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An experimental investigation of heat transfer enhancement for a shell-and-tube heat exchanger

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ABSTRACT

For the purpose of heat transfer enhancement, the configuration of a shell-and-tube heat exchanger was improved through the installation of sealers in the shell-side. The gaps between the baffle plates and shell is blocked by the sealers, which effectively decreases the short-circuit flow in the shell-side. The results of heat transfer experiments show that the shell-side heat transfer coefficient of the improved heat exchanger increased by 18.2–25.5%, the overall coefficient of heat transfer increased by 15.6–19.7%, and the exergy efficiency increased by 12.9–14.1%. Pressure losses increased by 44.6–48.8% with the sealer installation, but the increment of required pump power can be neglected compared with the increment of heat flux. The heat transfer performance of the improved heat exchanger is intensified, which is an obvious benefit to the optimizing of heat exchanger design for energy conservation.

1. Introduction

Shell-and-tube heat exchangers are commonly used in petrochemical and energy industries for their relatively simple manufacture and adaptability to different operating conditions. Although not the most compact solution, their robustness and shape make them well suitable for high-pressure operations [1]. The baffles are primarily used in shell-and-tube heat exchangers for inducing cross flow over the tubes, and as a result, improving heat transfer performance. In practice this objective is not quite achieved due to departure from cross flow and due to several leakages and bypass stream.

Pressure drop and heat transfer are interdependent and both of them essentially influence the capital and operating costs of any heat exchange system. The design and optimization of shell-and-tube heat exchangers including thermodynamic and fluid dynamic design, strength calculations, cost estimation represents a complex process containing an integrated whole of design rules, calculating methods and empirical knowledge of various fields [2]. The optimization of shell-and-tube heat exchangers requires a good knowledge of the local and average shell-side heat transfer coefficients. In the past few years there were realized several developments to improve the thermal effectiveness of shell-and-tube heat exchangers. New types of tube-side turbulence promoters (e.g. tube inserts, corrugated tubes) and tube supports (e.g. helical baffles) have been successfully introduced. Thome et al. [3] put forward that the proper application of tubular heat transfer augmentations is able to reduce heat exchanger tubing linear footage by 25–75% compared with conventional plain tube units. Hosseini et al. [4] experimentally investigated the effect of different types of external tube surfaces on shell-side heat transfer coefficient and pressure drop of a shell-and-tube heat exchanger. The results showed that the performance of the heat exchanger greatly improved for micro-finned tubes at a higher Reynolds number. Another feature of optimization is to select the optimum inter-baffle spacing. Li et al. [5] found that the increased baffle spacing can increase the heat transfer coefficient in the whole baffle. The local heat transfer coefficient distribution at an individual tube is slightly affected by the baffle spacing. Taborek et al. [6] suggested that the space between the baffles could vary between a minimum of 20% of shell diameter and a maximum equal to the shell diameter. Mukherjee et al. [7] pointed out that the optimum baffle spacing normally ranges from 0.3 to 0.6 times the shell diameter. Saffar-Avval et al. [8] have studied the effect of baffle spacing on heat transfer area and pressure drop, and conclude that the baffle spacing has a decisive effect on pumping power and noticeable effect on required heat transfer area, where a guideline has been also developed to calculate the optimum baffle spacing for single phase E-type shell-and-tube heat exchanger. In a recent study, Eryener et al. [9] analyzed the optimum ratio of baffle spacing to shell diameter by applying the thermoeconomic analysis method. Although all these investigations are able to improve the performance of the heat exchanger to some extent, the results are not so obvious.

There are also a few researchers who have studied the effect of leakage flow on thermal performance of shell-and-tube heat exchangers. Roetzel and Lee [10] experimentally investigated the leakage flow in shell-and-tube heat exchangers with segmental baffles. They found that the shell-baffle leakage has great influence on

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Nomenclature

C_p	average specific heat capacity at constant pressure (kJ/(kg K))
d_i	internal diameter of tubes (mm)
d_o	external diameter of tubes (mm)
E	exergy (kJ/s)
E_{gain}	gained exergy (kJ/s)
E_{pay}	consumed exergy (kJ/s)
h	enthalpy (kJ/kg)
N_e	pump power consumption (W)
K	overall coefficient of heat transfer (W/m^2 K)
Q	total heat transfer in the heat exchanger (kJ/s)
Re	Reynolds number
R_i	water-side fouling resistance (m^2 K/W)
R_o	oil-side fouling resistance (m^2 K/W)
T_a	air temperature (K)
U	velocity (m/s)
V	shell-side volume flow (m^3/s)
W	mass velocity (kg/s)

Greek symbols

α_0	oil-side heat transfer coefficient (W/m^2 K)
α_i	water-side heat transfer coefficient (W/m^2 K)
δ	tube thickness (mm)
$\varDelta$	error
ΔP	shell-side pressure drop (mmHg)
ΔT	temperature change from inlet to outlet in the exchanger (K)
ΔT_m	logarithmic mean temperature difference (K)
λ	heat conduction coefficient of tubes (W/m K)
η_{ex}	exergy coefficient of heat exchanger

Subscripts

c	cold fluid
ex	exergy
h	hot fluid
o	oil
w	water
1	inlet
2	outlet

the apparent overall heat transfer coefficient, which is based on the ideal plug flow model. This reduction will be even greater when the tube-side Reynolds number increases. Roetzel and Lee [11] studied experimentally the influence of baffle-shell leakage flow on the thermal performance in baffled shell-and-tube heat exchangers with different distances between baffles. The results have shown that baffle-shell leakage flow causes a reduction in the thermal performance. This reduction increases as the tube-side Reynolds number increases, and the distance between baffles decreases. Li and Kottke [12] performed experiments to determine the response of the pressure drop and local heat transfer on the shell-side of shell-and-tube heat exchangers to a change in the leakage between baffles and shell in the fully developed regime. They found that the leakage between baffles and shell can greatly reduce the pressure drop and the per-compartment average heat transfer coefficient. They found that baffle-shell leakage reduces greatly the heat transfer by 17–21% among their experimental Reynolds range.

All the above research results demonstrate that the baffle-shell leakage is negative for the improvement of the heat transfer in shell-and-tube heat exchangers. However, there is still an apparent lack of literature on the topic of configuration improvements of shell-and-tube heat exchangers to decrease the leakage flow. For manufacturing reasons, the internal diameter of the shell is always bigger than the external diameter of tube bundle for the successful installation. So according to the GB151 national standards of China, there is always a circular gap of around 3–7 mm between the shell and tube bundle for the shell-and-tube heat exchangers with diameter between 400 and 2000 mm. And with the development of larger heat exchangers, the gap will increase accordingly. A part of the fluid in the shell will flow through the gap and does not participate into heat exchange, thus diminishing thermal performance of the heat exchangers. Hence experimental investigation is performed in this paper to effectively decrease the shell-baffle leakage flow through the configuration improvement of shell-and-tube heat exchanger.

2. Configuration improvement

2.1. Flow mode of conventional heat exchanger

The flow modes of the conventional shell-and-tube heat exchangers are demonstrated in Fig. 1. There are three types of flow modes in the shell. A is cross flow of fluid through the tube bundle. B is the flow through the gaps of segmental baffles and C is the shell-baffle leakage flow (short-circuit flow).

2.2. Flow mode of improved heat exchanger

The so called configuration improvement is to install sealers on each baffle in order to block the baffle-shell gap. The flow distribution for baffled shell-side flow of improved heat exchanger is shown in Fig. 2. There are only two kinds of flow modes (A and B) after the installation of sealers. The flow mode of C is prevented, and this part of fluid is forced to join modes A and B to participate in heat exchange.

As to the shell-and-tube heat exchanger AES300-2.5-10-3/25-2 used in the experiment, the cross-sectional area of the baffle-shell gap (circular flow passage) engages about 1/6 of the total flow area in shell-side. At the same pressure head, the flux inside two flow passages relates to not only the flow area but also the resistance inside the flow passages. The circular flow passage through the gap is short and straight, which causes little resistance. While the flow passage within the tube bundle is Z-shaped and long, which results in more resistance. Thus the unit area flux in the short-circuit flow passage is larger than that of the other one. So the sealers may block more than 1/6 of all the flux in the shell. The effect of the baffle-shell leakage flow on the thermal performance cannot be

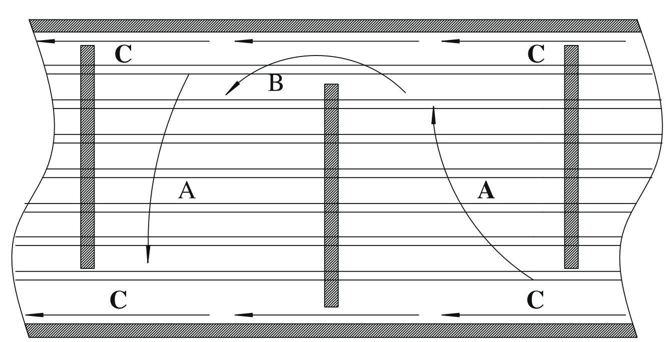

Fig. 1. Schematic flow distribution for baffled shell-side flow of conventional heat exchanger.