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The coordination distribution analysis on the series schemes of heat exchanger system

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ABSTRACT

The influences of series schemes on the heat exchanger system are investigated using matrix analysis method in the present work. The performance of heat exchanger system can be improved by arranging the series schemes without an obvious increase of pressure drop or heat transfer area. The matrix analysis indicates that the series scheme has important effect on the parameter distribution over the heat exchanger system. The heat transfer can be enhanced by improving the distributed coordination between heat transfer coefficient and temperature difference besides increasing their values. The better distributed coordination between heat transfer coefficient and temperature difference corresponds to the better uniformity of heat transfer rate over the heat exchanger system, which is favorable to safety running of system. The matching performance improvement between the entransies of hot and cold fluids could lead to the better distributed uniformity of entransy dissipation over the heat exchanger system, which results in the reduction of the total entransy dissipation finally. The present work might provide a new approach to the optimization and layout of heat exchanger system for the fluids with drastic changes of properties.

1. Introduction

As an important device, heat exchanger is widely applied in petroleum, power engineering and chemical industries, etc. The performance improvement of heat exchanger is of great significance for energy saving. The commonly used heat transfer enhancement techniques include increasing heat transfer area, reducing the boundary layer thickness and generating the secondary flow [1,2]. However, the above techniques enhance heat transfer at the expense of pumping power. Guo et al. [3,4] proposed a novel field synergy principle for the heat transfer enhancement, which indicated that the heat transfer depends not only on the values of velocity and temperature gradient, and also on their synergy. Tao et al. [5] further stated that all the existing enhancement techniques could be ascribed to field synergy improvement for the single phase convective heat transfer. Until now, the field synergy principle has been widely used in the mechanism interpretation for heat transfer phenomenon [6–10], the development of enhancing components [11], heat exchanger optimization [12,13], etc.

Guo et al. [14,15] further proposed a new physical concept to describe the heat transfer ability, which could be adopted as a merit criterion to evaluate the performance of heat exchanger based on the second law of thermodynamics. The entransy and entransy dissipation have been widely applied to the analysis of heat transfer [16–20], the optimization and performance evaluation of heat exchanger [21–25], heat storage system [26–28], and chemical heat pump [29,30], etc. Cheng and Liang [31,32] further proposed the concept of entransy loss to analyze the entransy change in heat-work conversion processes.

Supercritical CO_2 power cycle has been paid more and more attentions due to its promising potentials in nuclear and solar energy [33,34]. Heat exchanger has crucial influences on the efficiency, stable running, and cost of the cycle system [34]. Therefore, the performance optimization and efficiency improvement are very important for the development and application of the cycle. The drastic variation of thermophysical properties near the pseudo-critical temperature under supercritical pressure conditions makes the heat transfer and fluid flow very complex, which challenges the conventional heat transfer design and optimization theory seriously. Guo et al. [35] discussed the distribution relation between heat transfer coefficient and temperature difference through the vector analysis using supercritical CO_2 as working fluid, they found the total heat transfer rate directly relate to the coordination degree between heat transfer coefficient and temperature difference besides their values. The distributed coordination principle was adopted to analyze the nonuniform inlet fluid

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Nomenclature

A	heat transfer area (m^2)
c	constant
c_p	specific heat (J/kg K)
d_{eq}	equivalent diameter (m)
f	friction factor
g	enthalpy entransy (W K)
G_n^*	entransy dissipation number
G_d	entransy dissipation rate (W K)
$\mathbf{G_d}$	entransy dissipation matrix (W K)
$\mathbf{G_h}$	entransy matrix of hot fluid (W K)
$\mathbf{G_c}$	entransy matrix of cold fluid (W K)
h	specific enthalpy (J/kg)
K	heat transfer coefficient in one side (W/m^2 K)
L	length of channel (m)
$\dot{m}$	mass flow rate (kg/s)
M	number of grids in y-direction
N	number of grids in x-direction
Ntu	number of heat transfer units
Nu	Nusselt number
P	pressure (Pa)
Pr	Prandtl number
q	local heat flux rate (W)
Q	heat transfer rate (W)
$\mathbf{Q}$	the matrix of heat transfer rate (W)
R_c	heat capacity rate ratio
Re	Reynolds number
T	temperature (K)
U	heat transfer coefficient (W/m^2 K)
$\mathbf{U}$	the matrix of heat transfer coefficient (W/m^2 K)
v	velocity (m/s)

Greeks

ΔP	pressure drop (Pa)
$\mathbf{\Delta T}$	the vector of local temperature difference (K)
ϕ_G	distributed uniformity of entransy dissipation
β	matching angle between entransies of hot and cold fluids (rad)
θ	coordination angle between heat transfer coefficient and temperaturedifference (rad)
λ	thermal conductivity (W/m K)
ρ	density (kg/m^3)

Subscripts

ΔP	pressure drop
ΔT	temperature difference
a	average
c	cold
h	hot
i	inlet
o	outlet
tot	total

conditions effect, the results indicated that the nonuniform inlet conditions may enhance heat transfer when supercritical CO_2 is employed as working fluid [36].

As we all know, several heat exchangers are commonly applied in series for practical applications. Therefore, the series schemes of heat exchanger system are investigated using supercritical CO_2 as working fluid in the present work, the vector analysis method is further expanded to the whole heat exchange matrix, the distributed relations among some important parameters are discussed. The present work may provide a practical guidance on optimization design and layout type of heat exchanger system for fluids with sharply variable properties.

2. Theoretical analysis

The unmixed-unmixed crossflow heat exchanger which is widely applied in compact heat exchanger is adopted to observe the two-dimensional distributions of parameters in the present work, and the two-dimensional simplified model is illustrated in Fig. 1(b). The thermophysical properties of CO_2 sharply vary near the critical and pseudo-critical temperatures under supercritical pressure conditions as shown in Fig. 2. When supercritical pressure CO_2 is adopted as the working fluid, the numerical method has to be adopted to capture the sharp variations of properties. For ease of calculation, we assume that: fluids are unmixed in heat exchanger, and no phase change occurs; longitudinal heat conduction is neglected; both fluids are in steady state; the average inlet temperature and the total mass flow rate for both fluids are constant; the total heat transfer area remains constant; the heat exchange between heat exchanger and environment is neglected; the pressure drop in the connected pipe outside heat exchanger is neglected. The heat exchanger is divided into M grids in the y-direction, and N grids in the x-direction as shown in Fig. 1(b). The energy balance in one heat exchanger unit can be expresses as [37]:

$$\begin{cases} \dot{m}_{h,ij} \cdot \left(h_{h,ij} - h_{h,ij+1}\right) = \frac{A}{MN} U_{ij} \Delta T_{ij} \\ \dot{m}_{c,ij} \cdot \left(h_{c,i+1j} - h_{h,ij}\right) = \frac{A}{MN} U_{ij} \Delta T_{ij} \end{cases}, \quad \begin{pmatrix} i = 1, 2 \cdots M \\ j = 1, 2 \cdots N \end{pmatrix} \tag{1}$$

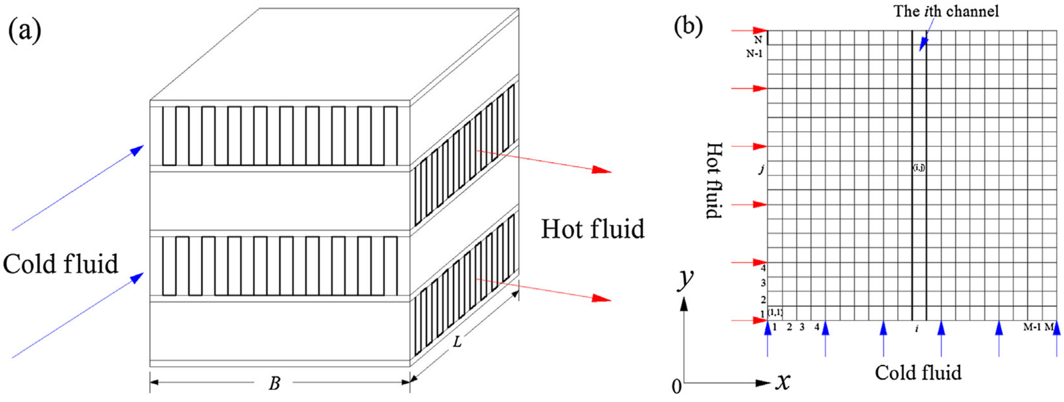

Fig. 1. (a) A schematic of crossflow heat exchanger, and (b) the analytical model.