Energy Conversion and Management 150 (2017) 134–147

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Performance simulation on unilateral ladder type helical baffle heat exchanger in half cylindrical space

Shifan Yang, Yaping Chen*, Jiafeng Wu, Huaduo Gu

Key Laboratory of Energy Thermal Conversion and Control, Ministry of Education, School of Energy and Environment, Southeast University, Nanjing 210096, China

ARTICLE INFO

Keywords:
Countercurrent U-tubes heat exchanger
Unilateral ladder type helical baffle
Half cylindrical space
Flow pattern
Heat transfer enhancement
Numerical study

ABSTRACT

A unilateral ladder type helical baffle heat exchanger (ULHBHX) which is a novel countercurrent U-tube heat exchanger was proposed and investigated for better characteristics of high heat transfer coefficient, low resistance, anti-vibration and anti-fouling with a spiral flow pattern than those of the conventional segment one. The numerical model of ULHBHX was established and simulated by CFD software with 38 heat transfer tubes and 2 rod and spacing tube assemblies in the lower half cylindrical space under the parameters of subcooling of a high pressure feedwater heater in power plants. Different views such as on baffle-parallel slices and polygonal slices were presented to show the flow patterns of the main helical flow, secondary vortex flow and the leakage flow. The influences of geometrical parameters of baffle pitch and projection length of the inclined section on heat transfer and pressure drop were discussed quantitatively. The results show that the shell-side heat transfer coefficient h_o of the ULHBHXs is 13.2%–18.2%, with an average of 16.0%, higher than those of the corresponding segment schemes, and the comprehensive index $h_o \Delta p_o^{-1/3}$ is 15.7%–46.4%, with an average of 28.3%, higher than those of the corresponding segment schemes with identical baffle pitches in the discussed range.

1. Introduction

Heat exchangers have numerous applications in industries such as power plants, oil refineries, food, pharmacy and refrigeration. The most applied type in industries is shell-and-tube heat exchangers (STHXs) which are of robust construction and feasible applications fitting almost all heat and mass transfer processes, of which the U-tube type heat exchangers are especially preferred with their free end structure for remediating thermal stress to withstand high temperature/pressure conditions [1–4]. In a power plant for instance, the high pressure feedwater heaters are typically horizontal U-tube heat exchangers to preheat the feedwater by extraction steam from steam turbines [5]. Improving their heat transfer performance, especially for the shell-side, can make a great enhancement in system performance.

The segment baffle shell-and-tube heat exchangers are the most commonly used ones of STHXs, which are easy in manufacture and installation, but they have shortcomings of lower heat transfer coefficient (h.t.c.) with stagnant zones, higher pressure drop and propensities of fouling and vibration damage on the tube bundles. Lutcha and Nemcansky [6] proposed and developed quadrant HBHXs (helical baffle heat exchangers), which are regarded as one of the best improvements for shell-side heat transfer enhancement. Since then the helical baffle heat exchangers have been widely studied and also applied in industries [7–10]. Stehlik et al. [11] and Kral et al. [12] compared the shell-side h.t.c. and pressure drop of quadrant HBHXs with different helix angles (or inclined angles) to those of the segment baffle ones, and the results showed that the HBHX with helix angle 40° demonstrated the best comprehensive behavior. Andrews and Master [13] performed 3D model simulation of HBHXs, and the results revealed that by increasing the helix angle, the fluid behavior became more similar to a plug flow. Shen et al. [14] proposed a mathematical model of flow and heat transfer for HBHXs to simulate the effect of helical baffles on heat transfer and flow characteristics, and the preliminary mechanisms of spiral-like flow for heat transfer enhancement were discussed. Zhang et al. [15] experimentally compared the performance of shell-and-tube oil cooler of mid overlap quadrant helical baffles to the segment baffle one, the results showed that the comprehensive index of the helical baffle scheme, which designated shell-side h.t.c. over pressure drop, was higher but the shell-side h.t.c. was lower than those of the segment baffle one. Saeedan and Bahiraei [16] applied neural network to find optimum helix angle and baffle axial overlap for quadrant HBHXs.

In view of the fact that the quadrant baffles do not well fit the mostly applied equilateral triangle tube layout of STHXs, Chen [17] proposed the trisection HBHXs. Then Chen et al. [18–20] proposed and investigated the circumferential overlap trisection HBHXs. The results showed that the structure of circumferential overlap of helical baffles

* Corresponding author.
E-mail address: ypgchen@sina.com (Y. Chen).

http://dx.doi.org/10.1016/j.enconman.2017.07.062
Received 1 June 2017; Received in revised form 19 July 2017; Accepted 28 July 2017

Nomenclature

Latin letters

a	tube pitch, m
c_p	specific heat, J·kg^{-1}·K^{-1}
D_s	inner diameter of shell, m
d	diameter of tube, m
h	heat transfer coefficient, W·m^{-2}·K^{-1}
K	overall heat transfer coefficient, W·m^{-2}·K^{-1}
k	turbulence kinetic energy, m^2·s^{-2}
L	effective length of tube, m
l	projection length of the inclined section, m
m	mass flow rate, kg·s^{-1}
P	baffle pitch, m
p	pressure, Pa
Q	heat, kW
$Re_{z,o}$	axial Reynolds number
T	temperature, K
u	velocity vector or velocity component in the x direction, m·s^{-1}
v	velocity component in the y direction, m·s^{-1}
w	velocity component in the z direction, m·s^{-1}

Greek letters

β	inclined angle, °
Δ	difference
δ	thickness of baffle, m
ε	turbulence dissipation rate, m^2·s^{-3}
λ	thermal conductivity, W·m^{-1}·K^{-1}
ρ	density, kg·m^{-3}
μ	dynamic viscosity, kg·m^{-1}·s^{-1}
τ	shear stress, N·m^{-2}

Subscript

i	tube-side
o	shell-side
in	inlet
out	outlet

can restrain the leakage at conjunctions of adjacent baffles. Dong et al. [21] numerically compared four trisection helical baffle schemes with identical helix pitch, including circumferential overlap, end-to-end, blocked V-notch and axial overlap, and the results showed that the circumferential overlap scheme performed the best over the other schemes. To solve helical baffle assembly problems, Wang et al. [22,23] presented two ways by adding wedge-shaped washers at both sides of the baffles around the holes for fasten rods or folding the "baffle ears" at the corners of curved edge and straight edges of the circumferential overlap baffles, and numerically simulated the flow models of these new structures. Tang et al. [24] numerically investigated the performances of axial separation HBHXs that forming greater helical pitch with small incline angled baffles which made it possible for baffle inclined angle seriation to reduce manufacturing cost of helical baffles. It is concluded that the baffle pitch rather than the inclined angle of baffles plays a main role in determining the performances of the HBHXs.

There have been other structural improvements on the HBHXs. Du et al. [25] put forward a sextant helical baffle heat exchanger using quadrant baffles and indicated that the leakage flow can be reduced by circumferential overlap. Wang et al. [26] proposed folded quadrant helical baffles which can intensify the heat transfer by blocking the outer triangle leakage zones of mid axial overlap helical baffle scheme. Wen et al. [27] proposed a ladder-type folded half baffle scheme with the same intention to block the leakage zones between two adjacent baffles of the HBHXs, the numerical results showed that with circumferential overlapping adjacent baffles, the shell-side fluid flow is more close to the spiral flow, thus the shell-side heat transfer of the heat exchanger can be improved.

Nevertheless, the abovementioned studies on the HBHXs were all in a cylindrical space or an annular cylindrical space. For the half cylindrical space of countercurrent U-tubes heat exchangers, the existing schemes are dominantly of the segment baffle ones.

Adopting helical baffles to replace the segment ones is a significant alternative and a worthwhile attempt for heat transfer enhancement. In this paper, the unilateral ladder type helical baffle heat exchangers (ULHBHXs) were proposed and the performances of the ULHBHXs were investigated in comparison with those of the segment baffle ones. The aim of this research is not only to widen the application of helical baffle technique, but also to make a comprehensive insight into the mechanisms of the shell-side heat transfer enhancement with such an irregular configuration for guiding possible practical application in industries.

The ULHBHX is a novel countercurrent U-tube STHX with the unilateral ladder type helical baffles consisting of two groups of plates, i.e. the folded strip baffles with arc ends (Baffle 1) and the segment ones (Baffle 2). This configuration can more preferably suit the half

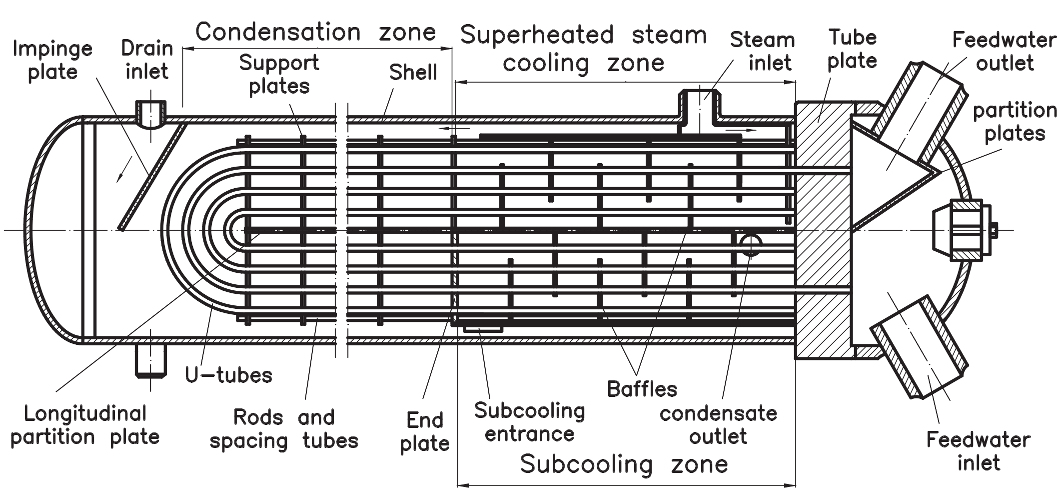

Fig. 1. Structure of a U-tube high pressure feedwater heater with three exothermic zones.