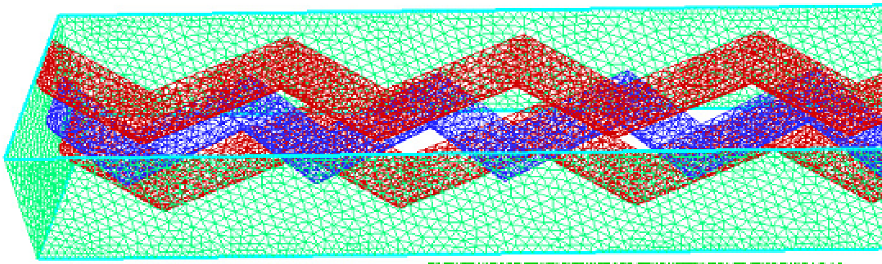
Choi, B.I, et al. (2010)
- ✓ Airfoil shape

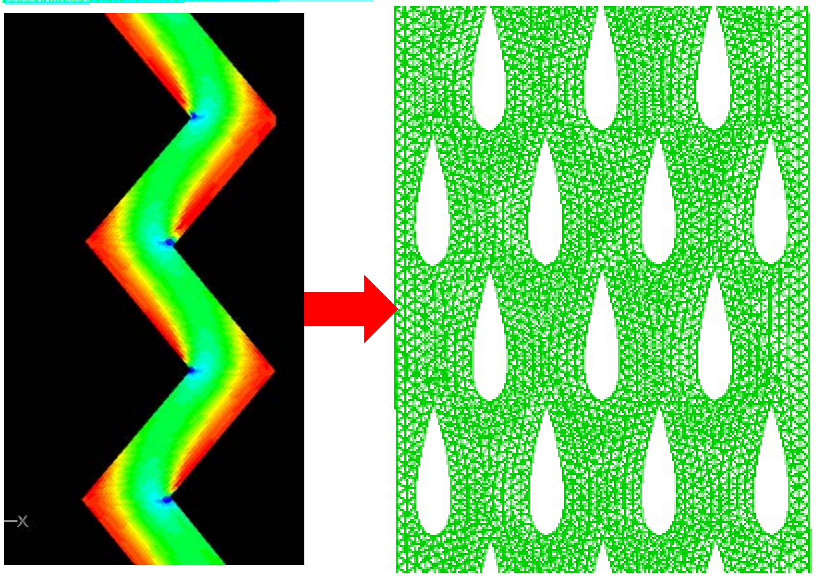
Kim, J.E, et al. (2012), Kim H. S. (2014~)
- ✓ Na – SCO2 HEX and SC Interaction

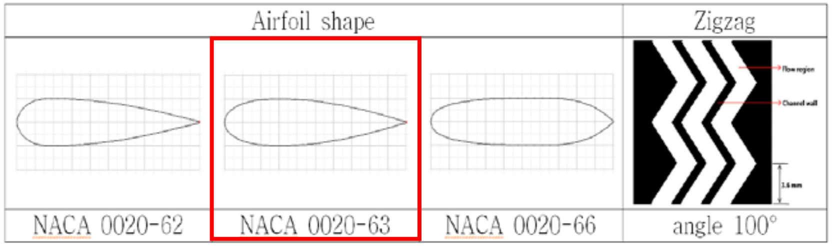
Yoon, S.H, et al. (2013)
- ✓ Fin array optimization

Kim, T.H, et al. (2013~)
- ✓ SCO2 HEX Experiments

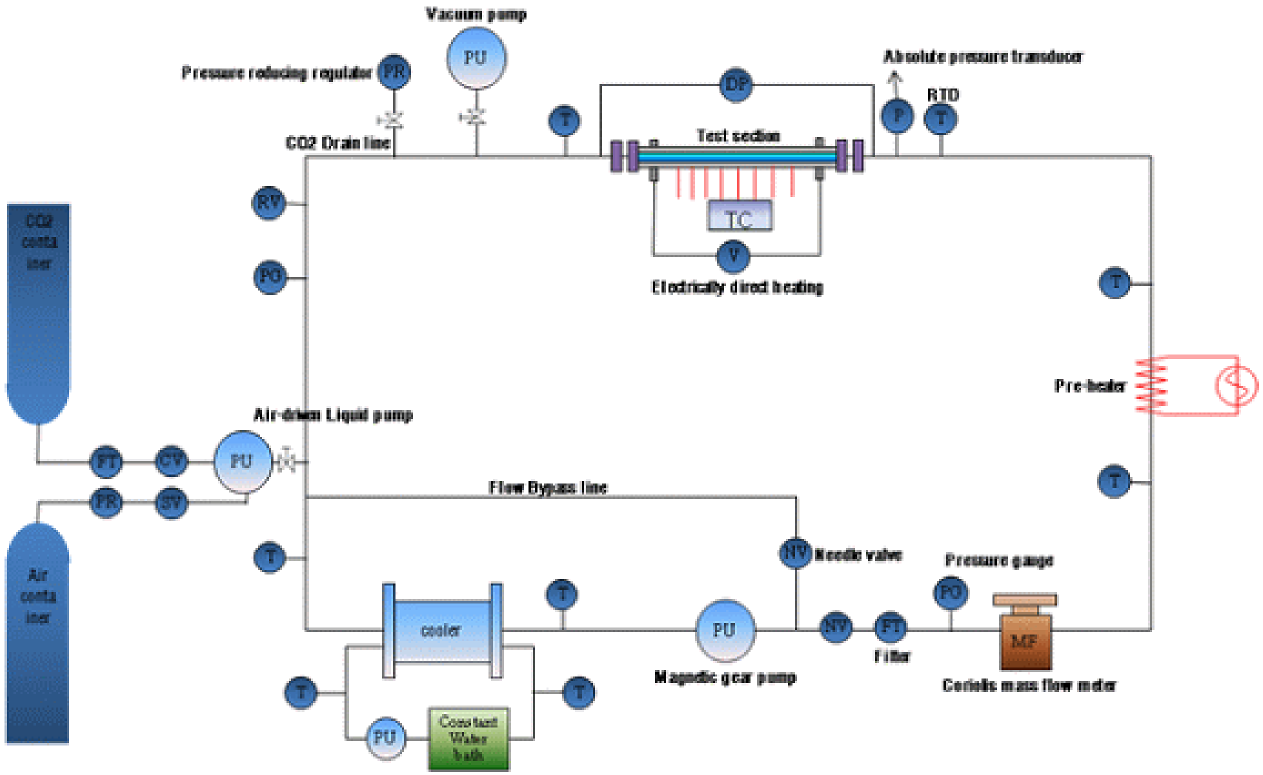
Kwon, J.G, et al. (2014~)
- ✓ CFD analysis for optimized design





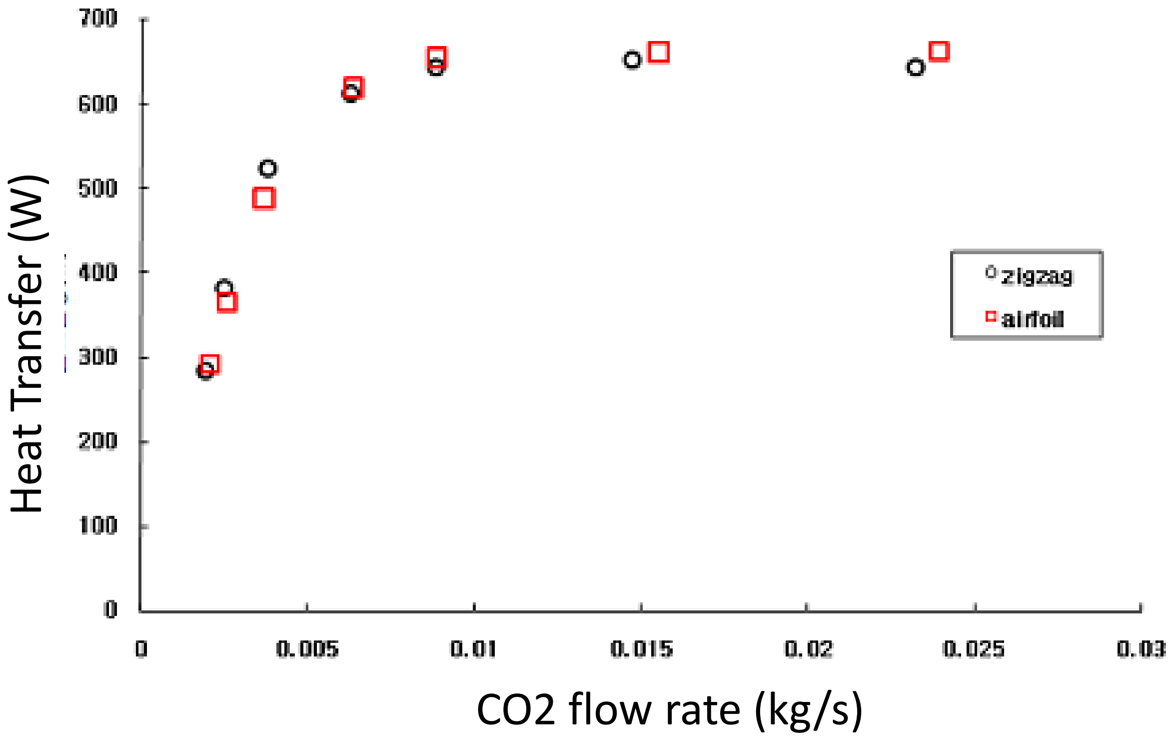


Experimental validation of Proposed Airfoil Shape Fin Model (1/4)



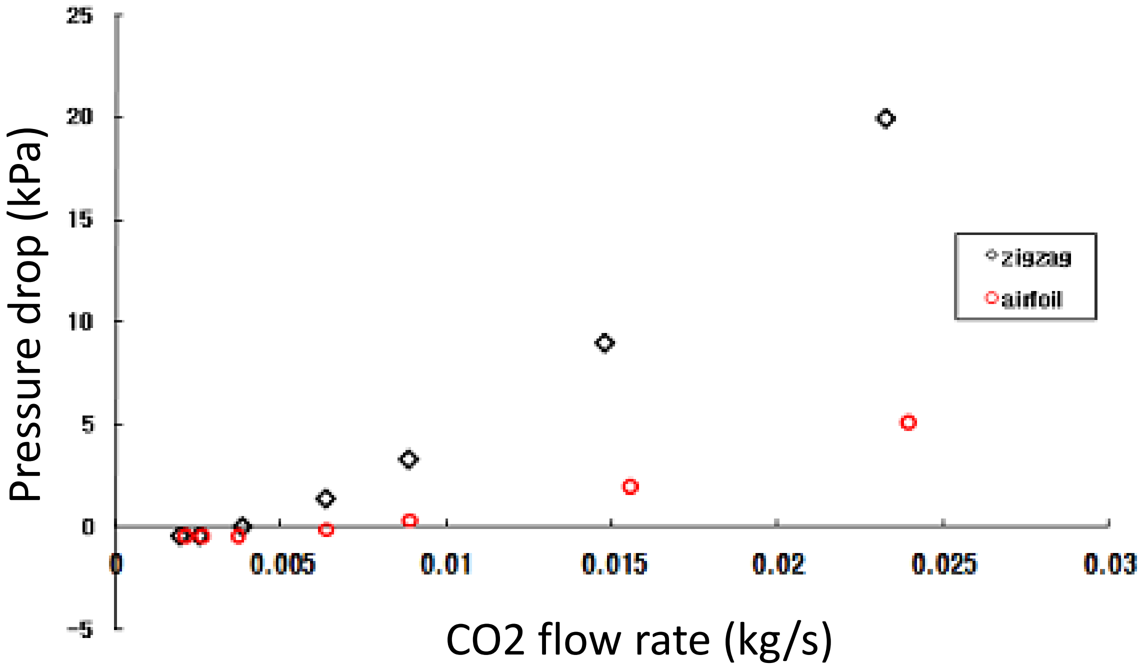
Experimental validation of Proposed Airfoil Shape Fin Model (2/4)

→ **Total Heat Transfer Rate with respect to the CO2 Flow Rate**



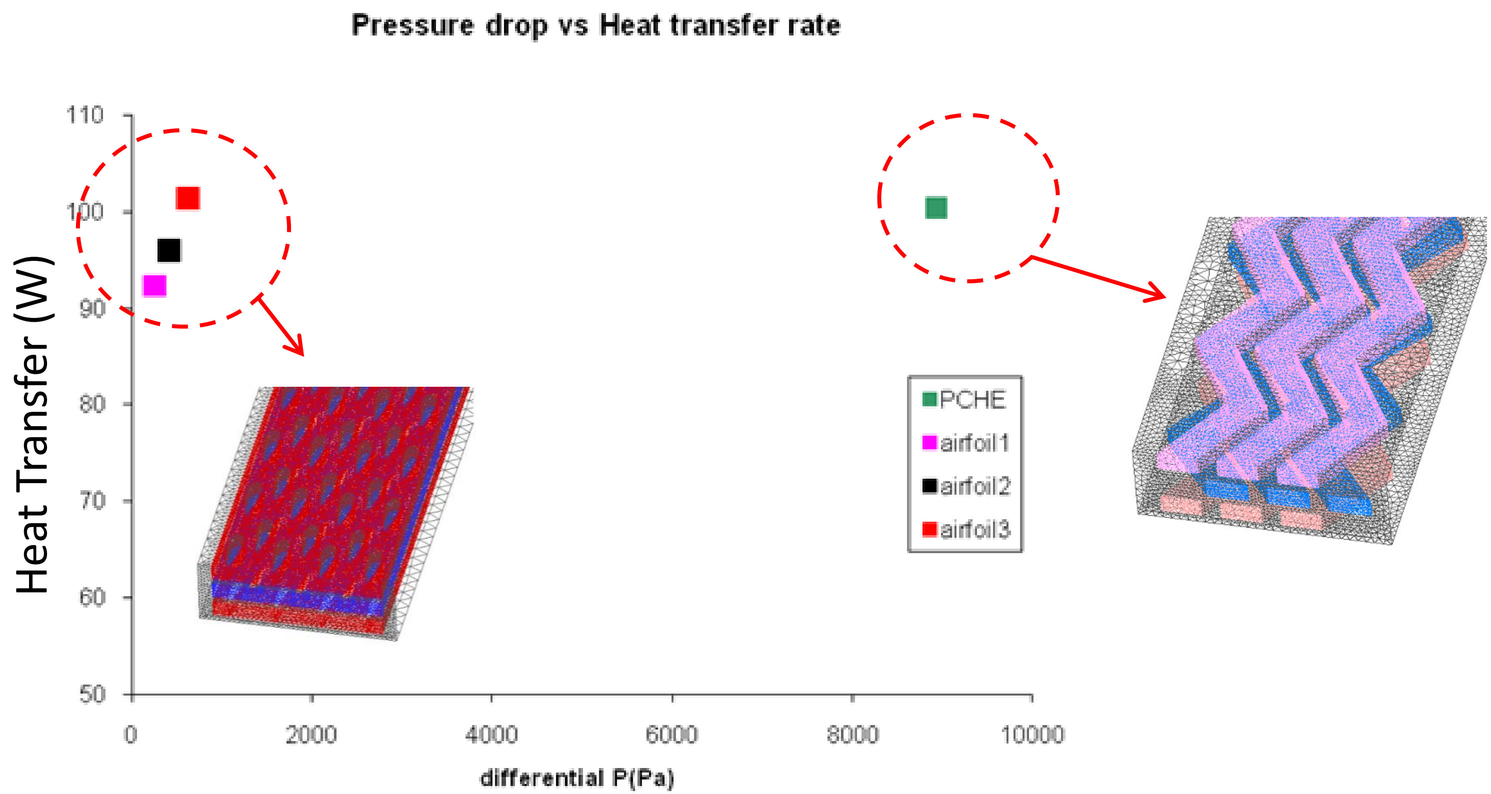
Experimental validation of Proposed Airfoil Shape Fin Model (3/4)

→ **Total Pressure Drop with respect to the CO_2 Flow Rate**

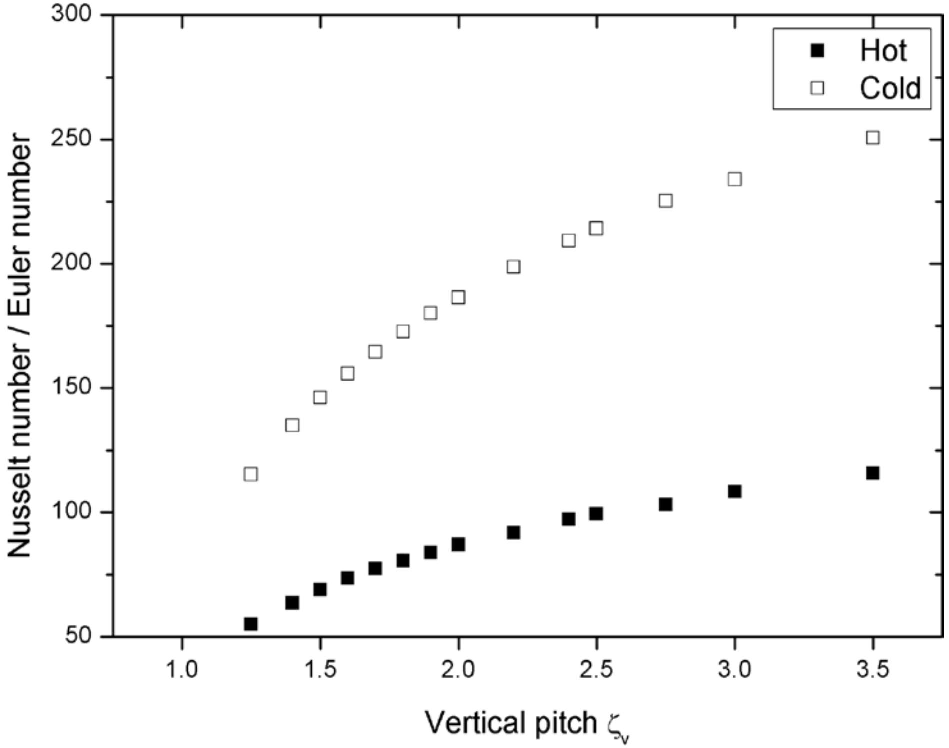


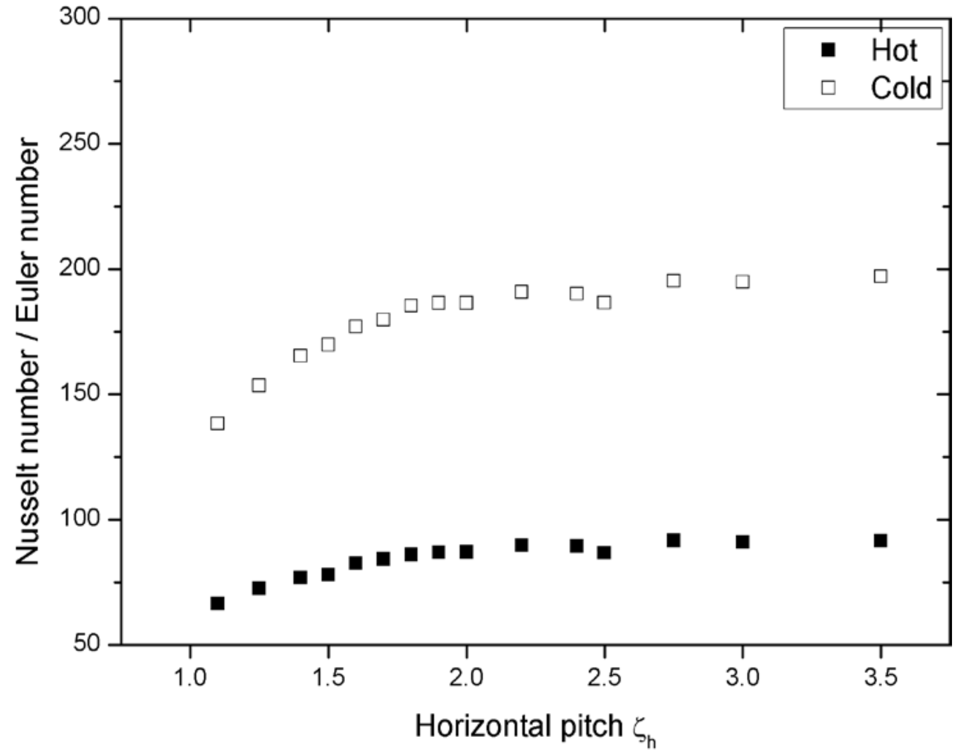
Experimental validation of Proposed Airfoil Shape Fin Model (4/4)

→ **At the same heat transfer performance, airfoil ΔP < 1/14 of Zigzag, 1/6 of S-shape**



Airfoil type PCHE Optimization





These result shows the unlimited increase of the objective function Nu/Eu.
We should select other objective function or reasonable restriction.

[1] Park, H.-S et al., 2014, "Development of Heat Exchanger Miniaturizing Technology for the Supercritical Gas Brayton Cycle." NRF: 4; 2014 International Heat Transfer Conference, Kyoto, Japan

Previous Optimization

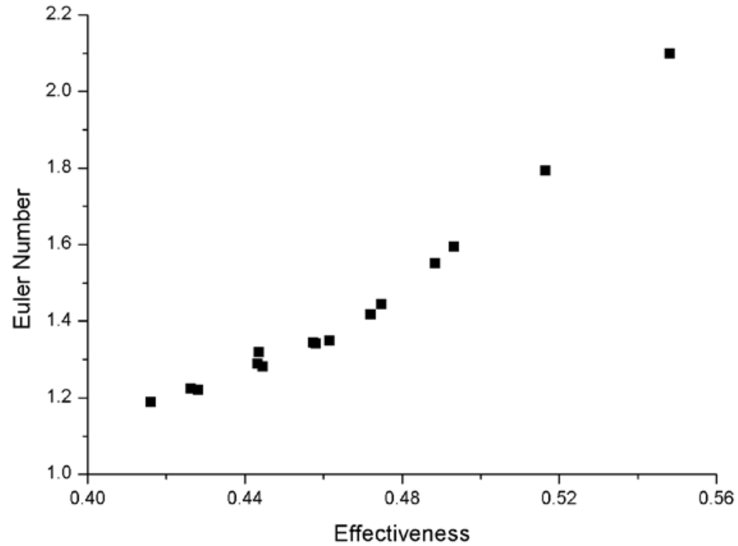
Effectiveness

Euler Number

Factors to find optimized point

Method

Pareto optimal front[2]



Problem: the consideration of the weights to each factors

Adequate objective function[3]

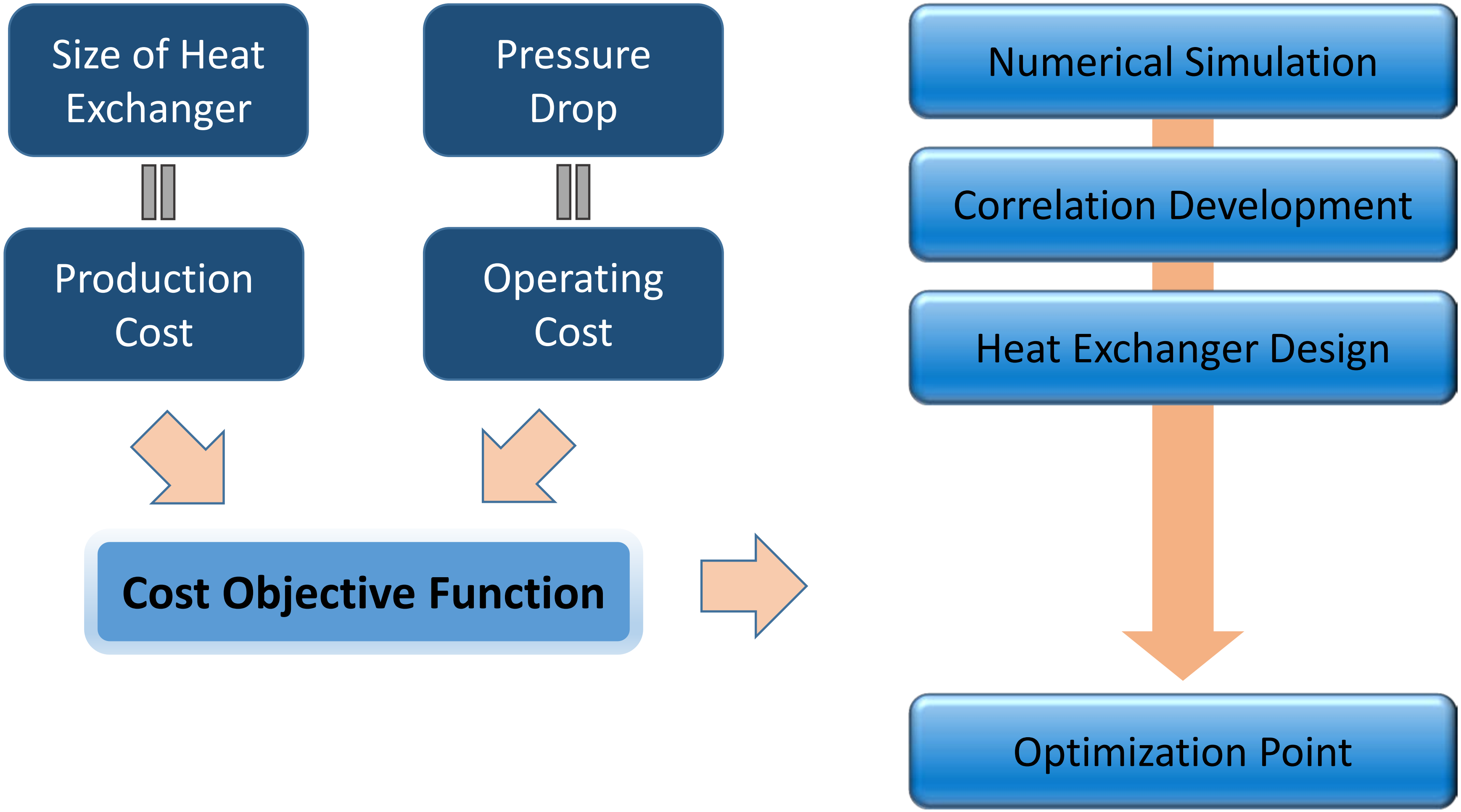
$$f_{objective} = 1/effectiveness + 0.09Eu$$

Problem: the lack of physical rationale of the weights to each factors

Other methodology is required to optimization of the airfoil type PCHE.

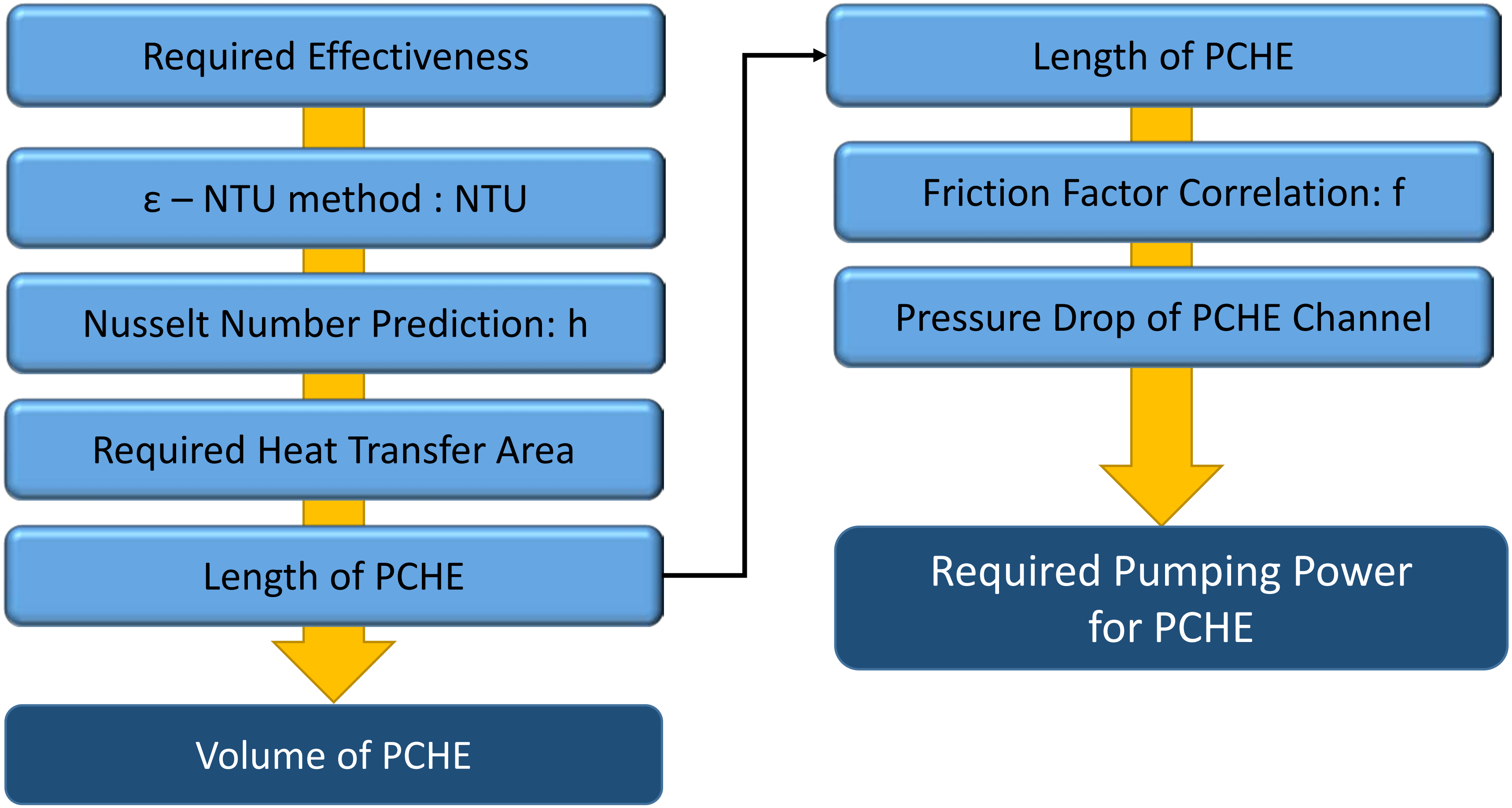
[2] Lee, S.-M., K.-Y. Kim, 2012, “Shape Optimization of a Printed-circuit heat exchanger to enhance thermal-hydraulic performance.” ICAPP, Chicago, USA.
[3] Lee, S.-M., K.-Y. Kim, 2012, "Optimization of zigzag flow channels of a printed circuit heat exchanger for nuclear power plant application.", Journal of Nuclear Science and Technology 49(3): 343-351.

Selected Methodology



[4] Kim, I.-H., No, H.-C., 2012, "Physical model development and optimal design of PCHE for intermediate heat exchangers in HTGRs." Nuclear Engineering and Design 243: 243-250.

Heat Exchanger Design



Size of PCHE and energy loss could be calculated from Heat Exchanger Design Process.

[4] Kim, I.-H., No, H.-C., 2012, "Physical model development and optimal design of PCHE for intermediate heat exchangers in HTGRs." Nuclear Engineering and Design 243: 243-250.

Cost Analysis

Production Cost	Operating Cost
Size of heat exchanger	Required power for the recuperator from pressure drop
Production cost: 1.072$/cm^3 Corhex Coroperation	Cost of Electricity: 0.04$/kWh Production cost of the Korean NPP

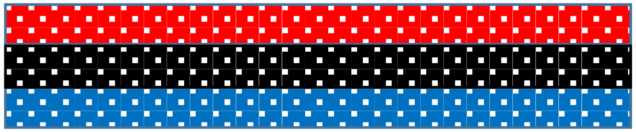
Standardize the value of each costs to finished time of power system with
The interest rate of 3,82% for the 5-year averaged value of the Korea bank

Total Cost

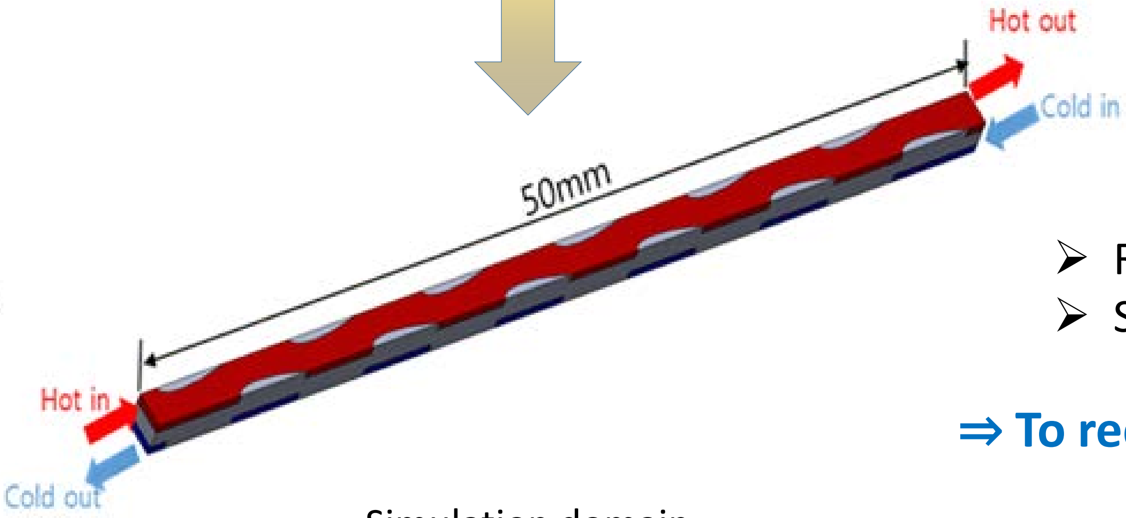
[4] Kim, I.-H., No, H.-C., 2012, "Physical model development and optimal design of PCHE for intermediate heat exchangers in HTGRs." Nuclear Engineering and Design 243: 243-250.

Actual PCHE geometry[5]

⇒ **Heavy computational cost!**



<Single banking type>



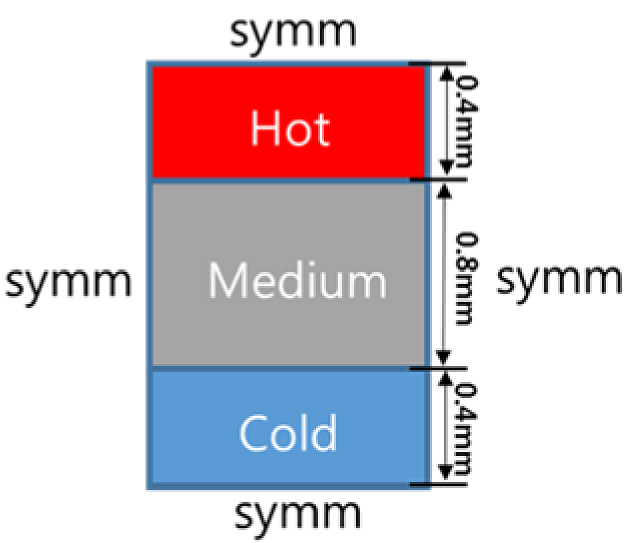
Simulation domain

- Representative length of 50 mm
- Single unit channel

⇒ **To reduce the computational cost!**

[5] Corhex Incorporation product

CFD Simulation Conditions



Wall boundary condition

SCIEL operation condition
(designed for high temperature recuperator)

Conditions	Hot channel	Cold channel
Inlet temperature, °C	451.3	216.1
Inlet pressure, MPa	7.8	19.8
Mass flux, kg /m^2s	937.5	937.5

- Continuity equation
- Momentum equation
- Energy equation

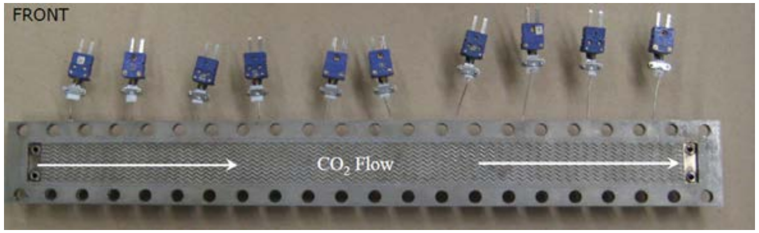
\+

- ANSYS CFX
- About 2 million tetrahedral mesh
- NIST chemistry CO_2 properties
- k-ε turbulence model*
- Standard wall function

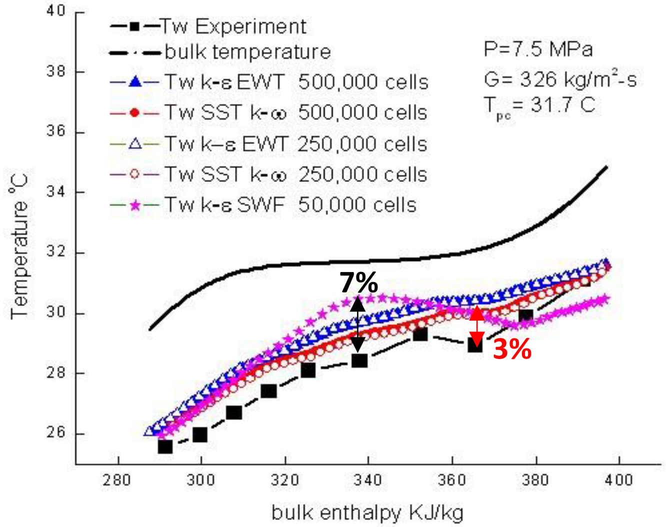
⇒ The SIMPLE algorithm
(Semi-Implicit Method for Pressure Linked Equations)

Turbulence Model Validation

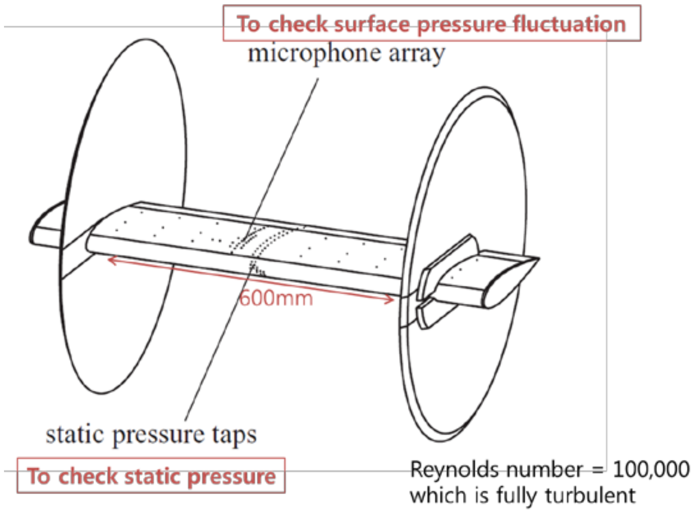
UWM S-CO_2 PCHE test

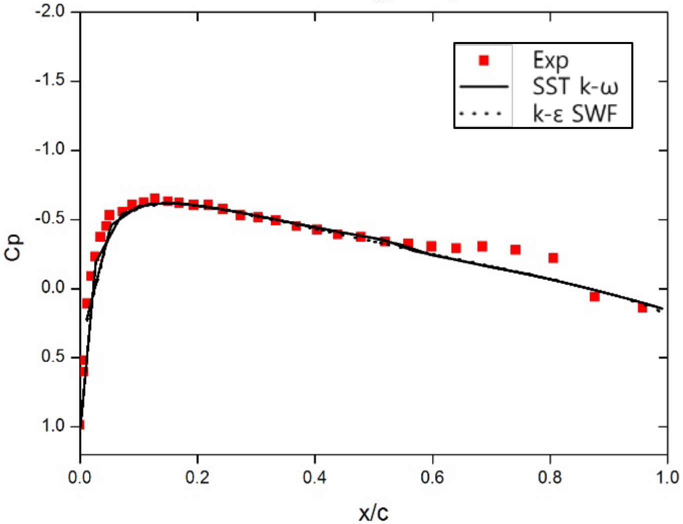


[6] A. Kruizenga et al., 2012

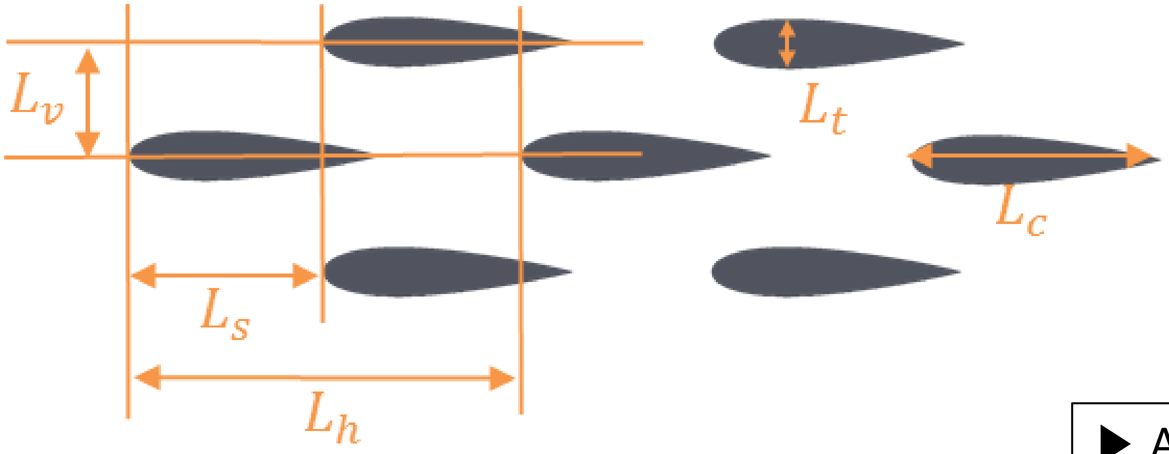


NACA0020 wind tunnel experiment





[7] Michael S. H. Boutilier and Serhiy Yarusevych "Separated shear layer transition over an airfoil at a low Reynolds number, Physics of Fluids, Vol.No.24, 2012, pp. 084105.1-23



L_v: Vertical pitch
L_h: Horizontal pitch
L_s: Staggered pitch
L_t: Thickness
L_c: Chord length

▶ Airfoil fin shape
NACA0020 (Choi, 2010)
L_t = 0.8 mm
L_c = 4 mm

Dimensionless

$$\zeta_s = 2L_s / L_h$$

$$\zeta_h = L_h / L_c$$

$$\zeta_v = L_v / L_t$$

→ **Fin Configuration**

Correlation Development - Factors

	Heat Transfer	Pressure Drop
Name	Nusslet number	Fanning friction factor
Definition	$Nu = \frac{h}{k/D_h} = \frac{q''D_h}{k(T_w - T_m)}$	$f = \frac{\tau_w}{\rho u_m^2}$
Physical Meaning	Ratio of convection heat transfer to conduction heat transfer	Ratio of wall shear stress to the flow kinetic energy per unit volume
Traditional Equation	Dittus-Boelter Equation $Nu = 0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^n$	Blasius Equation $f = 0.079\,\mathrm{Re}^{-0.25}$

Modified Equation with correction factor

- Nusselt number

$$Nu = a\,\mathrm{Re}^{b}\,\mathrm{Pr}^{c}\,\zeta_v^{d}\,\zeta_h^{e}$$

- Fanning friction factor

$$f_{total} = f_{surface} + f_{airfoil} = a\,\mathrm{Re}^{b} + c\,\mathrm{Re}^{d}\,\zeta_v^{e}\,\zeta_h^{f}$$

(a,b,c,e,d,f = arbitrary constant)

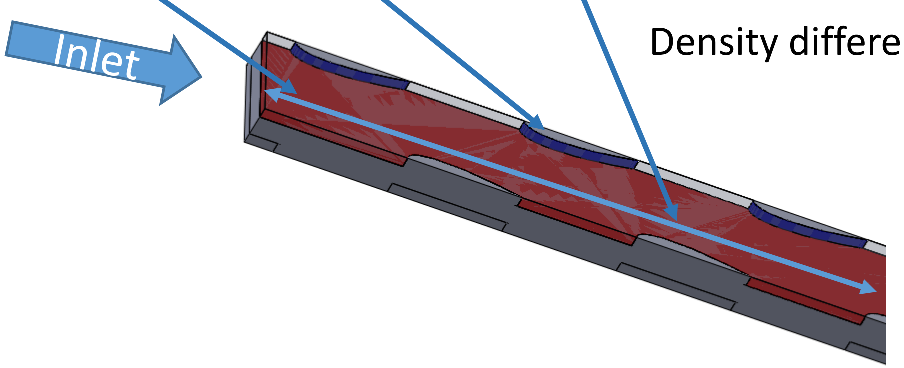
	CFD SCOPE	#
Mass Flux	312.5kg /m²s – 2187.5kg /m²s	5
Vertical Pitch	1.25 - 3.5	14
Horizontal Pitch	1.1 - 3.5	15

Boundaries of Regression Analysis

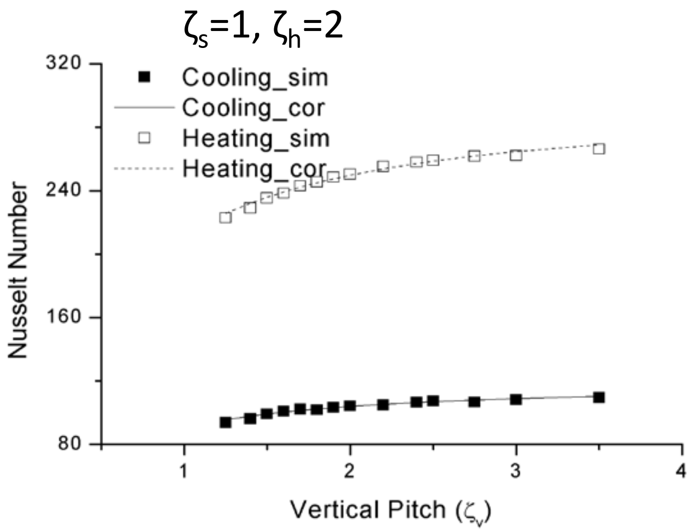
Separated Pressure drop with its reason

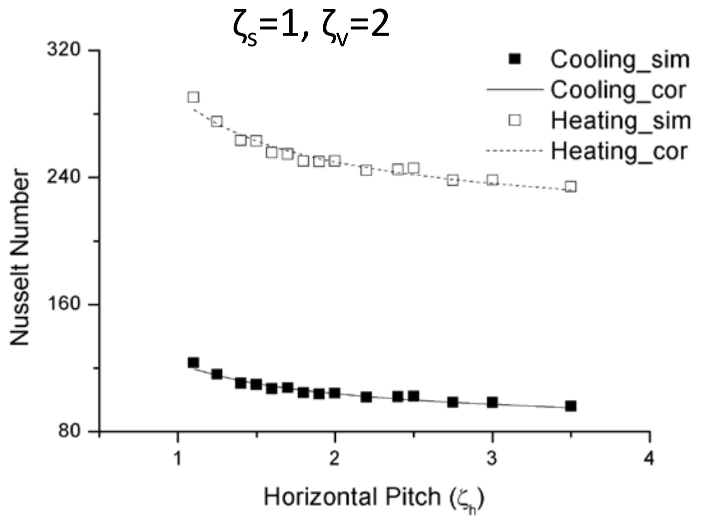
$$\Delta P_{Total} = \Delta P_{surface\_friction} + \Delta P_{airfoil} + \Delta P_{acceleration}$$

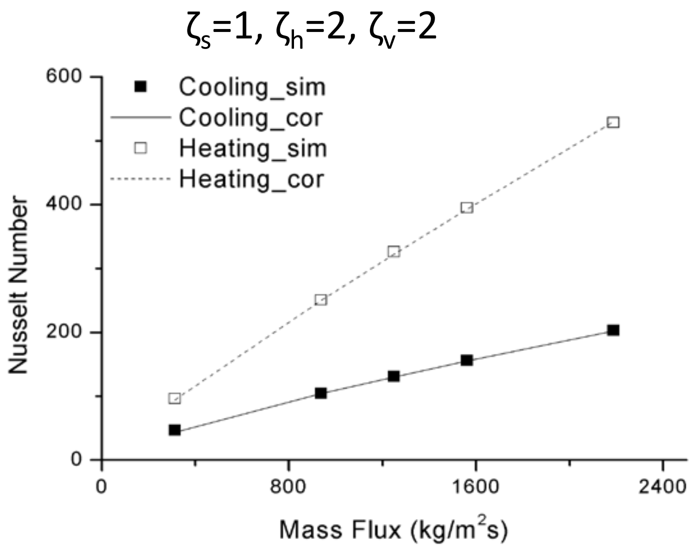
Density difference between inlet and outlet



Results – Heat Transfer





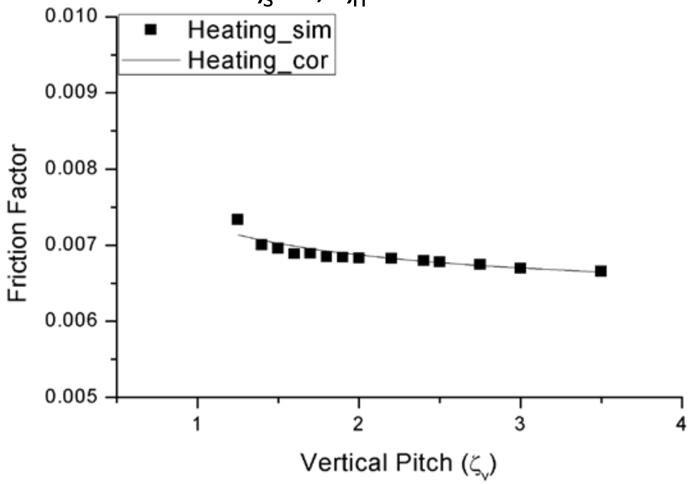


Nusselt number almost linearly increases with the increase of the mass flux.

Correlation results are matched well to simulation results with the maximum 6% error.

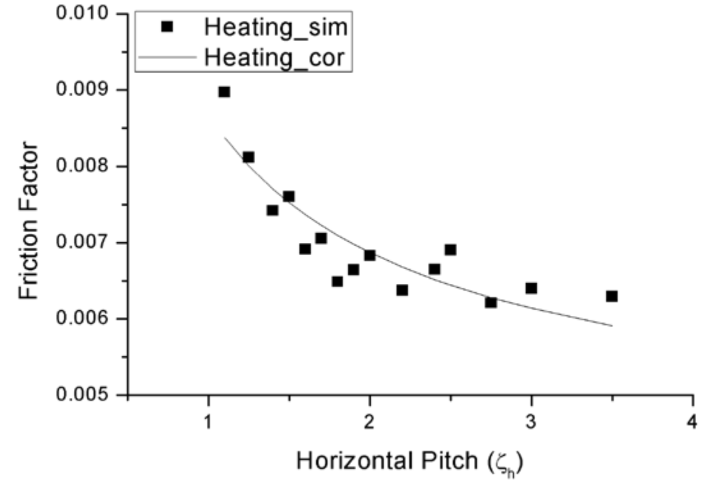
Results – Pressure Drop

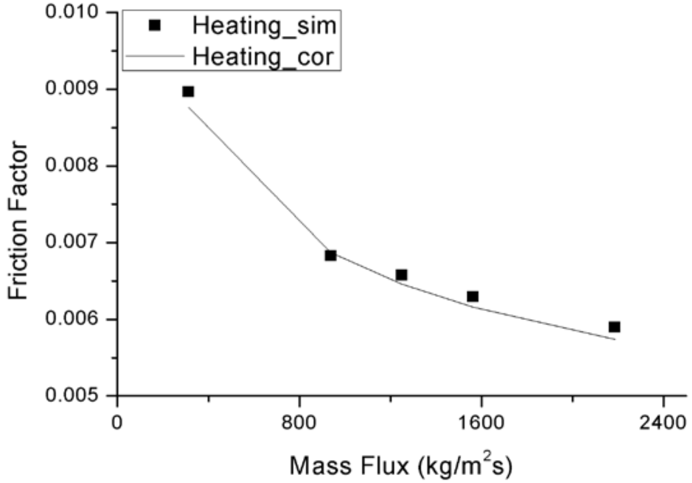
ζ_s=1, ζ_h=2



ζ_s=1, ζ_h=2, ζ_v=2

ζ_s=1, ζ_v=2





Friction factor shows inverse proportional relationship of the mass flux.

Correlation results are matched well to simulation results with the maximum 10% error.

Regression Analysis: Modified Equations

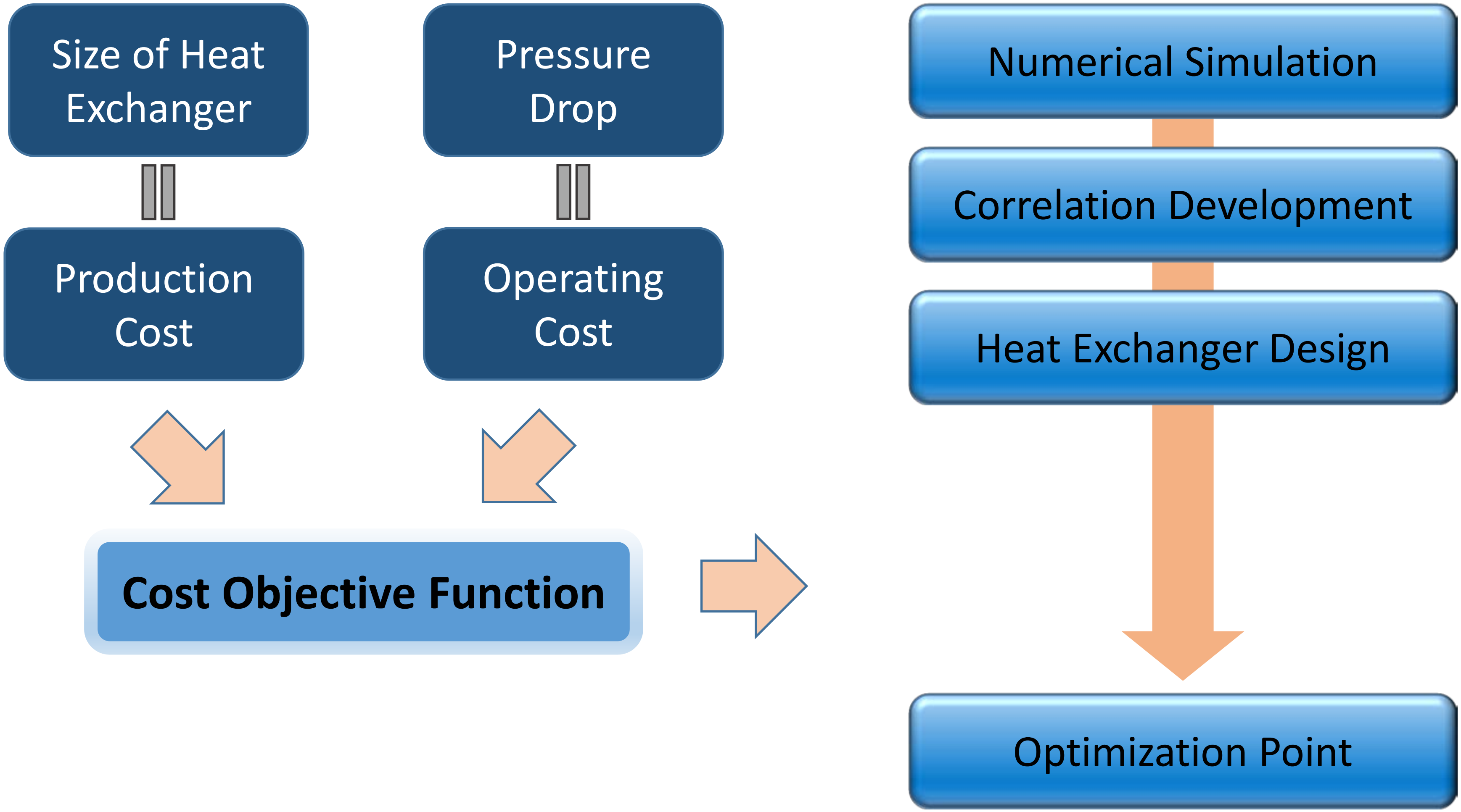
$$Nu = a\,\mathrm{Re}^{b}\,\mathrm{Pr}^{c}\,\zeta_{v}^{d}\,\zeta_{h}^{e}\,(a, b, \mathrm{c}, \mathrm{d}, \mathrm{e} = \mathrm{constant})$$

Mode	a	b	c	d	e	R^2	Average Error	Maximum Error
Cooling mode	0.0314	0.794	0.3	-0.0509	-0.0846	0.996	0.09%	5.72%
Heating mode	0.0113	0.889	0.4	-0.0488	-0.0492	0.998	0.02%	2.63%

$$f_{total} = f_{surface} + f_{airfoil} = a\,\mathrm{Re}^{b} + c\,\mathrm{Re}^{d}\,\zeta_{v}^{e}\,\zeta_{h}^{f}$$

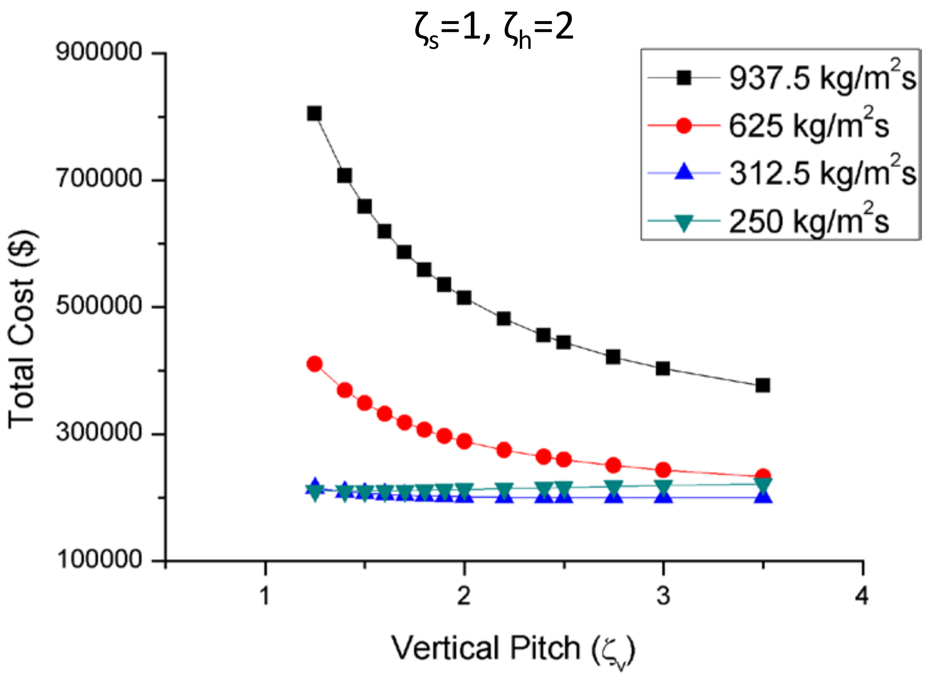
Mode	a	B	c	d	e	f	R^2	Average Error	Maximum Error
Cooling mode	0.0237	-0.211	0.0306	-0.182	-0.768	-0.153	0.83	0.05%	9.9%
Heating mode	0.0087	-0.301	0.0171	-0.113	-0.726	-0.0346	0.85	0.03%	9.4%

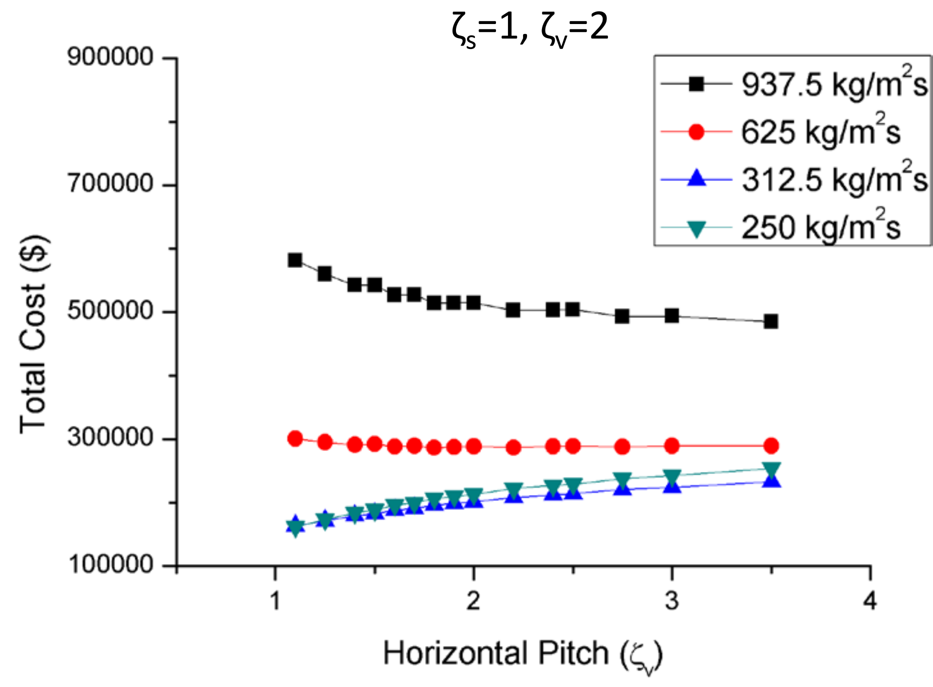
Selected Methodology



[4] Kim, I.-H., No, H.-C., 2012, "Physical model development and optimal design of PCHE for intermediate heat exchangers in HTGRs." Nuclear Engineering and Design 243: 243-250.

Cost Analysis Optimization





Low mass flux make the low total cost, both vertical and horizontal cases.
At low mass flux, variation of horizontal pitch makes much changes.
Optimal point of Vertical cases: Mass flux = 312.5kg/m^2, Vertical pitch = 2.75
Optimal point of Horizontal cases: Mass flux = 312.5kg/m^2, Horizontal pitch = 1.1

Conclusion

- Airfoil type PCHE provide better performance than zigzag type PCHE, and requries fin array optimization.
- Defining objective functions with cost factor provide reasonable weight to 2 factors which shows the performance of the PCHE.
- Nusselt number and Fanning friction factor are selected and modified to predict the value of these factors with the maximum error of 10%.
- Cost analysis shows the optimized point of the airfoil type PCHE configuration (Mass flux = 312.5kg/m^2, Vertical pitch = 2.75, Horizontal pitch = 1.1)
- The results show that the cost analysis could provide the constraint on the objective function of PCHE, since the minimum costal point exists in the domain.
- Still, pressure drop work as the dominant part of PCHE.
- There are many uncertainties in the assumptions and also manufacturing difficulties (such as DB issues at the mechanical stress at the airfoil edge) can also be considered as a constraint factor for the cost analysis.

Appendix

Appendix 1: ε-NTU method

$$\varepsilon = \frac{q}{q_{\max}} = \frac{q}{C_{\min}(\mathrm{T}_{h,i} - T_{c,i})}$$

Definintion of Effectiveness

$$NTU = \frac{UA}{C_{\min}} = \frac{1}{C_r - 1}\ln\left(\frac{\varepsilon - 1}{\varepsilon C_r - 1}\right)$$

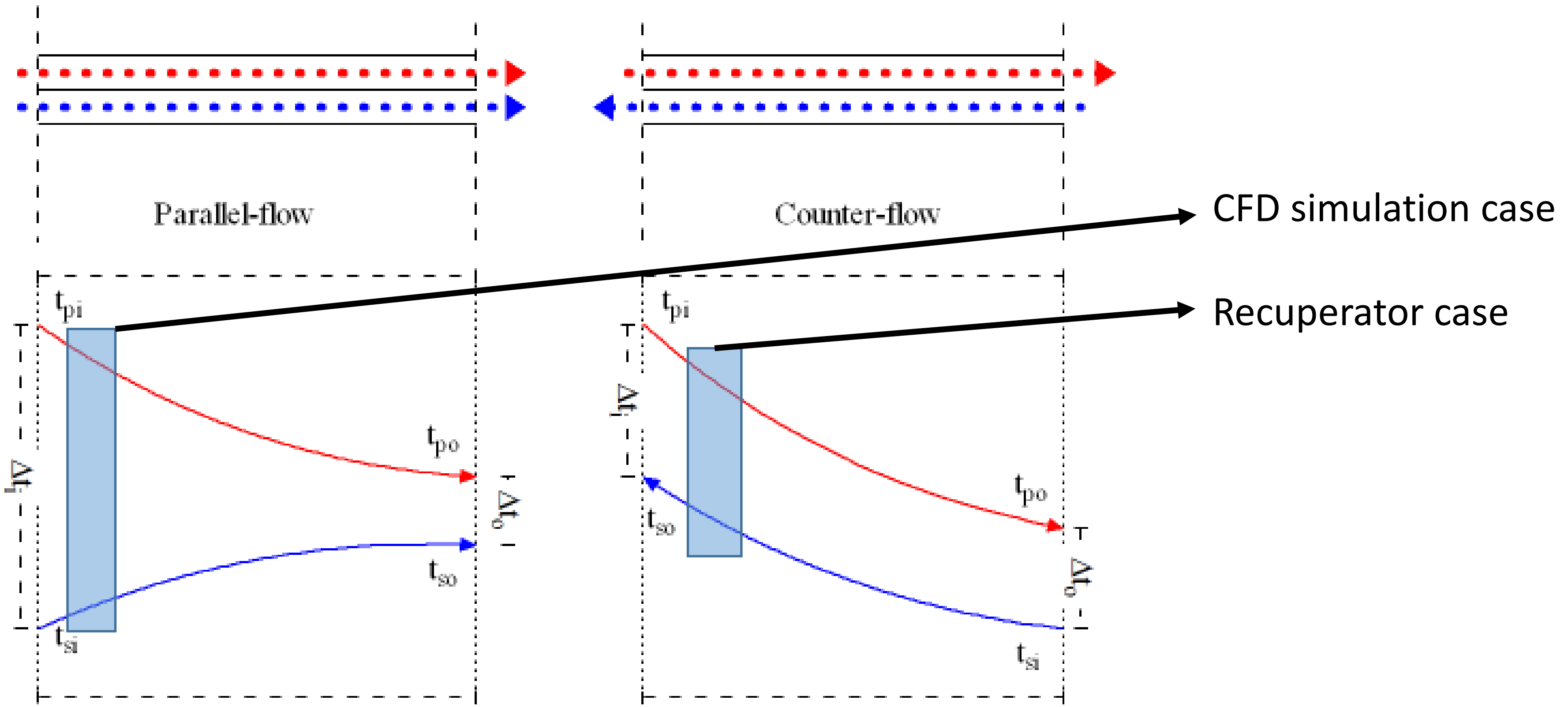
Definintion of NTU (assume that pipe flow)

$$\frac{1}{UA} = \frac{1}{(hA)_c} + \frac{1}{(hA)_h} = \frac{1}{A}\left(\frac{1}{h_c} + \frac{1}{h_h}\right)$$

Definintion of UA
(ignore the wall heat resistance)

From these equation, we could know the NTU, UA from effectiveness and thermodynamic properties. Heat transfer coefficient h could be predicted from Nusselt number correlation. Finally, required heat transfer area is obtained.

Appendix 2:Future Work



Inlet boundary condition of counter flow heat exchanger is used to analyze small parts of whole PCHE channel, so it represent concurrent flow heat exchanger. Obtained correlation should be tested on the case of counter flow Heat exchanger.

Reference

[1] Park, H.-S et al., 2014, "Development of Heat Exchanger Miniaturizing Technology for the Supercritical Gas Brayton Cycle." NRF: 45

[2] Lee, S.-M., K.-Y. Kim, 2012, "Shape Optimization of a Printed-circuit heat exchanger to enhance thermal-hydraulic performance." ICAPP, Ckicago, USA.

[3] Lee, S.-M., K.-Y. Kim, 2012, "Optimization of zigzag flow channels of a printed circuit heat exchanger for nuclear power plant application.", Journal of Nuclear Science and Technology 49(3): 343-351.

[4] Kim, I.-H., No, H.-C., 2012, "Physical model development and optimal design of PCHE for intermediate heat exchangers in HTGRs." Nuclear Engineering and Design 243: 243-250.

[5] Corhex Incorporation product

[6] Kruizenga, A., et al., 2012, "Supercritical Carbon Dioxide Heat Transfer in Horizontal Semicircular Channels." Journal of Heat Transfer 134(8): 081802.

[7] Boutilier, M. S. H., Yarusevych, S., 2012, "Separated shear layer transition over an airfoil at a low Reynolds number." Physics of Fluids, vol. 24, pp. 1-23, 084105.