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Design analysis of supercritical carbon dioxide recuperator

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HIGHLIGHTS

- Segmental design method is applicable for the S-CO_2 recuperator.
- Local heat capacity rate ratio has crucial effects in local thermal performance.
- The inflection point often appears when local heat capacity rate ratio is about one.
- Local entransy dissipation number has relatively coherent performance behavior.

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ABSTRACT

The segmental design method is employed to accurately capture the drastic variations of properties in the supercritical carbon dioxide (S-CO_2) recuperator. The local heat capacity flow rates of both fluids have drastic changes in sub-heat exchangers even the mass flow rates of both fluids remain unchanged. When the heat duty is given, the local heat conductance, local temperature difference, local effectiveness and local entransy dissipation number have extremums, which appear in the vicinity of the heat capacity rate ratio is one. The heat transfer performance of recuperator improves at the expense of heat conductance. When the total heat conductance is fixed, there exist the maximum local heat flux rates, and the local effectiveness tends to be constant after the local heat capacity rate ratio reaches one, the local entransy dissipation number has the relatively coherent performance behavior in the sub-heat exchangers. The local heat capacity rate ratio has crucial influences on the heat transfer performance of recuperator, and the design parameters must be considered carefully in the design of S-CO_2 recuperator.

1. Introduction

The supercritical carbon dioxide (S-CO_2) power cycle has very high efficiency and high compactness, has competitive advantages in the mild turbine inlet temperature range (450–650 °C) [1,2]. The promising potentials in nuclear and solar energy make the S-CO_2 power cycles become more attracted in recent years [3–6]. Turchi et al. [2] reported that the recompression cycles combined with intercooling and/or turbine reheat appear able to achieve greater than 50% efficiency even when the dry cooling is employed, and the intercooled cycles is suitable for concentrated solar power with sensible heat thermal energy storage. In order to achieve higher efficiency with higher pressure ratio, Ahn et al. [1] designed a S-CO_2 integral experimental loop, in which the performance of system and components could be investigated. Pham et al. [7] carried out thermodynamic performance analysis of S-CO_2 cycles for different cycle configurations, and the optimal operating conditions relied on the balance between cycle efficiency, recuperation power, and the margin with respect to the critical point. Dyreby et al. [8] reported that the performance of S-CO_2 recompression cycle depends on pressure ratio, the outlet conditions of low temperature regenerator, etc. There exists an optimal compressor outlet pressure to achieve the highest thermal efficiency depending on the recuperator size and operating temperatures.

The recuperator is one of the most important components in S-CO_2 Brayton cycles, whose performance has important influences on the efficiency and stable running of the cycles [9]. However, the drastic variation of thermophysical properties near the pseudo-critical point of S-CO_2 makes the heat transfer and fluid flow of S-CO_2 very complex, and the conventional heat transfer and pressure drop correlations are no longer applicable [10]. Forooghi and Hooman [11] experimentally investigated the heat transfer of S-CO_2 near pseudo-critical temperature in plate heat exchangers, the results indicated that the effect of wall-to-bulk property ratio is important and should be accounted for correlations, and the buoyancy effects have influences under some conditions. Kruizenga et al. [12] examined the heat transfer of S-CO_2 in

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Nomenclature

c_p	specific heat (J/kg °C)	t	Celsius temperature (°C)
G	entransy (J K)	T	thermodynamic temperature (K)
G_{dis}	entransy dissipation (J K)	UA	heat conductance (J/°C)
G_N	total entransy dissipation number		
h	specific enthalpy (J/kg)	*Greeks*	
m	mass flow rate (kg/s)	ε	effectiveness
N	number of sub-heat exchanger		
Ntu	number of heat transfer units	*Subscripts*	
P	pressure (MPa)	c	cold fluid
q	local heat flux rate (J)	h	hot fluid
Q_{tot}	total heat duty (J)	i	inlet
R_c	the ratio of minimum heat capacity rate to maximum heat capacity rate	j	local parameter
$R_{c,hc}$	the ratio of heat capacity rate of hot fluid to that of cold fluid	o	outlet

horizontal semicircular channels, they reported that the existing correlations over-predict heat transfer near the critical point, and they proposed a new correlation to have the best prediction. An experimental heat transfer of S-CO_2 near the pseudo-critical point under cooling conditions was carried out in [13], and the results showed that a substantial heat transfer increases near the pseudo-critical point, and the numerical results had good agreements with experimental results for the near pseudo-critical point region. The heat transfer characteristics of S-CO_2 are different under heating and cooling conditions, a heat transfer correlation of S-CO_2 was proposed in [14] through experimental and numerical studies on heat transfer of S-CO_2 under both heating and cooling conditions, which had good predictions in both heating and cooling conditions. Yadav et al. [15] conducted an transient analysis of subcritical and supercritical carbon dioxide based on natural circulation loop with end heat exchangers. A number of heat transfer and pressure drop correlations were proposed for S-CO_2, but some results contradict with each other, therefore, more studies are necessary to develop appropriate heat transfer and pressure drop correlations [16]. A coupled heat transfer between S-CO_2 and water was numerically investigated in a concentric heat exchanger in [17], the results indicated that the performance of heat exchanger strongly depends on the inlet velocity when S-CO_2 is near the pseudo-critical point. A direct S-CO_2 solar receiver based on compact heat exchanger was analyzed, and the influences of different parameters on the performance of the receiver were presented through parameter analysis in [18]. A micro-channel equipped with an array of airfoil fins to enhance heat transfer and reduce pressure drop of S-CO_2 was numerically analyzed in [19], and the results indicated that the fully staggered arrangement has the best performance considering both heat transfer and pressure drop.

One of the important features of S-CO_2 power cycle is that the heat exchangers take up a large proportion of total investment [6], therefore, their performance and efficiency have to be carefully considered and investigated. The above literature shows that most of the existing works focus on the heat transfer characteristics of S-CO_2 under heating and/or cooling boundary conditions. Factually, the drastic variations of thermophysical properties of S-CO_2 in two sides of recuperator occur simultaneously, and the heat transfer boundary conditions of S-CO_2 vary violently in one side of recuperator. Therefore, the studies on the coupled heat transfer between S-CO_2 and S-CO_2 in both sides of recuperator are necessary for the design and optimization of recuperator. In order to capture the coupled heat transfer information of low temperature recuperator of S-CO_2 Brayton cycle, where the thermophysical properties of S-CO_2 changes sharply in both sides, the segmental design method is employed for the heat transfer calculation of S-CO_2 in both sides in the present work. The local heat transfer performance and whole performance of recuperator are presented and analyzed, and the entransy theory proposed recently [20] is employed to analyze the irreversible degree of heat transfer happened in the recuperator. The present work may provide a practical guidance on optimization design and heat transfer enhancement of recuperator in S-CO_2 power cycle.

2. Theoretical analysis

The properties of S-CO_2 have drastic changes near the critical point (30.98 °C, 7.38 MPa) and pseudo-critical point as shown in Fig. 1, which is advantageous to reduce the compression work, but very difficult for the heat exchanger design. The conventional fixed properties heat exchanger design method is no longer applicable. In order to accurately capture the effects of changing S-CO_2 properties, the recuperator is discretized into numerous sub-heat exchangers connected in series as shown in Fig. 2 [21]. The total heat transfer rate is evenly divided among the sub-heat exchangers when the total heat duty is given. The energy balance in each sub-heat exchanger relies on the inlet and outlet states of each section.

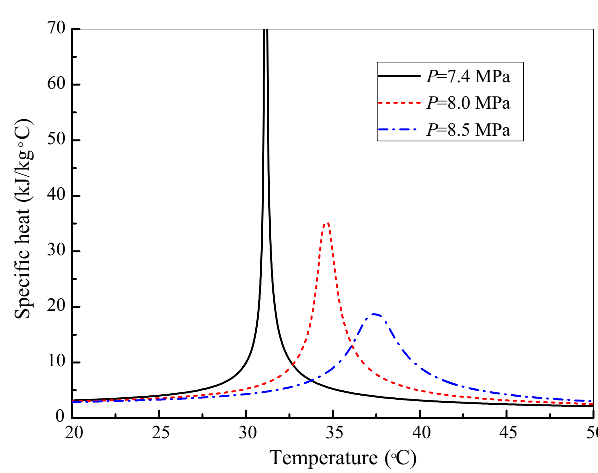

Fig. 1. The relations of specific heat of carbon dioxide with temperature at P = 7.4 MPa, P = 8.0 MPa and P = 8.5 MPa.