Studies of Shell-and-Tube Heat Exchanger with Helical Baffles

Tejas Manojkumar Chauhan[a], Dr. Hemant Kumar Gupta[b*,] Hirenkumar Ranjitsinh Mahida[c]
Department of Mechanical Engineering, Shroff S. R. Rotary Institute of Chemical Technology, Vataria 393135, Gujarat, India

*Corresponding author Email: hemant.gupta@srict.in

Conventional segmental baffles used in shell-and-tube heat exchanger have limitations such as high pressure drop, dead zones, flow induced vibrations and bypass flows. These shortcomings of segmental baffles may be eliminated using helical baffles. In helical baffle, the shell side flow reaches to near plug flow and guides the shell side fluid smoothly. In this paper, experimental and numerical work done using different helical baffles are studied. The comprehensive performance of helical baffle shell-and-tube heat exchanger is better than the segmental baffle shell-and-tube heat exchanger. Despite of initial high cost and manufacturing limitations, the use of helical baffle may reduce the operating and maintenance cost, save energy and gives good service life.

Keywords: Shell-and-tube heat exchanger, helical baffles, heat transfer co-efficient, pressure drop

1. Introduction

A heat exchanger is a device which transfer the thermal energy between two or more fluids, or between the solid surface and a fluid[1]. Heat transfer occur in heat exchanger in three modes: conduction, convection and radiation. The heat exchangers are classified based on geometrical conditions (e.g. Plate heat exchanger, double pipe heat exchanger, shell-and-tube type heat exchangers etc.), based on transfer processes (e.g. Direct contact and indirect contact), based on heat transfer mechanism (e.g. Single phase and two phase) and based on flow arrangements (e.g. Parallel flow, counter flow and cross flow)[2]. Among these types of heat exchangers, shell-and-tube heat exchanger (STHX) is versatilely accepted due to relatively large ratios of heat transfer area to volume, ease of cleaning, reliable design methods and suitable for high pressure applications[3]-[4]. STHX finds its application in number of fields such as chemical process, petroleum refinery, refrigeration, air conditioning, power generation, condensation and evaporation[5]. It has been reported that among the different type of heat exchangers used, 55-70% are STHX[6].

In the STHX, baffle is used to support the tubes and prevent the sagging effect in long tubes and divert the flow towards the tubes to increase the heat transfer co-efficient. In past, various types of baffles were reported namely single segmental, double segmental, triple segmental, disk-doughnut type, helical, double helical and flower type[7]. Among them, segmental baffles were used traditionally. There are many problems reported with the use of conventional segmental baffles(SB) in STHX[8]-[10], e.g., (1) since the SB comes perpendicular to flow directions, a high pressure drop occurs. There are sudden contraction and expansion in flow due to baffle geometry. This leads to the high pressure drop and high pumping power requirement; (2) a large cross flow strikes on the tube bundles, induces the vibrations and reduce the service life of the exchanger; (3) flow stagnation region called dead zones generated at the joint of shell walls and baffles which considerably reduced the heat transfer rates;(4) the mass of shell side flowing on the tube bundle reduces due to bypass flows and leak flow between the shell walls and baffles and between heat exchange tubes and baffles.

J Lutcha and Nemcansky firstly proposed the helical baffle(HB) and showed the effect of different helical baffles on the flow field[12]. Using HB, dead zones and pressure drops considerably reduced as compared to SB[7]. The flow pattern in case of HB-STHX is smooth

and moving in screw shape[13]. Due to this flow pattern, there is reduction in flow induced vibration, shell side fouling and increased the heat transfer rate to pressure drop ratio[11].

In this paper, studies of using different types of HB and the factors affecting the performance of STHX are discussed.

2. Factors affecting the performance of STHX

The performance of STHX is affected by many parameters such as type of fluid, mass flow rate of fluids, turbulence, pressure drop (Δp), heat transfer co-efficient (h), fouling, and type of baffle. The high value of h leads to the higher heat transfer, while the higher Δp leads to the higher pumping power requirement.

The fluid properties like viscosity, density, thermal conductivity and specific heat affect the h and Δp. By increasing the mass flowrate, the heat transfer increases at an expense of increase in Δp. As the turbulence intensity increases the flow resistance increases, which leads to the enhancement in heat transfer[14]. Fouling reduces the performance of STHX by increasing the conduction resistance as well as increases the Δp[15].

The flow pattern of shell side fluid depends upon the type of baffle. A good baffle shape diverts the flow towards the tube bundle, create turbulence and hence increase the heat transfer at a low Δp. A properly designed continuous HB leads to reduction in fouling[17]. Several researchers have done the numerical and experimental investigation for evaluating the performance of STHX by varying the baffle shape. The different shape of baffles studied in STHX are single segmental baffle, double segmental baffle, triple segmental baffle, disc and doughnut baffle, flower type baffle, orifice baffle, tre-foil hole baffle, helical baffles[7]. Among the different type of baffle studied over a decade, a HB proves to be the better option over the traditional SB and gives higher performance than others.

3. Helical Baffle Shell-and-Tube Heat Exchanger (HB-STHX)

There are two type of HB: continuous helical baffle (CHB) and discontinuous helical baffle (DHB) studied over the period to evaluate the performance of STHX.

3.1 Continuous Helical Baffle STHX (CHB-STHX)

CHB is fabricated by linking the end to end of several continuous helical baffle cycles. One continuous helical cycle is manufactured by stretching the plate by one pitch of screw in axial direction and rotating it by 2π angle along the circumferential direction. However, the manufacturing of CHB is difficult than DHB[18].

Peng et al.[17] conducted the experimental study of HB-STHX with 2 configurations, one with middle-in-middle-out continuous helical baffle(CM) and one with side-in-side-out continuous helical baffle(CS) and compared with SB-STHX. The performance of CS configuration found better than CM and SB-STHX, since in CS configuration the fluid can be effectively forced in helical passage and there is no direct impingement of fluid on shell wall as in CM. Shinde et al.[16] carried out numerical analysis of CHB-STHX with α =10°, 19°, 21°, 25°, 30°, 38°, 50° and experimental analysis with α =25° by varying the mass flow rates. They concluded that as the helix angle increases the h and Δp decreases. The initial and installation cost of HB-STHX is higher than the SB-STHX, however they concluded that the maintenance and operating cost of HB-STHX is 20-40% lesser than SB-STHX. Also, energy saving of 15-20% may be achieved using HB-STHX.

Lei et al.[11] studied the effect of baffle inclination angle on flow and heat transfer of HB-STHX with α=15°, 20°, 30°, 40°, 45°, 50° using numerical simulation. They observed near-plug flow on shell side using the CHB. The ratio of h/Δp with all value of α in HB-STHX is higher than that of the SB-STHX, while the α = 45° is optimum. Maakoul et al.[19] numerically compared the performance of STHX with tre-foil baffle, CHB and SB. They found that the velocity distribution in case of HB-STHX is more uniform and homogeneous as compared to the SB and tre-foil baffles.

The ratio of h/Δp in case of HB-STHX is 39% and 192% higher than SB-STHX and tre-foil baffle respectively. Ahmed et al.[20] conducted 3-dimensional numerical simulation to compare SB-STHX and CHB-STHX by varying the mass flow rate. The fluid flow pattern of CHB-STHX found rotational while of SB-STHX was in zig-zag manner inducing the dead zones. The ratio of h/Δp of HB-STHX found 72-127% higher as compared to the SB-STHX.
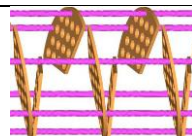
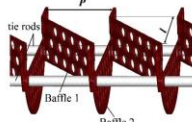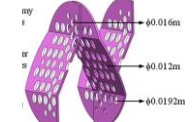## 3.2 Discontinuous Helical Baffle STHX (DHB-STHX)

DHB are formed using oval-shaped plates which are placed at an angle to the axis of heat exchanger. The ends of the plates may be joined to each other which forms the continuous helical baffle at periphery.
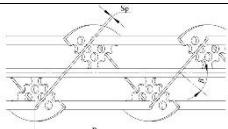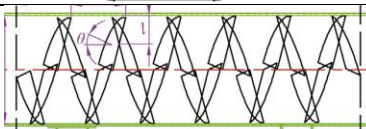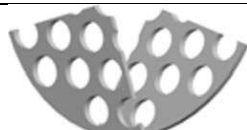
Zhang et al.[21] conducted an experimental comparison of overlapped HB-STHX and SB-STHX with α=15° in HB-STHX and cut ratio=25% for SB. The h/Δp of HB-STHX found 51.8%-76.4% higher than SB-STHX. Gao et al.[23] experimentally studied elliptical sector shaped discontinuous HB-STHX with α =8°, 12°, 20°, 30°, 40°. Based on the ratio of $j/f^{1/3}$, the 40° helix angle gives the best comprehensive performance at same volume flow rate. They suggested that in existing STHX, if retrofitting of HB is required than one must give priority to smaller helix angle from second-law thermodynamic analysis.

Wenjing et al.[22] numerically investigated 3 HB shapes (trisection, quadrant and sextant sector) using 3 helix angle(10°, 25° and 40°). The sextant HB gave the better performance in terms of fluid flow due to reduction in leakage through triangle area and close to ideal spiral flow observed. The flow in trisection and quadrant HB found more scattered and disordered. Zheng et al.[24] numerically analysed the performance of STHX using 3 trisection HB with α =10°, 15°, 20° and one axial overlap sector baffle with α=20° and one ellipse shape baffle with α=15° and compared with SB-STHX. The performance of trisection HB-STHX with α=20° was best comparatively. Chen et al.[25] performed numerical simulations to compare the unilateral ladder type HB with SB. Using unilateral ladder type baffle, spiral plug flow induced which is accompanied by secondary flow. This type of flow pattern enhances the heat transfer efficiency and decreases the Δp. The comprehensive index $h \, \Delta p^{-1/3}$ was almost 16% higher than the SB-STHX. Wang et al.[26] proposed ladder-type fold baffle for pre-heating of coal water slurry(CWS) which is non-Newtonian fluid. They concluded that the Nusselt number(Nu) and friction coefficient(f) increases with increase in helical angle. $Nu \cdot f^{-1/3}$ was giving the best performance at 18° among the helical angle investigated.

Table.1 shows the different helical baffle configuration studied.

Table. 1. Different helical baffles configurations

Authors/ type	Type of baffle	Numerical / Experimental	Geometry
Maakoul at al. (2016)	Continuous HB-STHX	Numerical	
Zheng at al. (2017)	Trisection HB	Numerical	
Chen et al. (2017)	Unilateral ladder type HB	Numerical	
Wen at al.	Ladder type fold HB	Numerical	

Zhang et al. (2013)	Ovelapped HB	Experimental	
Gao et al. (2015)	Elliptical sector shaped HB	Experimental	
Wang et al. (2015)	Quadrant circumferential overlap HB	Numerical	
Wenjing et al. (2014)	Sextant HB	Numerical	

3.3 Continuous Helical Baffle STHX(CHB-STHX) vs Discontinuous Helical Baffle STHX (DHB-STHX)

Zhang et al.[8] numerically compared the CHB-STHX with α=40° and middle overlapped DHB-STHX with α=30°, 40° and 50°. The DHB-STHX with α=40° gave the best performance based on the ratio of h/Δp. The performance of DHB-STHX was superior as compared to the CHB-STHX at same baffle inclination angle. Dong et al.[24] numerically simulated 4 different HB-STHX configurations, which were trisection circumferential overlap baffle with α=20° (20°TCO), a quadrant circumferential overlap baffle with α=18°, a quadrant end-to-end baffle with α=18° (18°QEE), and a CHB with α=18.4° (18.4°CH). The comprehensive index j/f was used to compare the performance of STHX. The 20°TCO gave the best performance within the mass flow rate studied.

4. Conclusion

The shortcomings of conventional segmental baffle may be overcome using helical baffle. The present study gives the general view of performance of shell-and-tube heat exchangers with different helical baffle. With the use of helical baffle, the performance of shell-and-tube heat exchanger increased as compared to segmental baffle which depends on many parameters. The discontinuous helical baffle is easy to manufacture and gives better performance than continuous helical baffle. Despite of high initial cost, the use of helical baffle reduce the operating and maintenance cost (20-40%), save the energy (15-20%) and increase the service life. In future work, the helical baffle may be curved in order to reduce the pressure drop which further increases the performance of shell-and-tube heat exchanger.

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