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Research Paper

3D design of a medium temperature pressure (B system) heat exchanger for ammonia synthesis

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ABSTRACT: *In this paper, A synthetic ammonia medium temperature pressure (B system) heat exchanger has been designed. A 3D diagram of this heat exchanger was drawn. Design temperature, design pressure metal, wall temperature, fluid density, fluid flow velocity, pipe diameter, pipe length all have been calculated. Flow rate at the pipe has been checked. Discharge pipe, exhaust pipe, flange pipe and shell connection form between shell side and pipe position, the connection of the nozzle with the shell and the head also have been designed. Finally the structure of the tube box has been designs.*

KEY WORDS: *3D Design, Structure Design, Calculation and Checking, First Heat Exchanger.*

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I. INTRODUCTION

Ammonia synthesis process takes anthracite as raw material, coal and steam are heated and burned in gas producer and coke oven to produce semi-water gas coke oven gas and derived gas of coke oven gas.

The sulfur-containing substances in coke oven gas are changed from organic sulfur to inorganic sulfur through wet desulphurization system. Finally, CO is converted into CO_2 through medium temperature transformation A and B system, which greatly reduces the content of CO in methanation outlet system and makes it lower than 0.3% to provide ultra high concentration of CO_2 for urea synthesis system.

Through a series of physical and chemical reactions in different large-scale equipment, ammonia is eventually generated. The chemical reaction equation in the ammonia synthesis process is:

$$3H_2 + N_2 = 2NH_3 + Q$$

$$2NH_3 + CO_2 = NH_2COONH_4 + Q$$

$$NH_2COONH_4 = CO(NH_2)_2 + H_2O - Q$$

1 Brief description of section transformation process

Gas flow of transformation section: first remove oil from semi-water gas, add steam to become saturated semi-water gas, and then convert most CO in saturated semi-water gas into CO_2 and H_2 through transformation process.The main chemical equation of transformation section as follows:

$$\mathrm{CO} + \mathrm{H_2O} \Leftrightarrow CO_2 + H_2 + Q$$

$$Cu\ O + H_2 = Cu + H_2O$$

$$CuO + CO = Cu + CO_2$$

The diagram of its control transformation system is shown in figure1.

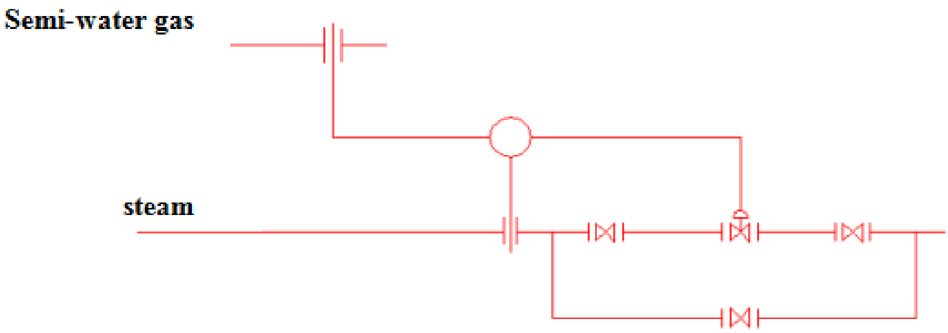

Figure 1 Schematic diagram of semi-water gas conversion

1.2 Selection of heat exchanger

Selection of heat exchanger probably follows the following standards: (1) Meet the production process conditions, the equipment safe and stable operation of the whole working cycle; (2) Strength is enough and the structure is reliable. (3) Manufacture, installation and maintenance are reasonable and the design is carried out considering practical problems. (4) Economic and practical, reducing the cost of production. Design of the heat exchanger tube side and shell are gas, the corrosion of metals is small, the amount of dirt in pipe wall and the wall is very small, so don't often clean, operation cost is reduced greatly. So design a simple structure, low cost of heat exchanger of fixed tube plate heat exchanger is the best choice.

With the rapid development of industrialization, heat exchanger is widely used in chemical, petroleum, energy, food and other chemical industries, greatly accelerating the rate of industrial production. Heat exchanger is a kind of equipment and integral part of the unit, in industrial demand for heat exchanger is varied, the types of heat exchanger is also different, not the same to the requirement of the heat exchanger, the tube plate heat exchanger used in this design because of its heat transfer performance is better, design simple, installation of cheap, used widely, maintenance cost is low.

1.3 Primary data

In this paper, the technological conditions as table 1.

Table 1 Technological conditions

Operation of medium	Semi-water gas	Shift conversion gas
Operating temperature ℃	35/260	365/280
Operating pressure(List)*MPa*	2.06	1.76
Thermal load (*KCal*)	1104241	

Semi-water gas component material as table 2.

Table 2 Semi-water gas component material

Component	H_2	CO	CO_2	O_2	N_2	CH_4	Ar
%	38.67	30.38	8.35	0.3	21.3	0.73	0.27

Shift conversion gas component material as table 3.

Table 3 Shift conversion gas component material

Component	H_2	CO	CO_2	N_2	CH_4	Ar
%	51.203	2.600	27.997	17.240	0.010	0.950

Production capacity: (1) the maximum gas consumption of half water gas is 14800NM^3/h; (2) Operating system 330 days per year and 24 hours per day. Site conditions of use: (1) Installation method: outdoor independent foundation fixed; (2)Site second-class site soil.

II. DETERMINATION OF DESIGN CONDITIONS

Design conditions as table 4.

Table 4 Design conditions

Items		Shell program	Tubeprogram
Name of Material		Semi-water gas	Shift conversion gas
Operating temperature（*IN/OUT*）℃		35/260	365/280
Design temperature （*IN/OUT*）℃		280	380
Operating pressure(*MPa*)		2.06	1.76
Design pressure(*MPa*)		2.2	2.0
Density ρ（Kg/m^3）		11.97	7.21
Viscosity μ ($Pa{\cdot}s$)		1.85×10^{-5}	2.51×10^{-5}
Thermal conductivity λ (*W/℃m*)		0.08425	0.11075
specific heat C_p ($J/Kg\cdot$℃)		6692.8	8805.96
fouling resistance ($m^2{\cdot}K/W$)		0.0002	0.0002
Allowable pressure drop (*KPa*)		35000	35000
Heat transfer coefficient		328	491
Thermal load (*KJ*)		4015727	
Range number		1	2
Heat exchange area m^2		143	
Heat exchange tube	Count:800	Size：φ25×2.5	spread pattern：regular triangle
Baffle plate/support plate	Count：6	Lack of edge location	Lack of edge height：350

Under the highest temperature, design pressure is slightly higher or equal to the highest working pressure 1.05-1.10 times. so the design pressure of the heat exchanger is: shell side *P*=2.2 *Mpa*, tube side *P*=2.2 *MPa*.

Design temperature refers to the maximum or minimum temperature that the container may reach under a certain pressure during normal operation. When the medium contacts the shell side and the working temperature is higher than 0 ℃, the theoretical temperature must be within 10 ℃ to 20 ℃ higher than the maximum working temperature, so the shell side *t*=280 ℃ and the tube side *T*=380 ℃.

III. METAL WALL TEMPERATURE AND FLUID CALULATION

Symbols description as table 5.

Table 5 Symbols description

Symbols	Meaning	Units
K	Total heat transfer coefficient was calculated based on the external area of the heat exchange tube	$W/(m^2{\cdot}$℃)
rd	Fouling resistance	$m^2{\cdot}$℃$/W$
q	Thermal intensity	W/m^2
T_m	The average temperature of a hot fluid	℃
t_m	The average temperature of a cold fluid	℃
$T_{i,}$	Hot fluid inlet temperature	℃
T_o	Hot fluid outlet temperature	℃
T_i	Cold fluid inlet temperature	℃
t_o	Cold fluid outlet temperature	℃
Δt_m	The effective average temperature difference of the fluid	℃
t_t	Pipe surface temperature	℃
t_s	The wall temperature	℃
α	Heat transfer coefficient calculated based on the surface area of heat exchanger	*W/（m2•℃)*

Subscript :h	Thermal fluid side	
Subscript :c	Cold fluid side	

Pipe wall temperature calculation. The wall temperature of hot fluid is calculated by the follow formula:

$$t_{th} = T_m - K(\frac{1}{\alpha_h} + r_{dh})\Delta t_m = 269 \ ℃$$

The wall temperature of the cold fluid side is calculated according to the follow formula:

$$t_{tc} = t_m + K(\frac{1}{\alpha_c} + r_{dc})\Delta t_m = 225 \ ℃$$

The wall temperature of the pipe as follow:

$$t_t = \frac{t_{th} + t_{tc}}{2} = 247 \ ℃$$

The metal wall temperature calculation of the shell. To ensure working safety, the outside of the shell will be insulated. The metal wall temperature of the shell is the average temperature of the fluid on the shell side as: t_s=147.5 ℃.

3.1 Fluid density

Pipe flow: the average molecular weight is 19.19.

Density in scale case: $\rho_0 =$ 0.8607 *kg/m*^{2}.

According to the ideal gas equation of state: $P = \frac{\rho R T}{M}$ So under work pressure,

Fluid density at the inlet: $\rho_{入} = \frac{P_{入} T \rho_0}{T_{入} P}$ =8.1 *kg/m*^{3}.

Fluid density at the outlet: $\rho_{出} = \frac{P_{出} T \rho_o}{T_{出} P}$ =9.3 *kg/m*^{3}.

Shell side fluid: the average molecular weight is 19.28.

Density in scale case: $\rho_0 = \frac{M}{22.4}$ =0.8125 *Kg/m*^{2}.

Fluid density at the inlet: $\rho_{入} = \frac{P_{入} T \rho_0}{T_{入} P}$ =16.8 *kg/m*^{3}.

Fluid density at the outlet: $\rho_{出} = \frac{P_{出} T \rho_o}{T_{出} P}$ =9.7 *kg/m*^{3}.

3.2 Fluid flow measurement

Weight flow rate of pipe side fluid: q=8.03 kg/s

Entrance: $V_{s入} = \frac{q}{\rho_{入}}$ =1.05 *m*^{3}*/s*

Export: $V_{s出} = \frac{q}{\rho_{出}}$ =0.87 *m*^{3}*/s*.

Mass flow rate of shell side fluid: q=3.53 kg/s

Entrance: $V_{t入} = \frac{q}{\rho_{入}}$ =0.22 *m*^{3}*/s*.

Export: $V_{t出} = \frac{q}{\rho_{出}}$ =0.31 *m*^{3}*/s*.

3.3 Selection of flow rate

Heat exchanger with straight pipe diameter and gas as fluid, the range of flow velocity is tube pass 5-30 *m/s*, shell pass3-15 *m/s*, choose tube pass ut=30 *m/s*，shell pass us=10 *m/s*.

3.4 Pipe diameter calculation and selection

Pipe side (head pipe) inlet: $d_{t入} = \sqrt{\frac{4V_{t入}}{\pi u_t}}$ =0.30 *m*.

Export: $d_{t出} = \sqrt{\frac{4V_{t出}}{\pi u_t}}$ =0.28 *m*.

The inlet of the shell side pipe: $d_{s入} = \sqrt{\frac{4V_{s入}}{\pi u_s}}$ =0.17 *m*.

Export: $d_{s出} = \sqrt{\frac{4V_{s出}}{\pi u_s}}$ =0.20 *m*.

3.5 Selection of nozzle diameter

Table 6 pipe dimensions

	Nominal diameter *mm*	OD *mm*	wall thickness *mm*	protruding length *mm*
Aerofluxus、bleeder tube	20	25	3.5	250
Shell side over	200	212	5	200
Inner pipe nozzle	400	418	6	300

Maximum diameter of convex head opening: $d \leqslant \frac{1}{2} D_i$ =700 *mm*.

Nozzle material selection 16Mn, At the same time, the thick wall reinforcement is carried out.

3.6 Check flow rate at nozzles

Pipe pipe inlet: $u_{t入} = \frac{4V_{t入}}{\pi d^2}$ =8.4 *m/s*.

Export: $u_{t出} = \frac{4V_{t出}}{\pi d^2}$ =7.3 *m/s*.

Shell side pipe inlet: $u_{s入} = \frac{4V_{s入}}{\pi d^2}$ =7.0 *m/s*.

Export: $u_{s出} = \frac{4V_{s出}}{\pi d^2}$ =9.9 *m/s*.

Table 7 Common flow rate of heat exchanger

Fluid	Pipe shape	Flow rate *m/s*	
Gas	Straight pipe	Tube pass	Shell pass
		5~30	2~15

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IV. STRUCTURAL DESIGN

4.1 Set of the exhaust pipe

Install exhaust pipes at the top and bottom of the heat exchanger path. Exhaust pipes are used to remove liquid or gas residues from vertical heat exchangers during maintenance. Choose exhaust pipes and drainpipes of the same size in order to reduce difficulties and costs. Fix holes with seamless steel tube. The steel is 20 steel, as shown in the figure2.

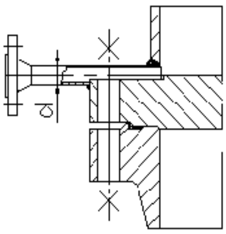

Figure 2 Adapter tube structure

4.2 Select of adapter tube flange

Because of the design temperature $t > 300$ ℃ , So the butt welding flange is used. Flange pressure grade is *P*=2.5*MPa*, Corresponding operating temperature and maximum operating pressure limits are taken into account.

Equipment is a medium pressure vessel, the use of flammable and explosive medium, therefore, choice of concave flange for flange sealing. Flange shape and flange *3D* model are shown in figure3 and figure 4.

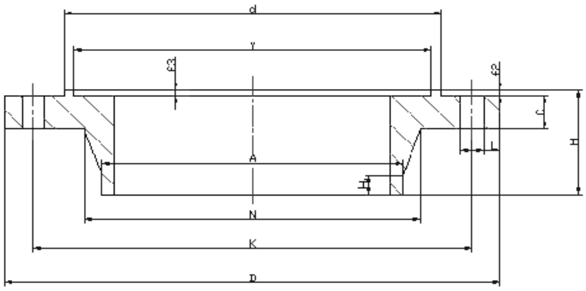

Figure 3 Flange-type

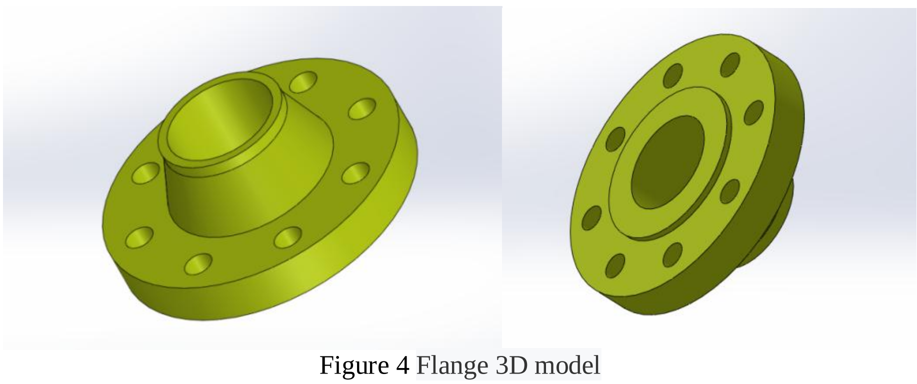

Figure 4 Flange 3D model

Flange material: 16Mn forgings, dimensions as shown in table 8.

Table 8. Adapter tube Flange

	Exhaust and discharge pipe	Shell side over	Inner pipe nozzle
nominal pressure (*PN*)	2.5	2.5	2.5
Nominal diameter (*DN*)	20	200	400
Pipe Outside Diameter (*A1*)	25	219	426
Flange outer diameter (*D*)	105	340	580

Diameter of bolt hole center circle (*K*)	75	295	525
Diameter of bolt hole (*L*)	14	22	30
Quantity (*n*)	4	8	16
Thread (*Th*)	M12	M20	M27
Flange thickness (*C*)	16	24	38
N	40	246	450
S	3.2	5	8.8
H1	6	12	16
R	4	8	10
Flange height (*H*)	40	4	85
Weight (*kg*)	1.05	10.6	96

Length of adapter tube: $L \geq h+h_1+\delta+15$ *mm*,
Inner pipe nozzle: $L \geq 85+16+150+15=166$，$L=200$ *mm*,
Shell side over: $L \geqslant 4+12+150+15=181$，$L=200$ *mm*,
Exhaust and discharge pipe: $L \geqslant 40+6+150+15=201.8$，$L=250$ *mm*.

4.3 Connecting form of pipe and shell

The nozzle shall not extend out from the inner surface of the tube box shell (including the head).

Axial nozzle is used for pipe side, and radial nozzle is used for shell side welding with single-side groove and double-side. Full-penetration welding as shown in figure 5.

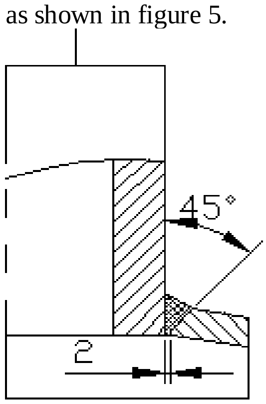

Figure 5 Type of welding

4.4 Nozzle position of shell side

There are reinforcing rings to take over, $L_1 \geq DH\ /2+(b-4)+C$
D_H: Outside diameter of reinforcing ring,
B: The thickness of the tube plate,
According to the calculation results, the outer diameter of the reinforcing ring is 680 *mm*,
$C \geq 4\delta$（δ is shell thickness, *mm*）$\delta \geq 30$ *mm*，$C=60$ *mm*.

$L_1 \geq \frac{680}{2}+(76-4)+60=472$ *mm*, $L_1=480$ *mm*.

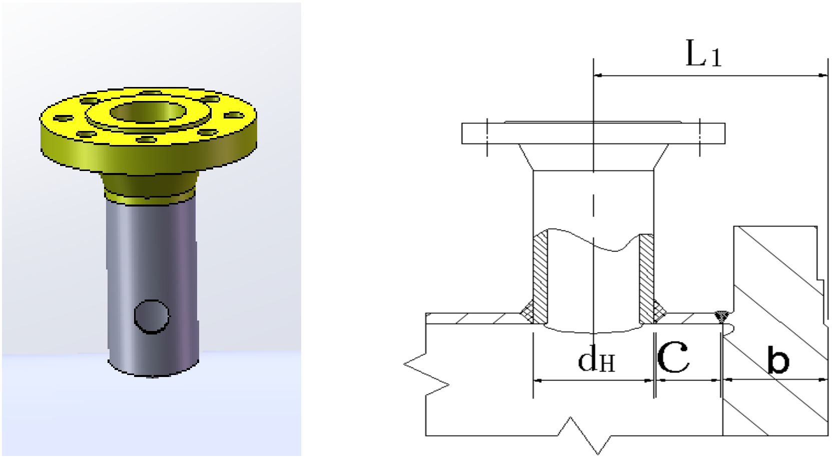

Figure 6 Shell side nozzles position model (left) and structure diagram (right)

4.5 Connection between nozzles and shell heads

Sealing parts shall be connected by embedded welding, and receiving shell will not exceed. Internal surface structure of the shell as shown in the figure7.

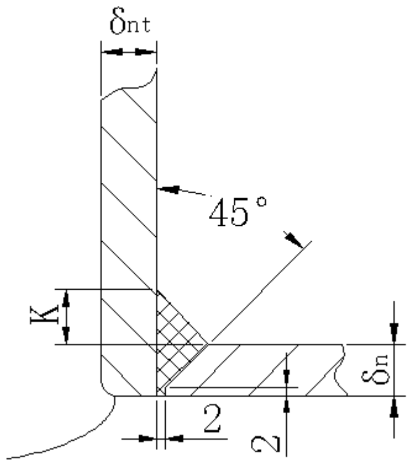

Figure 7 Connection of nozzles to shell heads

4.6 Structural design of tube box

The equipment uses standard oval head, material selection 16MnR,

Table 9 Size of end socket

Name	Number
DN	1400
Highly of curved surface	375
Highly of straight flange	59
Thickness	16
Internal surface area	2.2346 m^2
Volume	0.3977 m^3
Quality	461.5 *Kg*

Tube box Type B tube box is selected $Lg_{min} \geq 1/3d_2 = 133.33$ *mm*, head pipe diameter is: $d_2 = 400$ *mm*.

Minimum depth of equipment tube box: $Lg = H + h = 434mm \geq 85mm$.

Meet the minimum depth requirements of the tube box, so there is no need to add short section. Stratified partition design, It is found that the minimum thickness should be 10, and the current value is 10. The material is *Q235-B*.

Selection of container flange. In order to ensure the safety of the equipment, please don't leak, etc. In the choice bump, to better the shape of the fixed gasket and multiple design parameters by the use of the container medium decide, nominal diameter box equipment flange in more than 400 *mm*, 3 flange welding way respectively is a flat welding flange and b flat welding flange and long neck flange. As shown in the Figure 8, choose the welding flange with long neck and choose the 16MnR material.

Table 10 Flange dimensions

Name	Number
PN	2.5
DN	1400
D	1595
D1	1540
D2	1598
D3	1478
D4	1475
δ	100
H	195
h	48
R	15
d	30
Bolt specification	M27
Quantity	60
Minimum cylinder thicknessδ_0	16
Mass *kg*	397.6

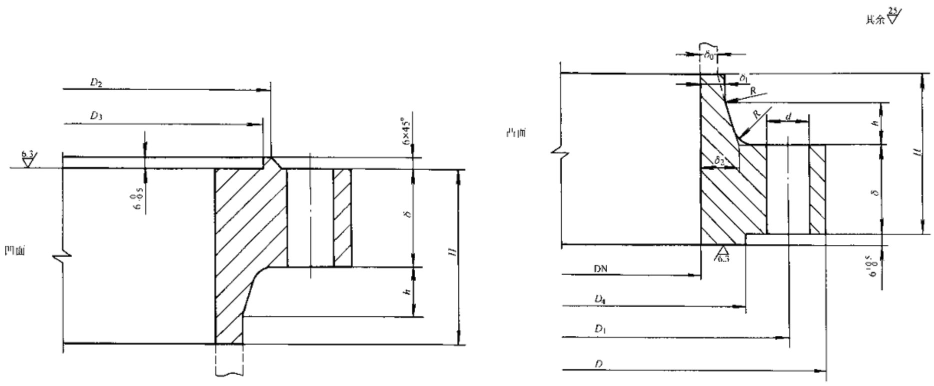

Figure 8 Concave and convex face welded steel flange

In order to prevent running and leaking in production and use, it is necessary to seal the sealing surface of the flange connection by adding gaskets for tight sealing. In this design, the gasket is made of metal gasket, and the material is *0Cr19Ni9*.

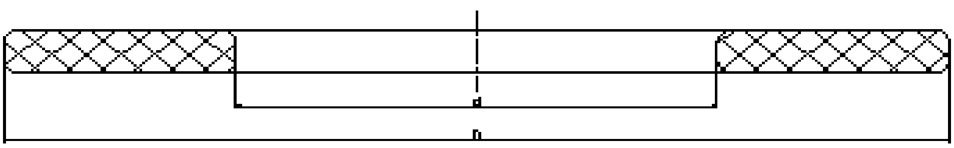

Figure 9 Spacer

The dimensions of gaskets are shown in table 11.

Table 11 The gasket size

Name	Number
Nominal Pressure *MPa*	2.5
Nominal diameter *mm*	1400
d mm	1422
D mm	1458
S mm	3

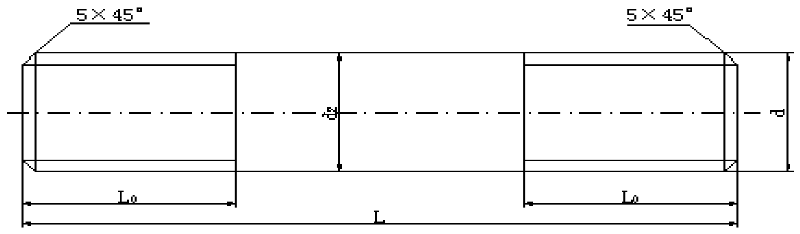

Figure 10 Screw

Table 12 Screw Dimensions

Name	Number
Nominal diameter of stud *mm*	27
L0, mm	65
C, mm	4
d2, mm	27
Nominal dimension *L, mm*	220

Because the thickness of the head is too small, Head and flange are connected by a side double-sided welding. Connection form is as Figure 11.

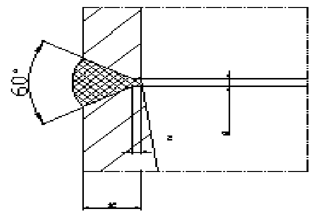

Figure 11 Welding form

3-D model of the pipe box is show in figure 12.

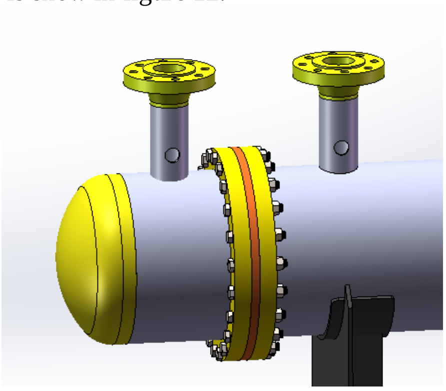

Figure 12 3-D model of the pipe box

V. CONCLUSION

The design temperature of medium temperature pressure (B system) heat exchanger for ammonia formation is calculated. The design pressure and the temperature of the metal wall are calculated and the density and flow rate of the fluid are calculated. The nozzle diameter and nozzle length are calculated. Check the flow rate at nozzles. The drainage pipe and exhaust pipe are designed. Designed to take over the flange.The connection form between nozzle and shell is designed. The position of shell side nozzles and the connection between nozzles and shell and head are designed. Finally, the structure of the tube box is designed. The 3D design of intermediate temperature pressure (B system) heat exchanger for synthetic ammonia is emphasized.

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