A New Method for Modelling Off-design Performance of sCO2 Heat Exchangers Without Specifying Detailed Geometry.

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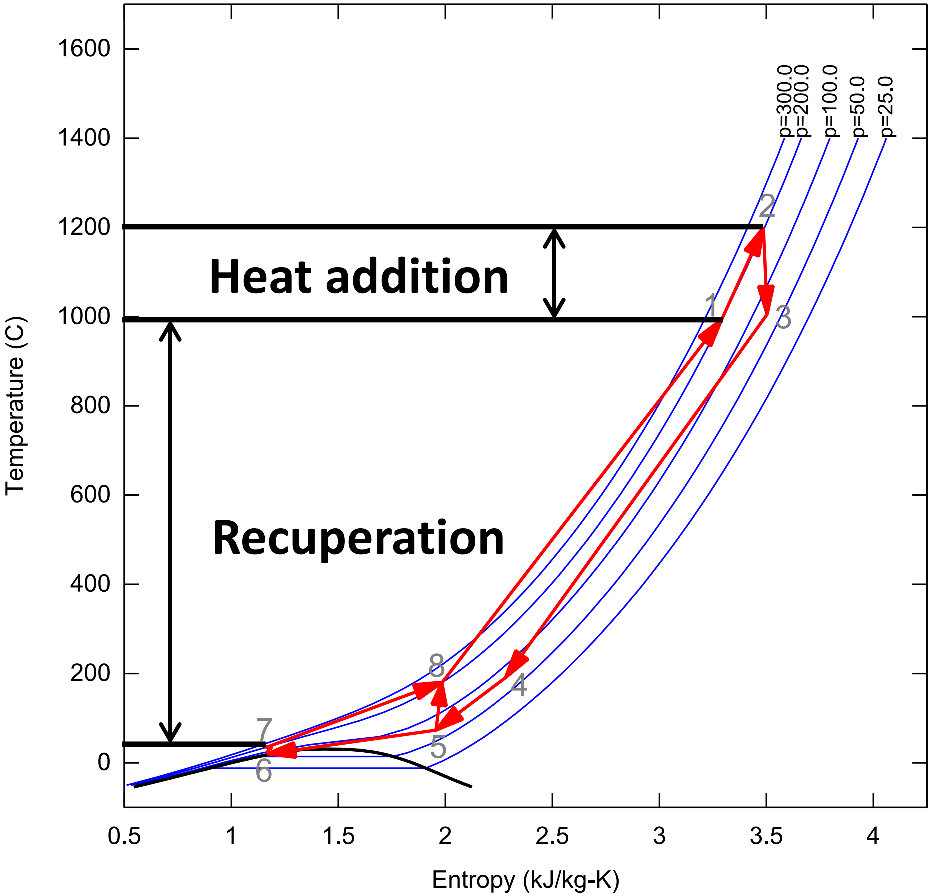
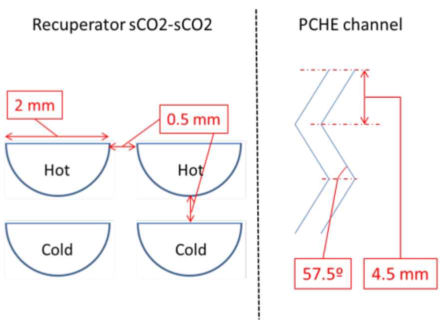


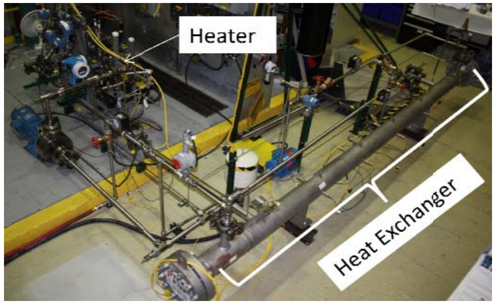
This talk focuses on a new method for estimating heat exchanger off-design performance without detailed geometry with special attention given to sCO2 cycles.

$$hA_{ratio} = \frac{hA_{hot}}{hA_{cold}}$$

Motivation, Classic heat exchanger modeling, and Method details



Comparison to PCHE design code



Comparison to experimental sCO2 HX data

Motivation

Off-design prediction of heat exchanger performance in sCO2 cycles is important.

All power generation cycles experience off-design. CSP plants will also experience off-design operation due to unsteady solar irradiance and daily startup and shutdown cycles.

Classic heat exchanger modeling, on and off-design

It is straightforward to obtain the initial rough design of a heat exchanger.

Specify duty, temperatures and pressures from desired performance

$$Q = UA \cdot f(\Delta T)$$

Calculate overall resistance required

$$\frac{1}{UA} = \underbrace{\underbrace{\left.\frac{1}{hA}\right|_{hot}}_{\text{Hot resistance}} + \underbrace{R_{wall}}_{\text{Wall resistance}} + \underbrace{\left.\frac{1}{hA}\right|_{cold}}_{\text{Cold resistance}}}_{\text{Specify geometry to create required overall resistance}}$$

Required UA is calculated for desired performance then geometry is specified to obtain the required UA from the constituent resistance terms.

This same method can be used in reverse as well to predict heat exchanger off-design performance

Use UA term and energy conservation to predict outlet temperatures

$Q = UA \cdot f(\Delta T) = \dot{m}\,\Delta h_{hot} = \dot{m}\,\Delta h_{cold}$

$$\frac{1}{UA} = \frac{1}{hA}\bigg|_{hot} + R_{wall} + \frac{1}{hA}\bigg|_{cold}$$

Calculate new overall resistance

Hot resistance

Wall resistance

Cold resistance

Specify geometry and flow conditions (off-design temperature, pressure, massflow etc.)

Geometry and off-design flow conditions are used to calculate new UA term, then this term along with energy conservation is used to calculate off-design heat exchanger performance.

Our method

With a new term, hA_{ratio}, and scaling laws we are able to predict off-design performance without detailed geometry.

$$\frac{1}{UA_{on-design}} = \frac{1}{hA_{on-design}^{hot}} + \frac{1}{hA_{on-design}^{cold}}$$

$$hA_{ratio} = \frac{hA_{hot}}{hA_{cold}}$$

This allows us to divide the required UA into its constituent terms

$$hA_{off-design}^{hot} = hA_{on-design}^{hot} * f(hot\ off-design\ conditions)$$

$$hA_{off-design}^{cold} = hA_{on-design}^{cold} * f(cold\ off-design\ conditions)$$

$$\frac{1}{UA_{off-design}} = \frac{1}{hA_{off-design}^{hot}} + \frac{1}{hA_{off-design}^{cold}}$$

$$Q = UA \cdot f(\Delta T) = \dot{m}\,\Delta h_{hot} = \dot{m}\,\Delta h_{cold}$$

Defining hA_{ratio} and using scaling laws allows us to scale the on-design UA term without specifying detailed geometry ultimately allowing an estimate the off-design performance.

Physically, the hA_{ratio} represents which side of the heat exchanger provides the most resistance to heat flow.

$$hA_{ratio} = \frac{hA_{hot}}{hA_{cold}}$$

$$\left.\frac{1}{hA}\right|_{hot} + R_{wall} + \left.\frac{1}{hA}\right|_{cold} = \frac{1}{UA}$$

$$hA_{ratio} = \frac{hA_{hot}}{hA_{cold}} = 100$$

$$\frac{1}{10{,}000} + 0 + \frac{1}{100} = \frac{1}{99.0}$$

Double hot h

$$\frac{1}{20{,}000} + 0 + \frac{1}{100} = \frac{1}{99.5}$$

Double cold h

$$\frac{1}{10{,}000} + 0 + \frac{1}{200} = \frac{1}{196.1}$$

A high hA_{ratio} means that the hot side of the heat exchanger is better at allowing heat flow thus the heat exchanger performance will be dominated by changes in the cold flow.

Scaling laws using Reynolds and Prandtl number are used.

$$\frac{1}{UA_{on-design}} = \frac{1}{hA^{hot}_{on-design}} + \frac{1}{hA^{cold}_{on-design}}$$

$$hA_{ratio} = \frac{hA_{hot}}{hA_{cold}}$$

$$hA^{hot}_{off-design} = hA^{hot}_{on-design} * f(hot\ off - design\ conditions)$$

$$hA_{off-design} = hA_{on-design} * \left[\frac{\lambda_{off-design}}{\lambda_{on-design}}\right] * \left[\frac{Re_{off-design}}{Re_{on-design}}\right]^{x} * \left[\frac{Pr_{off-design}}{Pr_{on-design}}\right]^{y}$$

$$hA_{off-design} = hA_{on-design} * \left[\frac{\lambda_{off-design}}{\lambda_{on-design}}\right] * \left[\frac{\dot{m}_{off-design}/\mu_{off-design}}{\dot{m}_{on-design}/\mu_{on-design}}\right]^{x} * \left[\frac{Pr_{off-design}}{Pr_{on-design}}\right]^{y}$$

$$\Delta P_{off-design} = \Delta P_{on-design} * \frac{\dot{m}^2{}_{off-design}/\rho_{off-design}}{\dot{m}^2{}_{on-design}/\rho_{on-design}}$$

For simplicity in this paper, we used exponents from the Dittus Bolter pipe flow Nusselt number correlation.

$$hA_{off-design} = hA_{on-design} * \left[\frac{\lambda_{off-design}}{\lambda_{on-design}}\right] * \left[\frac{Re_{off-design}}{Re_{on-design}}\right]^{0.8} * \left[\frac{Pr_{off-design}}{Pr_{on-design}}\right]^{0.3\ or\ 0.4}$$

Any exponents or other scaling law could potentially be used, this is an area for future work.

Method Overview

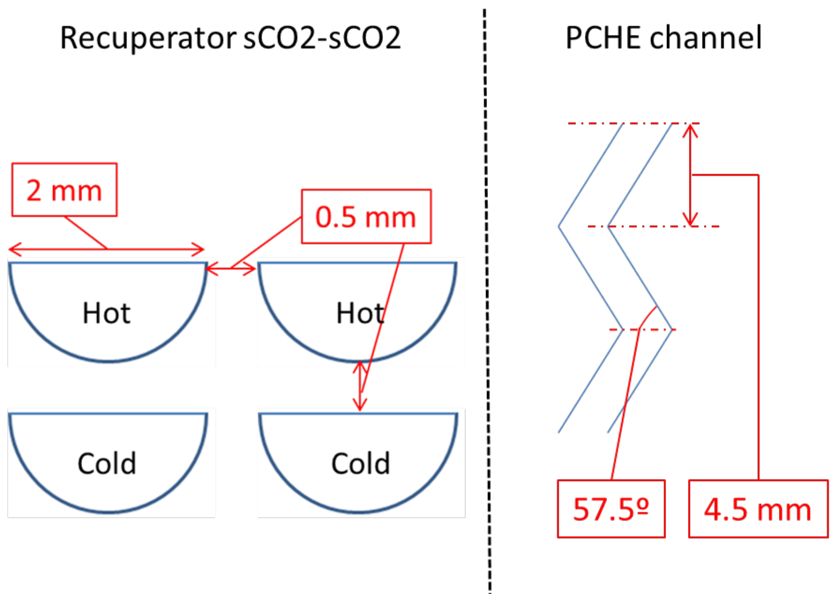
1. Discretize heat exchanger to account for fluid property nonlinearity
2. Compute on-design UA for each division
3. Set hA ratio (equal for all divisions)
4. Using hA ratio, divide UA in each division into constituent hA terms for both hot and cold side
5. Define off-design flow conditions
6. Scale each hA term in each division using a scaling law which is a function of the new off-design conditions
7. Scale pressure drop for accurate fluid properties
8. Assemble off-design UA term for each division
9. Use new UA term for each division and energy conservation to solve for off-design performance in an iterative manner

Use cases for our method

1. **During the cycle analysis/optimization, optimize cycle for off-design performance by setting a value of hA ratio depending on anticipated heat exchanger type.**
2. **During the cycle analysis/optimization, analyze potential off-design scenarios based on choice of hA ratio**
3. **Given a heat exchanger with off-design experimental data, calibrate hA ratio and predict heat exchanger operation at new off-design points**

Analytical comparison

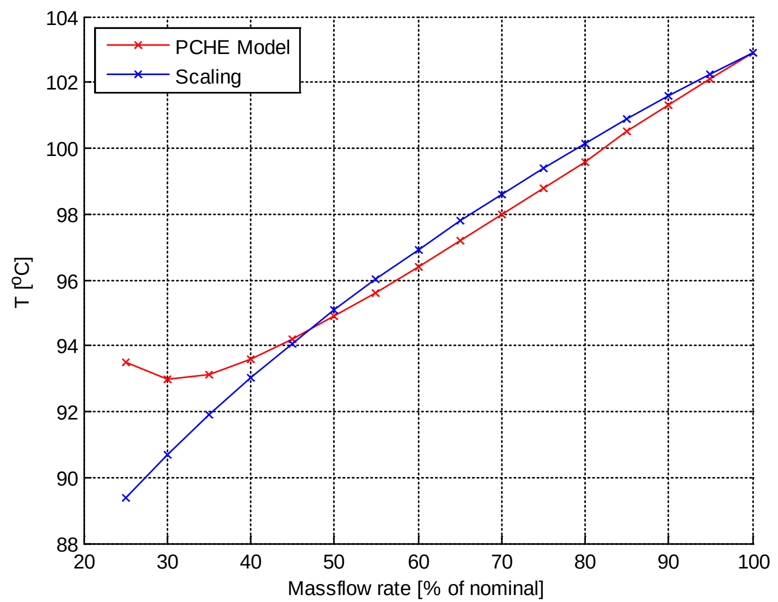
The University of Seville has developed a PCHE design tool which we used to predict sCO2 recuperator performance.



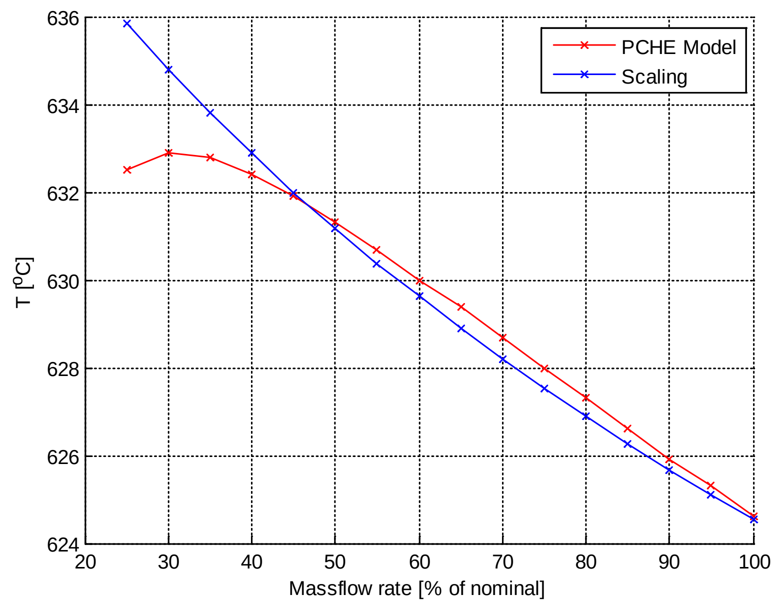
	T_{in} [ºC]	p_{in} [bar]	T_{out} [ºC]	p_{out} [bar]	$\dot{m}$[kg/s]
sCO2 (hot side)	776.9	30.86	102.9	30.05	290
sCO2 (cold side)	81.9	297.62	624.6	297.48	290

The PCHE geometry was chosen to represent a typical geometry for this application. Conditions are from the Allam cycle.

Our method is able to predict HX off-design performance down to 40% load.



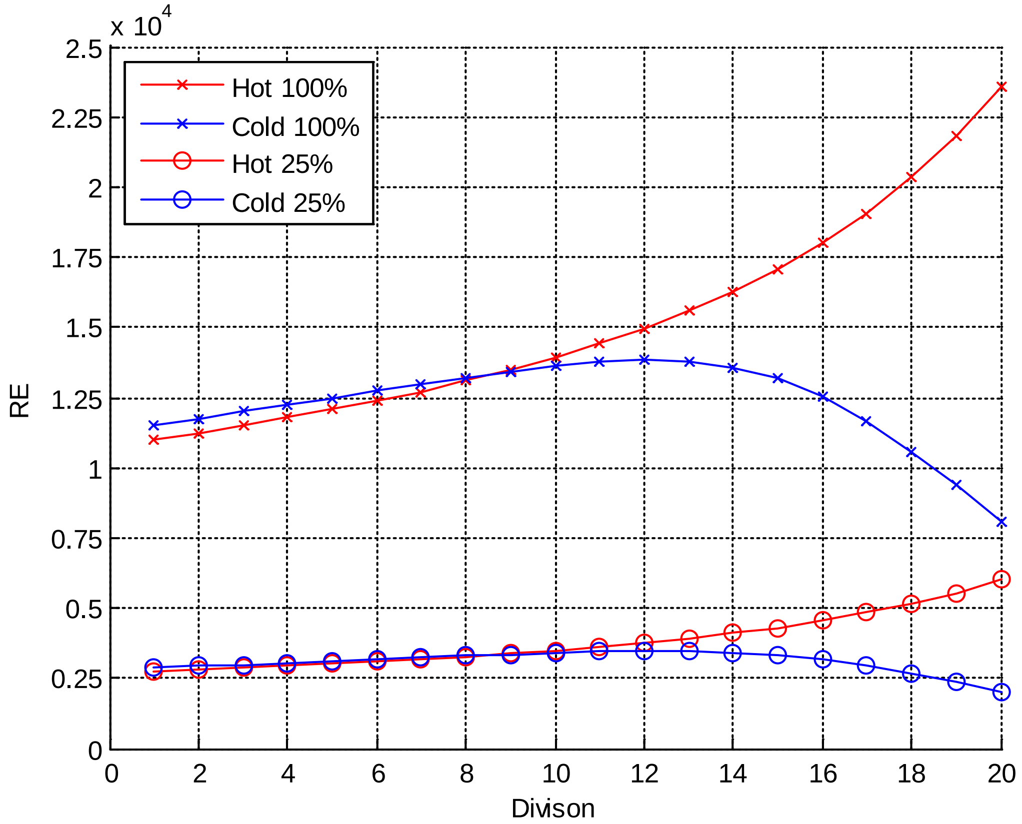
hot



cold

Note, these results are not very sensitive to hA ratio as both sides of the heat exchanger are scaled in the same manner.

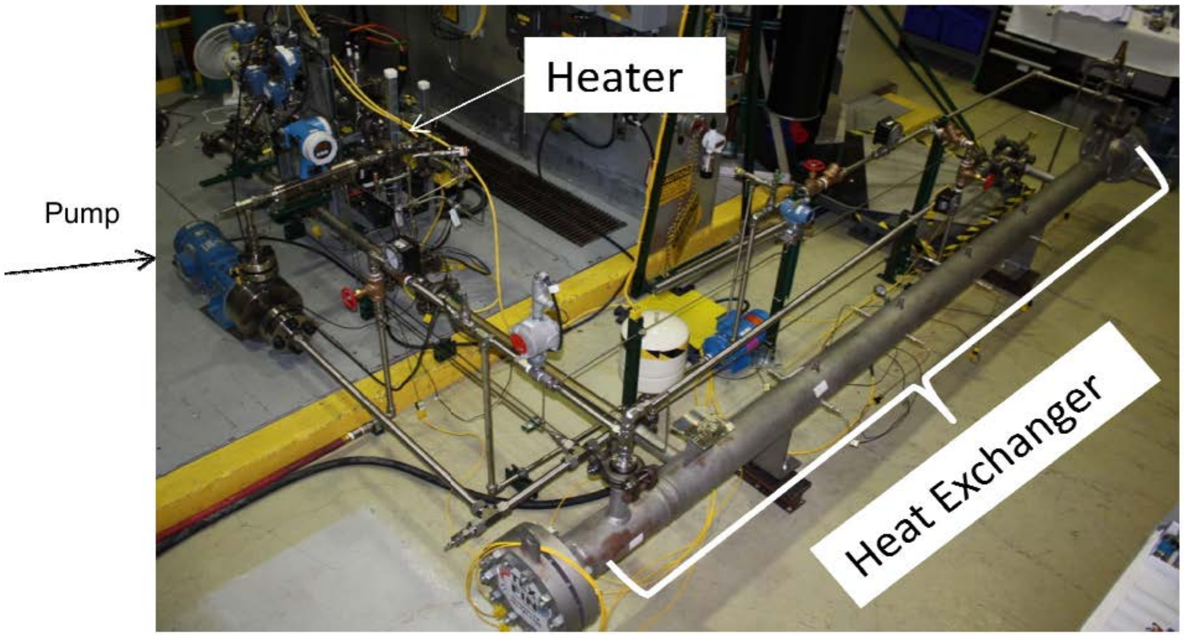
At low flows, the PCHE model uses laminar heat transfer correlations, this is not captured by the scaling laws.



This is a known limitation with our method, as it does not know anything about heat exchanger geometry it is not able to adjust for laminar flow.

Experimental comparison

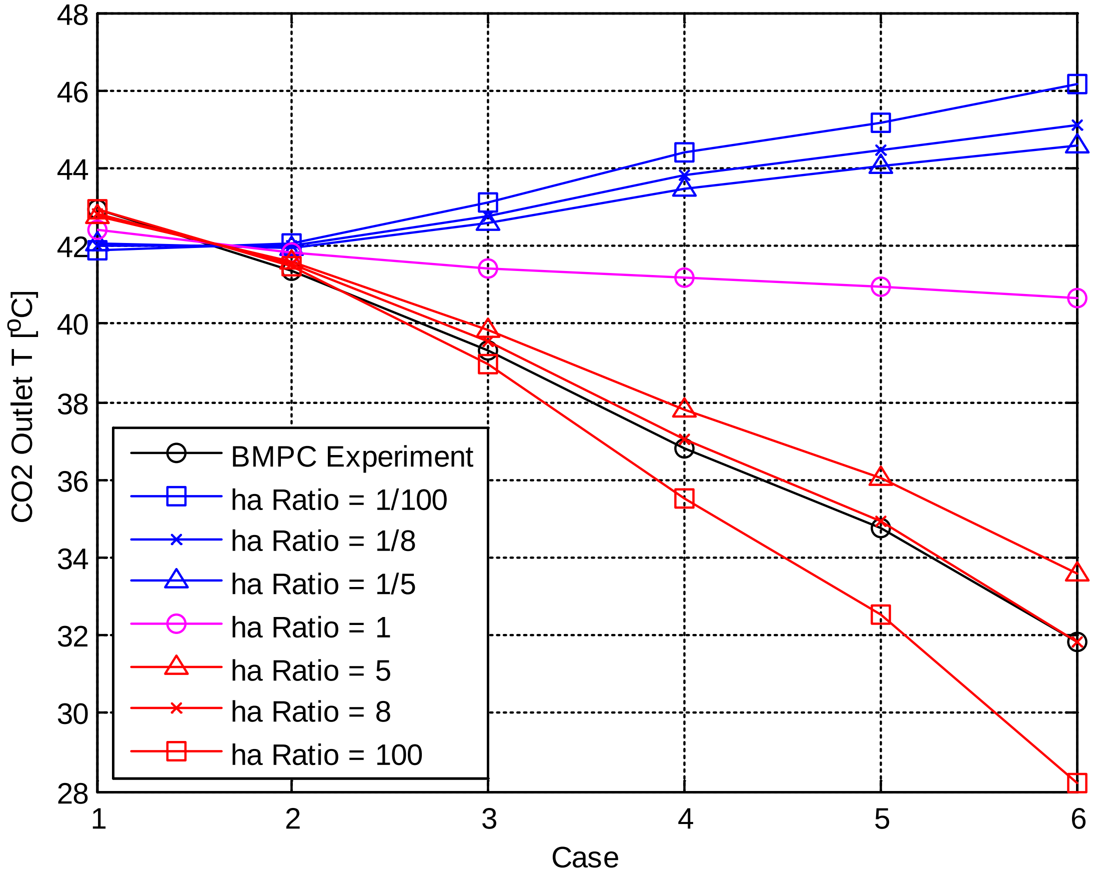
In 2015, Fourspring and Nehrbauer published experimental HX off-design results from their testing at BMPC



	$\dot{m}\ \left[\frac{kg}{s}\right]$	T_{in} [ºC]	$\overline{p}$ [bar]	Δp [bar]	Q [kW]
sCO2	1.36	58.89	95.15	<2.07	100
Water	1.41	18.33	4.83	<2.76	100

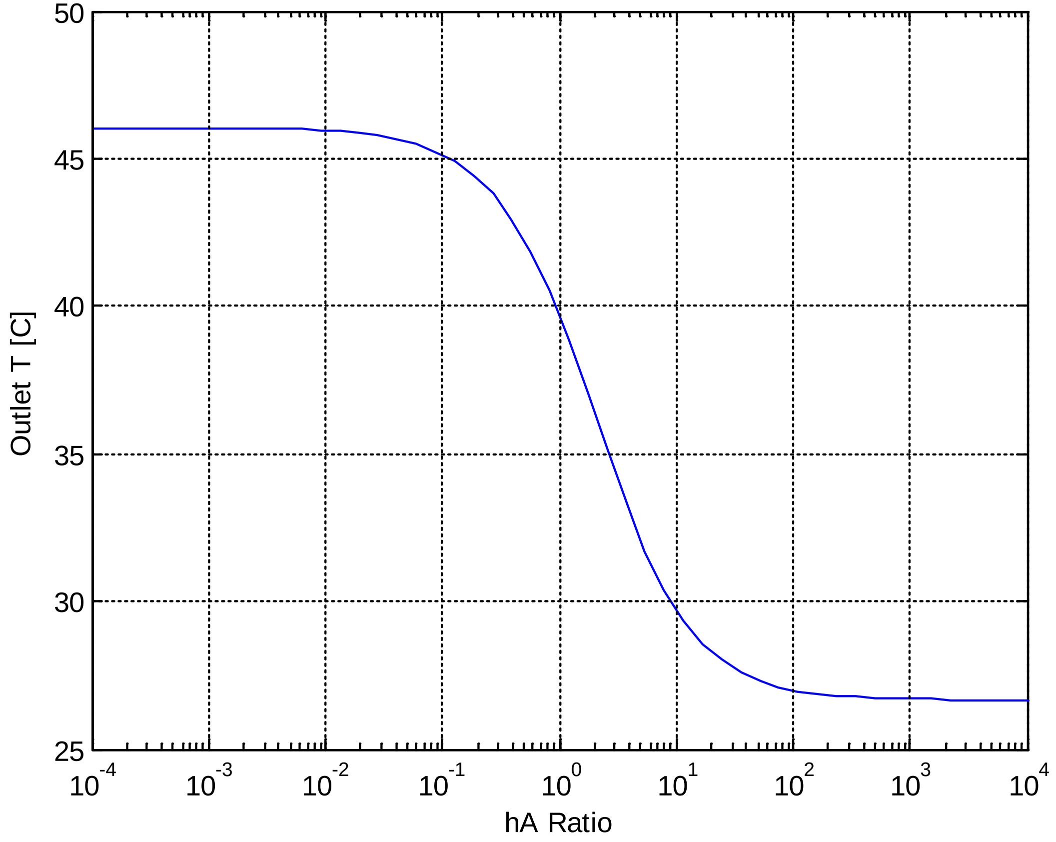
Complete result set is proprietary. For this reason, only sCO2 outlet conditions for the various different cases, which were also reported in the original paper, are presented here.

Using our method, we are able to accurately predict the sCO2 outlet temperature of the heat exchanger.



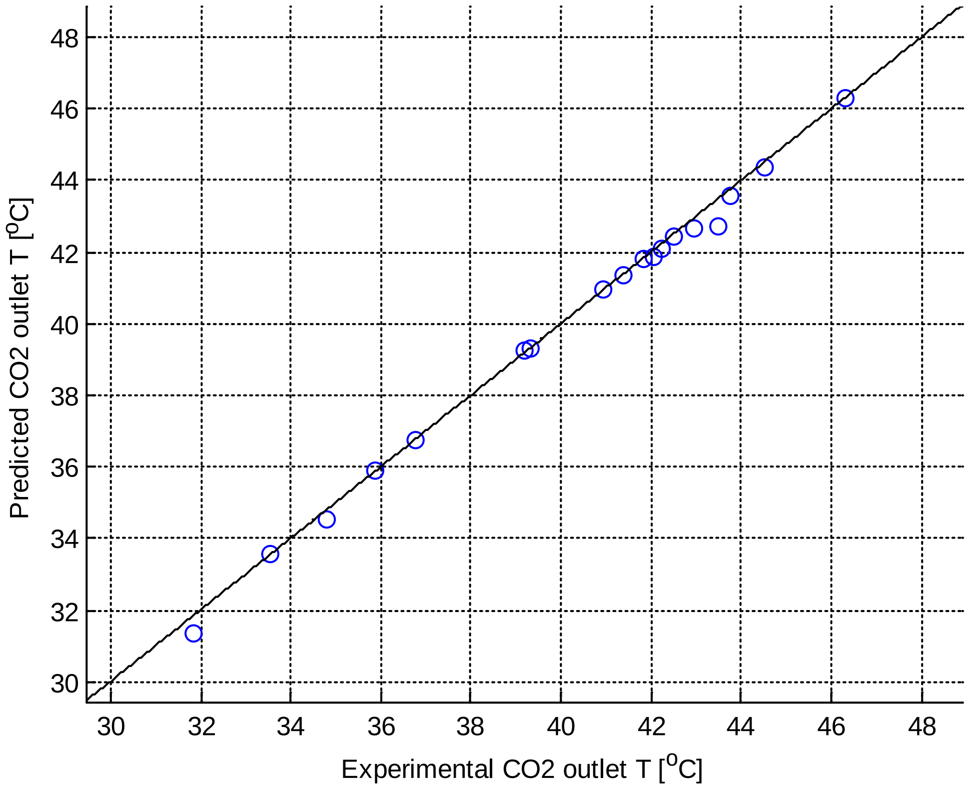
When an hA ratio of 8 is used, our method is able to accurately predict the off-design points. The further from design, the more impact hA ratio has on the result.

Looking at one off-design point in detail reveals the impact of hA ratio on HX performance prediction



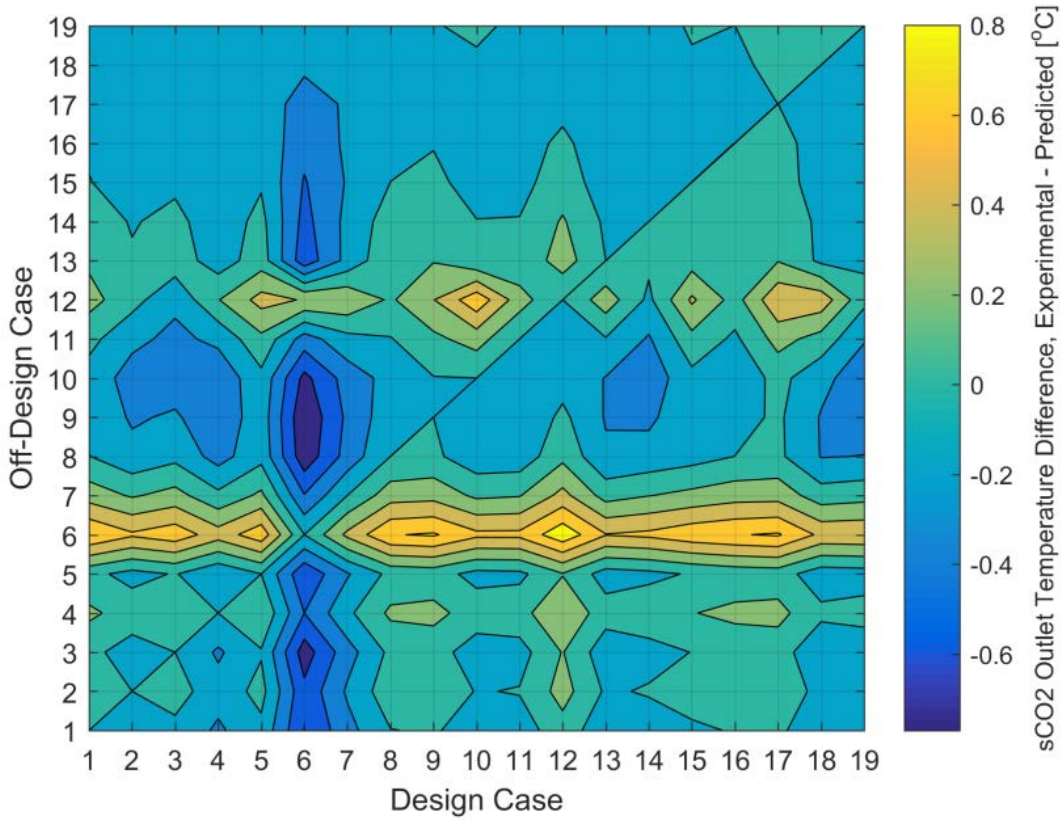
A heat exchanger could be designed at each of these values of hA ratio which could have the desired on-design performance, but the off-design performance would be very different.

Using our method, we are able to predict all off-design points.



With the hA ratio that matches the BMPC design, all off-design conditions can be predicted. Also, any off-design case can be used to predict any other case, either on or off-design.

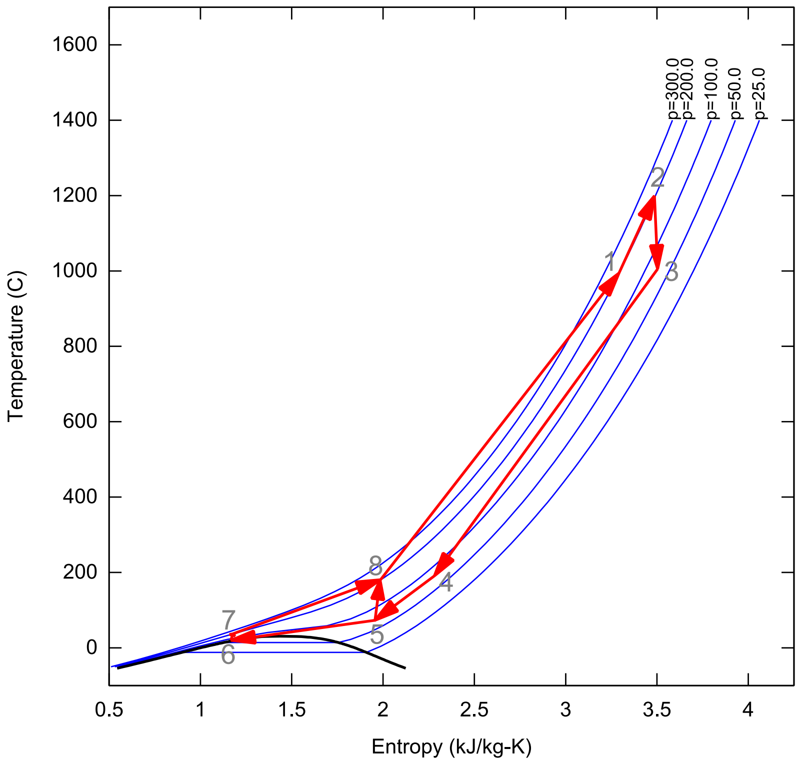
Our method is able to use any of the conditions to predict any of the other conditions in the test matrix.

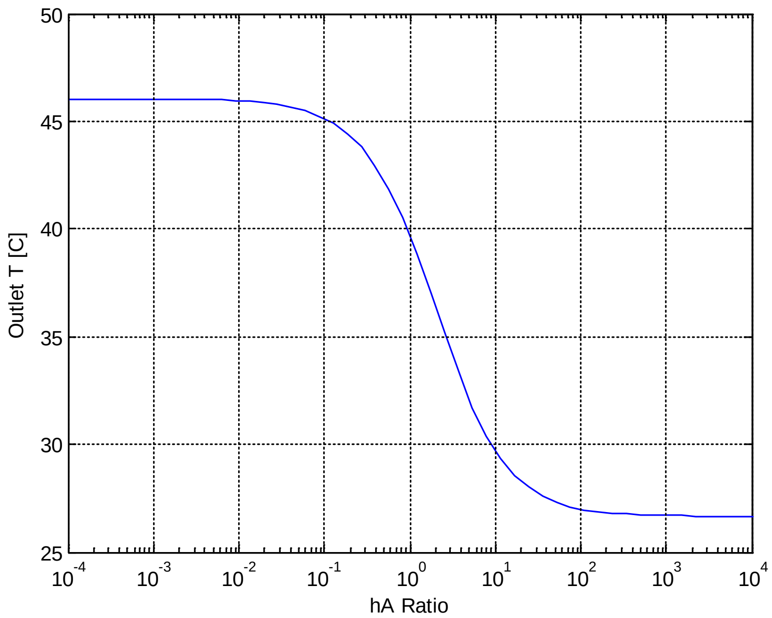


Any point in the test matrix can be used to predict any other point in the test matrix. This result uses a custom hA ratio for each case that minimizes RMS error to predict all other cases in the test matrix. The value of hA ratio ranged from 2 to 15.

Conclusion

The real power of our method is in design space exploration during cycle analysis phase.





By varying the hA ratio, the designer can explore different potential off-design conditions and create a heat exchanger design with favorable off-design performance.

Conclusion

Using our method, one is able to predict off-design heat exchanger performance without specifying detailed geometry.

This allows the designer to explore potential off-design scenarios and choose a heat exchanger design for the desired off-design performance.

$$hA_{ratio} = \frac{hA_{hot}}{hA_{cold}}$$

Questions?