The power flow topology of heat transfer systems at supercritical conditions for performance analysis and optimization

CrossMark

Qun Chen *, Si-Yu Zhao, Xi Chen, Xia Li

Key Laboratory for Thermal Science and Power Engineering of Ministry of Education, Department of Engineering Mechanics, Tsinghua University, Beijing 100084, China

A B S T R A C T

Heat transfer processes with supercritical fluids are more complex than those with ordinary fluids due to the drastic variation of physical properties. In this study, with consideration of the changes of specific heat and heat transfer coefficient, the power flow topology of a multi-loop heat exchanger network is developed to investigate heat transfer processes at supercritical conditions. Simulation of a cooling process with supercritical CO_2 validates the newly proposed method, where the maximum relative error of heat transfer rate is −2.72%. Meanwhile, optimization of a heat exchanger network discovers several design criteria for the optimal heat transfer performance. For instance, the mass charge of CO_2 in the heat exchanger network influences its supercritical heat transfer performance significantly, which has the optimal value. Furthermore, the optimal mass charge nearly keeps constant with the heat transfer rate and the temperature boundaries, and increases linearly with the rise of the total heat transfer area, which indicates the optimal average density keeps constant. Substituting this constant density into the state equation of CO_2 establishes the matching relation of the temperature range and the pressure for the optimal heat transfer performance.

© 2017 Elsevier Ltd. All rights reserved.

1. Introduction

Supercritical fluid has been widely applied in various industrial fields including refrigeration systems, power plants and nuclear reactors [1–3], where the operation pressures and temperatures are higher than the corresponding thermodynamic critical values. Meanwhile, in the supercritical region, the fluid physical properties vary sharply with both pressure and temperature, and thus the heat transfer processes with supercritical fluids are more complex than those with ordinary fluids [4–13]. For instance, the constant pressure specific heat of supercritical fluid is no longer constant but varies during a heat transfer process. The temperature gradient from the wall to the core areas inevitably leads to the uneven density distribution on the cross section, which induces the buoyancy force together with the gravity. Besides, the density gradient along the flow direction causes the variation of flow velocity, which is called flow acceleration in a heating process of supercritical fluid.

Based on the experimental and numerical data, some empirical correlations to calculate the convective heat transfer coefficients with supercritical fluids were proposed, as reviewed by Pioro et al. [14] and Huang et al. [15], which could be classified into two categories. One is to predict the average convective heat transfer coefficient during a heat transfer process, where the average of the inlet and outlet temperatures is taken as the characteristic temperature to determine the fluid properties [9]. It is convenient to calculate the total heat transfer rates, but the application ranges of each correlation are relatively narrow because they oversimplify the variations of heat transfer coefficients and physical properties of supercritical fluids. The other is to calculate the local heat transfer coefficients based on the fluid properties evaluated at local reference temperatures [6,16]. It benefits the investigation of local heat transfer characteristics but involves a large quantity of local data. Besides, the coupling relation between heat transfer coefficient and temperature increases the difficulty of calculation. Some scholars [1,17] divided heat exchangers into a number of small volume elements, solved the heat transfer, the energy conservation and the property equations for each element in sequence, and obtained the total heat transfer rates in heat exchangers by iteration. Due to the low efficiency of calculation, this approach does not have many advantages over the method of directly calculating the partial differential equations [12,18,19].

For a heat transfer system employing supercritical fluids, the relations of each physical quantity become more intricate. As illustrated in Fig. 1, the physical relations are represented by circles and lines. The predominant circle connecting heat transfer area, mass

* Corresponding author.
  E-mail address: chenqun@tsinghua.edu.cn (Q. Chen).

Nomenclature

A	area, m^2
c_p	constant pressure specific heat, J kg^{-1} K^{-1}
d	diameter, m
f	friction coefficient
F	Lagrange Function
G	heat capacity rate, W K^{-1}
h	enthalpy, J kg^{-1}
U	heat transfer coefficient, W m^{-2} K^{-1}
L	length, m
m	mass flow rate, kg s^{-1}
M	mass charge, kg
N	number of segments
p	pressure, MPa
Pr	Prandtl number
Q	heat transfer rate, W
r	radius, m
R	thermal resistance, K W^{-1}
Re	Reynolds number

T	temperature, K
u	velocity, m s^{-1}
α	convective heat transfer coefficient, W m^{-2} K^{-1}
Δp	pressure drop, Mpa
λ	thermal conductivity, W m^{-1} K^{-1}
ρ	density, kg m^{-3}
μ	viscosity, Pa s
ε	thermal-motive, K
ζ, ψ, φ	Lagrange multiplier

Subscripts

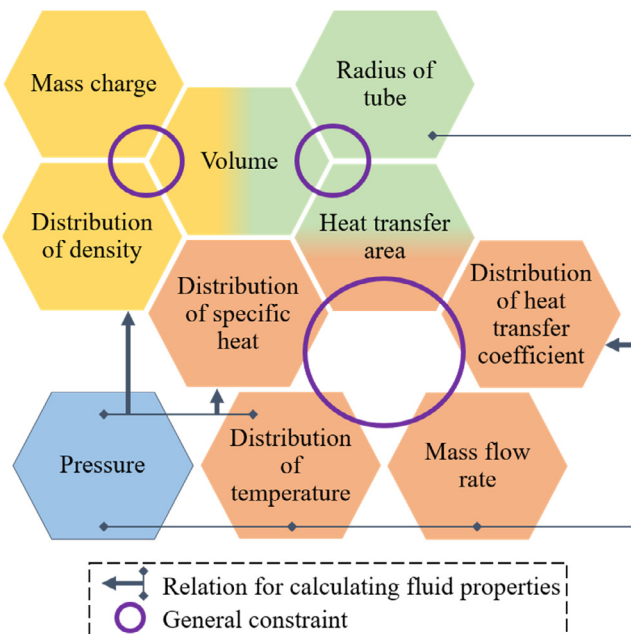|	
g	entransy dissipation-based
in	inlet
out	outlet
m	arithmetic average value
w	wall

Fig. 1. The relations of each physical quantity in heat transfer systems with supercritical fluids.

flow rate, and distributions of heat transfer coefficient, temperature, and specific heat stands for the heat transfer and the energy conservation equations. The pressure, the density, and the temperature are connected by the state equation. The volume of supercritical fluid is related to the radius and the heat transfer area by the geometrical condition. Meanwhile, because each fluid physical property is a function of temperature and pressure, the distribution of specific heat is determined by the pressure and the temperature, while the distribution of heat transfer coefficient depends on the tube radius, the mass flow rate together with the properties determined by the pressure and the temperature. Moreover, most heat transfer systems with supercritical fluids are closed cycles, and the integration of density in the entire volume is the mass charge, which influences the operating pressure.

Due to the complex relations of multiple variables, scientists usually divided the whole heat transfer system into individual heat exchangers, estimated the heat transfer conditions of each heat exchanger empirically based on the system requirements, and optimized each heat exchanger by comparing the heat transfer performances with different pressures, mass flow rates and other parameters to obtain a better system performance [1–3]. This approach obviously simplifies the optimization process, but hardly obtains the global optimal performance of the system. What's more, it is nearly impossible to explore the influence of the mass charge of supercritical fluid on the overall system performance, which is very important in closed cycles with fluid property variation. For instance, the previous investigation of vapor-compression refrigerator [20–22] showed that the system performance peaked at a specific mass charge of refrigerant, which always relies on experiments, not theoretical analysis. Therefore, an efficient method for both simulation of supercritical heat transfer processes and optimization of heat transfer systems is highly desired.

Recently, Zhao and Chen [23] applied the thermal circuit method to investigate heat transfer processes with fluid property variation. This study established the global governing equations of a heat transfer system without involving any intermediate fluid temperature, which were applied to performance simulation and optimization of the whole system. However, it only took the variation of constant pressure specific heat into account but did not consider the variation of heat transfer coefficient and the mass charge of fluid in the system, which are severe during supercritical heat transfer processes.

This paper takes a multi-loop heat exchanger network as the research subject, constructs the corresponding thermal circuit diagram, i.e. power flow topology, with consideration of the variations of specific heat and heat transfer coefficient, and builds the system heat transfer and energy conservation constraints by Kirchhoff's law in circuitous philosophy to analyze and optimize the overall heat transfer performance of the heat exchanger network at supercritical conditions. Herein, a new iterative scheme is developed to separate the calculation of both specific heats and heat transfer coefficients from the solution of heat transfer equations. The physical properties of fluids could be obtained from thermophysical property library and taken as constant when solving other variables. This scheme makes it possible to establish the global optimization equations without making the partial derivatives of the