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Thermal design of shell and tube heat exchanger for waste heat recovery

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Abstract
In process industries where huge boilers are used, large amount of water is wasted intentionally which is called as blow down. This blow down water possess large amount of heat which goes as waste if not utilized or recovered properly. To recover this heat for particular application, a shell and tube heat exchanger (STHE) is designed to give required LMTD and heat transfer. In this study it is expected to increase the temperature of cold fluid by 12ºC from the hot blow down water which is discharged at 100 ºC. Also an excel sheet is developed with the help of macros which will certainly help designers to reduce their time that they invest in thermal calculations of heat exchangers. The results obtained using this developed excel program are validated with the help of HTRI (Heat Transfer research incorporation.) software which is used in industries for effective design of heat exchangers.

Keywords: Blow down, waste heat recovery, macros, ms-excel, HTRI software.

1. Introduction

STHE are the devices that offer heat transfer from one fluid to another without actually allowing the fluids to mix with each other. Such type of heat exchanger is used in chemical and process industries as they are capable of handling high pressures and their ability to offer high heat transfer rates and higher LMTD. As its name suggests it consists of a bundle of tubes which are parallel to each other inside the shell. The surface of tubes acts as a medium for transfer of heat from one fluid to another. The heat transfer in STHE occurs in three stages i.e. two convection stages in both the fluids and conduction in the wall separating fluids. In this study we are concerned about the design and performance analysis of STHE. This heat exchanger design involves different geometric and operating variables. Tubes and baffles are the main design elements. Standards are always used for design of STHE's TEMA (tubular exchanger manufacturers association). In the present paper also TEMA standards are used to decide geometric parameters of STHE. For calculating shell side parameters like heat transfer rate and pressure drop, well known Bell Delaware method is used. This method based on different fluid streams throughout the shell:

- A – Leakage stream passes as the clearance between tubes and baffles;
- B – It is the main stream flowing through baffle window and cross flow section;
- C – Bundle bypass stream which is flowing around the tube bundle between the outermost tubes in the bundle and inside of the shell;
- E – Leakage stream passing through the distance between baffles and inside of the shell;
- F – Stream passing through channels within tube bundle;

Experimentation was carried out to study the effect of shell-to-baffle clearances on the overall heat transfer coefficient. But they did not analyze the effects of tube-to-baffle clearances; it was proven the reduction of thermal performance due to presence of E-stream (Roetzel & Lee, et al, 1994). After three years,

The effect of stream A&E on local heat transfer and pressure drop was studied It is found that shell-to-baffle leakage stream reduces heat transfer efficiency and pressure drop compared to tube-to-baffle stream (Li & Kottke, et al, 1998).

The effect of baffle clearances on a heat exchanger design was analyzed. It is found that as the baffle clearance increases shell side heat transfer and pressure drop decreases (G.Batalha Leoni, etal, 2016).

The enhancement of heat transfer for STHE was experimentally investigated The sealers installed inside the STHE to block the gap between baffle plates and shell, which increases shell side overall heat transfer coefficient and heat transfer coefficient (Simin Wang, et al, 2009).

The ladder type fold baffle to block the triangular leakage zone in STHE was proposed. Because of ladder type fold baffle overall heat transfer coefficient increases (Jain Wen, et al, 2014).

The effect of using different tube layout, different tube count and tube diameter at different baffle sections on pressure losses, heat transfer rate of STHE with segmental baffles was studied. As results shows that as the number of tube reduces, heat transfer performance increases. By eliminating window section baffles will allow for mixing window and cross flow at different mass flow rate, heat transfer performance increases (Amir Asgari Tahery, et al, 2017).

2. Analytical Approach

The following are the process parameters which are used for the STHE design.

Table 1 Process Data

Parameters	Shell		Tube	
	Inlet	Outlet	Inlet	Outlet
Mass flow rate (kg/h)	4000		20065	
Temp (°C)	100	40	33	45
Inlet pressure(kpa)	147		53	

2.1Design calculation of STHE

In the present study to design the STHE Bell-Delaware method is adopted. The formulae of which are as follows;

i) The formula for shell side HTC calculation is given below:

$$h_o = h_{ld} J_c J_l J_b J_s$$

Where,

- h_{ld} is the ideal heat transfer coefficient

$$h_{ld} = j_l C_{ps} \left(\frac{k_s}{C_{ps}\mu_s}\right)^{\frac{2}{3}} \left(\frac{\mu_s}{\mu_{s,w}}\right)^{0.14}$$

- J_c is the correction factor consider for baffle cut and spacing

$$J_c = 0.55 + 0.72F_c$$

- J_l is the correction factor for baffle leakage effects, including both shell-to-baffle and tube-to-baffle leakage

$$J_l = 0.44(1 - r_s) + [1 - 0.44(1 - r_s)]e^{-2.2rlm}$$

- J_b is the bundle bypass flow

$$J_b = e^{\left\{-C_{bh}F_{sbp}\left[1-(2r_{ss})^{\frac{1}{3}}\right]\right\}}$$

- J_s is the correction factor for variable baffle spacing in the inlet and outlet section

$$J_s = \frac{(N_b - 1) + (L_i)^{(1-n)} + (L_o)^{(1-n)}}{(N_b - 1) + L_i + L_o}$$

ii) The formula for calculating shell side pressure drop is given below:

1. The pressure drop in the cross flow section

$$\Delta P_c = \Delta P_{bi}(N_b - 1)R_l R_b$$

2. The pressure drop in the window section

$$\Delta P_w = \Delta P_{wi} N_b R_l$$

3. The pressure drop in the entrance and exit sections

$$\Delta P_e = 2\Delta P_{bi} \frac{N_c + N_{cw}}{N_c} R_b R_s$$

Total shell side pressure drop are

$$= \Delta P_c + \Delta P_w + \Delta P_e$$

Table 2 – Geometry parameters of designed heat exchanger

Sr.No.	Parameters	Value
1	Length(mm)	7000
2	Shell inside diameter(mm)	574
3	Number of tubes	172
4	Tube outside diameter	25.4
5	Tube pitch ratio	1.25
6	Shell passes	1
7	Tube passes	2
8	Tube thickness(mm)	2.5
9	Tube layout(ºC)	45
10	No. of baffles	16
11	Baffle cut(%)	25
12	Baffle spacing(mm)	400
13	Shell and tube type	AES

2.2Development of macro in ms-excel

In this particular excel sheet we have created a database of fluids with their respective physical and thermal properties which are commonly used as working fluids in STHE. In this study we have created a macro which will allow us to check whether the working fluid is present in our database or not.

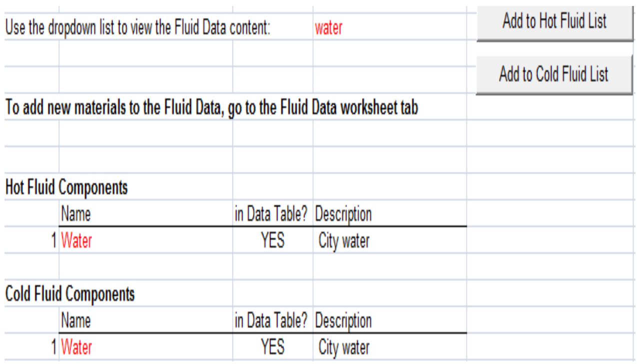


Fig.1. Fluid database

If the fluid is not present in the database, we can add it using another macro which is also developed during this study.

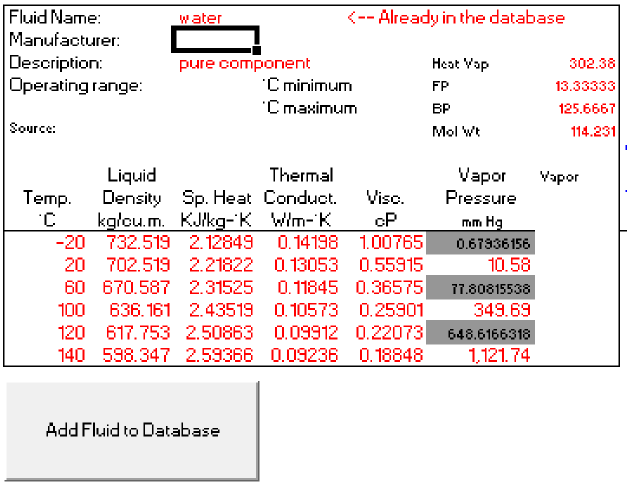


Fig.2. Add fluid to database

If one of the parameter in the heat balance is not known, rather than solving it manually we have also developed a macro to solve the heat balance.

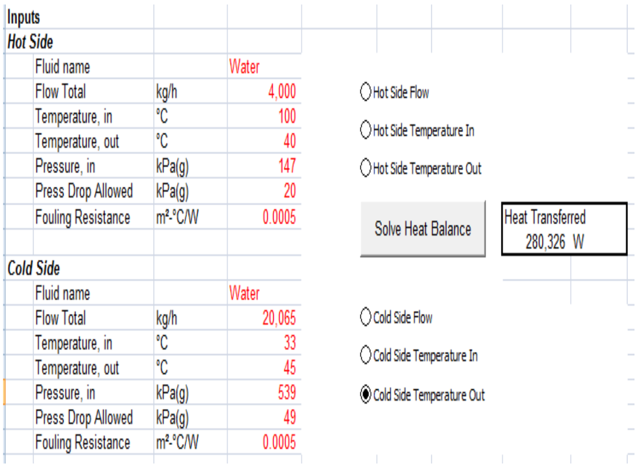


Fig.3. Solve heat balance

This particular excel sheet is created in such way that, flexibility in unit systems is taken care of with the help of macro. For example, if parameters are required in SI units it can be selected and if the parameters are required in US units it can also be done.

2.3Geometry of heat exchanger

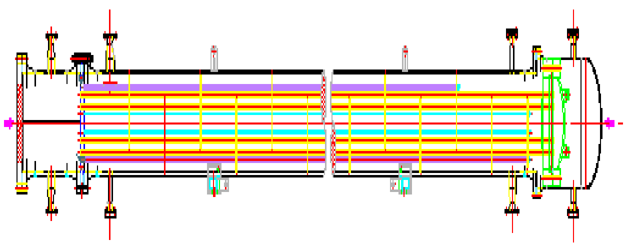
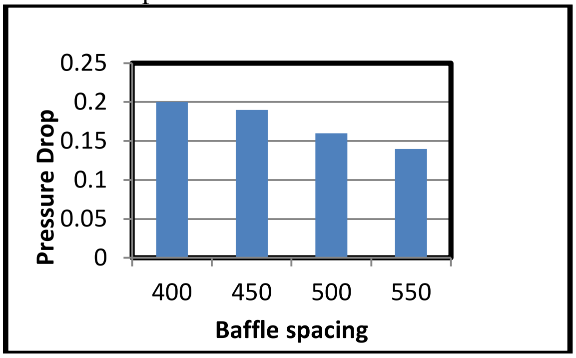


Fig.4 Schematic view of shell and tube heat exchanger

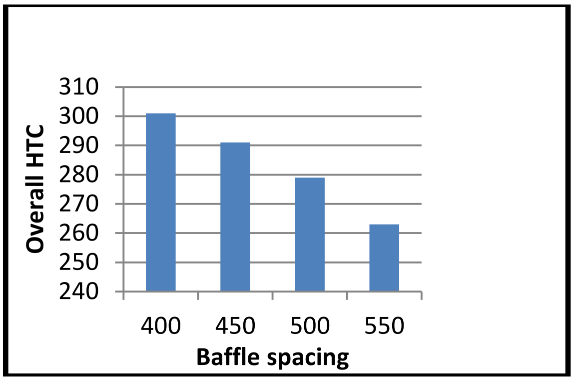
3. Results and Discussion

1. Baffle spacing Vs Pressure drop



From the above graph it can be seen that as the baffle spacing increases shell side pressure drop is decreasing. This is due to the fact that as the baffle spacing is increased, Reynolds number will decrease because of change in velocity and eventually pressure drop will also decrease.

2. Baffle spacing Vs overall heat transfer coefficient(HTC)



From the above plot we can see that as the baffle spacing goes on increasing, overall HTC is decreasing due to decrease in Reynolds number.

Table 3: Analytical Results comparing with HTRI

Parameters	Excel	HTRI
Heat duty(W)	280326	270300
Tube side heat transfer coefficient (W/m²k)	1274	1189.05
Shell side heat transfer coefficient (W/m²k)	545.82	600
Tube side pressure drop(kpa)	1.83	1.81
Shell side pressure drop(kpa)	0.34	0.35
Overall heat transfer coefficient(W/m²k)	258	280
Over surface	12	11.68

4. Validation

The results obtained using developed ms-excel sheet are validated using HTRI software which is used to design shell and tube heat exchangers in industry. The results obtained using developed excel sheet are found to be in agreement with those obtained using HTRI software. Hence it can be said that the excel sheet is developed correctly as it gives results within acceptable limits.

HTRI **Output Summary** Page 1
Released to the following HTRI Member Company:
tharmax ltd
sameer pawale

Xist Ver. 6.00 1/11/2012 15:01 SN: 1500214169 **MKH Units**

Rating - Horizontal Multipass Flow TEMA AES Shell With Single-Segmental Baffles

See Data Check Messages Report for Informative Messages.
See Runtime Message Report for Informative Messages.

Process Conditions		**Hot Shellside**		**Cold Tubeside**	
Fluid name			Blow Down		Cooling water
Flow rate	(1000-kg/hr)		4.0000		20.0647
Inlet/Outlet Y	(Wt. frac vap.)	0.000	0.000	0.000	0.000
Inlet/Outlet T	(Deg C)	100.00	40.00	33.00	45.00
Inlet P/Avg	(kgf/cm2A)	1.500	1.498	5.500	5.490
dP/Allow.	(kgf/cm2)	3.582e-3	0.200	0.019	0.500
Fouling	(m2-hr-C/kcal)		0.00050		0.00050

Exchanger Performance

Shell h	(kcal/m2-hr-C)	515.9	Actual U	(kcal/m2-hr-C)	297.50
Tube h	(kcal/m2-hr-C)	1022.8	Required U	(kcal/m2-hr-C)	220.12
Hot regime	(--)	Sens. Liquid	Duty	(MM kcal/hr)	0.23
Cold regime	(--)	Sens. Liquid	Area	(m2)	92.0
EMTD	(Deg C)	12.00	Overdesign	(%)	11.68

Shell Geometry			**Baffle Geometry**		
TEMA type	(--)	AES	Baffle type	(--)	Single-Seg.
Shell ID	(mm)	574.000	Baffle cut	(Pct Dia.)	25.00
Series	(--)	1	Baffle orientation	(--)	Perpend.
Parallel	(--)	1	Central spacing	(mm)	400.000
Orientation	(deg)	0.00	Crosspasses	(--)	17

Tube Geometry		
Tube type	(--)	Plain
Tube OD	(mm)	25.400
Length	(mm)	7300.
Pitch ratio	(--)	1.2500
Layout	(deg)	45
Tubecount	(--)	172
Tube Pass	(--)	2

Conclusions

On the basis of above study, a blow down cooler is designed using Bell Delaware method. It is found that variation of calculated shell side heat transfer coefficient and pressure drop with HTRI software are found to be within 9%, 2%. Also it was seen that as baffle spacing increases, shell side pressure drop and overall heat transfer coefficient decreases. This heat transfer coefficient is more when calculated through Bell Delaware method as compared to other methods. This is due to the fact that Bell Delaware method considers leakage streams and heat transfer even bypass.

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