Powerful Heat Transfer Solutions for Supercritical CO_2 Recuperators

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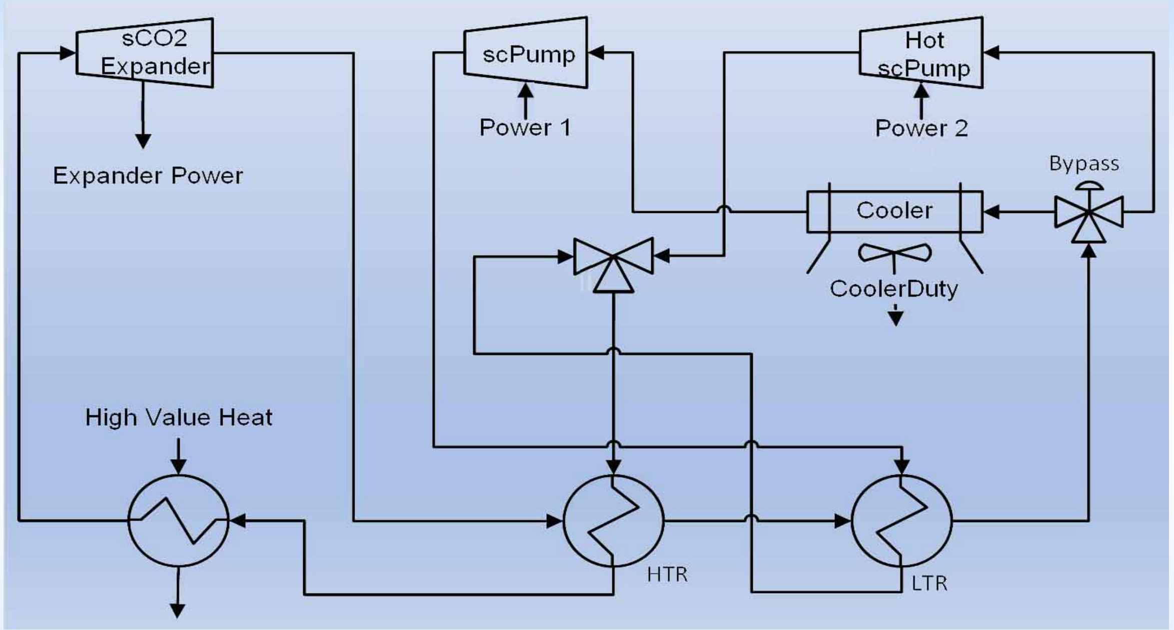
Introduction and Purpose of Study:

- RECUPERATORS are the WEAK LINK of sCO_2 Cycles
  - Recuperator must recover over 500 MW of heat in a 100 MWe power plant, which is 70 to 75% of the cycle's heat
  - More surface area is required for the recuperator than for the primary heater and cooler/condenser combined
- Current heat exchanger alternatives (e.g., PCHE, STE, MSTE) are challenged at 100 MWe and greater
  - Size Limitations
  - System Operability
  - Cycle efficiency versus Heat Transfer Coefficient and ΔP
  - Piping Complexity
  - Fouling potential
- Describe the Powerful Heat Transfer Solutions™ sCO_2 recuperator system and evaluate it versus the current alternatives

Current Recuperator Technologies

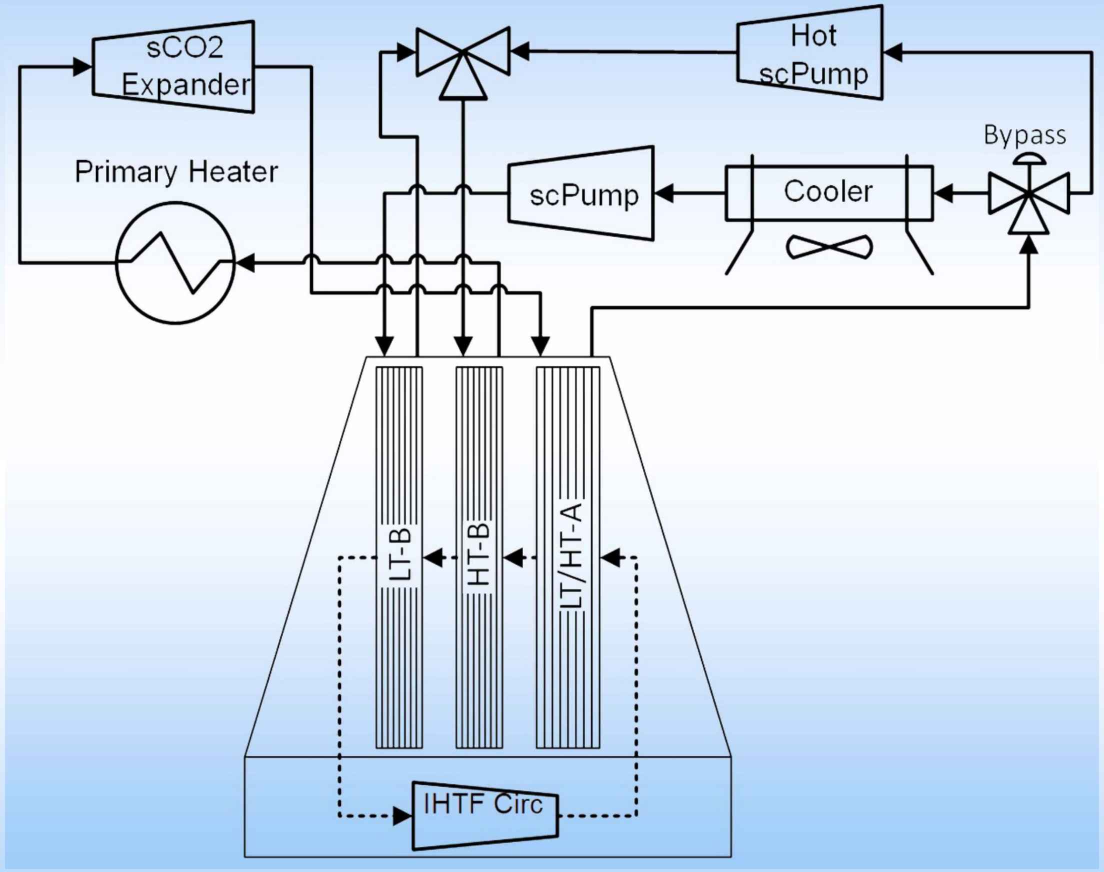
- Shell & Tube exchanger (STE)
  - Ubiquitous heat exchanger selection
  - Tube sizes of 10 mm to 25 mm or greater
  - Limited for high pressure and temperature differences
- Printer Circuit Heat Exchanger (PCHE)
  - Diffusion bonded stack of etched plates to form fluid passages, typically ~2 mm semi-circle passages
  - Excellent application for high pressure and temperature differences
  - Limited size due to manufacturing constraints, diffusion oven limit
- Micro Shell and Tube exchanger (MSTE)
  - Addresses limitations of conventional STE
  - Tube sizes of 1 to 3 mm
  - Manufacturing at large sizes may be challenging
- PCHE and MSTE Share Common Problems
  - Higher velocities to achieve good heat transfer coefficients
  - Increased pressure drops
  - Greater fouling potential, especially for open-cycle sCO2 applications

Typical sCO2 Recuperator Solution



Description of Novel Recuperator System

- New recuperator based on HRSG technology that allows scaling to commercial size power plants
  - Finned tube coils sized to accommodate heat duty needs
  - Coils hang in LP enclosure; no pressure vessels; free growth
- Resolves piping complexity issues and provides better response to startup and transient operations
- Less prone to fouling due to larger diameter tubes
- Recuperator splits the heat transfer into three services: LT/HT-A, HT-B and LT-B
- Intermediate Heat Transfer Fluid is heated and cools the expander exhaust within the LT/HT-A
- High pressure sCO_2 is pre-heated in LT-B and then to near exhaust temperature in HT-B by hot IHTF
- IHTF can be a range of fluids like low-pressure air, nitrogen, or even a liquid metal
- IHTF continuously recirculated using a fan or pump

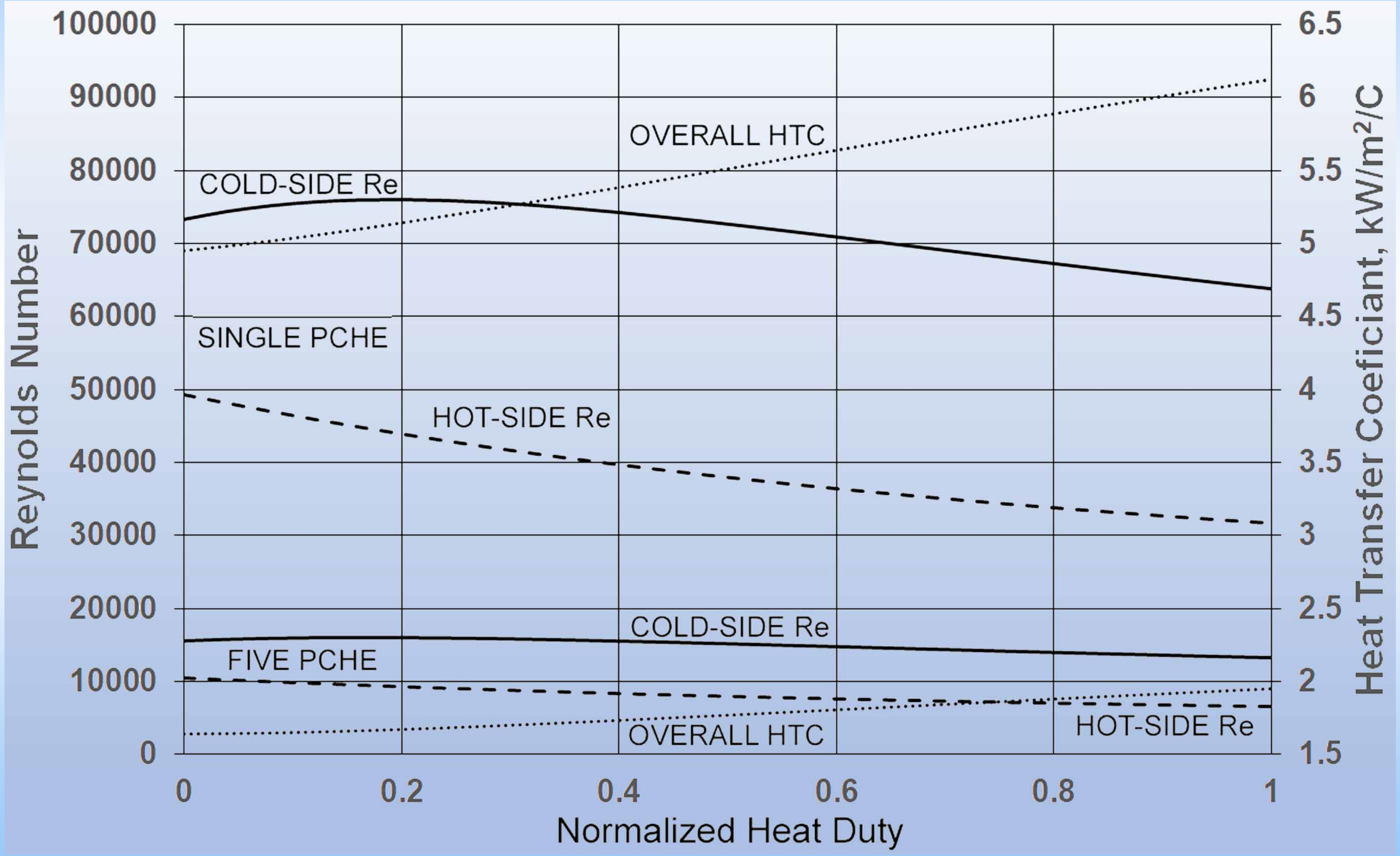


Bases for 100 MWe Power Plant Simulations

Motive Fluid	Supercritical CO_2	Units
Expander Flow Rate	1001.7	Kg/s
Expander Inlet Pressure	235	bara
Expander Inlet Temperature	700	°C
Cooler Inlet Pressure	85	Bara
Cooler Pressure Drop	2	Bar
Cooler Outlet Temperature	34.5	°C
Turbomachinery Efficiency	85%	Adiabatic Efficiency
Pipe Losses (various)	1.5	bar

PCHE Have High HTC, But at a Cost

HTR for sample 100 MWe Power Plant

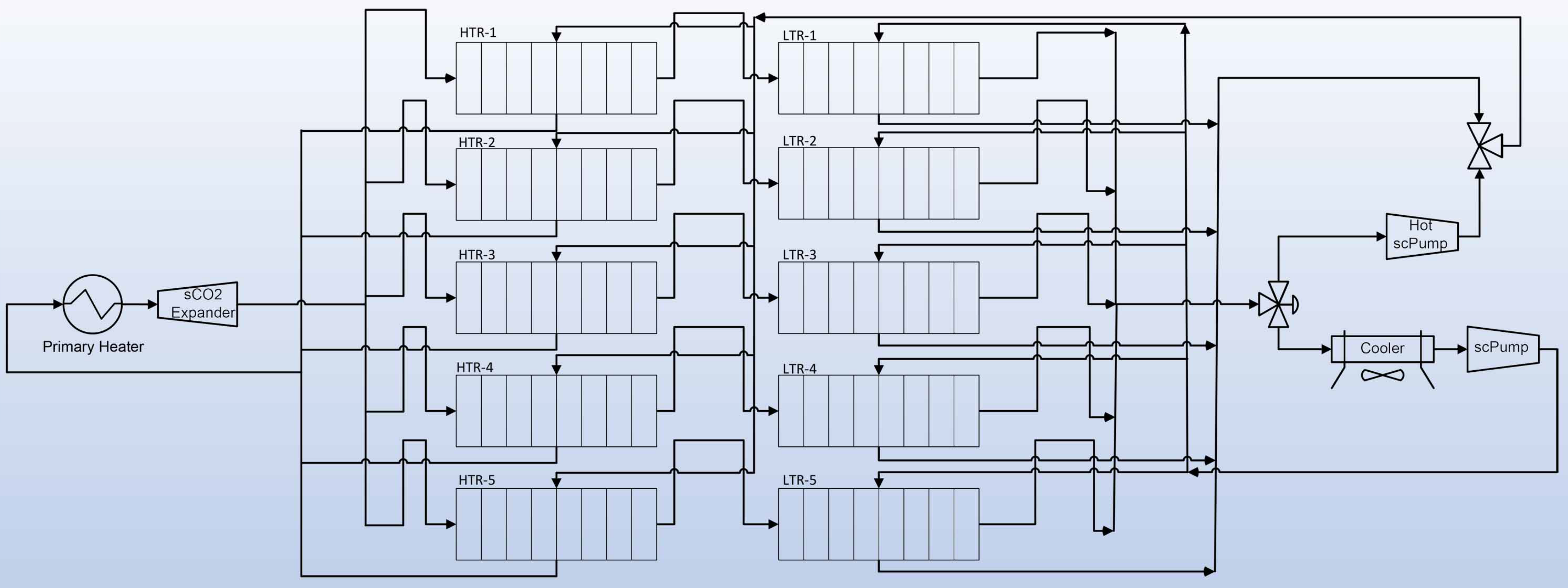


Many PCHE Units in Parallel Are Needed

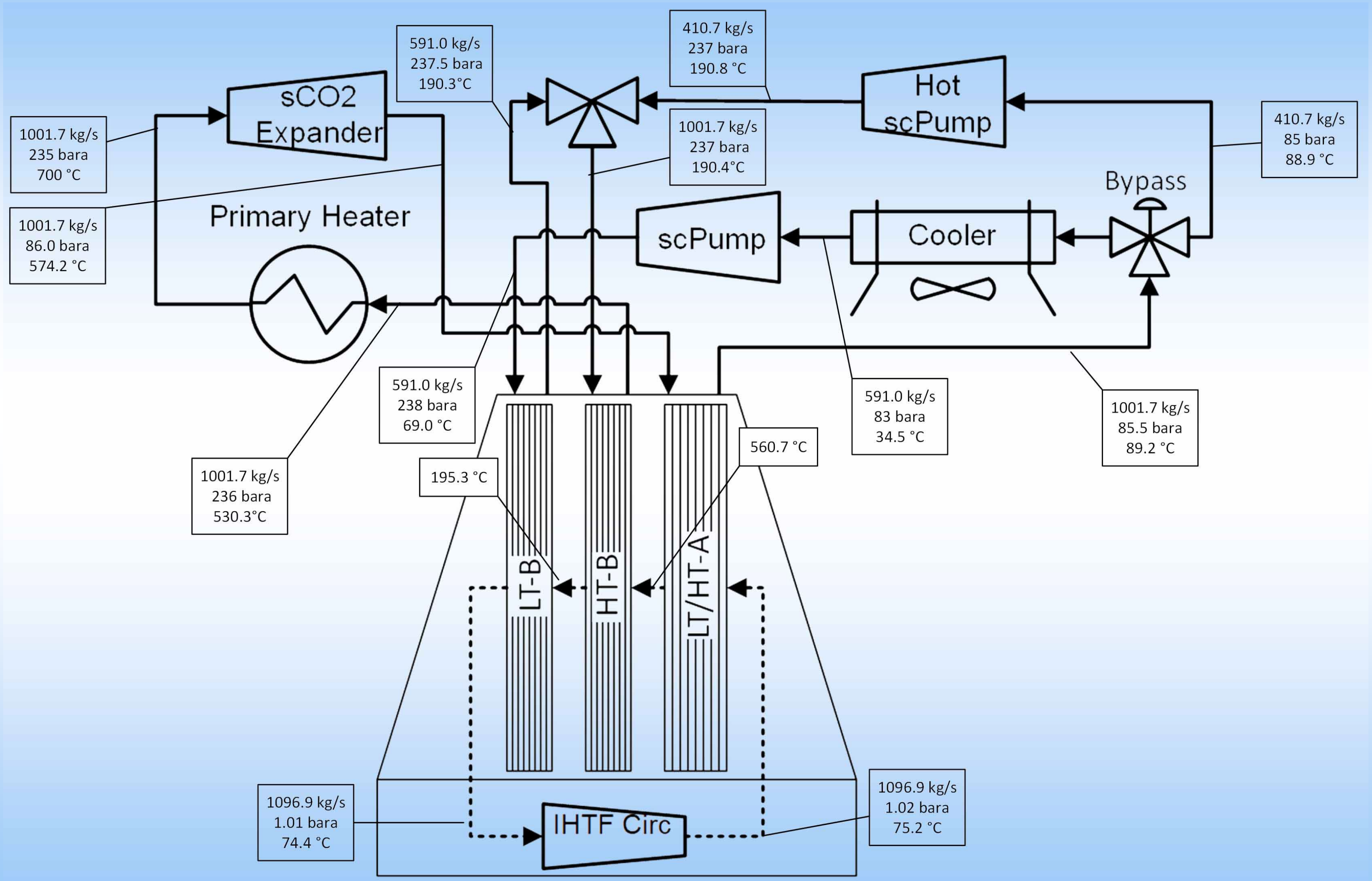
No. of PCHE in Parallel (HTR & LTR)	Expander Outlet Pressure (bar)	Expander Outlet Temp (°C)	HTR Heat Duty (MW)	LTR Heat Duty (MW)	LTR + HTR Hot ΔP (bar)	LTR + HTR Cold ΔP (bar)	Plant Cycle Efficiency (%)
1	130.6	624.2	485	151	44.6	50.2	24.0%
2	97.0	588.8	464	140	10.5	10.8	43.7%
3	90.9	581.2	459	139	4.3	4.4	46.6%
4	88.9	578.6	456	138	2.4	2.4	47.6%
5	88.0	577.4	456	138	1.5	1.5	48.0%

Note: PCHE maximum size of 1.6 x 0.6 x 8m

Complex Piping Arrangement with PCHE



New Recuperator: Sample Operating Conditions



New Recuperator System Has Similar Performance with Better Operability and Scaling

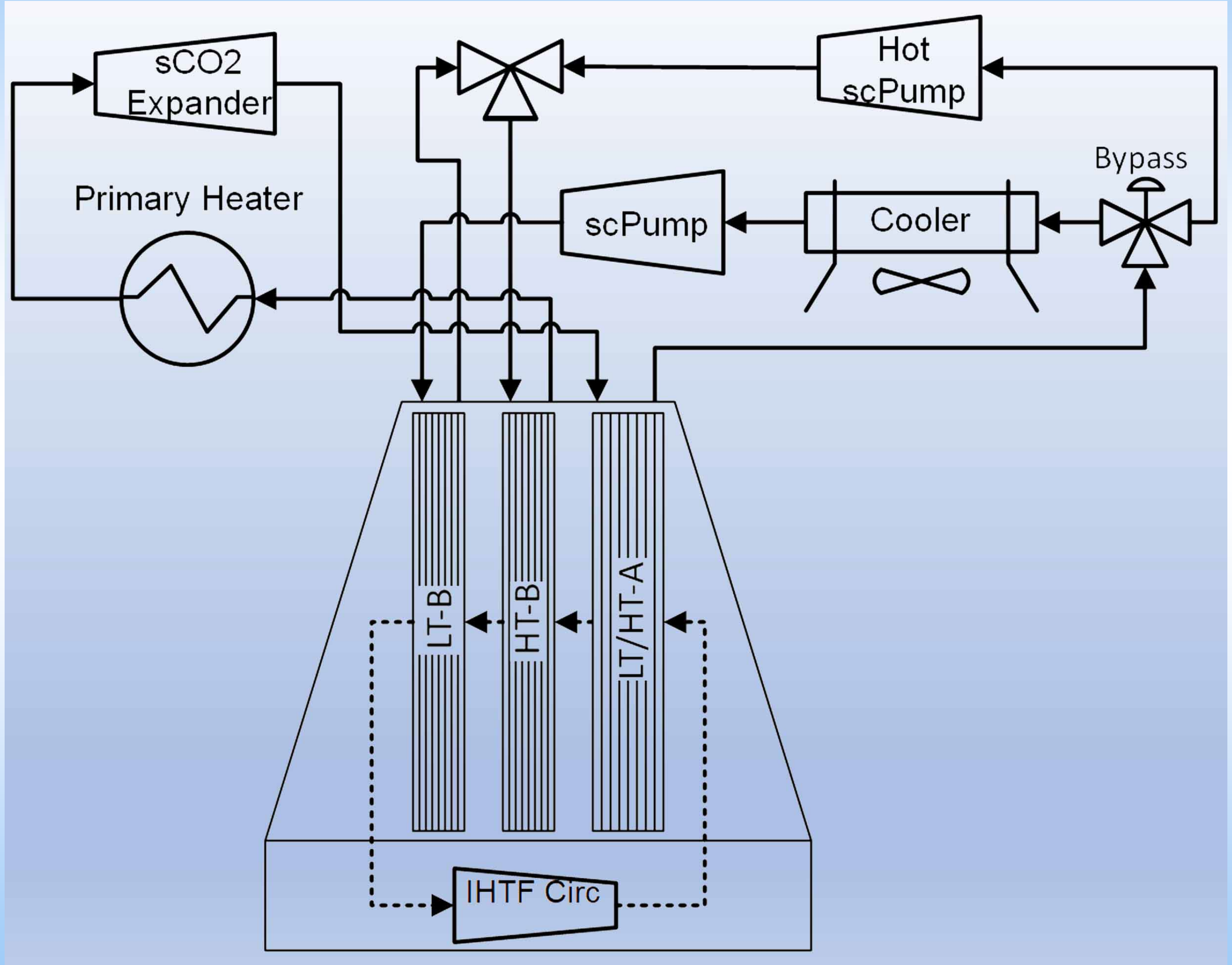
	PCHE (5+5) (2mm)	STE Bare Tube (10mm)	STE Finned Tube (10mm)	New Recuperator N_2 IHTF HRSG (10mm)	New Recuperator NaK78 IHTF (10mm)
Net Power (MW)	103.1	103.0	103.7	101.8	105.3
Cycle Efficiency (%)	48.0	48.0	48.2	47.6	48.0
Total Hot ΔP (bar)	1.45	1.58	0.82	0.5	0.42
Total Cold ΔP (bar)	1.44	1.40	0.74	1.0	0.53
Avg HTC ($kW/m^2/C$)	1.71	0.90	1.73	0.61	7.11
HTR or HT/LT-A Area (m^2)	8,380	16,490	8,740	162,000	11,340
LTR or HT-B Area (m^2)	7,960	12,970	6,320	29,000	2,390
LT-B Area (m^2)	-	-	-	18,000	2,120
Total Surface Area (m^2)	16,340	29,460	15,060	209,000	15,850

Conclusions

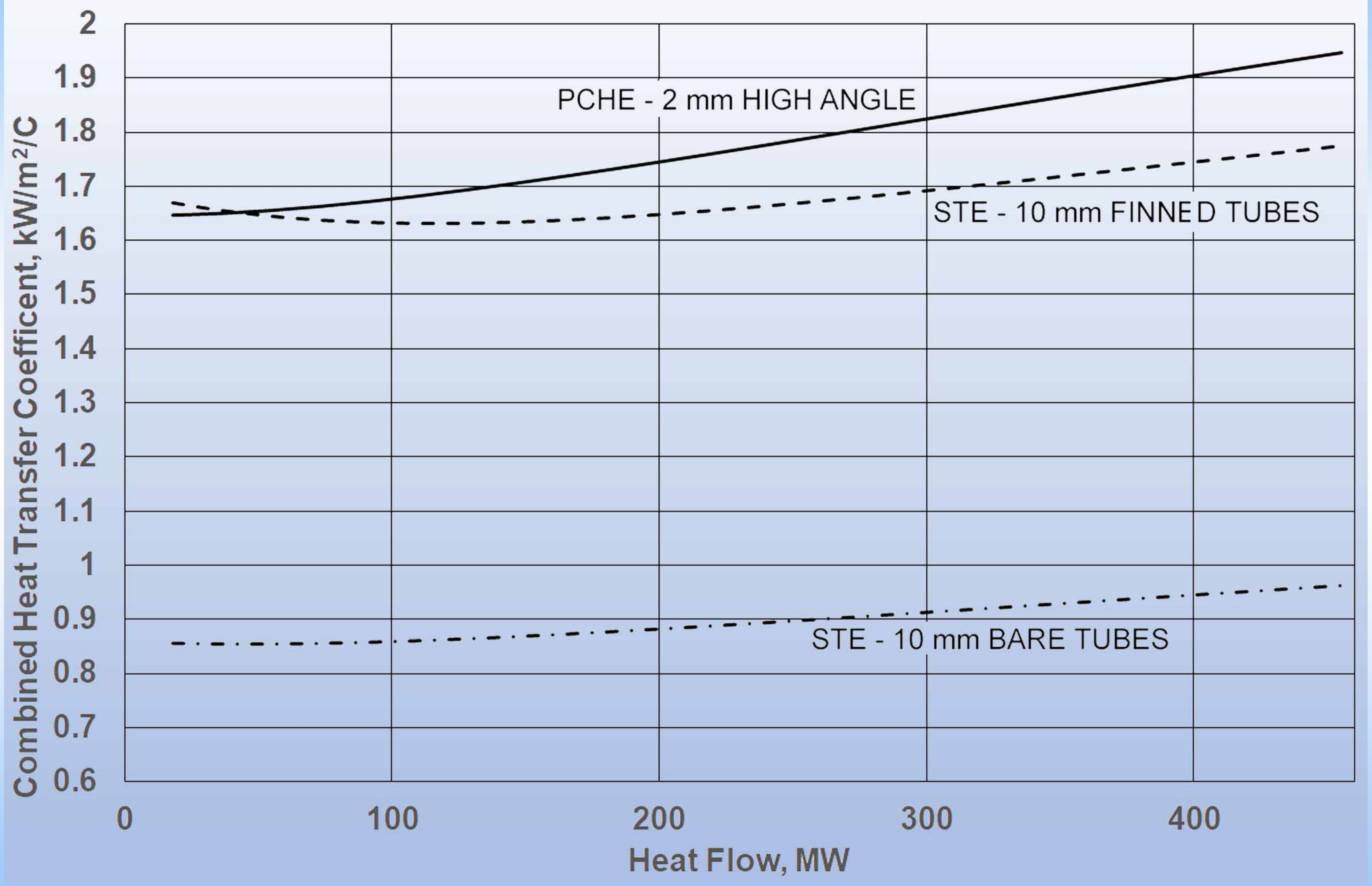
- For PCHE, STE, and MSTE multiple parallel heat exchangers are needed for commercial scale power plants
  - Requires complex piping arrangements and equipment spacing to compensate for the large operating temperature differences
  - Impacts operability, especially during transient operations like startup or shutdown
- Powerful Heat Transfer Solutions™ has developed a new recuperator system to solve these problems with similar cycle efficiency and allow heat exchanger optimization
- New recuperator is constructed like an HRSG and has few constraints on size or surface area
  - More surface area needed when LP air or nitrogen used as the intermediate fluid
  - Incremental surface area using finned tubes is cost effective
  - No pressure vessels are required
- Eliminates the need for multiple parallel trains of heat exchangers with complex piping
- Less prone to fouling, which causes loss of cycle efficiency and lower availability, especially for open sCO_2 cycles like the Allam Cycle
- New recuperator system can also use liquid metals with substantial improvement to overall heat transfer coefficients, reduced surface area, and reduced footprint

BACK UP

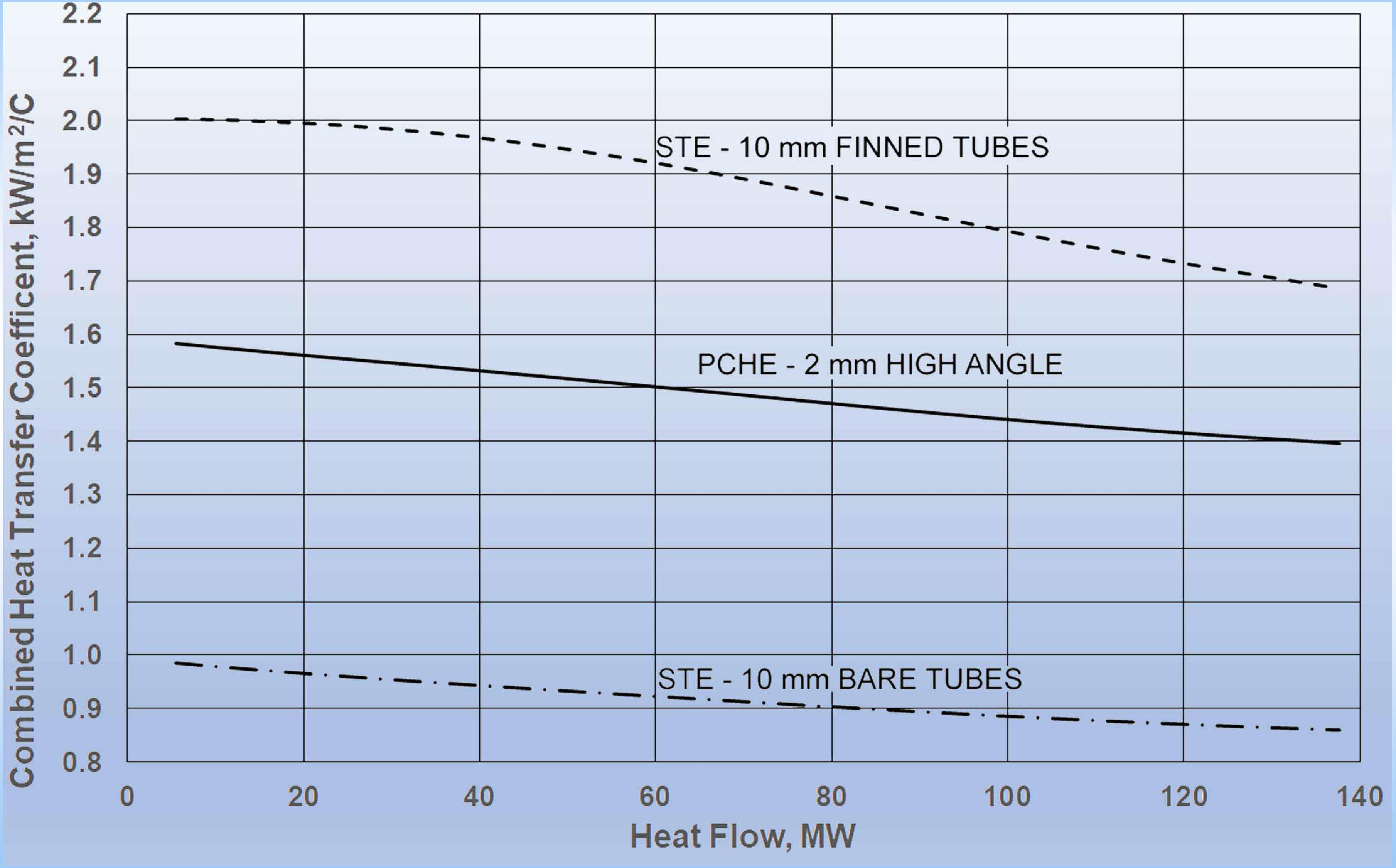
Simple Piping Arrangement with New Recuperator System



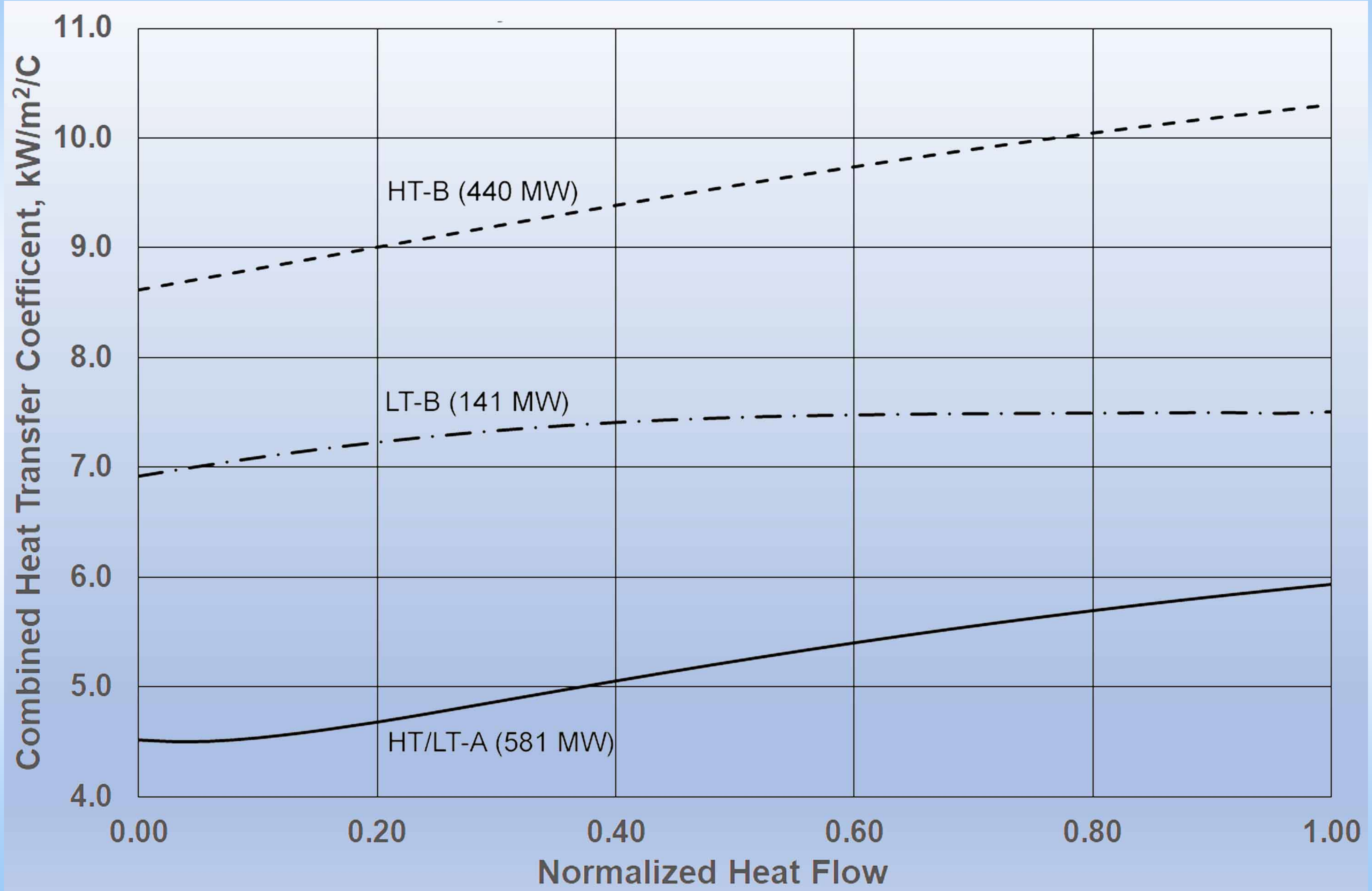
Comparison of HTC for HTR: PCHE and Finned & Bare Tube STE



Comparison of HTC for LTR: PCHE and Finned & Bare Tube STE



Comparison of HTC for New Recuperator System with NaK78



Selected Design Equations:

Printed Circuit Heat Exchanger Design Equations:

$$Nu = 0.0845Re^{0.721}Pr^{1/3}$$

$$f = 1.336Re^{-0.1268}$$

Tubular Heat Exchanger Design Equations:

$$Nu = 0.0225Re^{0.795}Pr^{0.495}exp[-0.0225(\ln Pr)^2]$$

$$f = 0.184Re^{-0.2}$$

Finned Heat Exchanger Design Equations:

$$Nu_D = 0.3 + \frac{0.62{Re_D}^{0.5}Pr^{1/3}}{[1 + (0.4/Pr)^{2/3}]^{0.25}}\left[1 + \left(\frac{Re_D}{28200}\right)^{5/8}\right]^{0.8}$$

$$\Delta P = \frac{1}{2}\rho V_{max}^2\left(1 + \sigma^2 + N_r K_f\right)$$

Liquid Metal Tubular Design Equation:

$$Nu = 10.0652(RePr)^{-0.1219} + 0.0373(RePr)^{0.7531}$$

Selected Properties of Sodium-Potassium Eutectic Mixture

Temp (°C)	Specific Gravity (-)	Dyn Viscosity (cP)	Thermal Conductivity (W/m/°C)	Specific Heat (kJ/kg/°C)
-13	0.877	1.125	21.136	1.004
0	0.874	1.002	21.400	0.995
200	0.826	0.362	24.660	0.908
400	0.778	0.234	26.160	0.878
600	0.730	0.167	25.900	0.876
800	0.682	0.134	23.880	0.893