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Design of Na-CO_2 PCHE for Large Capacity Thermal Energy Storage System

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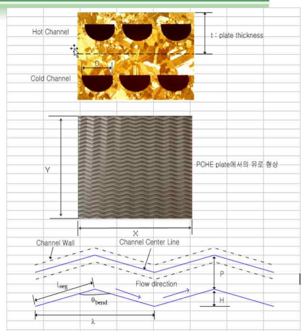
Introduction

- One of fundamental limitations of renewable energy is intermittent nature of its energy source. To make up the weak points means such as thermal energy storage (TES) system can be utilized.
- A conceptual design of thermal energy storage and utilization system was considered for which sensible heat with two tanks and S-CO_2 Brayton cycle were chosen. For the storage system, sodium is used to have advantages of wide range operability of working temperature over general molten salt.
- For heat exchanger from the sodium side to the CO_2 side, compact printed circuit heat exchanger (PCHE) is employed. Lumped PCHE design code had been developed but varying properties of working fluids on temperature may require more refined design approach. Therefore, the lumped PCHE design code was upgraded to have option of discretization along the flow directions of both tube sides and the 1D PCHE design code was used for PCHE design.

PCHE Channel Geometry

- ***Input for design***
  - ✓ channel bending angle of hot channel (θ_{hot})
  - ✓ half length of bent channel segment (L_{seg})
  - ✓ pitch between cold flow channels (P_{cold})
  - ✓ width of single plate (Y)
- ***Output from design***
  - ✓ channel bending angle of cold channel (θ_{cold})
  - ✓ number of bend in single hot and cold channels ($N_{bend,hot}$, $N_{bend,cold}$)
  - ✓ length of single plate (X)



Channel configuration

Correlations for Heat Transfer

- Hesselgreaves correlation was chosen to calculate convective heat transfer coefficient for CO_2 side and Lockart-Martinelli correlation was applied for sodium side. Idelchik model was employed to calculate pressure loss.

- Hesselgreaves correlation for CO_2 side

$$Nu = 4.089 \; for \; Re \le 2300$$

$$Nu = 4.089 + \frac{Nu_{Re=5000} - 4.089}{5000 - 2300}(Re - 2300) \; for \; 2300 < Re < 5000$$

$$Nu = 0.125 Re^{0.8} Pr^{0.4} \; for \; Re \ge 5000$$

- Lockart-Martinelli correlation for sodium side

$$Nu = 5.0 + 0.025 Re^{0.8} Pr^{0.8}$$

- Ishizuka friction loss and Idelchik form loss correlations

$$f = 4(0.0014 + 0.125 Re^{-0.32})$$

$$K = N_{bend}\left(0.946 \sin^2\left(\frac{180 - \theta_{bend}}{2}\right) + 2.047 \sin^4\left(\frac{180 - \theta_{bend}}{2}\right)\right)$$

Code Validation

- 1D code was validated by using the design data of ABTR, KALIMER-600, G4SFR PCHEs (0D vs 1D).

Input parameters

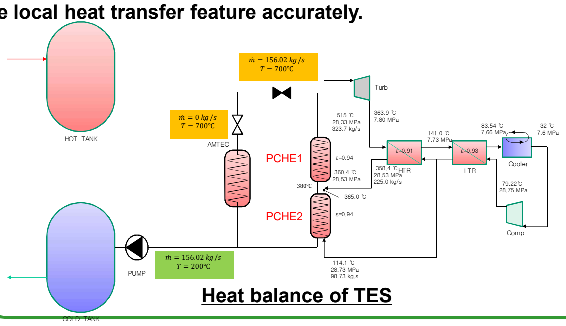
Parameter	ABTR	K-600	G4SFR
D_{ch} [mm]	2.0	2.0	2.0
θ_{hot} [deg]	180	180	180
P_{cold} [mm]	3.0	4.0	4.0
t [mm]	2.0	2.0	2.0
L_{seg} [mm]	5.0	5.0	5.0
Y [m]	0.6	0.6	0.6
Hot channel path	Straight	Straight	Straight
Cold channel path	Zig-Zag	Zig-Zag	Zig-Zag
Hot fluid	Sodium	Sodium	Sodium
Cold fluid	CO_2	CO_2	CO_2
$T_{hot,in}$ [°C]	488.0	526.0	526.0
$T_{hot,out}$ [°C]	333.0	364.0	364.0
$T_{cold,in}$ [°C]	323.6	353.9	353.8
$T_{cold,out}$ [°C]	471.5	508.0	508.0
$P_{hot,in}$ [MPa]	0.2	0.1094	0.1094
$P_{hot,out}$ [MPa]	0.192	0.1014	0.1014
$P_{cold,in}$ [MPa]	19.91	19.94	19.94
$P_{cold,out}$ [MPa]	19.84	19.74	19.74
$\dot{m}_{hot}$ [kg/s]	19.67	7400.2	14800.4
$\dot{m}_{cold}$ [kg/s]	21.52	8076.6	16147.5

Comparison of designed data

		ABTR			K-600			G4SFR		
		0D	1D	Diff [%]	0D	1D	Diff[%]	0D	1D	Diff[%]
Heat transfer area [m²]		129.8	130.7	0.69	42683	43121	1.03	85077	86242	1.37
N_{ch} [-]	Hot	209	208	-0.48	179	180	0.56	179	180	0.56
	Cold	199	199	0.00	149	149	0.00	149	149	0.00
Unit [m]	Length	1.17	1.17	0.00	1.05	1.04	-0.95	1.05	1.04	-0.95
	Width	0.6	0.6	0.00	0.6	0.6	0.00	0.6	0.6	0.00
	Height	0.41	0.42	2.44	176.5	178.6	1.18	352.5	357.1	1.30
θ_{cold} [deg]		145.9	145.5	-0.31	113.1	112.5	-0.53	113.1	112.5	-0.50
P_{hot} [mm]		2.875	2.885	0.34	3.349	3.338	-0.32	3.349	3.338	-0.31
$\dot{m}_{ch}$ [g/s]	Hot	0.913	0.907	-0.67	0.934	0.920	-1.49	0.935	0.920	-1.59
	Cold	1.045	1.034	-1.01	1.222	1.208	-1.17	1.223	1.207	-1.28
Q_{total} [MW]		3.906	3.892	-0.35	1529	1528	-0.02	3057	3055	-0.08

PCHE Design for TES

- Two Na-CO2 PCHEs were designed preliminarily based on a heat balance.
- For PCHE2 the variation profile of overall heat transfer coefficient is not linear. Therefore, 0D approach which can be considered as averaging method of values of two ends may not be enough to reflect the local heat transfer feature accurately.



Heat balance of TES

Input parameters for TES PCHEs

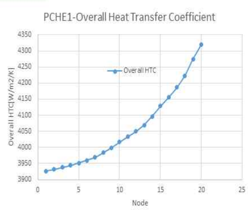
Parameter	PCHE1	PCHE2
D_{ch} [mm]	2.0	2.0
θ_{hot} [deg]	180	180
P_{cold} [mm]	4.0	4.0
t [mm]	2.0	2.0
L_{seg} [mm]	5.0	5.0
Y [m]	0.6	0.6
Hot channel path	Straight	Straight
Cold channel path	Zig-Zag	Zig-Zag
Hot fluid	Sodium	Sodium
Cold fluid	CO_2	CO_2
$T_{hot,in}$ [°C]	700.0	380.0
$T_{hot,out}$ [°C]	380.0	200.0
$T_{cold,in}$ [°C]	360.4	114.1
$T_{cold,out}$ [°C]	515.0	360.4
$P_{hot,in}$ [MPa]	0.1174	0.1094
$P_{hot,out}$ [MPa]	0.1094	0.1014
$P_{cold,in}$ [MPa]	28.53	28.73
$P_{cold,out}$ [MPa]	28.33	28.53
$\dot{m}_{hot}$ [kg/s]	156.02	156.02
$\dot{m}_{cold}$ [kg/s]	323.70	98.73

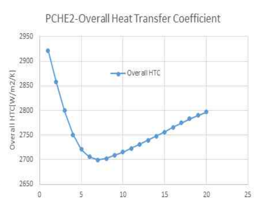
Comparison of designed data

		PCHE1			PCHE2		
		0D	1D	Diff[%]	0D	1D	Diff[%]
Heat transfer area [m²]		206.9	208.8	0.92	271.7	278.6	2.54
N_{ch} [-]	Hot	159	159	0.00	272	250	-8.09
	Cold	150	150	0.00	149	149	0.00
$N_{ch,total}$ [-]	Hot	103710	103434	-0.27	115243	114413	-0.72
	Cold	97369	97523	0.16	63183	68266	8.04
L_{total} [mm]	Hot	388.07	392.58	1.16	458.59	473.63	3.28
	Cold	413.34	419.32	1.45	836.45	793.71	-5.11
Unit [m]	Length	0.39	0.39	0.00	0.46	0.47	2.17
	Width	0.6	0.6	0.00	0.6	0.6	0.00
	Height	2.60	2.60	0.00	1.69	1.83	8.28
θ_{cold} [deg]		139.72	139.04	-0.49	66.50	73.30	10.23
P_{hot} [mm]		3.7647	3.7810	0.43	2.2018	2.3960	8.82
$\dot{m}_{ch}$ [g/s]	Hot	1.5044	1.5084	0.27	1.3538	1.3637	0.73
	Cold	3.3245	3.3192	-0.16	1.5626	1.4462	-7.45
Q_{total} [MW]		63.1905	62.9285	-0.41	36.2439	36.8457	1.66

Conclusion

- A lumped PCHE design code was upgraded to 1D design code to reflect 1D local effect along the flow direction. The upgraded code was validated through several PCHE designs for SFRs.
- The code was employed to design PCHEs installed for thermal energy storage and utilization system. Partial heating configuration of the system is equipped with two PCHEs to transfer heat from sodium to CO2.
- For some cases, overall heat transfer coefficient along the nodes varies in a nonlinear pattern. For this case, 0D design approach may not fully reflect the local heat transfer features of PCHE and for this case 1D design approach can be a more proper tool for PCHE design.





Overall heat transfer coefficients of PCHE1(left) and PCHE2(right)