High Effectiveness, Compact, High Pressure and Low-Cost Recuperator

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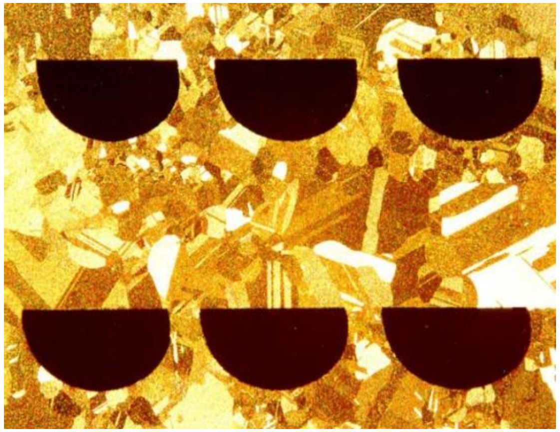
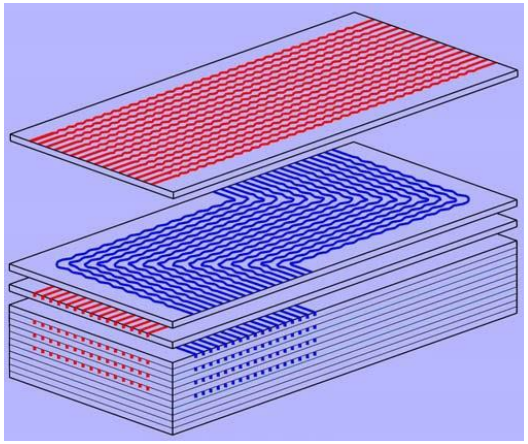
High Pressure Recuperative Heat Exchangers





- Many small channels maximize heat transfer for compactness
- Platelets allow bonding to a strong structure for high pressure capability
- Chemical etch or micromachining channels are costly processes
- Diffusion bonding is costly

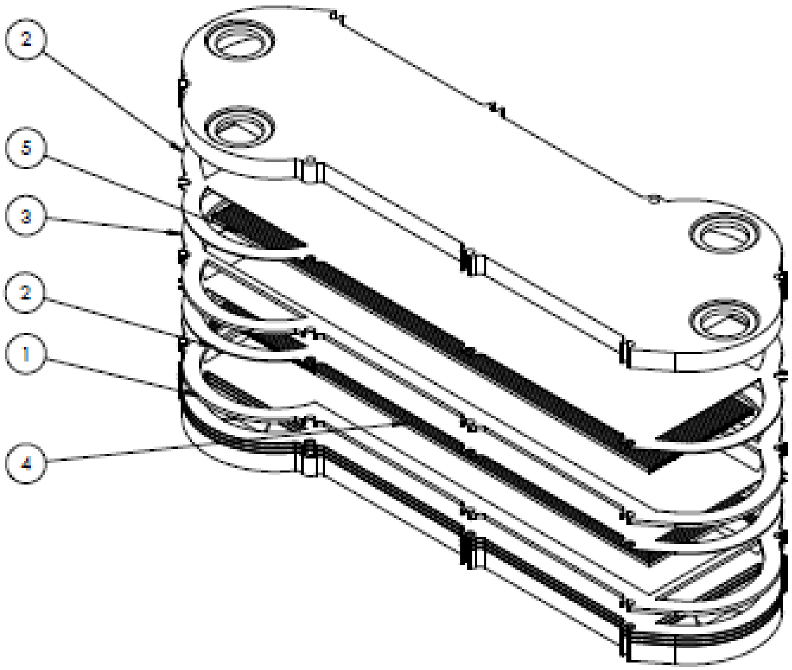
High Effectiveness Low Cost (HELC) Heat Exchanger

Purpose built high pressure and high effectiveness ScCO2 power system recuperator

- Low cost high surface area inserts
- Lower overall cost load-assisted brazing process
- Better weight, material cost and volume per surface area characteristics
- Has fewer bond joints and parts per volume

HELC Layered Construction for Best Braze Bonding

50KWt subscale test article



- Higher capacities achieved by adding more layers
- Inlets and outlets attached after furnace bonding

ITEM NO.	PART NUMBER	Revision	Description	QTY.
1	667-101	A-02	HP Frame	2
2	667-103	A-02	Plate 42	5
3	667-102	A-02	LP Frame	2
4	667-104 mockup	A-01	HP insert	2
5	667-104 mockup	A-01	HP insert	2
6	667-122	A-03	Top Inner Endplate	1
7	667-123	A-03	Bottom Endplate	1

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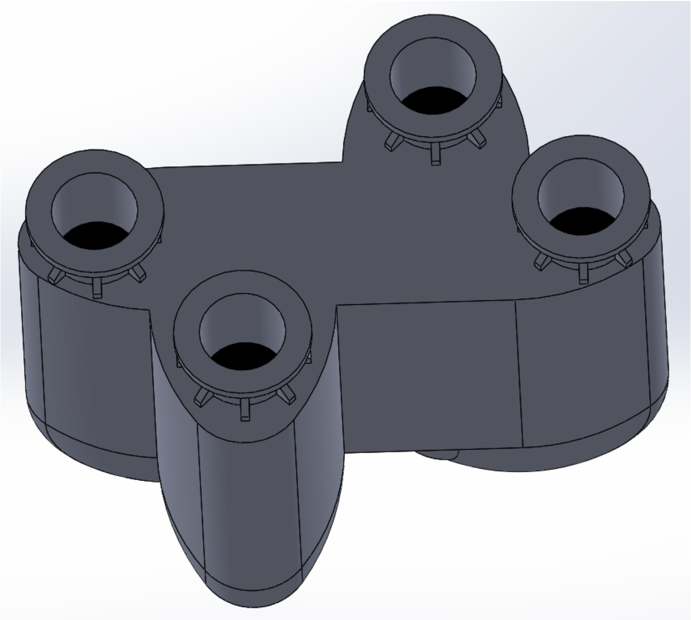
HELC Configurational Advantages

Geometrical factors indicate HELC has better characteristics than PCHE for application of interest

Heat Exchanger	Solidity	Area/Volume	Weight/Area	Volume/Area
	(%)	(ft2/ft3)	(lbm/ft2)	(ft3/ft2)
PCHE	63.6	447	.697	.00223
HELC	52.6	816	.315	.00123
HELC/PCHE	.893	1.82	.453	.548

Full Scale 46 MWt HELC Module

HELC full-scale module dimensions and estimated performance



46.6 MWt Module Configuration

Parameter	Value
Core length	78 inches
Core width	32 inches
Core height	66 inches
Heat transfer	46.6 MWt
Effectiveness	97.6%
Maximum length	114 inches
Maximum width	74 inches
Maximum height	103 inches
Core volume metric	.0016 M^3/UA
Core weight metric	6.1 Kg/UA

HELC Sub-scale Test Article Frames and Plates

50 KWt HELC frames and plates

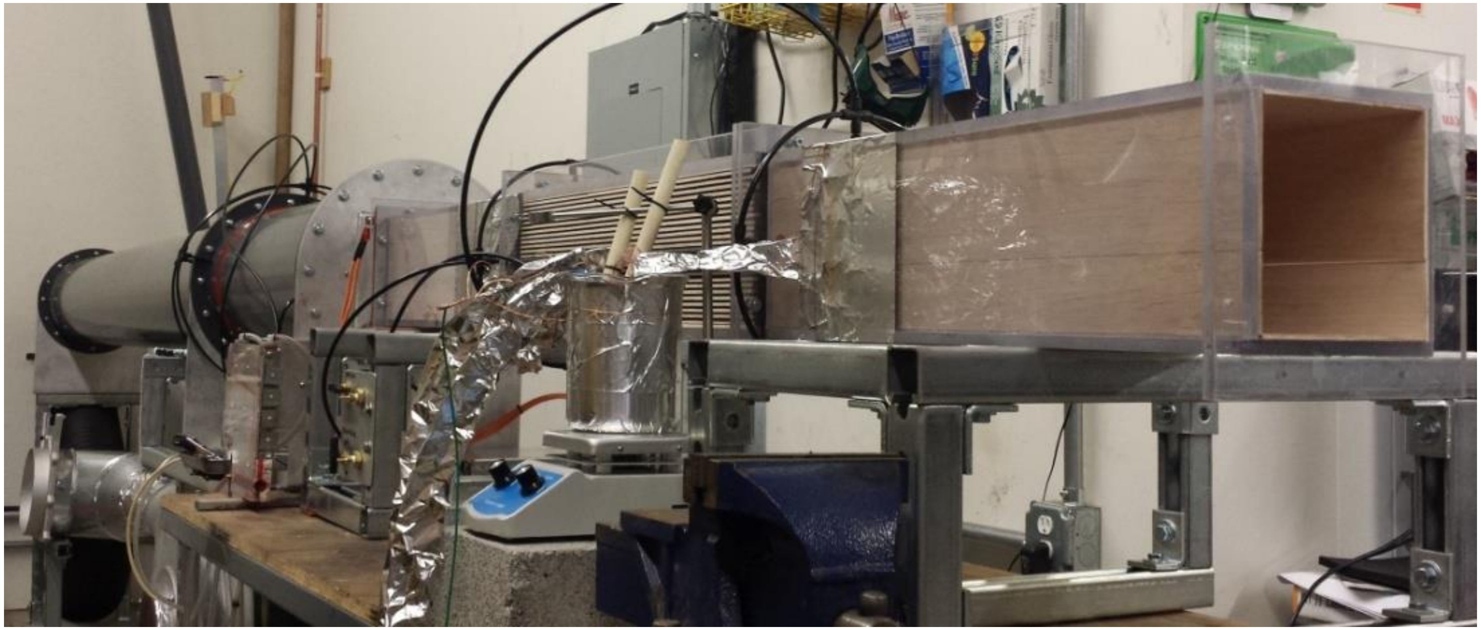
- Common parts for different capacities
- Frames provide good faying surfaces for bonding to plates
- Different inserts for enhanced performance

Braze Bonding Vacuum Furnace

- Load assisted braze bonding at VPE under ISO9001 and AS9100 certification
- Stainless steel and nickel-based braze alloys
- Cleaning and quality check at Vacuum Process Engineering (VPE)
- Bonding using VPE process and furnaces
- Integrity tests at VPE and Altex

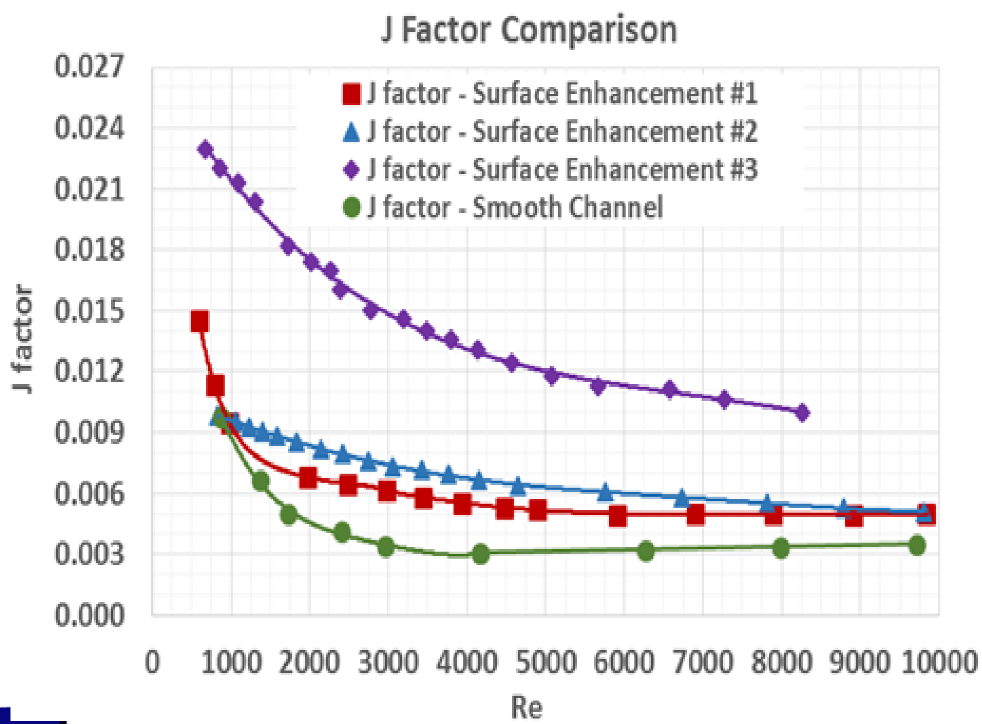
HELC Insert Heat Transfer Enhancement

Channel heat transfer and pressure drop performance test apparatus



Comparison of Smooth Channel and Surface Feature Heat Transfer Enhancements

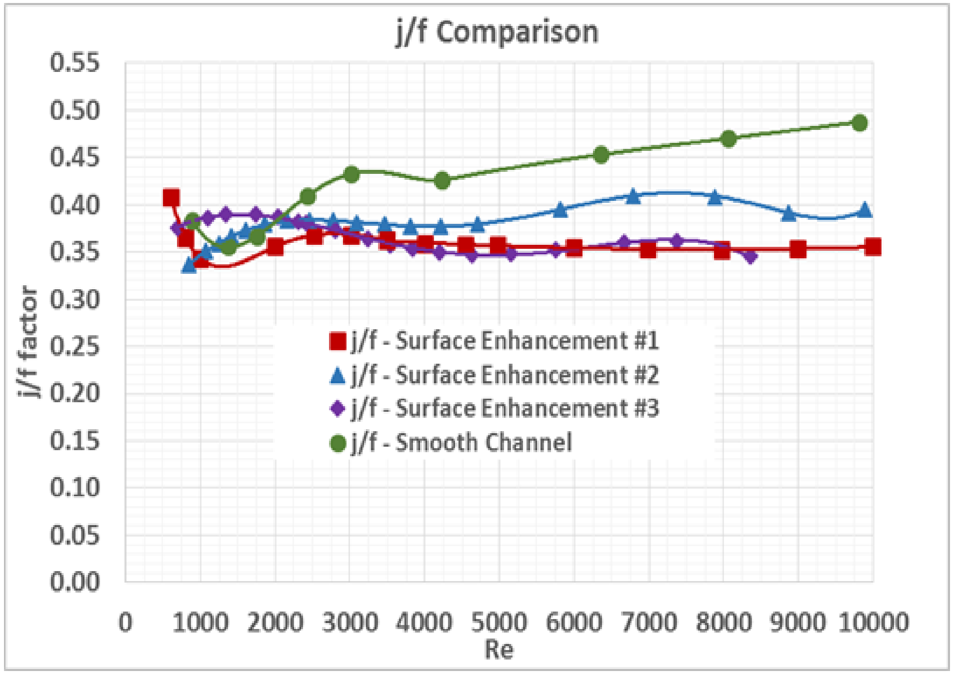
Surface features significantly increase heat transfer coefficient



- Surface features 1, 2 and 3 have approximately 71%, 100% and 342% higher J factors than smooth channel for Re 3000
- Core volumes, weight and material cost for enhancements 1, 2 and 3 reduced by 42%, 50% and 77%, respectively

Comparison of Smooth Channel and Surface Feature Enhancements Thermal Efficiency

Surface features have good thermal efficiency



- Surface features 1, 2 and 3 have similar thermal efficiencies to smooth channels at Re 2,000
- Surface features 1, 2 and 3 have 14% lower thermal efficiencies than smooth channels at Re 4,000

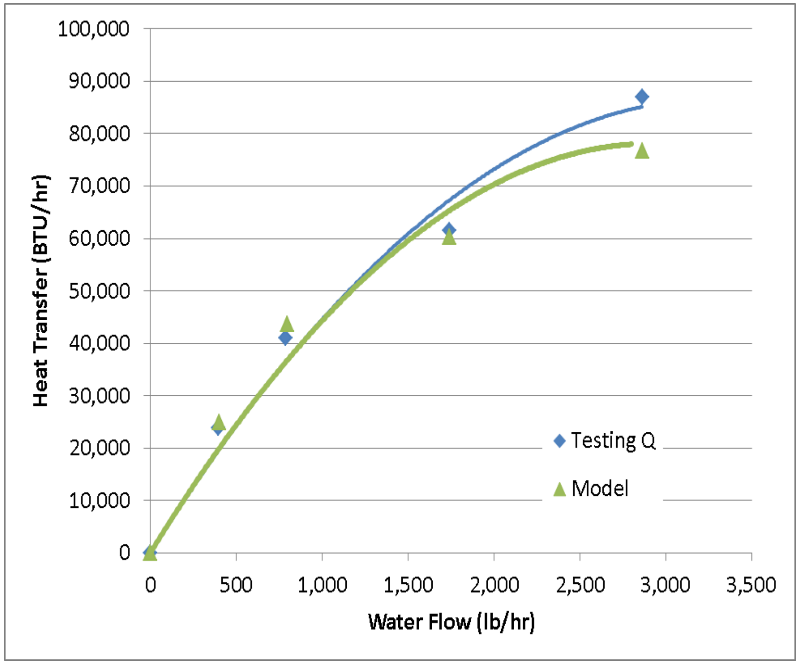
Comparison of HELC and Conventional Enhancements

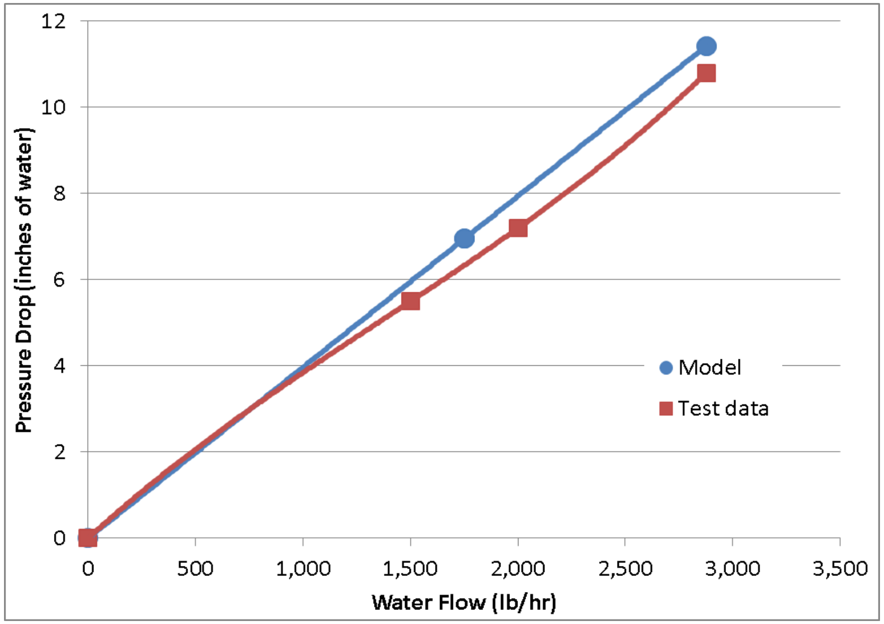
Surface features are more efficient than conventional enhancements

Surface	J	J/f	Efficiency Reduction versus Smooth Channel (%)
Smooth Channel Baseline	.0033	.43	--
Surface Enhancement 1	.0062	.365	15.2
Surface Enhancement 2	.0075	.380	11.6
Surface Enhancement 3	.0148	.365	15.2
Louvered Surface	.009	.225	47.7
Wavy Surface	.0105	.202	53.0

HELC Performance Testing

Water test and model heat transfer and pressure drop results for 50 KWt unit comparable to within 12%





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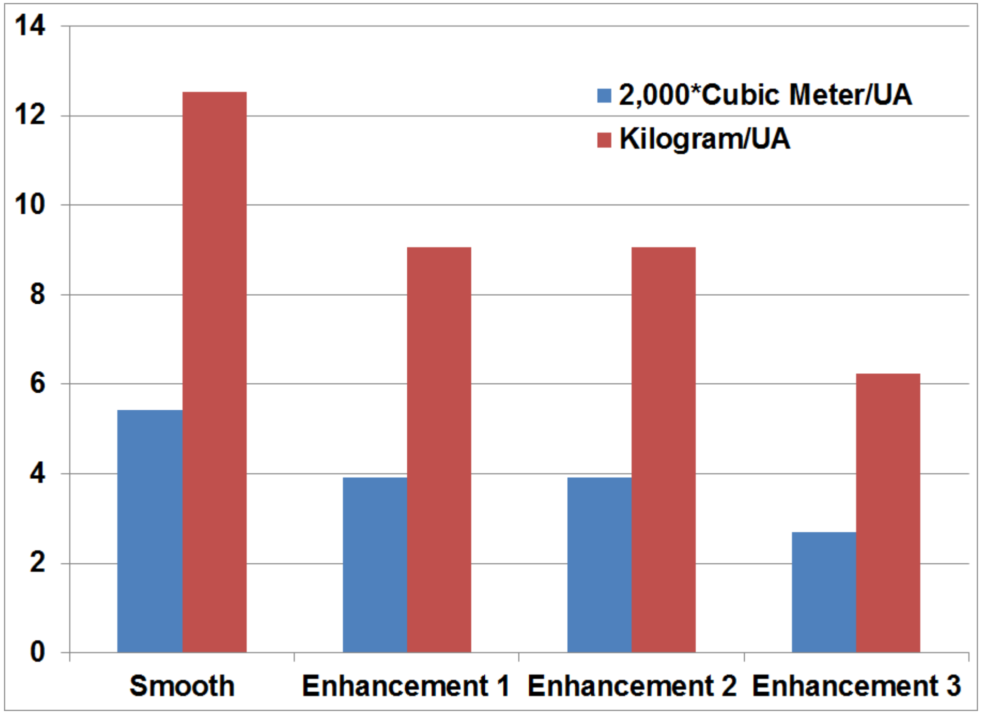
HELC Performance Enhancement

548KWt class HELC at 95% effectiveness



- **Surface enhancements reduce weight and volume metrics by 27% to 50%**
- **Maximum pressure drops are 8.8 to 12.5 psi**
- **Enhancement 1 and 2 pressure drops are 10.0 and 8.8 psi**
- **Reducing weight should reduce cost**

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Conclusions and Plans

- HELC design has potential to lower PCHE type weight, volume and material cost by 55%, 45% and 55%, respectively, based on geometrical factors
- Three surface enhancements tested show 71%, 100% and 342% higher heat transfer coefficients than those for smooth channels, with good thermal efficiency
- Water tests and model heat transfer and pressure drop results compare within 12% supporting usefulness of model
- Model results show that CM/UA and Kg/UA heat exchanger metrics can be reduced by 27% to 50% by special surface enhancements
- Plan to build and test larger unit with ScCO2