Applied Thermal Engineering 70 (2014) 1216–1227

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Shell-side thermal-hydraulic performances of multilayer spiral-wound heat exchangers under different wall thermal boundary conditions

Xing Lu, Xueping Du, Min Zeng, Sen Zhang, Qiuwang Wang*

Key Laboratory of Thermo-Fluid Science and Engineering, MOE, Xi'an Jiaotong University, Xi'an 710049, Shaanxi, PR China

HIGHLIGHTS

- Shell-side flow and heat transfer of a spiral-wound heat exchanger is experimentally studied.
- Effects of three kinds of thermal boundary conditions are numerically investigated.
- The constant temperature thermal boundary condition could be employed for simulation.

ARTICLE INFO

Article history:
Received 5 January 2014
Accepted 20 February 2014
Available online 4 March 2014

Keywords:
Multilayer spiral-wound heat exchanger
Shell-side heat transfer performance
Thermal boundary conditions

ABSTRACT

The multilayer spiral-wound heat exchanger (SWHX) is used extensively in many industrial fields, but little research on the shell-side thermal-hydraulic performances in SWHXs has been performed. So an investigation on the shell-side flow and heat transfer performances of multilayer SWHXs under turbulent flow is implemented by using experimental and numerical methods. An experiment on the shell-side flow and heat transfer performance of a self-manufactured SWHX with three layers of coils is carried out under heat flux specified boundary condition (BC) to validate a numerical method. The results obtained by the simulations agree well with those from the experiment. Furthermore, to study the effects of different thermal BCs of the tube wall on the shell-side heat transfer performance in the multilayer SWHXs, numerical simulations are performed under the thermal BC of constant heat flux and constant temperature. Then the results are compared to those of the water-to-water conjugate heat transfer. It is found that the maximum relative deviation is 11.4% and 3.5%, respectively. Finally, the correlation of the shell-side Nusselt number, Nu_s is obtained by the Wilson plot method, which is $Nu_s = 0.179 \cdot Re_s^{0.862}$, with the available range of Re_s from 500 to 3500.

1. Introduction

The spiral-wound heat exchangers (SWHXs) are widely applied in rectisol process [1], air separation plants, liquefied natural gas (LNG), chemical process [2], coal gasification and liquid nitrogen [3] due to their overwhelming advantages, including:

- Highly compact structure

According to Zhang [4], the SWHXs have large heat transfer area per unit volume. Generally in shell-and-tube heat exchangers, a straight tube with the diameter of 8 mm–21 mm usually makes the heat transfer area from 54 $m^2\ m^{-3}$ to 77 $m^2\ m^{-3}$, while a spiral pipe with the same diameter 100 $m^2\ m^{-3}$ to 170 $m^2\ m^{-3}$ [5].

- High pressure endurance

The stress intensity of the spiral-wound tubes in SWHXs which are usually made of copper, aluminium and stainless steel is quite high to endure high-pressure working fluid as high as around 20 MPa [5].

- Good thermal compensation performance

The free-ends of the spiral-wound tubes benefit for the heat exchanger a good response for thermal expansion [5].

- Multi-stream heat transfer

* Corresponding author. Tel./fax: +86 29 82665539.
E-mail address: wangqw@mail.xjtu.edu.cn (Q. Wang).

http://dx.doi.org/10.1016/j.applthermaleng.2014.02.053
1359-4311/

Nomenclature

A_i	Heat transfer area of inner walls of coils, m^2
A_o	Heat transfer area of outer walls of coils, m^2
$A_{s,min}$	Minimum cross-section area in shell-side flow passage, m^2
B	Thickness of space bar, mm
c_p	Specific heat capacity in constant pressure, J kg^{-1} K^{-1}
De_t	Dean number of helix pipe
$D_{s,i}$	Outer diameter of centre cylinder, mm
$D_{s,o}$	Inner diameter of shell, mm
D_t	Outer diameter of spirally coiled pipes, mm
d_t	Inner diameter of spirally coiled pipes, mm
dp	Pressure drop, Pa
G_s	Mass flow rate of shell-side fluid, kg s^{-1}
H	Effective height for heat transfer, mm
h	Heat transfer coefficient, W m^{-2} K^{-1}
k	Turbulent kinetic energy, m^2 s^{-2}
L	Tube length, mm
N_c	Number of spirally wound pipes in one layer of coil
N_{lay}	Number of layer
Nu	Nusselt number
P	Pressure, Pa
Pl	Helix pitch, mm
Pl_r	Axial distance of two adjacent layers of coils, mm
q	Heat flux, W m^{-2}
q_v	Volume flow rate of gas, m^3 h^{-1}
Ra	Rayleigh number
Re	Reynolds number
S_{ij}	Mean rate of strain tensor, s^{-1}
T	Temperature, K
U	Overall heat transfer coefficient, W m^{-2} K^{-1}
v_m	Maximum velocity of shell-side fluid, m s^{-1}
v_t	Inlet velocity of tube-side fluid, m s^{-1}
x, y, z	Coordinates, m

Greek symbols

α	Helix angle, °
ΔT	Temperature difference, K
ε	Dissipation of turbulent kinetic energy, m^2 s^{-3}
λ	Thermal conductivity, W m^{-1} K^{-1}
μ	Dynamic viscosity, Pa s
μ_t	Turbulent viscosity, Pa s
υ	Kinematic viscosity, m^2 s^{-1}
ρ	Density, kg m^{-3}
Φ	Heat transfer rate, W

Subscripts

a	Averaged value
D_{eq}	Varieties using shell-side equivalent diameter as characteristic scale
s	Shell-side
t	Tube-side
w	Wall

The SWHXs are classified into mono-stream SWHXs and multi-stream SWHXs according to the species of tube-side working fluid [6]. The mono-steam SWHXs have one kind of fluid in the flow passages of the coils, while the multi-stream SWHXs have several different working fluids in different layers of coils.

The structure of the multilayer SWHXs is quite complicated, with several layers of spirally coiled tubes inside a shell. Ever since Eustice [7] first observed a secondary flow inside a curved pipe in his experiment, lots of studies on flow and heat transfer inside curved pipes have been performed. Naphon and Wongwises [8] presented a literature review on heat transfer and flow characteristics of single-phase and two-phase flow in curved tubes which have been used as one of the passive heat transfer enhancement techniques in several heat transfer applications. They categorized the curved tubes into three kinds, including helically coiled tubes and spirally coiled tubes and other coiled tubes, to make classification discussion.

To a large extent, the flow and heat transfer enhancement mechanisms in curved pipes have been investigated and clarified a lot since before, but the mechanisms of the shell-side fluid flow and heat transfer are not clear yet. In engineering fields, the manufacturing of multilayer SWHXs remains some problems on the characteristics and mechanisms of the shell-side flow and heat transfer performance, which needs to further investigate the shell-side performance of SWHXs. However, there are only scattered reports on investigations of the shell-side thermal-hydraulic performance in SWHXs.

Ho et al. [9] experimentally investigated a spiral coil heat exchanger consisted of horizontal layers of spirally wound, finned tubes connected to vertical manifolds at the inner and outermost turns of each coil, which is widely used in air conditioning and heat recovery. Charts of the effectiveness vs. NTU (Number of Transfer Units) suitable for the heat exchanger design were also presented.

Naphon et al. [10] investigated the heat transfer characteristics under cooling and dehumidifying conditions in a spiral coil heat exchanger which is consisted of a steel shell and a six-layer spirally coiled tube unit. They developed a mathematical model based on mass and energy conservation to determine the heat transfer characteristics and the results obtained from the model were in reasonable agreement with their experimental data.

Neeraas et al. [11] constructed a test plant for measurements of local heat-transfer coefficients and frictional pressure drops on the shell side of LNG SWHXs. The heat transfer coefficients from the experimental results were compared with those from the Gnielinski formula [12], with an average deviation of ±5%. For frictional pressure drop, a modified method from Barbe et al. [13] was employed, with an average deviation of ±3%. Neeraas et al. [14] also conducted an experiment of the shell-side liquid falling film in LNG SWHXs to measure the shear flow of single phase steam, liquid film and two-phase fluid. The experimental results of heat transfer coefficients for gravity dominated liquid falling film flow were validated against the method from Bays and McAdams [15], with an average deviation of ±7%.

Jayakumar et al. [16] numerically calculated the mixed convective heat transfer in a helix coiled heat exchanger to obtain correlations for tube-side Nusselt number. The helix coiled heat exchanger had one helical pipe with two turns inside the shell. Also, Jayakumar et al. [17] described the variation of local Nusselt number along the length and circumference at the wall of vertically oriented helical coils with the aid of numerical simulation. Geometrical parameters such as pitch circle diameter, tube pitch and pipe diameter were varied to study their influence on the heat transfer and obtain the correlations for prediction of Nusselt number.

Gupta et al. [18] experimentally studied the pressure drop characteristics of the tube-side and shell-side flow of cryogenic cross-counter flow coiled finned tube heat exchangers. All