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Experimental investigation on enhanced heat transfer of vertical condensers with trisection helical baffles

Jiafeng Wu [a], Jiahao Zhou [a], Yaping Chen [a,*], Mingchao Wang [a], Cong Dong [a,b], Ya Guo [a,c]

[a] Key Laboratory of Energy Thermal Conversion and Control of Ministry of Education, School of Energy and Environment, Southeast University, Nanjing 210096, PR China
[b] School of Mechanical and Automotive Engineering, Zhejiang University of Science and Technology, Hangzhou 310023, PR China
[c] Mcquay Air Conditioning Refrigeration (Suzhou) Corporation, Suzhou 215126, PR China

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ABSTRACT

The vertical condensers have advantages of small occupation area, convenient in assemble or dismantle tube bundle and simple structure etc. However, the low heat transfer performance limits their applications. To enhance the heat transfer, a novel type of vertical condensers was designed by introducing trisection helical baffles with liquid dams and gaps for facilitating condensate drainage. Four configurations of vertical condensers with trisection helical baffle are experimentally studied and compared to a traditional segment baffle condenser. The enhancement ratio of trisection helical baffle schemes is about 1.5–2.5 and the heat transfer coefficient of the dual-thread trisection helical baffle scheme is superior to that of the single-thread one by about 19%. Assistant by the theoretical study, the experimental data is simulated and the condensation enhancement mechanisms by applying trisection helical baffle in vertical condenser are summarized as condensate drainage, short tube construct and reduce steam dead zone functions of the helical baffles.

1. Introduction

Tube-shell condensers have wide applications in various areas such as electric, chemical, refrigeration and building heating, ventilation and air conditioning (HVAC) industries [1,2] with arrangement of either horizontal or vertical. In the condensation side of the steam heaters or multi-effect evaporator-condensers in many industries, the vertical equipment has advantages such as small occupation area, convenient in assemble or dismantle tube bundle compared to horizontal layout [3]. In most industry plants, the lift equipment is available and adopting the vertical condenser can reduce the maintenance time and cost, which are quite attractive for these industries.

However, the vertical condenser has its own disadvantage of the low heat transfer performance due to thick film along the vertical tubes which limits its application. The condensate in vertical condenser flows along the tube bundle, leading to condensate accumulation in the tube surfaces and forming thick liquid film which results in larger thermal resistance. Additionally, in the vertical condenser with traditional segment baffles (SEGs), the steam in the shell side flows in zigzag pattern, and the stagnant zones are formed near the corners of baffle plates and inner shell, which can greatly influence the condensation heat transfer [3]. On the other hand, the liquid film thickness is much thinner on horizontal condenser tubes as the flow direction of condensate is orthogonal to the tube bundle with smaller vertical dimension of the tube bundle. Therefore, in the same conditions, the condensation heat transfer coefficient in shell side of a vertical condenser with traditional SEGs is lower than that of the horizontal one. It is critical to consider how to enhance the shell side condensation heat transfer of vertical condensers to promote their further applications.

Various methods have been used to enhance the condensation heat transfer, for example, making hydrophobic surface to realize dropwise condensation [4–6], and reducing non-condensable gas in the system [7,8]. However, the dropwise condensation is still not stably realized in the practical industry applications and the non-condensable gas is unavoidable in widespread condensers.

Using enhanced tubes is another important approach for condensation enhancement especially in horizontal condensers. Enhanced tubes such as, low-fined [9–11], wire-wrapped [9,12], Turbo-C [10,11,13,14], Gewa-C [13,14] and edge-shaped finned [15] tubes or tube coated with open cell copper foam [16] can effectively raise the condensation heat transfer coefficient of the horizontal tubes or columns. While for the vertical surface, Thomas [17] studied the condensation enhancement on tube with loosely attached vertical wires, a tripled condensing heat transfer

* Corresponding author at: Southeast University, Sipailou Campus, No. 2 Sipailou, Nanjing 210096, PR China. Tel.: +86 013851729402.
E-mail address: ypgchen@sina.com (Y. Chen).

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Nomenclature

A	heat transfer area, m^2
c	specific heat, J/(kg K)
d	diameter of the tube, m (mm)
G	volume flow rate, m^3/s (l/min)
g	gravitational acceleration, m/s^2
H_{fg}	latent heat, J/kg
h	heat transfer coefficient, W/(m^2 K)
K	overall heat transfer coefficient of the condenser, W/(m^2 K)
L	the effect length of the tube, m (mm)
L'	length of tube bundle section, m (mm)
l	baffle pitch, m (mm)
$\bar{l}$	average baffle pitch, m (mm)
l_e	the distance of the control element and the upstream baffle, m (mm)
m	condensing rate per unit area and unit time, kg/(m^2 s)
N	short tube number in each tube bundle section
n	tube number
n'	rod number
P	shell side pressure of condenser, Pa (kPa)
Q	condenser cooling load, W (kW)
T	temperature, K (°C)
X	volume fraction
x	coordinate, m (mm)
Y	mass fraction
y	coordinate, m (mm)

Greek symbols

Δ	film thickness, m (mm)
ΔP	shell side pressure drop, Pa (kPa)
ΔQ	heat transfer of one step-size, W
ΔT	logarithm mean temperature difference, K (°C)
Δx	step-size, m (mm)
δ	absolute error of the parameters
ε	relative error of the parameters
θ	inclined angle, °
λ	thermal conductivity, W/(m K)
μ	dynamic viscosity, Pa s
ρ	density, kg/m^3

Subscripts

1	inlet
2	outlet
A	the first section of tube bundle
B	the second section of tube bundle
C	the third section of tube bundle
c	condensate
DH	dual–threads helical baffle scheme
DHD	dual–threads helical baffle with liquid dam scheme
exp	experimental data
f	interface of condensate and vapor
i	inside of the tube (cooling water)
N	non-condensable gas
o	outside of the tube (vapor and condensate)
P	pressure
S	steam
SEG	segment baffle scheme
SH	single–thread helical baffle scheme
SHD	single–thread helical baffle with liquid dam scheme
sat	saturated
sim	simulation data
v	vapor phase
w	tube wall
x	local

coefficient was reported. Mori et al. [18] and Park et al. [19] simulated the condensation on the tube with longitudinally parallel tiny fins and vertical grooves respectively. They descripted that most of the condensation takes place on the bare portion of the enhanced surface, which clearly demonstrates how the heat transfer is enhanced. Recently, Tong et al. [20] experimental studied the condensation over a vertically longitudinal finned tube and distinct results are presented for different cases. At pure steam case, the longitudinal finned tube played a positive effect on the condensation, while at the steam–air case, the longitudinal finned tube generated restrictions on the condensation process when air mass fraction is below 75%. This result reminds the researchers to reconsider the effect of enhanced structure on condensation with non-condensable gas on vertical surface.

Gregorie effect [18,19,21,22] is the main mechanism for the condensation enhancement of enhanced tube. Surface tension is utilized to increase bare portion of the surface, while the drainage of condensation, which is the key problem of the condensation enhancement on vertical tube surface, is always not sufficiently considered in enhanced tube designing. And the complex structures on the enhanced tubes may lead large area of dead zoon, which is extremely detrimental to condensation with non-condensable gas conditions. In addition of the high cost and the inconvenient installation, the application of condensing enhanced tube in vertical condensers is much less than that in the horizontal ones.

Based on the fact that currently film condensation rather than dropwise one is widely applied in industrial applications, Cvengros et al. [23] reported a divided condenser instead of the undivided condenser to enhance the heat transfer in fractionation process of a molecular evaporator. Peng et al. [24] designed a plate-fin heat exchanger with condensation took place in the internal channel and draining the condensate at each returning header to enhance film condensation heat transfer by taking advantage of the thin film sections. The essence of this approach is condensation in short-section and intermediate drainage. Accepting this idea, the trisection helical baffle vertical condensers are proposed for replacing the conventional segmental ones [3].

Chen et al. [25–30] have proposed and investigated the trisection helical baffle tube-shell heat exchangers, which are the modification of the quadrant helical baffle ones [31,32], more suitable for the mostly adopted equilateral triangle tube layout. The circumferential overlapped trisection baffle scheme can effectively restrain the leakage flow in triangle area between adjacent baffles thus having better heat transfer performance verified by both simulation and experimental data. Furthermore, the trisection helical baffle approach has the prospect in application of electric heaters [33] which can not only improve the heat transfer coefficient of electric heater, but also make the flow field more uniform with reduced average and the highest temperatures of electric heater surfaces.

Helical baffles have been adopted in horizontal tube-shell condensers for enhancement by some experts [34,35], however, the inclined helical plates do not show any advantage at guiding or draining the condensate over the vertical segmental ones. In the proposed vertical condenser, beside still takes the role of guiding the steam flow, reducing the stagnant flow zone with plug flow effect, supporting the tube bundle etc., and the trisection helical baffles can provide a novel heat transfer enhancement mechanism