International Journal of Heat and Mass Transfer 120 (2018) 807–817

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

The effects of nonuniform inlet fluid conditions on crossflow heat exchanger

Jiangfeng Guo *, Xiulan Huai, Keyong Cheng, Xinying Cui, Haiyan Zhang

Institute of Engineering Thermophysics, Chinese Academy of Sciences, Beijing 100190, China
School of Engineering Science, University of Chinese Academy of Sciences, Beijing 100049, China

ARTICLE INFO

Article history:
Received 14 August 2017
Received in revised form 15 December 2017
Accepted 17 December 2017

Keywords:
Heat transfer
Crossflow heat exchanger
Distributed coordination
Entransy dissipation
Optimization design
Supercritical pressure CO_2 (S-CO_2)

ABSTRACT

The influences of uneven inlet flow and temperature conditions on performance of crossflow heat exchanger using supercritical pressure CO_2 (S-CO_2) as working fluid were investigated from the viewpoint of distributed coordination. The inlet flow maldistribution and inlet temperature nonuniformity in either side of both fluids could deteriorate or enhance heat transfer, and the deterioration or enhancement effect of both fluids could be superimposed. The inlet conditions with enhancement effect eases the uneven distributions of heat transfer coefficient and temperature difference, and improves the distributed coordination between them, and eventually enhances the heat transfer. The total heat transfer rate depends not only on the values of heat transfer coefficient and temperature difference, but also on their coordination. The distributed coordination analysis indicates that the uneven inlet flow and temperature conditions could be used to enhance heat transfer using the special characteristics of S-CO_2 without a significant increase of pressure drop. The present work may provide a new way to the optimization design of heat exchanger for the fluids with sharply variable properties.

1. Introduction

As an important process device, heat exchanger is widely used in power engineering, refrigeration, astronavigation, petroleum and chemical industries, etc. Therefore, to improve the performance of heat exchanger is of great significance for energy saving. The temperature and fluid flow are usually nonuniform in an actual heat exchanger due to heat exchanger geometry, heat exchanger operating conditions, etc. [1]. The nonuniformities of inlet temperature and fluid flow seriously affect the situations in the core. So the thermal response of heat exchanger with inlet temperature and flow nonuniformity is very helpful for the designer to solve the problems and develop novel heat exchangers.

In general, the flow maldistribution leads to the performance degradation of heat exchanger with constant properties fluids. Fleming [2] conducted the study on the effects of flow maldistribution on the heat exchanger, and the performance deterioration becomes severe in the balanced flow situation. Chiou [3] first investigated the effect of nonuniformity for single-pass crossflow heat exchanger under steady state conditions. The effectiveness and its performance deterioration were calculated for four typical fluid flow maldistributions, and a flow nonuniformity factor was proposed to predict the degree of performance deterioration of heat exchanger. Ismail et al. [4] numerically analyzed the effects of flow maldistribution on the crossflow compact heat exchanger due to the inlet headers, and the performance deterioration was calculated and the headers were modified to improve flow distribution. Anbumeenakshi and Thansekhar [5] experimentally investigated the flow maldistribution effect on microchannel heat exchanger, the flow distribution becomes better as the flow rate increases, and the flow distribution significantly depends on the header, entrance configuration and flow rate. Zhan et al. [6] experimentally investigated various distribution configurations with a plate-fin heat exchanger, they found that the distributor could cause severe flow maldistribution, affects the thermal performance seriously, and they proposed the optimal distributor that produces the most uniform flow distribution. Pistoresi et al. [7] numerically analyzed many shapes of distributor, and proposed an optimal distributor to achieve a uniform flow distribution for mini-channel heat exchanger.

The fluid steams may enter the heat exchanger with different temperature levels at the entrances of the compact heat exchanger when the streams are not well mixed [8]. Chiou [9,10] reported that the nonuniformity of fluid inlet temperature further worsens the performance deterioration of heat exchanger caused by the flow maldistribution. The effects of inlet temperature condition on the thermal performance of heat exchanger were complicated,

* Corresponding author at: Institute of Engineering Thermophysics, Chinese Academy of Sciences, Beijing 100190, China.

E-mail addresses: gjf1200@126.com, guojf@iet.cn (J. Guo).

https://doi.org/10.1016/j.ijheatmasstransfer.2017.12.084
0017-9310/

Nomenclature

A_{tot}	total heat transfer area (m^2)
c	constant
c_p	specific heat (J/kg K)
d_{eq}	equivalent diameter (m)
f	friction factor
G	entransy dissipation rate (J K)
G^*	entransy dissipation number
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
Nu	Nusselt number
P	pressure (Pa)
Pr	Prandtl number
$\dot{q}$	local heat flux rate (J)
Q	heat transfer rate (J)
Re	Reynolds number
R_{hc}	heat capacity rate ratio
T	temperature (K)
U	heat transfer coefficient (W/m^2 K)
$\mathbf{U}$	the vector 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)
α	increasing rate of local mass flow rate (g)
β	increasing rate of local inlet temperature (K)
θ	coordination angle between heat transfer coefficient and temperature difference (rad)
λ	thermal conductivity (W/m K)
ρ	density (kg/m^3)

Subscripts

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

and the heat transfer may enhance or deteriorate with nonuniform inlet temperature conditions as reported in [11,12], but the heat transfer mechanism needs further discussion. Mishra et al. [13] analyzed the transient responses of a crossflow heat exchanger under different inlet temperature and flow nonuniformity conditions; they found that the cold fluid has more influences on the thermal performance than the hot fluid. Gao et al. [14] further investigated the effect of nonuniform inlet temperature boundary conditions on the steady state and transient performance of crossflow heat exchanger, the results showed that the transient nonuniform inlet temperature affects both the steady and transient results, while steady nonuniform inlet temperature only affects the steady results.

As for the performance evaluation of heat exchanger, Guo et al. [15] proposed a novel concept of entransy to describe the heat transfer ability recently. The total entransy is always dissipated in the isolated systems, and the entransy dissipation can be a descriptive measure of irreversibility in heat transfer processes [15,16]. The extremum principle of entransy dissipation and the entransy-dissipation-based thermal resistance were proposed to the optimization of heat exchangers, and no paradox was found in the analysis of heat exchanger [17]. Until now, the entransy and entransy dissipation have been widely applied to the optimization and performance evaluation of heat exchanger [18–24], chemical heat pump [25,26], heat storage system [27–29], thermal systems with phase change [30,31], etc.

The effects of nonuniform inlet temperature and fluid flow boundary conditions on the thermal performance of heat exchanger have been studied by many researchers, however, most existing literature focuses on the conventional working fluids whose thermophysical properties can be regarded as constant. The thermophysical properties of supercritical pressure CO_2 (S-CO_2) change violently, especially near the critical point and pseudo-critical point, so the heat transfer and fluid flow become very complex, which challenges the conventional heat exchanger design and optimization theory seriously. In the present work, the effects of nonuniform inlet temperature and fluid flow boundary conditions on the thermal performance of crossflow heat exchanger using S-CO_2 are investigated, the deteriorated or enhanced heat transfer mechanism of heat exchanger is discussed and analyzed, and the optimal inlet temperature and fluid flow boundary conditions which enhance heat transfer and alleviate irreversible loss are proposed. The present work may provide a practical guidance on optimization design and heat transfer enhancement of heat exchanger for fluids with sharply variable properties.

2. Theoretical analysis

The type of crossflow is applied widely in compact heat exchanger as shown in Fig. 1(a), and has to be adopted sometimes due to the space and structure constraints. The unmixed-unmixed crossflow heat exchanger is adopted 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 S-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, 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 [1]. 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 [32]:

$$\begin{cases} \dot{m}_h(i,1)\cdot(h_h(i,j)-h_h(i,j+1))=\frac{U(i,j)A_{tot}}{MN}(T_{h,a}(i,j)-T_{c,a}(i,j)) \\ \dot{m}_c(1,j)\cdot(h_c(i+1,j)-h_c(i,j))=\frac{U(i,j)A_{tot}}{MN}(T_{h,a}(i,j)-T_{c,a}(i,j)) \end{cases},\quad \begin{pmatrix} i=1,2\ldots M \\ j=1,2\ldots N \end{pmatrix} \tag{1}$$

where $\dot{m}$ is the mass flow rate, h is the specific enthalpy, T is the temperature, U is the heat transfer coefficient, A_{tot} is the total heat transfer area, the subscript h, c and a represent hot, cold, and average.

The heat transfer rate for one unit can be written as:

$$\dot{q}(i,j)=\dot{m}_h(i,j)\cdot(h_h(i,j)-h_h(i,j+1))=U(i,j)\Delta T(i,j)\frac{A_{tot}}{MN} \tag{2}$$

The total heat transfer rate can be obtained: