Corrosion Prediction and Case Study of Plate Heat Exchangers Based on Artificial Intelligence

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Abstract. Corrosion can cause downtime, equipment damage, and safety hazards. To address this challenge, researchers are turning to artificial intelligence (AI) to predict corrosion events of heat exchangers Shell and tube heat exchanger is an important equipment in nuclear power, chemical industry and other industries. The working conditions of such equipment are often complex, and many nozzles on the cylinder and head are connected with pipes or various instruments. In this paper, the local stress analysis is carried out for the nozzle of the container by using the finite element analysis method, the distribution of stress intensity at the nozzle is obtained, and the safety of the nozzle area of the container under the specific nozzle load is verified.

Keywords: artificial intelligence; corrosion; finite element; style; heat exchanger.

1. Introduction

One of the challenges in the oil and gas industry is to prevent equipment degradation caused by corrosion. Corrosion can cause downtime, equipment damage, and safety hazards. To address this challenge, researchers are turning to artificial intelligence (AI) to predict corrosion events using shell and tube heat exchanger heat exchangers as a case study.

Shell and tube heat exchanger is an important equipment in nuclear power, chemical industry and other industries. The working conditions of such equipment are often complex, and there are many connecting pipes on the cylinder and head connected with pipelines or various instruments[1]. In order to connect the connecting pipe, holes must be made on the vessel wall, which destroys the continuity of the structure and weakens the strength of the cylinder. At the same time, the external pipeline or instrument will produce force and torque on the container through the connecting pipe, and a relatively large local stress will be generated in the connection area of the container connecting pipe

In order to analyze the influence of nozzle load on the container and verify the safety of the nozzle area of the container under specific load, the finite element modeling method is used to analyze the local stress of the nozzle connection area of a container, and the results are evaluated.

2. Overview of artificial intelligence (AI) and its applications in predicting corrosion

Plate heat exchangers are commonly used in industrial processes to transfer heat between two fluids. These fluids may have different chemical properties that can lead to corrosion if they interact with each other. Fluid flow, temperature, and environmental factors such as pH, dissolved oxygen levels, and pressure also play important roles in corrosion prevention.

2.1. Compatibility of media and materials

Corrosion can be caused by different factors, including the incompatibility of media and materials. When two different metals or alloys come into contact with each other, they can create a galvanic cell that leads to accelerated corrosion. This article discusses the data that AI needs to collect to solve the compatibility of media and materials and the types of analysis and calculations that can be done to predict corrosion events in plate heat exchangers.

AI algorithms need to collect data on the properties of metals and alloys used in the construction of plate heat exchangers. The data required includes chemical composition, mechanical properties, thermal properties, and electrochemical properties.

Chemical composition data refers to the percentage composition of each element in the metal or alloy. For instance, stainless steel may contain 18% chromium, 8% nickel, 0.08 % carbon, and other elements such as manganese, silicon, and sulfur. Knowing the chemical composition of each material helps identify the potential for the formation of galvanic cells.

Mechanical properties of metals refer to how a material responds to external forces. The AI algorithm should be able to collect data on the tensile strength, elastic modulus, yield stress, ultimate stress, ductility, and toughness of each metal or alloy. These properties determine the resistance of the material to deformation, cracking, and fracture under different operating conditions.

Thermal properties include the thermal conductivity, specific heat capacity, and coefficient of thermal expansion. These properties determine how well the material conducts heat, how much heat it can store, and how it changes dimensions when exposed to temperature variations.

Electrochemical properties refer to the behavior of the metal or alloy in an electrolytic environment. The AI algorithm should collect data on the anodic index, cathodic index, corrosion rate, and pitting potential. These properties determine the corrosive behavior of the materials.

Table Ⅰ shows an example of the data that AI algorithms can collect for different metals and alloys used in plate heat exchangers. The data is presented in percent by weight.

Table 1. Chemical composition of different metals and alloys

Material	**Fe**	**Cr**	**Ni**	**Mo**	**Cu**	**C**	**Si**	**Mn**
Stainless steel 304	70	18	8	-	-	0.08	1	2
Titanium	-	-	-	-	-	-	-	-
Monel 400	63	32	2	-	1.5	-	-	-
Copper	-	-	-	-	100	-	-	-
Carbon steel	98	-	-	-	-	0.1	0.5	-

Once the AI algorithm has collected the necessary data, it can perform various types of analysis and calculations to predict corrosion events in plate heat exchangers. Some of the analyses and calculations include:

Galvanic series: The galvanic series is a list of metals arranged in order of their tendency to corrode. The AI algorithm can use this list to determine which combinations of metals and alloys are most likely to create a galvanic cell and cause corrosion. Table Ⅱ shows the galvanic series of different metals and alloys.

Table 2. Galvanic series of different metals and alloys

Metal/Alloy	**Anodic Index**
Zinc	-1.04V
Magnesium	-1.60V
Aluminum	-0.90V
Stainless Steel 304	-0.40V
Titanium	-0.35V
Monel 400	-0.30V
Copper	-0.10V
Carbon steel	-0.52V

FEA: Finite element analysis is a computational method used to predict how materials behave under different operating conditions. By dividing the structure into small elements and solving complex mathematical equations, FEA predicts the stress and strain distribution and the corrosion

behavior of the materials. This analysis helps identify weak points in the structure and design modifications to prevent corrosion.

Corrosion rate calculation: The AI algorithm can calculate the corrosion rate of each material based on the electrochemical properties. The corrosion rate is the mass loss of metal per unit area of surface exposed to the electrolyte per unit time. Knowing the corrosion rate of each material helps identify susceptible portions of the structure and prevent premature failure.

Pitting potential: Pitting corrosion is a localized form of corrosion that results in the formation of small holes or pits in the metal surface. The AI algorithm can identify the potential for pitting corrosion by calculating the pitting potential of each material. The pitting potential is the minimum potential required to initiate pitting corrosion.

AI algorithms are essential for predicting and preventing corrosion events in plate heat exchangers. By collecting data on the properties of metals and alloys, AI algorithms can determine the potential for the formation of galvanic cells and other types of corrosion. [2] The data collected includes chemical composition, mechanical properties, thermal properties, and electrochemical properties. Additionally, different types of analysis and calculations can be done, such as the galvanic series, FEA, corrosion rate calculation, and pitting potential. By identifying and addressing potential incompatibilities between media and materials, operators can prevent equipment damage, save costs, and maximize the lifespan of the shell and tube heat exchangers.

2.2. Flow field situation

Corrosion can be caused by various factors, including fluid flow. When fluid flow creates turbulence or areas of high shear stress, it leads to localized erosion and corrosion. This article discusses the data that AI needs to collect to analyze the flow situation in the shell and tube heat exchanger, how to get this data, and the types of analysis and calculations that can be done to predict corrosion events.

To predict the effect of fluid flow on corrosion in shell and tube heat exchangers, AI algorithms need to collect relevant data. The data required includes flow rate, velocity, pressure drop, temperature, and fluid properties.

Flow rate refers to the volume or mass of fluid flowing through the heat exchanger per unit time. The AI algorithm should be able to collect data on the flow rate of each fluid in the heat exchanger. The flow rate of each fluid determines the overall heat transfer rate and the fluid velocity.

Velocity is the rate at which a fluid particle moves in a particular direction. The AI algorithm should be able to collect data on the fluid velocity at different points in the heat exchanger. The fluid velocity determines the Reynolds number, which is a dimensionless number that characterizes the flow regime. The flow regime influences the formation of turbulent eddies that lead to corrosion.

Pressure drop is the difference in pressure between the inlet and outlet of the heat exchanger. The AI algorithm should be able to collect data on the pressure drop across the heat exchanger. The pressure drop determines the resistance of the fluid flow and affects the fluid velocity.

Temperature refers to the temperature of each fluid at different points in the heat exchanger. The AI algorithm should be able to collect data on the temperature of each fluid in the heat exchanger. The temperature affects the viscosity and density of the fluid, which, in turn, affect the fluid flow behavior and the formation of turbulent eddies.

Fluid properties refer to the characteristics of each fluid in the heat exchanger, including density, viscosity, and thermal conductivity. The AI algorithm should be able to collect data on the fluid properties of each fluid in the heat exchanger. The fluid properties affect the heat transfer rate and the fluid flow regime.

Once the AI algorithm has collected the necessary data, it can perform various types of analysis and calculations to predict corrosion events in shell and tube heat exchangers. Some of the analyses and calculations include:

CFD simulation: Computational fluid dynamics (CFD) is a numerical method used to simulate fluid flow behavior in complex geometries. By dividing the heat exchanger into small elements and

solving complex mathematical equations, CFD predicts the velocity, pressure, temperature, and turbulence distribution. CFD helps identify areas of high shear stress and turbulence that lead to erosion and corrosion.

Particle image velocimetry (PIV): PIV is an experimental technique used to measure the velocity field of a fluid. PIV uses a laser light sheet and a high-speed camera to capture the motion of tracer particles in the fluid. The AI algorithm can use PIV data to validate CFD simulations and identify areas of high shear stress and turbulence that cause erosion and corrosion.

Friction factor calculation: The friction factor is a dimensionless quantity that characterizes the resistance of fluid flow in the heat exchanger. It is calculated based on the Reynolds number, which determines the flow regime. The AI algorithm can calculate the friction factor for each fluid and use it to predict areas of high shear stress and turbulence.

Table Ⅲ shows an example of the friction factor and wall shear stress calculations for different fluids in a shell and tube heat exchanger.

Table 3. Friction factor and wall shear stress calculations

Fluid	Reynolds number	Friction factor	Wall shear stress (Pa)
Water	5000	0.02	1.5
Ethylene glycol	2000	0.04	0.8
Oil	10000	0.01	2.5

Wall shear stress calculation: Wall shear stress is the force exerted by the fluid on the surface of the heat exchanger. It is calculated based on the fluid velocity and viscosity. The AI algorithm can calculate the wall shear stress for each fluid and use it to predict areas of high corrosion rates.

AI algorithms are essential for predicting and preventing corrosion events in shell and tube heat exchangers. By collecting data on the fluid flow behavior, AI algorithms can determine the potential for erosion and turbulence that leads to localized corrosion. The data collected includes flow rate, velocity, pressure drop, temperature, and fluid properties. Additionally, different types of analysis and calculations can be done, such as CFD simulation, PIV, friction factor calculation, and wall shear stress calculation. [3] By identifying and addressing potential flow-related issues, operators can prevent equipment damage, save costs, and maximize the lifespan of shell and tube heat exchangers.

2.3. Environmental factors

Corrosion can be caused by various factors, including environmental conditions such as temperature, pH, and dissolved oxygen levels. AI algorithms can help predict corrosion events by analyzing these environmental factors and making predictions about future corrosion events. This article discusses how AI analyzes environmental data and identifies the most important parameters that affect corrosion in plate heat exchangers. It also discusses the types of analysis and calculations that can be done to prevent corrosion events.

To predict the effect of environmental conditions on corrosion in plate heat exchangers, AI algorithms need to collect relevant data. The data required includes temperature, pH, and dissolved oxygen levels.

Temperature refers to the temperature of the fluids in the heat exchanger. The AI algorithm should be able to collect data on the fluid temperatures at different points in the heat exchanger. Temperature affects the rate of corrosion, with higher temperatures generally leading to faster corrosion rates.

pH refers to the acidity or alkalinity of the fluids in the heat exchanger. The AI algorithm should be able to collect data on the pH of the fluids at different points in the heat exchanger. pH affects the corrosion rate, with low pH values causing more corrosion.

Dissolved oxygen levels refer to the amount of oxygen that is dissolved in the fluids in the heat exchanger. The AI algorithm should be able to collect data on the dissolved oxygen levels at different points in the heat exchanger. Oxygen is a key factor in corrosion, with high dissolved oxygen levels leading to faster corrosion rates.

Once the AI algorithm has collected the necessary data, it can perform various types of analysis and calculations to predict corrosion events in plate heat exchangers. Some of the analyses and calculations include:

Corrosion rate calculation: Corrosion rate is the amount of material loss due to corrosion per unit time. The AI algorithm can calculate the corrosion rate based on the environmental data and fluid properties. For example, the corrosion rate can be calculated using Faraday's Law, which relates the amount of corrosion to the current flowing through the metal surface. The corrosion rate calculation helps to identify which factors are most critical to corrosion.

pH analysis: The AI algorithm can analyze the pH data to determine which fluids are more corrosive. Low pH values indicate that a fluid is more acidic and therefore more corrosive. The AI algorithm can use this information to predict the potential for corrosion and recommend appropriate measures to mitigate the risk.

Temperature analysis: The AI algorithm can analyze the temperature data to determine which fluids are more susceptible to corrosion. Higher temperatures generally lead to faster corrosion rates. The AI algorithm can use this information to predict future corrosion events and recommend measures to prevent them.

Dissolved oxygen analysis: The AI algorithm can analyze the dissolved oxygen data to determine the potential for corrosion. High dissolved oxygen levels indicate a greater risk of corrosion. The AI algorithm can use this information to recommend measures to reduce the risk of corrosion.

Table Ⅳ shows an example of the corrosion rate calculation, pH analysis, temperature analysis, and dissolved oxygen analysis for different fluids in a plate heat exchanger.

Table 4. Corrosion rate calculation and environmental analysis

Fluid	Corrosion rate (mm/yr)	pH analysis	Temperature analysis	Dissolved Oxygen analysis
Water	0.1	Corrosive	High risk	Low risk
Ethylene glycol	0.05	Non-corrosive	Medium risk	Low risk
Oil	0.2	Corrosive	Low risk	High risk

AI algorithms are essential for predicting and preventing corrosion events in plate heat exchangers. By collecting data on the environmental conditions, AI algorithms can determine the potential for corrosion events and recommend appropriate measures to mitigate the risk. [4] The data collected includes temperature, pH, and dissolved oxygen levels. Additionally, different types of analysis and calculations can be done, such as corrosion rate calculation, pH analysis, temperature analysis, and dissolved oxygen analysis. By identifying and addressing potential environmental-related issues, operators can prevent equipment damage, save costs, and maximize the lifespan of plate heat exchangers.

3. Basic parameters of heat exchanger

The main design parameters of the heat exchanger studied in this paper are shown in Table Ⅰ. The tube side medium of the heat exchanger is MCB + N2, explosive and toxic. The material of the pipe box is Q345R. The diameter of the tank is 600mm, the nominal thickness of the cylinder is 8mm, the nominal thickness of the head is 10mm, the working pressure is vacuum, the design pressure is 0.6MPa, the working temperature is 12 ℃ - 51 ℃, and the design temperature is - 10 ℃ - 200 ℃. The material performance parameters at design temperature are shown in Table Ⅴ, and this part of the data comes from GB150.[5] The parameters of vessel main material Q345R at design temperature are shown in Table Ⅵ

Table 5. Main design parameters of heat exchanger

Name	Shell Side	Tube Side
Material	Q345R	Q345R
Design Pressure/MPa	1.0/-0.1	0.6/-0.1
Design Temperature/℃	-10/200	
Max Working Pressure/MPa	0.9	0.54
Working Temperature /℃	10/28.73	51.01/12.7
Corrosion allowance /mm	2	2
Joint coefficient	1	1

Table 6. Parameters at material design temperature

Material	Q345R
Young's modulus/MPa	2.01×105
Poisson's ratio	0.30
Allowable stress at design temperature /MPa	189
Densityg/cm3	7.85

4. Finite element model

The model of heat exchanger mainly includes upper ellipsoidal head, lower ellipsoidal head, upper tube box cylinder, lower tube box cylinder, cylinder, flange, nozzle, support and other components. According to the drawings provided by the enterprise, the finite element analysis model for strength evaluation can be established. In order to carry out static analysis of the whole structure, because the overall structure and load of the heat exchanger do not have symmetry, the model must be built completely. In order to avoid stress concentration at the nozzle connection, fillet the connection. The final finite element model is shown in Figure 1&Figure 2.



Figure 1. Global geometric model

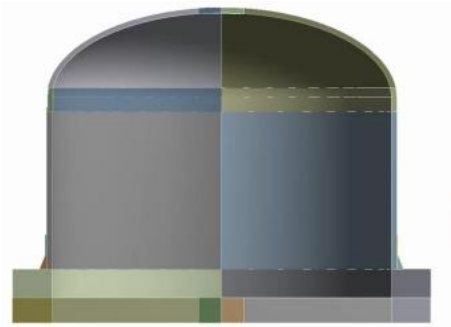


Figure 2. Geometric model of upper head

4.1. Element selection and meshing

Most of the whole model is meshed by hexahedral element (solid45)[6], and the girth weld and nozzle are meshed. The grid model is shown in Figure 3 and figure 4. In this model, the total number of elements is 347450.



Figure 3. Global meshing model

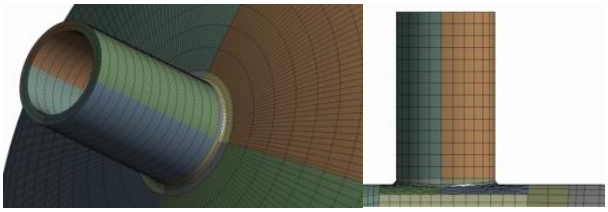


Figure 4. Meshing model of tube external nozzle

4.2. Boundary condition

The boundary conditions of the overall model are shown in Figure 5, mainly including:

Fixed constraint: a fixed constraint is applied to the upper surface of the flange in contact with the lower tubesheet.

Internal pressure: the pressure in the upper and lower tube boxes is 0.6MPa, and the pressure in the cylinder is 1.0MPa.

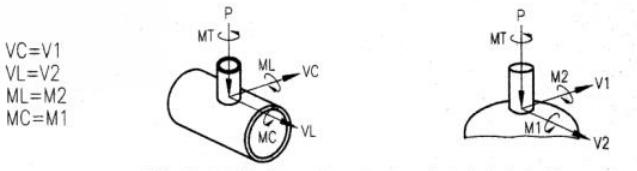
Weight of equipment: Apply 1 time of gravity as a whole, and the gravity acceleration is 9.8 m / s^2.

Balance surface load: N1, N2 1. Uniformly distributed tensile loads of 5.95 MPa, 2.86 MPa, 2.86 MPa, 3.24 MPa, 1.24 MPa, 1.24 MPa, 1.82 MPa and 1.82 MPa are applied on the upper surfaces of N3, N4, N5, N6, ht1 and HT2 respectively.

Nozzle load: apply corresponding load according to nozzle load table (TableⅦ).

Table 7. Nozzle loadtable

Nozzle	DN	P(N)	VC(N)	VL(N)	MC(N·m)	ML(N·m)	MT(N·m)
N1	300	9000	9000	12000	11570	11570	11570
N3	80	1200	1200	1600	820	820	820
N4	100	1500	1500	2000	1290	1290	1290
HT1、HT2	80	1200	120	1600	820	820	820
N2.1	25/80	380	380	500	80	80	80



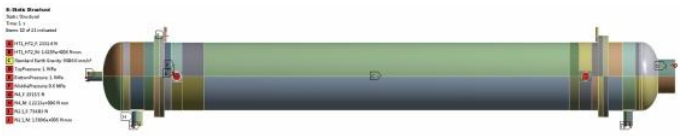


Figure 5. Boundary conditions of overall model

5. Analysis and evaluation of linear elastic stress of heat exchanger

5.1. Stress analysis

The stress intensity distribution of the heat exchanger is shown in Figure 6. It can be seen that although fillet is used to avoid stress concentration as much as possible, the maximum stress point is still located at the connection between nozzle N1 and upper head, and the maximum stress value is

378.85mpa. Therefore, the stress linearization path should be made, as shown in Figure 7. The selection principles of stress linearization path are as follows: (1) set the linearization path through the node with the maximum stress intensity and the shortest distance along the wall thickness direction; (2) For relatively high stress intensity areas, the path is set along the wall thickness direction. According to engineering experience, the discontinuous stress in the discontinuous area of structure can be classified as secondary stress.

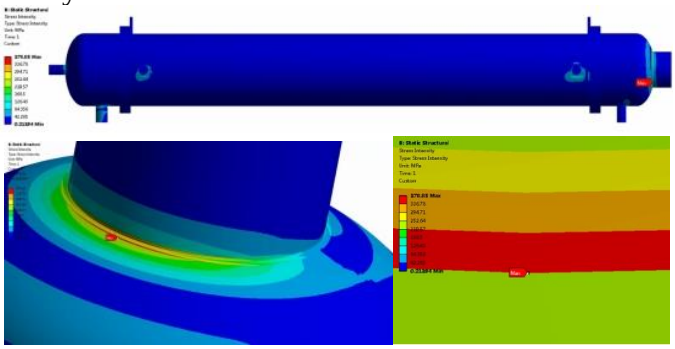


Figure 6. Stress nephogram of heat exchanger

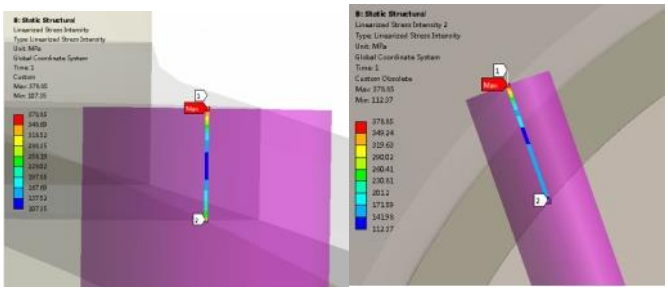


Figure 7. Variation of stress values along the two paths

5.2. Stress assessment

The overall structure of the heat exchanger under the design load is analyzed by finite element method, and the stress intensity of the analysis results is evaluated. The basis of evaluation shall refer to JB4732-1995.[6] It can be seen that the maximum stress occurs at the connection between N1 nozzle and upper pipe box head. Under working conditions, the allowable stress of the material is 189MPa. For conservatism, the stress value at this point is evaluated by stress linearization, and the results are shown in Table Ⅷ.

Table 8. Nozzle loadtable

Path No.	Stress combination type	Calculated value/MPa	Allowable value/MPa	Evaluation results
Path1	P_L	112.17	283.5	qualified
	P_L+P_b+Q	334.59	567	qualified
Path2	P_L	146.04	283.5	qualified
	P_L+P_b+Q	259.68	567	qualified

In the stress linearization evaluation, it can be found that the membrane stress and membrane plus bending stress on the path meet the strength evaluation requirements[7], that is, the strength check of the overall structure meets the standard requirements.

6. Conclusion

In this paper, the linear elastic stress analysis of heat exchanger is carried out by using the finite element stress analysis method. According to relevant codes of JB4732 [8]analysis and design, the

membrane stress caused by internal pressure near the nozzle or other openings and the bending stress caused by internal pressure in the spherical crown area of convex head belong to the category of primary stress. The self balancing stress required by the connection between the nozzle and the cylinder to ensure the continuity of the structure belongs to secondary stress. Secondary stress is the self balancing stress required to ensure the continuity of the structure, which can be caused by mechanical external load or temperature difference stress, and has self limitation. According to the specification, the sum of primary stress and secondary stress needs to be less than 3 times of allowable stress, and this case meets the requirements of relevant specifications.

References

[1] JB4732-1995 steel pressure vessels - analytical design standard [S]

[2] Mansour, S., & Al-Qahtani, H.. AI-based corrosion detection and protection: a review. [J] Journal of Materials Research and Technology, 2020,9(3), 6359-6373.

[3] Ahmed, I., & Ingham, D. B. Application of computational fluid dynamics in heat exchangers: A review. [J] International Journal of Heat and Mass Transfer, 2019,131, 965-983.

[4] Samimi, M., & Barati, M. R. (2018). A review of recent developments in plate heat exchanger technology. Applied Thermal Engineering, 142, 274-295

[5] Gb150-2011 pressure vessel [S].

[6] Li Qipeng, Chen Guohua Strength finite element analysis of radial multi nozzle of elliptical head [J] Chemical machinery, 2008, 36 (5): 299-494.

[7] Qin ShuJing, Wang Qi Comparative study on local stress calculation methods (Part 2) [J] Chemical equipment and pipeline, 2008, 45 (5): 7-12.

[8] Tang Qinghui, Li Lei, sang Zhifu Study on strength performance of perforated nozzle structure under combined load [J] Mechanical strength, 2010, 32 (5): 766-773.