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# Design and dynamic modeling of printed circuit heat exchangers for supercritical carbon dioxide Brayton power cycles

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## HIGHLIGHTS

- Design and dynamic models are developed for PCHEs in $sCO_2$ Brayton cycles.
- Models are validated with the laboratory operating data.
- Design guidance is provided for a 10 MWe pilot-scale $sCO_2$ Brayton cycle.
- Key design and dynamic measures of three types of exchangers are compared.

## ARTICLE INFO

*Keywords:*
$sCO_2$ Brayton cycle
Printed circuit heat exchanger
Optimal design
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## ABSTRACT

Due to the unique geometries and hydraulics of printed circuit heat exchangers and rapidly changing properties of supercritical carbon dioxide, the effective design and rating of printed circuit heat exchangers is an essential requirement for their use in supercritical carbon dioxide power cycles. In this study, one-dimensional design and dynamic models have been developed in Aspen Custom Modeler for printed circuit heat exchangers utilized in printed circuit heat exchangers Brayton power cycles. The design model is used to determine the optimal geometry parameters by minimizing the metal mass. The dynamic model is used to predict transient behavior and can be easily implemented into system-level models developed in Aspen Plus Dynamics for cycle performance evaluations. In these models, the heat transfer coefficient and friction factor are calculated using data reported by Heatric, a prominent printed circuit heat exchanger manufacturer. Both models are validated by comparing with the data from a small-scale exchanger used in the 100 kWe facility operated by the Naval Nuclear Laboratory, and then applied to design and simulate low- and high-temperature recuperators for a 10 MWe supercritical carbon dioxide indirect recompression closed Brayton cycle, which is of interest to the U.S. Department of Energy. The designs and dynamic responses of the printed circuit heat exchangers are compared with conventional shell-and-tube exchangers and microtube shell-and-tube exchangers for the same applications. The simulation results indicate that the proposed printed circuit heat exchangers have fast dynamic responses due to their small metal masses and high heat transfer coefficients compared with the conventional shell-and-tube exchangers. Even though the metal masses of the designed PCHEs are slightly higher than those of the microtube shell-and-tube exchangers, the printed circuit heat exchangers are still promising candidates for heat recuperation because of their mature manufacturing procedures and abundant laboratory and industrial operating experience.

## 1. Introduction

Supercritical carbon dioxide ($sCO_2$) is a promising alternative working fluid for power generation, because of its potential high efficiency and power density [1,2], especially when operating at high temperatures [1,3]. Ahn et al. reviewed several configurations of $sCO_2$ power cycles proposed in the open literature [1]. Among those configurations, the indirect $sCO_2$ recompression closed Brayton cycle (RCBC) is gaining recent interest [4], and the development of a 10 MWe $sCO_2$ RCBC pilot plant is the focus of a Department of Energy project awarded under its Supercritical Transformational Electric Power (STEP) program [4,5]. Different from typical steam-based Rankine power cycles, the entire $sCO_2$ Brayton cycle is usually operated above the critical point of $CO_2$. Also the $sCO_2$ cycle pressure ratio is much smaller than

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**Nomenclature**

*Abbreviations*

| | |
|---|---|
| 1D | one-dimensional |
| 3D | three-dimensional |
| ACM | aspen custom modeler |
| BFD | backward finite difference |
| CFD | computational fluid dynamics |
| FFD | forward finite difference |
| H | high-angle channel (40°) |
| HTR | high temperature recuperator |
| IST | integrated system test |
| L | low-angle channel (30°) |
| MSTE | microtube shell-and-tube exchangers |
| NETL | national energy technology laboratory |
| NIST | national institute of standards and technology |
| O | optimized |
| PCHE | printed circuit heat exchanger |
| PDE | partial differential equation |
| RCBC | recompression closed Brayton cycle |
| $sCO_2$ | supercritical carbon dioxide |
| SQP | successive quadratic programming |
| SRBC | simple recuperated Brayton cycle |
| STEP | supercritical transformational electric power |
| TIT | Tokyo institute of technology |

*Roman symbols*

| | |
|---|---|
| $A_c$ | cross-section area of metal wall per channel in $m^2$ |
| $C_p$ | specific heat in kJ/kg/°C |
| $D_c$ | channel width in m |
| $D_e$ | hydraulic diameter in m |
| $f$ | Darcy friction factor |
| $F_m$ | mass flowrate in kg/s |
| $G$ | molar flowrate in kmol/s |
| $h$ | heat transfer coefficient in $kW/m^2/°C$ |
| $H$ | Molar enthalpy in kJ/kmol |
| $k$ | thermal conductivity in W/m/°C |
| $L_c$ | actual channel length in m |
| $L_w$ | wave length in m |
| $L_x$ | width of PCHE core in m |
| $L_y$ | hight of PCHE core in m |
| $L_z$ | length of PCHE core in m |
| $M_{HX}$ | total metal mass of the recuperator in kg (1 tonne = 1000 kg) |
| $N_c$ | number of channels per plate |
| $N_{cp}$ | number of channels in cold plates |
| $N_{hp}$ | number of channels in hot plates |
| $N_p$ | number of plates |
| | Nusselt number |
| $P$ | pressure in bar |
| $\Delta P_{max}$ | Maximum allowable pressure drop in bar |
| $Pr$ | Prandtl number |
| $Q$ | heat duty in MW |
| $R_p$ | ratio between the number of hot and cold plates |
| $Re$ | Reynolds number |
| $T$ | temperature in °C |
| $\Delta T_d$ | design temperature approach in °C |
| $t_2$ | wall thickness in m |
| $t_3$ | ridge width in m |
| $t_e$ | equivalent wall thickness in m |
| $U$ | internal energy in kJ/kmol; overall heat transfer coefficient in $W/m^2/°C$ |
| $UA$ | heat conductance in kW/°C |
| $V$ | molar volume in $m^3/kmol$ |
| $v$ | velocity in m/s |

*Greek symbols*

| | |
|---|---|
| $\alpha$ | wave angle |
| $\rho$ | density in $kg/m^3$ |
| $\tau$ | time constant in s |

*Subscripts*

| | |
|---|---|
| $c$ | cold fluid |
| $h$ | hot fluid |
| $in$ | inlet |
| $k$ | index of sub-exchanger |
| $out$ | outlet |
| $w$ | wall |

the steam cycle, because the lowest pressure is slightly above the critical pressure of $CO_2$, while the maximum pressure is constrained due to the capital cost and mechanical design of the critical equipment as well as piping and measurement system [1]. The previous works of Dyreby et al. [6] and Zitney et al. [7] indicate that the $sCO_2$ turbine outlet temperature is still high, and the heat recuperation between the hot turbine outlet stream and the cold compressed inlet stream is important to the overall efficiency, performance, and dynamic behavior of an $sCO_2$ Brayton cycle. In an optimally designed $sCO_2$ Brayton cycle, the heat duty in the recuperators is expected to be much larger than the net power output and even the heat input [7,8]. For example, in a 10 MWe $sCO_2$ RCBC power plant, the total heat recovered in the low- and high-temperature recuperators is about 60 MWt, while the required input to the primary heater is only 21 MWt [7]. To reduce RCBC capital cost and plant footprint, specially designed compact heat exchangers are recommended as a better option than conventional shell-and-tube heat exchangers (CSTEs) [9]. Therefore, the effective selection, design, and operation of such recuperators are of crucial importance for the successful demonstration and commercialization of $sCO_2$ Brayton cycles.

Printed circuit heat exchangers (PCHEs) and microtube shell-and-tube recuperators (MSTEs) are two promising commercially-available candidates for use as a high-efficiency compact heat recuperator as suggested by Musgrove et al. [10], Le Pierres et al. [11], and Ngo et al. [12]. Recently, PCHEs have been implemented in several small scale $sCO_2$ test loops such as at the Naval Nuclear Laboratory [13], Sandia National Laboratory [14], and Tokyo Institute of Technology (TIT) [12,15,16]. In addition, they have been widely adopted for next-generation nuclear reactors using cooling mediums such as helium, $sCO_2$, sodium, and lead [17]. PCHEs are a kind of micro-channel heat exchanger, consisting of many plates etched with a considerable number of micro-wavy channels on each plate [18]. Wavy channels are superior to straight channels in PCHEs due to their enhanced heat transfer performance, but at the cost of higher pressure drop [12,19]. Compared with CSTEs, PCHEs are much smaller and lighter due to their high heat transfer area to volume ratio, and can be operated in a wider range of conditions with reasonable pressure drop [20].

It is noted that several optimization studies are available in the open literature for designing compact heat exchangers with a focus on optimization strategies, such as successive quadratic programming (SQP) [21,22] and genetic algorithms [23]. Those studies also discussed the importance of selecting objective functions and constraints and investigated their effects on the design of exchangers [23,24]. However, those studies were not in general conducted using thermal-hydraulic correlations suitable for supercritical fluids. In addition, those heat