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Coordination analysis of cross-flow heat exchanger under high variations in thermodynamic properties

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ABSTRACT

Supercritical pressure CO_2 was employed to investigate the improvement of a cross-flow heat exchanger with variable properties in the present work. The whole heat exchanger was uniformly divided into $M \times N$ heat exchange units, and the matrix analysis indicated that the total heat load of the heat exchange matrix depends not only on the vector norms of local heat transfer coefficient and local temperature difference, but also on their distributed coordination. A numerical example confirmed that the total heat load increased as the coordinative degree between the two vectors of local heat transfer coefficient and local temperature difference improved when the other conditions remained unchanged. The further analysis indicated that the coordination improvement between the two vectors of local heat flux density and local heat transfer area also increased the total heat load. A coordination angle was proposed to measure the coordination degree between the distributions of different parameters in heat exchange matrix; the smaller coordination angle means the better distributed coordination when the other conditions remain the same. The present work might provide a new approach to the improvement of heat exchange matrix for the fluids with drastic changes of properties.

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1. Introduction

Heat exchanger is an important device widely used in power engineering, petroleum and chemical industries, etc. Therefore, to improve the performance of heat exchanger is of great significance for energy saving. Heat transfer enhancement techniques have been developed rapidly in the past few decades, such as increasing heat transfer area, enhancing the turbulence, reducing the boundary layer thickness and generating the secondary flow [1,2]. However, the above enhancing techniques have the drawback that the pumping power increases significantly as the heat transfer enhances. In order to enhance heat transfer without the significant increase of pressure drop, Guo et al. [3,4] developed the field synergy principle for the heat transfer enhancement, which indicated that the heat transfer rate depends not only on the values of flow velocity and temperature gradient, and also on their synergy. From then on, the field synergy principle has attracted lots of attentions [5–8], and has been used to explain the heat transfer enhancement mechanism and develop new heat exchange augment components [9–11]. Tao et al. [12] further stated that the field synergy principle can reveal the essence of the existing enhancing techniques for single phase convective heat transfer.

Based on the second law of thermodynamics, the entropy generation minimization approach to heat exchanger optimization design was proposed by Bejan [13,14], in which the irreversible losses in heat exchanger could be divided into two groups: one is caused by heat transfer, the other one is associated with fluid friction. In attempt to overcome the neglect of frictional irreversibility, a multi-objective optimization method of heat exchanger based on the two irreversible losses was proposed in [15,16]. A new physical concept was defined by Guo et al. [17,18] to describe the heat transfer ability, which could be adopted as a merit criterion to evaluate the performance of heat exchanger. The novel concept has been widely used in the optimization design of heat exchanger until now [19–25].

Supercritical carbon dioxide (S-CO_2) power cycle has very high efficiency and high compactness, which is paid more and more attentions due to its promising potentials in nuclear and solar energy in recent years [26–31]. Heat exchanger is one of the most important components in S-CO_2 Brayton cycle, whose performance has crucial influences on the efficiency and stable running of the cycle [32]. The heat exchanger takes up a large proportion of total investment of S-CO_2 Brayton cycle [29], therefore, their performance optimization and efficiency improvement are very impor-

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Nomenclature

A	heat transfer area (m^2)
$\mathbf{A}$	the vector of local heat transfer area (m^2)
c	constant
c_p	specific heat (J/kg °C)
d_{eq}	equivalent diameter (m)
f	coefficient
C^*	heat capacity rate ratio
G	mass flow rate (kg/s)
h	specific enthalpy (J/kg)
K	heat transfer coefficient in one side (W/m °C)
$\dot{m}$	mass flow rate (kg/s)
M	number of grids in y-direction
N	number of grids in x-direction
Ntu	number of heat transfer unit
Nu	Nusselt number
P	pressure (MPa)
Pr	Prandtl number
$\dot{q}$	local heat flux density (W/m^2)
$\mathbf{q}$	the vector of local heat flux density (W/m^2)
Q	heat transfer rate (W)
Re	Reynolds number
T	temperature (°C)
U	heat transfer coefficient (W/m^2 °C)
$\mathbf{U}$	the vector of heat transfer coefficient (W/m °C)

Greeks

$\mathbf{\Delta T}$	the vector of local temperature difference (°C)
α	coordination angle between the vectors of local heat transfer coefficient and local temperature difference
β	coordination angle between the vectors of local heat flux density and local heat transfer area
ε	effectiveness
ζ	normalized length in x-direction
θ	dimensionless temperature
λ	thermal conductivity (W/m °C)
χ	normalized length in y-direction

Subscripts

a	average
h	hot
c	cold
i	inlet
o	outlet
tot	total

tant for the development and application of the cycle. However, the drastic variation of thermophysical properties near the pseudo-critical temperature under supercritical pressure conditions makes the heat transfer and fluid flow of CO_2 very complex, which challenges the conventional heat exchanger design and optimization theory seriously. The optimization theory and enhancing technique of heat exchanger are mainly based on the conventional heat exchanger design, in which the properties of fluids are often regarded as constant.

Therefore, the cross-flow heat exchanger is employed to analyze and discuss the enhancing mechanism and improvement method of heat exchanger for the fluids with drastic variations of properties in the present work. Being inspired by the field synergy principle, we attempt to improve the heat load of heat exchanger from a novel approach under the fixed heat transfer area condition, the present work may provide some guidelines for the improvement of heat exchange matrix with drastic variations of properties.

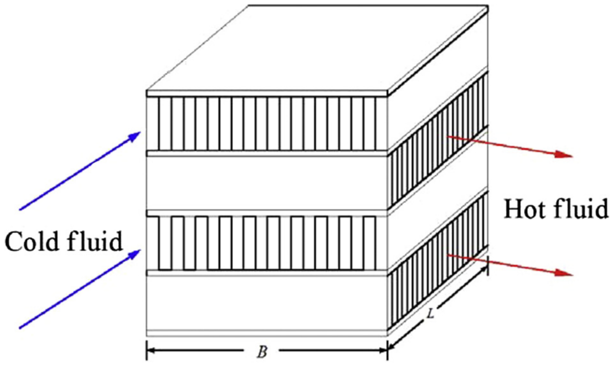

Fig. 1. Heat exchanger of cross-flow type.

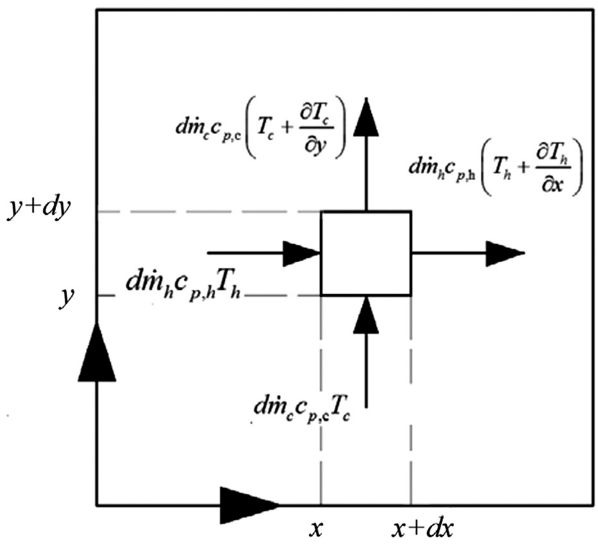

Fig. 2. Energy balance for cross-flow heat exchanger.

2. Theoretical calculation for conventional fluid

The type of cross-flow is employed widely in compact heat exchangers as shown in Fig. 1, and has to be adopted sometimes due to the space and structure constraints. The unmixed-unmixed cross-flow heat exchanger is adopted in the present work for the convenience of two-dimensional model establishment. Assume that the longitudinal conduction is neglected, the simplified energy balance model for cross-flow heat exchanger is shown in Fig. 2 [33].

For the hot fluid:

$$d\dot m_h c_{p,h} T_h - d\dot m_h c_{p,h}\left(T_h + \frac{\partial T_h}{\partial x}\right) = dQ \qquad (1)$$

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