International Journal of Applied Engineering Research ISSN 0973-4562 Volume 13, Number 3 (2018) pp. 1623-1627
© Research India Publications. http://www.ripublication.com

The Optimal Design of Prototype to Replace the Vapor Recovery Unit (VRU) Using Computational Fluid Dynamic Analysis

Nattadon Pannucharoenwong[1], Totsaphon Chabuanoi[2] and Chatchai Benjapiyaporn[2*], Snunkhaem Echaroj[3]

[1]Department of Mechanical Engineering, Faculty of Engineering, Thammasat University 12120 Thailand.
[2]Department of Mechanical Engineering, Faculty of Engineering, Khon Kaen University 40002 Thailand.

Abstract

This paper presents design and compared heat transfer efficiency of different shell and tube type heat exchanger as a technology for replacing the Vapor Recovery Unit (VRU). The Computational Fluid Dynamic (CFD) analysis was performed by the commercial software ANSYS-FLUENT 14.5 to calculate temperature of inlet and outlet of each heat exchanger. The results shows temperature of outer surface of tube U-tube heat exchanger decrease more than fixed tube sheet heat exchanger. Additionally, the temperature of pentane inside U-tube heat exchanger decrease more than fixed tube sheet heat exchanger. The U-tube heat exchanger might be an ideal choice to replace the VRU system.

Keywords Vapor Recovery Unit (VRU), heat exchanger, U-tube heat exchanger, Fixed tube sheet heat exchanger, Computational Fluid Dynamic

INTRODUCTION

Vapor of fuel oil is considered as volatile organic compounds (VOCs) that have an effect on human skin, eyes and the respiratory system. One of the most hazardous VOCs is emitted from benzene which have been known to cause leukemia [1]. Besides the effect on human health, VOCs can increase ozone in atmosphere. So it is important to control ozone and benzene level to a minimum. For this research we will use the concept of a Vapor Recovery Unit to reduce pollution by controlling vapor emission level in the range of 10 to 35 mg/L. According to the currently regulation, VOCs release from oil terminal must not be more than 17 mg/L. For this reason most we must install Vapor Recovery Unit (VRU) in every oil terminal. Now the installation cost is about 40-50 million baht per system. Currently, the Petroleum Authority of Thailand have idea to design and build VRU by themselves.

From conducting a literature review, Chasik Park et al.[2] has collected research relate to design of heat exchanger, Li Shi et al.[3], Enxi Lu et al.[4], Bin Gao et al.[5], Ming Pan et al.[6] has designed and constructed of pototype heat exchanger for performance testing, Guo-Yan Zhou et al.[7], Jian Wen et al.[8],Aniket Shrikant Ambekar et al.[9], Sirous Zeyninejad Movassag et al.[10], Ender Ozden et al.[11], Farhad Nemati Taher et al.[12], Jie Yang et al.[13], Najla El Gharbi et al.[14], Mustapha Mellal et al.[15] use Computational Fluid Dynamics (CFD) simulate working for find performance of heat exchager, Jian-feng Zhou et al.[16], Jian-Feng Yang et al.[17], Lu Ma et al.[18], Koichi Nakaso et al.[19], Jian Wen et al.[8], Yonghua You et al.[20], Yonggang Lei et al.[21] has changed design parameters and use numerical simuration compare performance of heat exchanger, Mohsen Amini et al.[22], Salim Fettaka et al.[23], Hassan Hajab dollahi et al.[24], Jie Yang et al.[25], Kai Wang et al.[26] have optimized design parameters of heat exchanger with total cost and performance are objective function

This research will reduce cost and size of the equipment for installation of the vapor recovery device by using heat transfer principle to condense oil vapor to liquid. The designed Vapor Recovery Unit (VRU) can be used to control VOCs before being released into the environment. Therefore, the first objective of this paper is to design a shell and tube type heat exchanger to install at VRU system and use theoretical calculation in combination of ANSYS- FLUENT 14.5 program. The second objective is to analyze the design using ANSYS- FLUENT 14.5 according to heat transfer theories. The last objective is to analyze the obtained results using fixed tube sheet heat exchanger and U-tube heat exchanger models.

MATERIAL AND METHODS

Designing the Heat Exchanger using the Governing equations. In designing a heat exchanger, we studied about the possibility and the limits of the VRU system as shown in Figure 1. So, the equations used were 1 – 8 as following.

Mass flow rate:

$$\dot{m} = \rho A v = \rho V \qquad (1)$$

Where $\dot{m}$ = Mass flow rate (kg/s),

ρ = Density of substance (kg/m^3),

A = Area (m^2),

v = Velocity (m/s^2),

V= Volume flow rate (m^3/s)

Log mean temperature:

$$\Delta T_1 = T_{hot,in} - T_{cold,out}$$

$$\Delta T_2 = T_{hot,out} - T_{cold,in} \qquad (2)$$

$$\Delta T_{lm} = (\Delta T_1 - \Delta T_2)/(\ln(\Delta T_1/\Delta T_2))$$

Overall heat transfer coefficient:

$$\frac{1}{U}=\frac{1}{h_o}+\frac{1}{h_{od}}+\frac{d_o\ln(\frac{d_o}{d_i})}{2k_w}+\frac{d_o}{d_ih_{id}}+\frac{d_o}{d_ih_i} \qquad (3)$$

Where

U_o = Overall heat transfer coefficient (W/m^2°C),

h_o = Outside fluid film coefficient (W/m^2°C),

h_i = Inside fluid film coefficient (W/m^2°C),

h_{od} = Outside fouling factor coefficient (W/m^2°C),

h_{id} = Inside fouling factor coefficient (W/m^2°C),

k_w = thermal conductivity of tube wall material(W/m˚C),

d_i = Tube inside diameter (m),

d_o = Tube outside diameter (m)

Rate of net heat transfer:

$$\dot{Q}=\dot{m}c_p\Delta T+\dot{m}L=AU_o\Delta T_{lm} \qquad (4)$$

Where

Q_{dot} = Rate of net heat transfer (kJ/s),

$\dot{m}$ = Mass flow rate (kg/s),

c_p = Specific heat of substance (kJ/kg·K),

L = Latent hear of substance (kJ/kg),

U_o = Overall heat transfer coefficient (W/m^2·K),

ΔT_{lm} = Log mean temperature (˚C)

Surface area of tube:

$$A_t=\pi d_oL \qquad (5)$$

Where A_t = Surface area (m^2),

d_o = Tube outside diameter (m),

L = Length of tube (m)

Number of tube:

$$N_t=\frac{A}{A_t} \qquad (6)$$

Where A = Area (m^2),

A_t = Surface area (m^2)

Velocity:

$$V=\frac{\dot{m}}{\pi/4\,\rho d_i^2} \qquad (7)$$

Where v = Velocity (m/s),

$\dot{m}$ = Mass flow rate (kg/s),

ρ = Density of substance (kg/m^3),

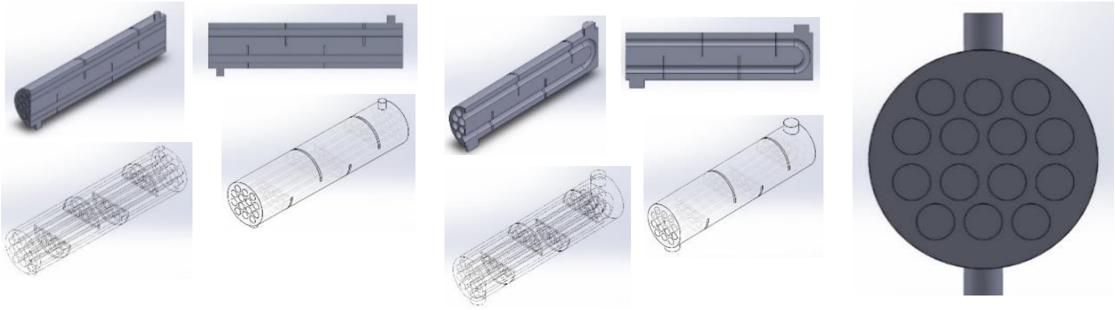
d_i = Tube inside diameter (m)

FINDING PARAMETERS AND CONDITIONS

A water-water 1–2 pass shell and tube heat exchanger is designed considering the data in the following Table 1. Figure 2a show using SOLIDWORK program design fixed tube sheet heat exchanger. Figure 2b show using SOLIDWORK program design U-tube heat exchanger. Figure 2c show the tube arrangement of heat exchanger.

Table 1: Data for design of shell and tube heat exchanger.

Property	Unit	Value
Shell side fluid-hot pentane		
T_{HI}	ºC	40
T_{HO}	ºC	18
Density	kg/m^3	3.87946
Specific heat capacity	kJ/kg K	1.732838889
Viscosity	kg/ms	11700000
Conductivity	W/m K	0.04
Fouling factor	m^2 K/W	0.0002
Flow rate	kg/s	0.003879463
Tube side fluid-cold water		
T_{CI}	ºC	12
T_{CO}	ºC	25
Density	kg/m^3	998.46
Specific heat capacity	kJ/kg K	4.1904
Viscosity	kg/ms	0.0012394
Conductivity	W/m K	0.5836
Fouling factor	m^2 K/W	0.0002
Flow rate	kg/s	0.029268063

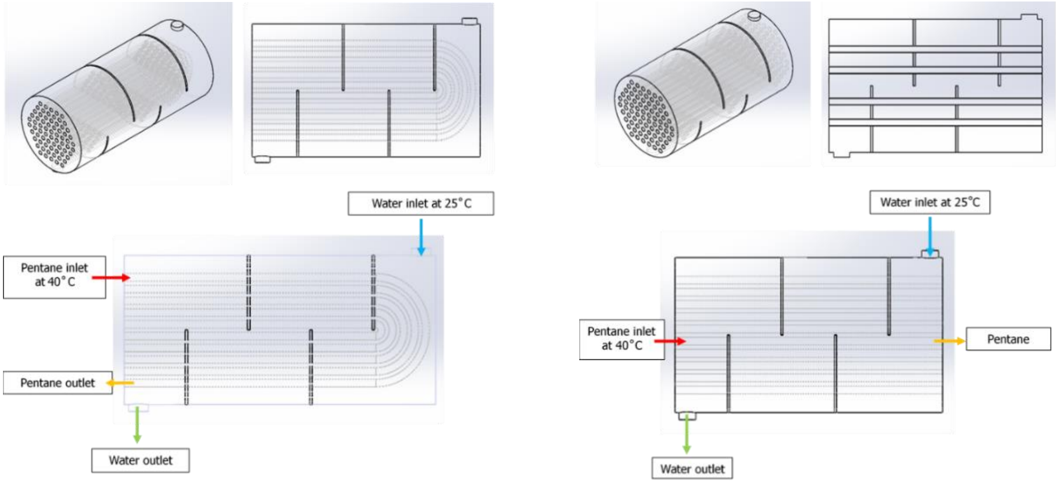


(a) Fixed tube sheet heat exchanger. (b) U-tube heat exchanger. (c) Tube arrangement

Figure 1. Design by using SOLIDWORK program: (a) fixed tube sheet heat exchanger. (b) U-tube heat exchanger. (c) Tube arrangement of heat exchanger.

Table 2: Inner and outer diameter for Copper tube

Nominal size	Outside diameter (OD) [in (mm)]	Inside diameter (ID) [in(mm)]		
		Type K	Type L	Type M
5/8	3/4 (19.05)	0.652(16.561)	0.668(16.967)	0.690(17.526)
3/4	7/8 (22.225)	0.745(18.923)	0.785(19.939)	0.811(20.599)
1	9/8 (28.575)	0.995(25.273)	1.025(26.035)	1.055(26.797)



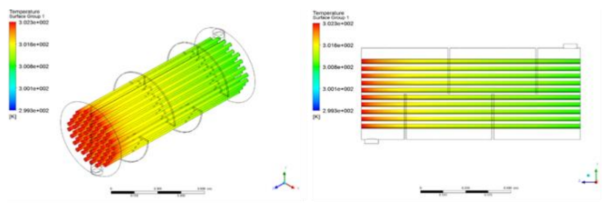
(a) U-tube heat exchanger design (b) Fixed tube sheet heat exchanger design

Figure 2. (a) U-tube heat exchanger design (b) Fixed tube sheet heat exchanger design

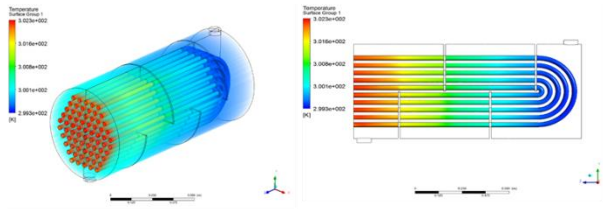
For Copper tube, we use type L Copper tube ¾ inches size due to the fact that Type L has a thinner pipe wall section, and is used in residential and commercial water supply and pressure applications listed in Figure 2a shows U-tube heat exchanger design, Figure 2b shows fixed tube sheet heat exchanger design.

RESULTS

Optimization of heat exchanges were performed to decide which type of heat exchanger is most effective for Results of heat exchanger from simulation Use ANSYS- FLUENT 14.5 Software simulation compare that the fixed tube sheet heat exchanger and U-tube heat exchanger while inlet temperature of water is approximately 25ºC and the inlet temperature of Pentane is approximately 40ºC. The results in Figure 3a show the temperature of outer surface of tube fixed tube sheet heat exchanger. Figure 3b show the temperature of outer surface of tube U-tube heat exchanger. It is observed from Figure 3 that temperature of outer surface of tube U-tube heat exchanger decrease more than fixed tube sheet heat exchanger. Figure 4 demonstrated temperature of fuel vapor along the shell and tubes inside the two different heat exchangers. It can be observed that the temperature of vapor inside the U-tube model reduced faster compared with fixed tube sheet model. This indicate the superior condensation efficiency of the U-tube model compared with the fixed tube sheet model.

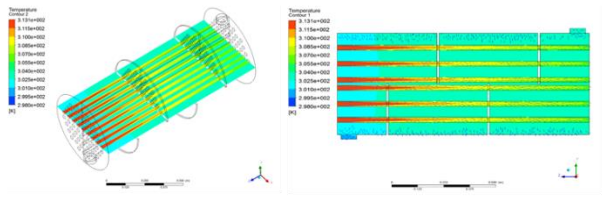


(a) Fixed tube sheet heat exchanger

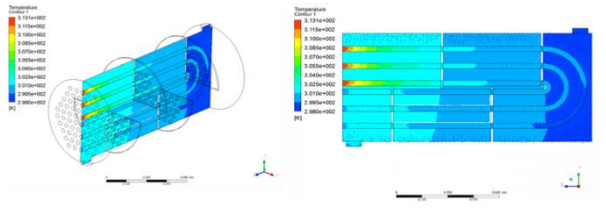


(b) U-tube heat exchanger

Figure 3. Temperature of outer surface of tube: (a) Fixed tube sheet heat exchanger (b) U-tube heat exchanger



(a) Fixed tube sheet heat exchanger



(b) U-tube heat exchanger

Figure 4. Temperature of vapor inside tube (a) Fixed tube sheet heat exchanger (b) U-tube heat exchanger

CONCLUSIONS AND DISCUSSION

The simulation from ANSYS- FLUENT 14.5 Software to compare U-tube heat exchanger and fixed tube sheet heat exchanger. The result show the temperature of pentane inside tube of U-tube heat exchanger decrease more than fixed tube sheet heat exchanger, which lading to lower pentane condensation efficiency in fixed tube sheet heat exchanger than U-tube heat exchanger. Therefore, U-tube heat exchanger might be an ideal choice to replace VRU system because the U-tube heat exchanger can condensed all Pentane vapor into oil.

ACKNOWLEDGEMENTS

The researchers would like to thank the Petroleum Authority of Thailand Phra Khanong, Energy Management and Conservation Office (KKU – EMCO), Khon Kaen University for providing facilities for this research. Additionally, researchers would like to thank Faculty of Engineering Thammasat University for providing research funds.

REFERENCES

[1] Snyder, R., Leukemia, and Benzene, 2012, International Journal of Environmental Research and Public Health., 9(8): pp. 2875-2893.

[2] C, Park., H, Lee., Y, Hwang., and R, Radermacher., 2015, “Recent advances in vapor compression cycle technologies,” Int. J. Refrig., vol. 60, pp. 118–134.

[3] L. Shi and W. Huang, 2014, “Sensitivity analysis and optimization for gasoline vapor condensation recovery,” Process Saf. Environ. Prot., vol. 92, no. 6, pp. 807–814.

[4] E. Lu, H. Zhang, and X. Zhu, 2000, “A novel design for vapor recovery units,” Comput. Chem. Eng., vol. 24, no. 2–7, pp. 1317–1322.

[5] B. Gao, Q. Bi, Z. Nie, and J. Wu, 2015, “Experimental study of effects of baffle helix angle on shell-side performance of shell-and-tube heat exchangers with discontinuous helical baffles,” Exp. Therm. Fluid Sci., vol. 68, pp. 48–57.

[6] M. Pan et al., 2013, “New insights to implement heat transfer intensification for shell and tube heat exchangers,” Energy, vol. 57, pp. 208–221.

[7] G. Y. Zhou, J. Xiao, L. Zhu, J. Wang, and S. T. Tu, 2015, “A Numerical Study on the Shell-Side Turbulent Heat Transfer Enhancement of Shell-and-Tube Heat Exchanger with Trefoil-Hole Baffles,” Energy Procedia, vol. 75, pp. 3174–3179.

[8] J. Wen, H. Yang, G. Jian, X. Tong, K. Li, and S. Wang, 2016, “Energy and cost optimization of shell and tube heat exchanger with helical baffles using Kriging metamodel based on MOGA,” Int. J. Heat Mass Transf., vol. 98, pp. 29–39.

[9] A. S. Ambekar, R. Sivakumar, N. Anantharaman, and M. Vivekenandan, 2016, “CFD simulation study of shell and tube heat exchangers with different baffle segment configurations,” Appl. Therm. Eng., vol. 108, pp. 999–1007.

[10] S. Zeyninejad Movassag, F. Nemati Taher, K. Razmi, and R. Tasouji Azar, 2013, “Tube bundle replacement for segmental and helical shell and tube heat exchangers: Performance comparison and fouling investigation on

the shell side," Appl. Therm. Eng., vol. 51, no. 1–2, pp. 1162–1169.

[11] E. Ozden and I. Tari,2010, "Shell side CFD analysis of a small shell-and-tube heat exchanger," Energy Convers. Manag., vol. 51, no. 5, pp. 1004–1014.

[12] F. Nemati Taher, S. Zeyninejad Movassag, K. Razmi, and R. Tasouji Azar, 2012, "Baffle space impact on the performance of helical baffle shell and tube heat exchangers," Appl. Therm. Eng., vol. 44, pp. 143–149.

[13] J. Yang, L. Ma, J. Liu, and W. Liu, 2014, "Thermal-hydraulic performance of a novel shell-and-tube oil cooler with multi-fields synergy analysis," Int. J. Heat Mass Transf., vol. 77, pp. 928–939.

[14] N. El Gharbi, A. Kheiri, M. El Ganaoui, and R. Blanchard, 2015, "Numerical optimization of heat exchangers with circular and non-circular shapes," Case Stud. Therm. Eng., vol. 6, pp. 194–203.

[15] M. Mellal, R. Benzeguir, D. Sahel, and H. Ameur, 2017,"Hydro-thermal shell-side performance evaluation of a shell and tube heat exchanger under different baffle arrangement and orientation," Int. J. Therm. Sci., vol. 121, pp. 138–149

[16] J. F. Zhou, S. W. Wu, Y. Chen, and C. L. Shao, 2015, "Semi-numerical analysis of heat transfer performance of fractal based tube bundle in shell-and-tube heat exchanger," Int. J. Heat Mass Transf., vol. 84, pp. 282–292.

[17] J. F. Yang, M. Zeng, and Q. W. Wang, 2015, "Numerical investigation on combined single shell-pass shell-and-tube heat exchanger with two-layer continuous helical baffles," Int. J. Heat Mass Transf., vol. 84, pp. 103–113.

[18] L. Ma et al., 2017, "Numerical study on performances of shell-side in trefoil-hole and quatrefoil-hole baffle heat exchangers," Appl. Therm. Eng., vol. 123, pp. 1444–1455.

[19] K. Nakaso, H. Mitani, and J. Fukai,2015, "Convection heat transfer in a shell-and-tube heat exchanger using sheet fins for effective utilization of energy," Int. J. Heat Mass Transf., vol. 82, pp. 581–587.

[20] Y. You, A. Fan, X. Lai, S. Huang, and W. Liu, 2013, "Experimental and numerical investigations of shell-side thermo-hydraulic performances for shell-and-tube heat exchanger with trefoil-hole baffles," Appl. Therm. Eng., vol. 50, no. 1, pp. 950–956.

[21] Y. Lei, Y. Li, S. Jing, C. Song, Y. Lyu, and F. Wang, 2017, "Design and performance analysis of the novel shell-and-tube heat exchangers with louver baffles," Appl. Therm. Eng., vol. 125, pp. 870–879.

[22] M. Amini and M. Bazargan, 2014, "Two objective optimization in shell-and-tube heat exchangers using genetic algorithm," Appl. Therm. Eng., vol. 69, no. 1–2, pp. 278–285.

[23] S. Fettaka, J. Thibault, and Y. Gupta,2013, "Design of shell-and-tube heat exchangers using multiobjective optimization," Int. J. Heat Mass Transf., vol. 60, no. 1, pp. 343–354.

[24] H. Hajabdollahi, M. Naderi, and S. Adimi, 2016, "A comparative study on the shell and tube and gasket-plate heat exchangers: The economic viewpoint," Appl. Therm. Eng., vol. 92, pp. 271–282.

[25] J. Yang, A. Fan, W. Liu, and A. M. Jacobi, 2014, "Optimization of shell-and-tube heat exchangers conforming to TEMA standards with designs motivated by constructal theory," Energy Convers. Manag., vol. 78, pp. 468–476.

[26] K. Wang, X. C. Tu, C. H. Bae, and H. B. Kim, 2015, "Optimal design of porous baffle to improve the flowdistribution in the tube-side inlet of a shell and tube heat exchanger," Int. J. Heat Mass Transf., vol. 80, pp.865–872.