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Thermal Design Optimization of Finned Shell and Tube Heat Exchanger Using Taguchi Approach

Hojin KIM
Gas Turbine Development Team,
Doosan Heavy Industries and Construction Co., Ltd., Korea

Abstract

Shell and tube heat exchanger is widely used to heat removal and thermal energy transfer for system safety, operation stability and efficiency of turbomachinery system. In turbomachinery system, it is generally used to cool down of hot compressed gas located between stage and stage. The cooling system strongly desired to high efficiency which means low electrical power, compact, wide operation range, operation stability and system safety. It is considerable several ways to enhance heat transfer capability. At first balance, it may enhance heat transfer area by design optimization. It can be achieved by optimizing the design combination of heat exchanger. To obtain optimize design and reduce time and cost, when the initial concept design phase, it strongly required design of case study which means statically approach, significant design parameter and optimum design combination. In the present study, we found that the increase fin per unit length was most significant design parameter and the optimum design combination was founded by delta value from S/N ratio variation of design parameter. Moreover, the optimum shell and tube heat exchanger designed by using Taguch approach and L9 orthogonal array. We can obtained optimum design case only 9 cases study as 3 levels and 4 parameters. The optimum surface area enhanced by 51.8% with optimum design combination. Additionally, the pressure drop is decreased by 13.1% that compared to that of initial design.

Keywords: shell & tube heat exchanger; compressor; taguchi method; s/n ratio; heat transfer surface area; pressure drop; optimum design; TEMA; HTRI; minitab

INTRODUCTION

A turbomachinery equipment is widely used in the energy industrial such as oil & gas, power generation, air sepration, and chemical plant. It can possible to supply of high purity compressed gas (Seo, 2016, Kim, 2016). The turbomachinery system strongly required high compression efficiency and safety based on heat transfer capability by cooling system. A thermal management is one of the vital issues to meet turbomachinery system's requirement. Increases of heat transfer capability can result in reduce compression aero power and cooling system's pumping power. It though can result in a CAPEX (Capital Expenditures) and OPEX (Operational Expense).

In general equation for heat transfer across a surface is (Holman, 2002)

$$Q = U. \quad (1)$$

Where, Q is heat transferred per unit time (W), U is overall heat transfer coefficient (W/m^{2}K), A is heat transfer area (m^2), ΔT_m is mean temperature difference (℃).

The major objective in the design of heat exchanger is to determine the surface area required for the specific heat duty using the temperature difference available [4].

The advanced heat transfer given by (Holman, 2002)

$$h = -\Big(\quad (2)$$

Where, h is heat transfer coefficient (W/m^{2}K), Nu is Nusselt number, D is system dimension or size (m), k_f is thermal conductivity of fluid (W/m^{2}K).

Also, heat flux is can be given by (Foruier, 1822)

$$q_x = -k \quad (3)$$

Where, q_x is heat flux (W/m^2), dT is temperature different (℃), dx is system size different (m).

From any heat related form, it is considerable way to improved heat transfer capability is increasing surface area, thermal conductivity, and temperature different. Thermal conductivity is typical material property, thus, it is very difficult to change itself. Others which temperature different and system size changer, are need more energy resources. The CAPEX and OPEX increased if using that approach.

In shell and tube heat exchanger, it is considerable several ways to enhance heat transfer capability. At first glance, it may think that for a given system, it may enhance surface area by changing tube and fin geometry. To find significant parameter and optimize design combination, for example, there is totally 81 design case study investigated if defined 3 levels and 4 design parameters. The large number of design case studies should be done to obtain that results and it has time and cost impact.

In the initial conceptual design phase, it strongly need to design of case studies which is a statistical technique. It’s primary goal is to determine the significant design parameter and optimum design combination needed to optimum design (Roy, 2001). Taguchi approach is a set of methodologies by which the inherent variability of materials and manufacturing process has been taken into account at the design phase(Bang *et. al*, 2007, Kim and Ha, 2016, Celik *et al.*, 2014, Yang *et al.*, 2006,Pablo *et al.*,2015).

The aim of the present study is to investigatethe significant design parameter, optimum design combination and optimum thermal design case by using Taguch approach L9 orthogonal array and S/N ratio. This is the parametric case study at initial conceptual design phase not compared experimental result.

METHODS

The centrifugal type compressor was designed using Hall’s equations (Hall, 2012). We investigated temperature and heat duty of compressed air.

$$T_d = (T_i + 273.15) \times \left(\frac{P_d}{\ }\right)^{\lfloor\ P_d\ \rfloor} - 2 \quad (4)$$

Where, T_d is inlet temperature (℃), T_i is outlet temperature (℃), P_d is inlet pressure (kPa), and P_i is outlet pressure (kPa).

$$p_p = h_p \times \frac{\dot{m}}{\ } \qquad (5)$$

Where, p_p is polytrophic gas power (kW), h_p is polytrophic head, m is inlet flow rate (kg/s), d_a is gas density (kg/m^3), and η_p is polytrophic efficiency.

Shell and tube heat exchanger designed using HTRI Xist. HTRI has developed as useful thermal design rating tool of commercial industries. Design case investigated using Taguchi method. L9 orthogonal array investigated and S/N ratio calculated by below equation (Roy, 2010, Taguchi and Yokoyama, 2993). S/N ratio is the ratio of “signal” representing desirable value and “noise” representing the undesirable value using output characteristic (Roy, 2001).

$$S/_N = -10 \log\left(\frac{1}{\ }\Sigma\right. \qquad (6)$$

Where, n is number of experiment and y_i is output characteristic. In this case, the characteristic is larger the better.

THERMAL DESIGN

Compressor Aero Design

Table 1 and Table 2 summarized a compressor aero design requirement and result, respectively. The machine is main air compressor. Air is main fluid and suction condition is standard condition. It is 3 stage machine with 6.7 of total pressure ratio, however, the design result only shown in 1st stage. The stage discharge temperature and pressure are 122.71℃and 222.86kPa, respectively. These are using heat exchanger input value.

Table 1. Compressor aero design requirement

Item		Content	Unit
Fluid		Air	-
Suction	Flow rate	1.50	kg/s
	Temperature	20.00	℃
	Pressure	101.3	kPa
Discharge	Temperature	42.00	℃
	Pressure	670.00	kPa
Humidity		60.00	%

Table 2. Compressor aero design result (1st stage)

Item	Content	Unit
Stage discharge pressure	222.86	kPa
Discharge temperature	131.29	℃
Temperature for next stage	42.00	℃
Polytropic gas power	136.32	kW

Cooling System

The given cooling system’s condition was shown in Table 3. Typically, the cooling system defined by purchaser.

From the Table 2 and Table 3, it should be cool down from 112.71℃ to 42.00℃ with 10℃ approach temperature. Fouling resistance based on industrial requirement from API or TEMA (API Standard 617, 2001, API Standard 672, 2004, TEMA Standard, 2007).

Table 3. Supply cooling system

Item		Content	Unit
Fluid		Water	-
Inlet	Temperature	32.00	℃
	Pressure	500.00	kPa
Outlet	Temperature	42.00	℃
Fouling resistance		0.00018	m^{2}K/W

Shell and Tube Heat Exhcnager Design

Table 4 shows heat exchanger’s process input. All of values are from process requirement and compressor design result. Table 5 summarized hot shell geometry. A compressed hot air passes in shell side.

Table 4. Heat exchanger design input

	Hot shell	Cold tube	Unit
Flow rate	1.50	3.24	kg/s
In/out temperature	131.3/42.0	32.0/42.0	℃
In/allowable pressure	222.86/4.5	500/100	kPa
Fouling	0.00018	0.00018	m^{2}K/W

Table 5. Hot shell geometry

		Unit
TEMA type	BEM	-
Inner diameter	350	mm
Orientation	Horizontal	-

Cold coolant passes in tube side. Table 6 shows tube side geometry. Fin type is continuous fin, tube dimension follows API standard (API Standard 617, 2001, API Standard 672).Tube dimension and material is request items from purchaser.

Table 7 shows fin geometry. Al as a fin material is cost effective material. From the tube and fin geometry, the design engineer has a flexibility select tube pitch, layout angle, passes, count, and fin. Among them tube passes related to tube side's velocity and it should be to meet velocity range. It recommended the range of 1.2 ~ 2.5m/s (API Standard 672, 2004). Therefore, tube pitch and layout angle, and fin geometry are main parameters to design heat exchanger.

Table 6. Tube geometry

Item	Content	Unit
Type	Continuous fin	-
Length	1,900	mm
Tube outer dia.	15.875	mm
Tube wall thickness	1.245	mm
Tube material	Cu/Ni 90/10	-
Tube pitch	21.166	mm
Tube layout angle	30	degree
Tube passes	4	-
Count	40	ea

Table 7. Fin geometry

Item	Content	Unit
Fins per unit meter	300	fin/meter
Fin thickness	1.5	mm
Fin material	Al	-

The initial heat exchanger investigated based on given system requirement. The thermal rating result shown in Table 8. The rating result to meet all of system requirements. The overdesign ratio is 0.54, it means that the heat exchanger designed cost effective to reduce CAPEX.

Fig. 1 shows a layout and hot and cold fluid passages. Inlet radial is top, flow in 1st tubepass is concurrent, and flow in train is countercurrent as a flow direction in hot shell side. Inlet position is front head, inlet type is axial, and outlet type is same as inlet in cold tube side.

Table 8. Heat exchanger thermal rating result

	Hot shell	Cold tube	Unit
Flow rate	1.50	3.24	kg/s
In/out temp.	131.3/42.0	32.0/42.0	℃
Pressure drop	4.14	63.06	kPa
Fouling	0.00018	0.00018	m^2K/W
Overall *h*	263.14		W/m^2K
Heat duty	135.57		kW
Surface area	17.25		m^2

Fig. 1. A layout and hot gas and cold coolant passage of shell and tube heat exchanger

OPTIMUM THERMAL DESIGN

Taguchi L9 Otrhogonal Design

To optimize surface area in given system, we investigated Taguchi method. In previous section, we define 4 major parameters to affect the surface area. It summarized in Table 9. The design variable as 3 levels and 4 parameters. It means totally 81 cases should be study to obtain optimum design case. The selection of L9 orthogonal array using Taguchi method shown in Table 10. We can obtain optimum surface area only 9 cases study by L9 orthogonal array.

Table 9. Design level with variable range

Level	Tube angle [degree]	Tube pitch [mm]	Fin thickness [mm]	Fin per unit length [fin/meter]
1	30	21.166	1.5	300
2	45	19.844	1.3	200
3	60	23.813	1.7	400

Table 10. L9 orthogonal array

Case	Tube angle	Tube pitch	Fin thickness	Fin per unit length
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

The final design cases including variable parameters are summarized in Table 11. Case 1 is initial design combination.

Table 12 shows the final design result of surface area as an output characteristic and S/N ratio from output characteristic. The surface area of initial design is 17.25m^2. The higher surface value is 28.81 m^2 of case 3. The highest S/N ratio is 29.19. It is clearly to match with higher surface area the case 3.

Table 11. L9 design study cases

Case	Tube angle	Tube pitch	Fin thickness	Fin per unit length
1	30	21.166	1.5	300
2	30	19.844	1.3	200
3	30	23.813	1.7	400
4	45	21.166	1.3	400
5	45	19.844	1.7	300
6	45	23.813	1.5	200
7	60	21.166	1.7	200
8	60	19.844	1.5	400
9	60	23.813	1.3	300

Table 12. Surface area and S/N ratio of case rating

Case	Surface area [m^2]	S/N ratio
1	17.25	24.74
2	10.44	20.37
3	28.81	29.19
4	26.36	28.42
5	17.45	24.84
6	17.17	24.70
7	11.78	21.42
8	19.87	25.96
9	21.96	26.83

Table 13 and Fig. 2 shows S/N ratio vs. variable level. High delta means that high S/N ratio variation of design parameter. Ranking means most significant design parameter the surface area. The optimum design combination is tube layout angle is 45 degree (2), tube pitch is 23.813mm (3), fin thickness is 1.5mm (1), and fin per unit length is 400 (3) as well as higher S/N ratio of each parameters.

Table 13. S/N ratio vs. level

Case	Tube angle	Tube pitch	Fin thickness	Fin per unit length
1	24.77	23.47	25.21	22.16
2	25.98	24.86	25.13	25.47
3	24.74	26.91	25.15	27.86
Delta	1.25	1.73	0.08	5.69
Ranking	3	2	4	1

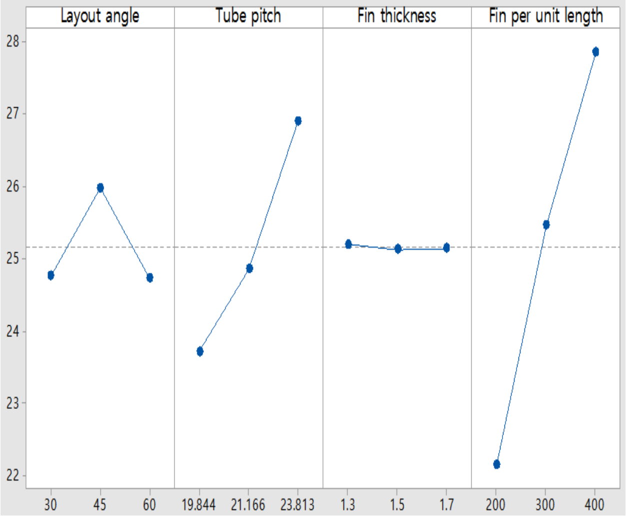

Fig. 2. Mean value of S/N ratio of design parameters

Optimum heat exchanger design

Shell geometry and tube dimension are same as initial design. We re-designed using optimum combination. The rating result shown in Table 14. The overdesign ratio is 26.74% and pressure drop is 3.66kPa of shell side. The surface area is 33.32m^2.

It is clearly find that the optimum design case is higher than that of any of design cases as shown in Fig. 3. The surface area increased by 51.8% and pressure drop decreased 13% compared than that of initial design case.

Table 14. Heat exchanger optimum thermal rating result

	Hot shell	Cold tube	Unit
Flow rate	1.50	3.24	kg/s
In/out temp.	131.3/42.0	32.0/42.0	℃
Pressure drop	3.66	63.01	kPa
Fouling	0.00018	0.00018	m^{2}K/W
Overall *h*	171.79		W/m^{2}K
Heat duty	135.57		kW
Surface area	33.32		m^2

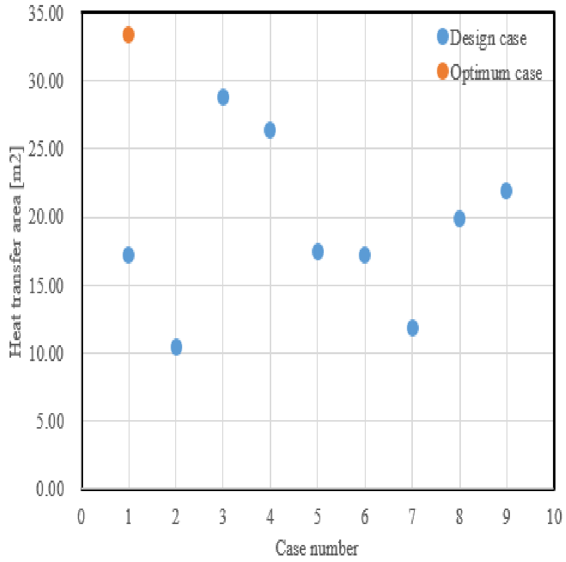

Fig. 3. Surface area of all cases including optimum case

SUMMARY

In the present study, we investigated the significant design parameter, optimum design combination and optimum design case by using Taguchi approach. We have been presented optimum design combination and optimum design case by only 9 design case study by Taguchi approach. Also, we found that the fin per meter is significant design parameter to increase heat transfer surface area by delta value from S/N ratio analysis.

From optimum design combination, the surface area of initial and optimum design is 17.25m^2 and 33.32m^2, respectively. The optimum surface area is increased by 51.8% compared that of initial design. The pressure drop of initial and optimum design is 41.44kPa and 3.66kPa, respectively. The pressure drop is decreased by 13.1% compared that of initial design.

LIMITATIONS OF THE STUDY

This study is limited by 1st stage condition of compressor, HTRI thermal rating and statically design case approach at the initial conceptual design phase. Although the experimental result is not compared, the present case study can provide better approach for designing finned shell and tube heat exchanger.

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