CENTER for ENVIRONMENTAL ENERGY ENGINEERING

Performance Evaluation Criteria and Selection Utility Function for Compact Air-to-Refrigerant Heat Exchangers

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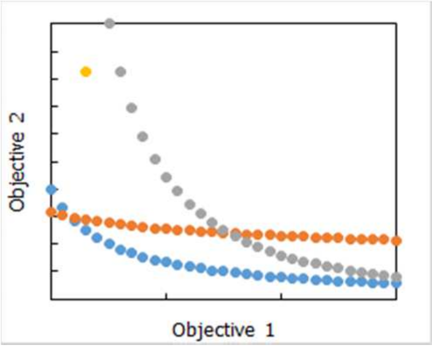
Objectives

- Multiple Heat eXchanger (HX) surface alternatives: evaluate, compare and select
  - Performance Evaluation Criteria (PEC):
    - Advantages and disadvantages
    - Meaning and the impact to the HX design
  - Decision-Making perspective:
    - Why did the optimizer choose those designs?
    - How to compare and select a design amongst two or more alternatives?
    - Multi-Attribute Utility Function (MAUF)



Introduction

- Heat Transfer Augmentation
  - ↑ Compactness (Surface-to-Volume ratio)
  - ↑ Thermal-Hydraulic performance
    - Subject to different interpretations and representations

- Performance Evaluation Criteria (PEC)
  - Energy-based
    - Premise: friction resistance is the sole responsible for the performance degradation
  - Entropy-based
    - Characterize all degradation mechanisms

Literature Review

- Area “goodness” factor (London, 1964)

$$\frac{j}{f}=\left[\frac{h}{\rho u_c c_p}\mathrm{Pr}^{2/3}\right]\Big/\left[\frac{2A_c\Delta P}{A_o\rho u_c^2}\right]=K\boxed{\frac{1}{A_c^2}}\boxed{\frac{N_{tu}}{\Delta P}},\qquad K=\frac{\dot{m}^2\,\mathrm{Pr}^{2/3}}{2\rho}$$

$$\Delta P\propto u_c^m, m>1.0;\quad h\propto u_c^n, 0.0<n<1.0;\quad A_c\propto u_c^{-1}$$

  - Comparison issue: Face area vs. $N_{tu}/\Delta P$
  - Design issue: ΔP, Face area, lastly N_{tu}
- Volume “goodness” factor (London, 1964)

$$\frac{h}{\dot{W}''}=\frac{h}{\Delta P\cdot\dot{V}/A_o}=\left(\frac{c_p\mu}{\mathrm{Pr}^{2/3}}\frac{j\,\mathrm{Re}}{D_h}\right)\Big/\left(\frac{\mu^3}{2\rho^2}\frac{f\,\mathrm{Re}^3}{D_h^3}\right)=\frac{2\,j\rho^2c_p\boxed{D_h^2}}{f\mu^2\,\mathrm{Pr}^{2/3}\,\mathrm{Re}^2}$$

  - Comparison and design issue: fixed D_h
- Variations: Q/W, Q’”/W.ΔT

Literature Review (cont'd)

- Entropy Generation Minimization (Bejan, 1977, 1996)

$$N_S = \frac{\dot{S}_{gen}}{C_{\min}}$$

- Production cost vs. Irreversibility Cost (Bejan, 1977)
  - Larger, "more expensive", HX is more thermodynamically efficient (Bejan, 1977)
- Better heat transfer ≠ minimum entropy generation (Bejan & Pfister, 1980; Seculik & Herman, 1986)

Proposed HX Evaluation Criteria

- Performance-Degradation Number
  (Ogiso, 2003)

$$\psi = \frac{N_{tu}}{N_s}$$

  - Ideal gas

$$\Delta s = \int \frac{\partial q}{T} + s_{gen} \rightarrow s_{gen} \approx c_p \ln\left(\frac{T_o}{T_i}\right) - \frac{q}{\bar{T}} - R\ln\left(\frac{P_o}{P_i}\right)$$

$$N_s = N_{s,\Delta T} + N_{s,\Delta P}, \quad N_{s,\Delta T} = \frac{\dot{S}_{gen,\Delta T}}{C} = \ln\left(\frac{T_o}{T_i}\right) - \frac{N_{tu}\Delta T_{ml}}{\bar{T}}, \quad N_{s,\Delta P} = \frac{s_{gen,\Delta P}}{R} = \ln\left(\frac{P_o + \Delta P}{P_o}\right)$$

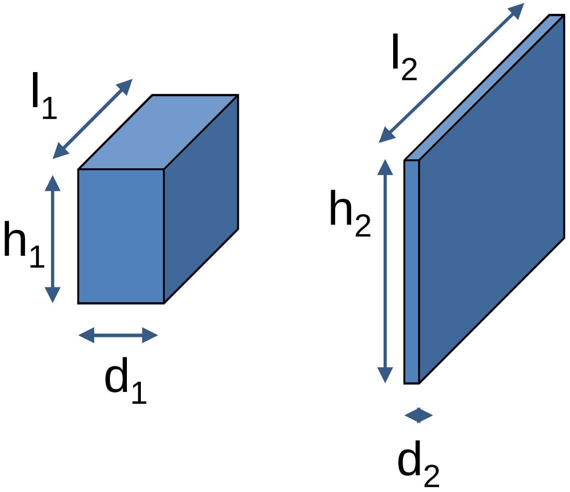
$$\psi = \frac{N_{tu}}{\ln\left(\frac{T_o\left(P_o + \Delta P\right)}{T_i P_o}\right) - \frac{N_{tu}\Delta T_{ml}}{\bar{T}}} = \frac{\boxed{N_{tu}}}{\boxed{\ln\left(\frac{T_o\left(P_o + \Delta P\right)}{T_i P_o}\right) - \frac{\varepsilon \Delta T_{\max}}{\bar{T}}}}$$

Conventional Heat Transfer Surfaces

- Trade-off between size and low entropy generation
- Larger HX’s have larger heat transfer surfaces
- Novel shapes and smaller tube sizes result in higher heat transfer coefficients
  - Less need for surface area (~UA, ↑U)
  - Geometrical limitations might be different for these novel surfaces (face area, aspect ratio, etc.)

HX "Size"

- HX "size" is a broad term
- What aspect of the size is the most critical / important?
- How are two HX's sizes comparable?



$l_1 < l_2$ $h_1 < h_2$ $d_1 > d_2$	Individual Dimensions
$h_1 l_1 < h_2 l_2$	Face Area
$h_1 l_1 d_1 > h_2 l_2 d_2$	Envelope Volume

Size Metrics

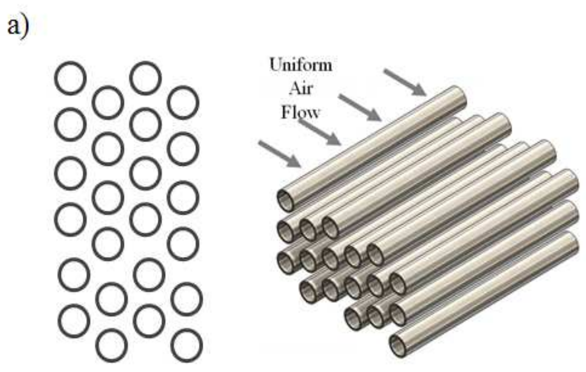
- Compactness
  - More meaningful than volume or surface area alone
  - Independent to HX scale (surface characteristic)
  - Surface hydraulic diameter

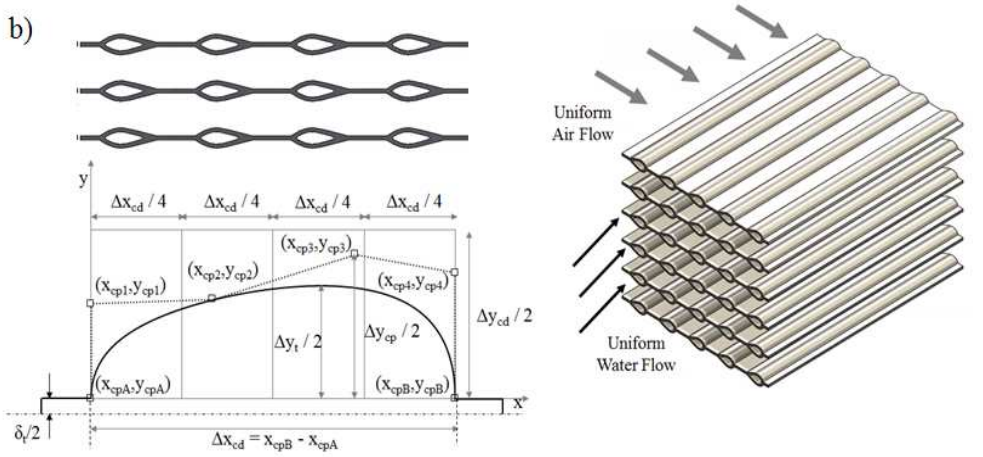
$$D_h = 4\,A_c \big/ A_o\, d = 4\sigma V \big/ A_o \rightarrow A_o \,/\, V = 4\sigma \,/\, D_h$$

- Face Area
  - Smaller tubes compromise on friction resistance requiring smaller flow passage depths thus increasing face area

HX DESIGN AND OPTIMIZATION

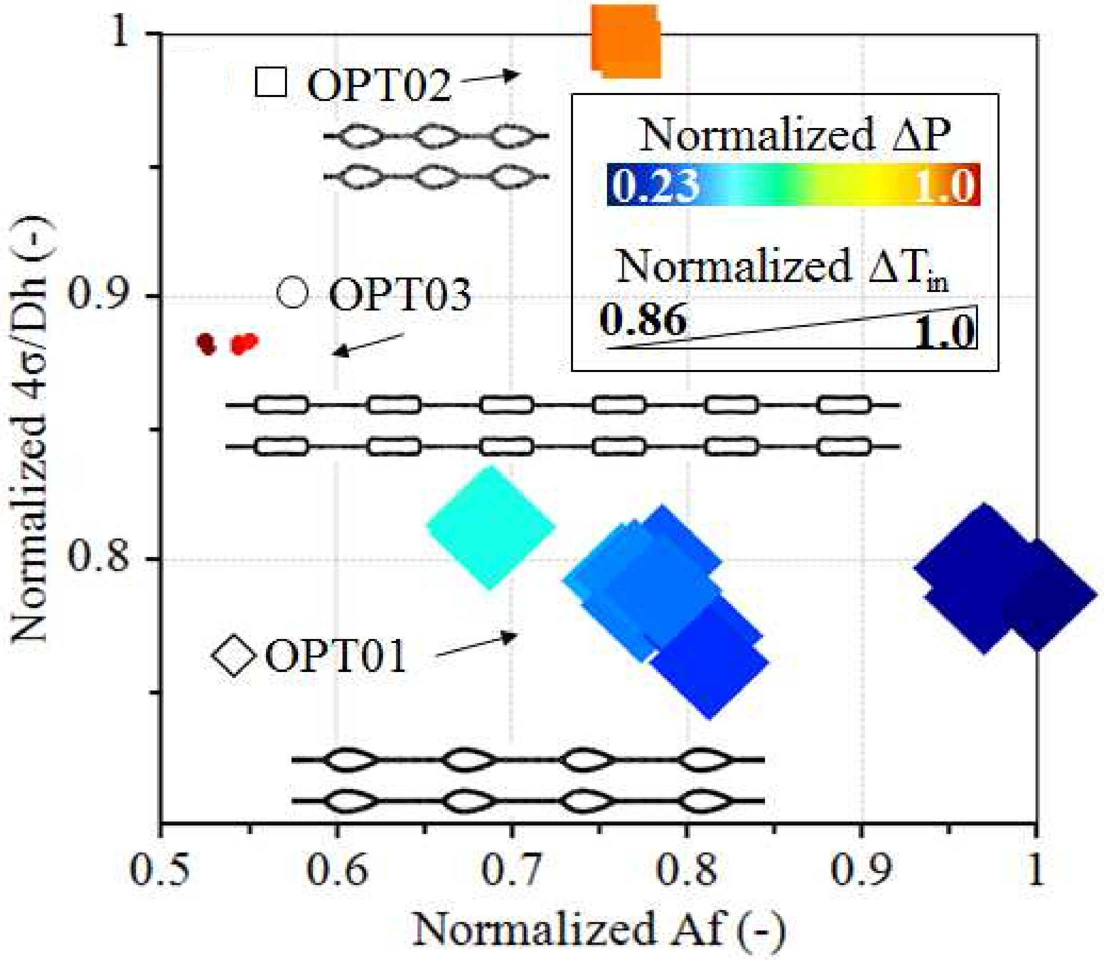
Problem Definition





Optimization	OPT01	OPT02	OPT03
Objectives	Conventional PEC min A_f max $h/\Delta P$	Conventional PEC min A_f max j/f	Alternative PEC min A_f max ψ
Constraints	$1.0 < Q < 1.01$kW $V_{HX} \leq V_{HX,\ baseline}$ $\Delta P_{air} \leq \Delta P_{air,\ baseline}$ $\Delta P_{water} \leq \Delta P_{water}$ $0.61<AR<1.61$		
Parameters	$\dot{m}_{air}$ = fixed $\dot{m}_{water}$ = fixed $0.5 \leq u_{air} \leq 7.0$m/s $0.8\ \Delta T_{in\_baseline} \leq \Delta T_{in} \leq \Delta T_{in\_baseline}$		

Results



OPT01: h/ΔP
OPT02: j/f
OPT03: ψ

PEC	h/ΔP	j/f	ψ
Compactness		↑	
Face Area			↓
Thermal Resistance			↓
Friction	↓		
Entropy Generation			↓

HX SELECTION

Multi-Attribute Utility Function

- Weighted Lp-norm expression

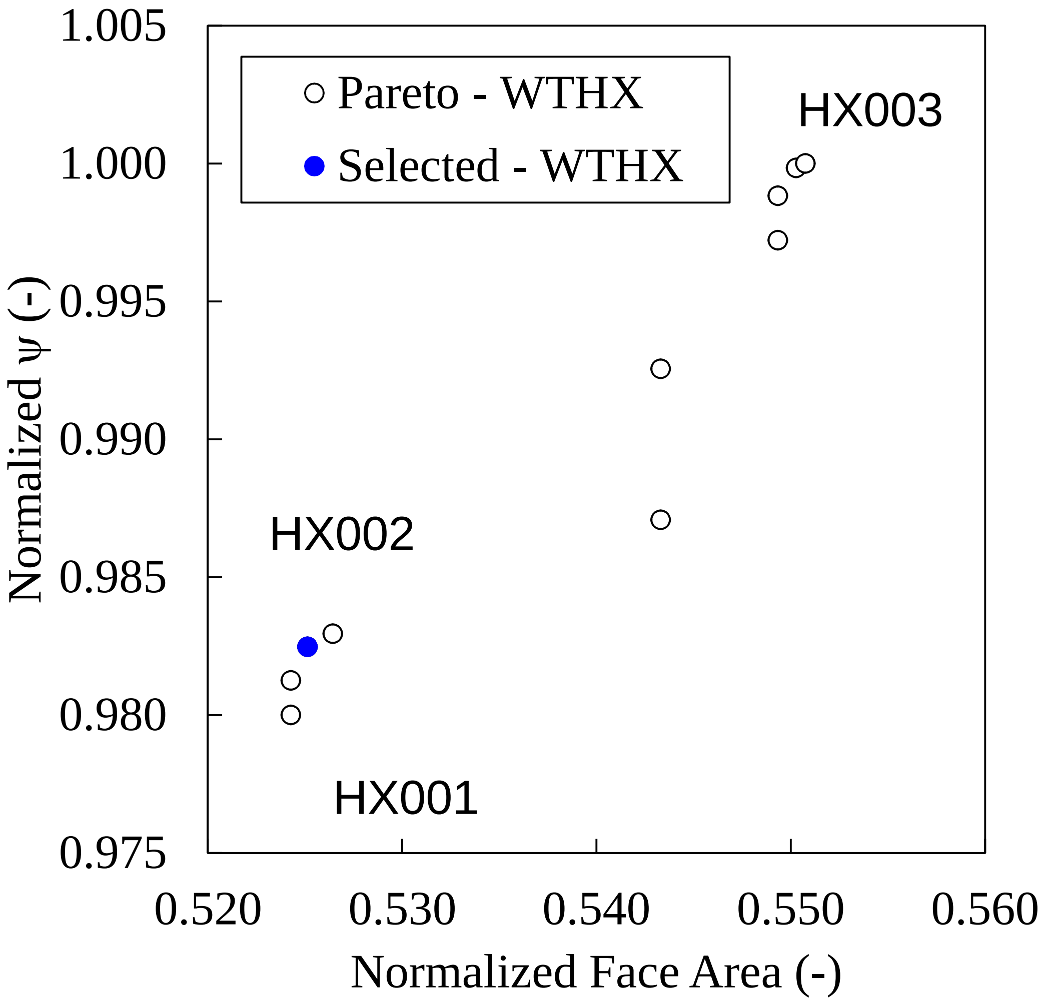
  (Scott and Antonsson, 2005), (Herrmann, 2015)

$$U(\underset{\sim}{x}) = \left(\frac{\sum w_i u(x_i)^p}{\sum w_i} \right)^{1/p}, \quad \text{if } p = 0 \;\rightarrow\; U(\underset{\sim}{x}) = \left(\sum u(x_i)^{w_i} \right)^{1/\sum w_i}$$

  - Objective: Find the maximum aggregate utility (U(x))

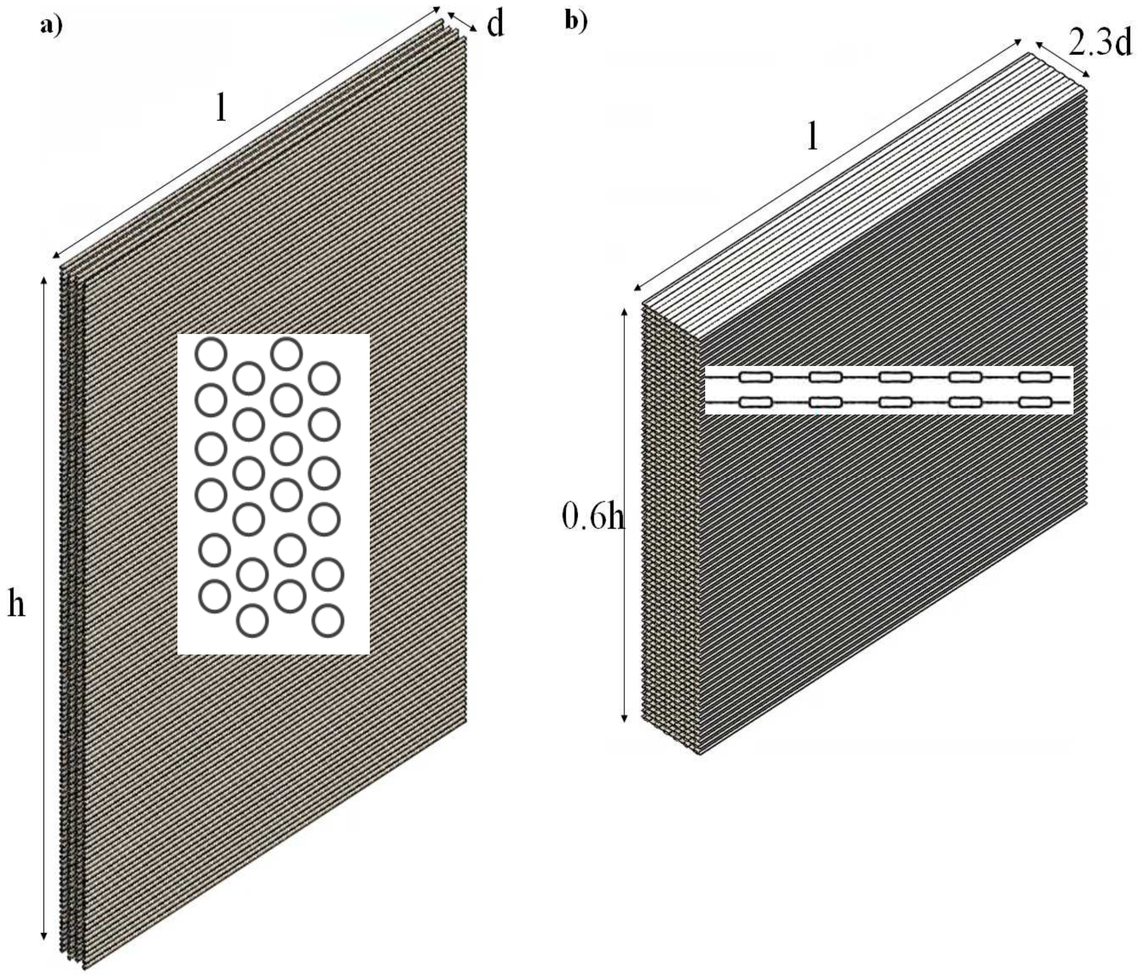
- Attributes (normalized): ψ, $4\sigma/D_h$, $1/A_f$

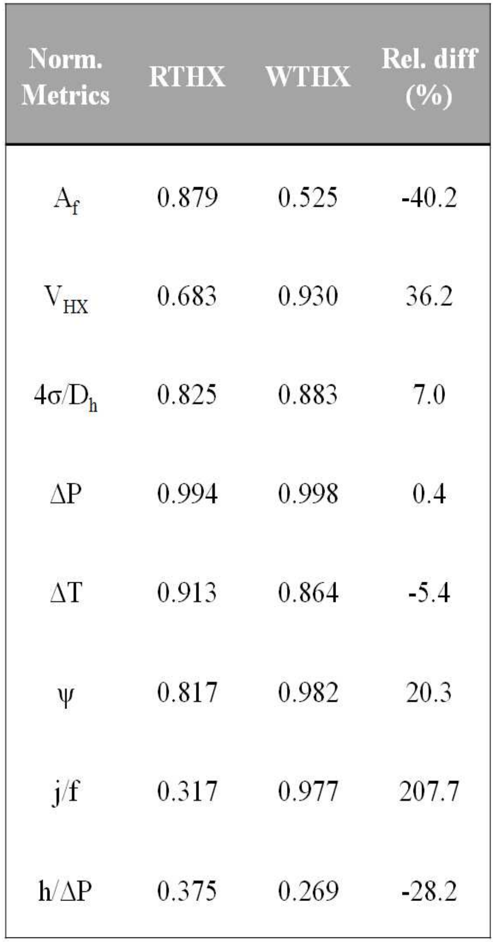
HX Selection Results (1 Pareto)



	HX001	HX002	HX003
ψ	0.980	0.982	1.000
h/ΔP	0.269	0.269	0.288
j/f	0.978	0.977	0.998
4σ/Dh	0.883	0.883	0.883
Af	0.524	0.525	0.551
U(x)	0.997	1.000	0.999

HX Selection Results





Norm. Metrics	RTHX	WTHX	Rel. diff (%)
A_f	0.879	0.525	-40.2
V_{HX}	0.683	0.930	36.2
$4\sigma/D_h$	0.825	0.883	7.0
ΔP	0.994	0.998	0.4
ΔT	0.913	0.864	-5.4
ψ	0.817	0.982	20.3
j/f	0.317	0.977	207.7
$h/\Delta P$	0.375	0.269	-28.2

Conclusions

- Impact of PEC on design, optimization and selection
    - Mixed approach lead to better thermal performance and good compactness
- MAUF is one way of decision-making
- Introduction to a broader robust methodology that allows one to compare and select HX's from multiple Pareto sets, including various surfaces types and sizes, on a fair basis

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