Fluid-solid-thermal coupling analysis of an underwater valve

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Abstract. An underwater valve at 3000 meters underwater was chosen as the research object, aiming at obtaining the force characteristics of the underwater valve under high pressure and large temperature difference in the deep sea. The principle of fluid-solid-thermal three-field coupling was analyzed by using Fluent and ANSYS Workbench. Through numerical simulation, the fluid temperature distribution, the stress and deformation of the valve were obtained, and the valve was loaded. The influence of pressure and temperature on the performance of underwater valve was discussed. The results show that the fluid medium inside and outside the valve exchanged heat due to the large temperature difference, and vortexes were generated at the bottom of the valve seat, and the fluid pressure energy was converted into heat energy. The force of thermal stress generated by heat exchange on the valve body was greater than the equivalent stress generated by thermal-mechanical load.

1. Introduction

With the development of deep-water oil and gas exploration technology, the current ocean oil and gas exploration has expanded from the continental shelf area with a water depth of 200-300m to the deep-water area with a depth of 3000m [1]. In the development of deep-water oil and gas resources, it is necessary to transfer part or all of the oil and gas production equipment and auxiliary facilities from the water to the underwater to form an underwater production system of automatic oil production, oil gathering and oil transportation. The underwater production system needs to develop underwater valves and actuators that are corrosion-resistant, storm-resistant, reliable, flexible, and easy to maintain [2]. Underwater valve is the key component of underwater oil and gas production, and its performance directly affects the reliability and safety of underwater production system. Due to the extremely harsh conditions in the deep sea, the strength and reliability of the underwater valve must be guaranteed, and the valve should be free from maintenance during its working cycle.

When the underwater valve is placed in the deep sea for more than 3000 m, the sea water temperature is about 0°C, while the oil and natural gas from the wellhead can reach 200°C [3]. The huge temperature difference will cause a lot of heat loss and temperature drop in the structure of underwater valve, even form wax deposit, asphalt deposition and hydrate. Inconsistent temperature inside and outside the valve body will produce thermal stress and reduce the reliability of the valve. On the other hand, the underwater valve bears the high pressure of seawater and internal fluid outside the valve body, resulting in deformation and stress [4]-[5]. In order to prevent structure damage caused by deformation or stress exceeding allowable value, the structure of underwater valve must be calculated.

In view of the above problems, Fluent and ANSYS Workbench are used to simulate and analyze the equivalent stress and deformation of the valve body under the joint action of internal crude oil pressure,
external sea water static pressure and internal and external temperature difference, which is based on the principle of fluid-solid-heat three-field coupling [6]. It provides guidance for the design and manufacture of underwater valves. Fluid-solid-thermal coupling refers to the interaction among fluid, solid and temperature field. Because the structure deformation of the underwater valve is very small, and has little influence on the change of fluid flow state and temperature, only the influence of fluid pressure and temperature on the valve structure is considered, that is, unidirectional coupling effect.

2. Theoretical Analysis

In the deep sea, the outside of the valve is in the seawater with high pressure and low temperature, and the inside is full of crude oil with high pressure and high temperature. Therefore, the valve body not only bears the external seawater pressure and the internal crude oil pressure, but also has the heat conduction phenomenon with the oil and seawater. The convection heat transfer will occur between the two fluids and the valve body, and the valve body will be subject to thermal stress [7]. The external area of the valve is set as forced convection, and the inner area is set as natural convection (buoyancy driven). Because of the small temperature difference in the internal area, Boussinesq hypothesis is used to solve the problem according to the constant problem. The crude oil and seawater are set as incompressible three-dimensional flows without considering the viscous dissipation. The flow law meets the law of conservation of mass, law of momentum, law of conservation of energy, and law of heat conduction [8]. The equations are solved by Fluent and ANSYS Workbench.

2.1. Flow equation

Mass-conservation equation:
\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0
\]  

Momentum conservation equation:
\[
x \text{ direction: } \nabla \cdot (\rho u \mathbf{u}) = \frac{\partial P}{\partial x} + \nabla \cdot (\mu \nabla u)
\]

\[
y \text{ direction: } \nabla \cdot (\rho v \mathbf{u}) = \frac{\partial P}{\partial y} + \nabla \cdot (\mu \nabla v)
\]

The Boussinesq hypothesis is used for the y direction, the equation is converted into:
\[
\nabla \cdot (\rho v U) = -\frac{\partial P}{\partial y} + \nabla \cdot (\mu \nabla v) + \rho g \beta (T - T_0)
\]

\[
z \text{ direction: } \nabla \cdot (\rho w \mathbf{u}) = -\frac{\partial P}{\partial z} + \nabla \cdot (\mu \nabla w)
\]

Energy conservation equation:
\[
\nabla \cdot (\rho C_p U T) = \nabla \cdot (\lambda \nabla T)
\]

Where \( U \) is the velocity vector; \( x, y, z \) are coordinate directions; \( u, v, w \) are velocity components in three directions; \( P \) is pressure; \( \mu \) is dynamic viscosity; \( \rho \) is density; \( g \) is acceleration of gravity; \( \beta \) is thermal expansion coefficient; \( T \) is temperature; \( T_0 \) is working temperature; \( C_p \) is specific heat capacity; \( \lambda \) is thermal conductivity.

2.2. Heat conduction equation

\[
\rho C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left( \lambda \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( \lambda \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( \lambda \frac{\partial T}{\partial z} \right) + Q
\]

Where \( t \) is the time; \( Q \) is the heating rate per unit volume.
3. Modeling

3.1. Model calculation and parameter setting
In this study, the valve body was mainly analyzed, and the valve body structure was established by SolidWorks and simplified some features that did not affect the overall performance of the valve body, and ignored some unnecessary chamfers. The model mainly included: the valve body and the pipes (inner diameter 50mm) connected at both ends, the seawater space body enclosing outside the valve body, and the crude oil body filling the valve body, as shown in Figure 1. In order to ensure the full flow of the fluid, the pipeline before and after the valve was lengthened by 6 times the pipe diameter outside the seawater body. Seawater and hot oil flew along Z direction and X direction respectively.

![Figure 1. Model of valve body and fluid domain.](image)

3.2. Meshing
The grid was generated using ANSYS ICEM. An unstructured grid was used to mesh the entire flow field, and the grid around the valve seat and plug was refined. Figure 2 shows the grid model of the control valve. The grid size was approximately 1200000 cells.

![Figure 2. Grid model](image)

3.3. Material properties
The physical parameters of seawater and crude oil are shown in Table 1.

| Material   | Density (kg/m³) | Specific heat capacity (J/(K·kg)) | Thermal conductivity (W/(m·K)) | Dynamic viscosity coefficient (kg/(m·s)) |
|------------|-----------------|----------------------------------|--------------------------------|----------------------------------------|
| Crude oil  | 840             | 2100                             | 0.14                           | 0.00603                                |
| Seawater   | 1000            | 4200                             | 0.58                           | 0.001236                               |

Table 1. Physical parameters of fluid
The physical parameters of valve body are shown in Table 2.

| Material | Density (kg/m³) | Yield strength (MPa) | Poisson's ratio | Elastic modulus (GPa) | Thermal expansion coefficient (10^{-6/℃}) | Thermal conductivity (W/(m·K)) |
|----------|-----------------|----------------------|----------------|----------------------|------------------------------------------|---------------------------------|
| ANSI 8630 | 8240            | 517                  | 0.308          | 205                  | 12.3                                    | 9.1                             |

3.4. **Boundary conditions and solution settings**
The $k - \varepsilon$ turbulence model suitable for engineering problems was selected [9]. The inlet of seawater adopted the velocity inlet ($v$=0.1m/s, $T$=0℃), and the crude oil inlet adopted the velocity inlet ($v$=0.45m/s, $T$=100℃), and both outlets adopted free outflow. The fluid-solid interface inside and outside the valve body met the condition of no sliding, and the outer side of seawater body was smooth without heat exchange. The separation solver was used and the SIMPLE algorithm was used to couple the pressure and velocity, and the second-order upwind style was used for all discrete schemes [10].

4. **Results & Discussion**

4.1. **Analysis of temperature field**
Using FLUENT for fluid simulation, the temperature field distribution of the two fluids on the outer and inner surfaces of the valve was obtained according to the above boundary conditions, as shown in Figure 3.

![Temperature field distribution](image)

Figure 3. The distribution of temperature field on the surface of valve body: (a) the outer surface; (b) the inner surface

From Figure 3, the temperature distribution of the two fluids on the outer surface of the valve body is around 83℃, while the temperature of the fluid on the inner surface of the valve body is relatively high, about 95℃. This phenomenon mainly because that the temperature of crude oil inside the valve body is higher than that of the external seawater, and heat exchange occurs during fluid flow, resulting in temperature difference between the inner and outer surfaces of the valve body. The temperature of the bottom of the wall behind the valve seat is slightly increased, which is caused by the vortex generated here and the fluid pressure energy is converted into heat energy. In addition, since the valve cover and flanges at the inlet and outlet are only in contact with seawater, there is less heat exchange and the temperature gradient is more obvious.

4.2. **Analysis of stress field**
Using ANSYS Workbench to calculate. Firstly, according to the results of the valve body temperature field obtained in the previous Fluent simulation, the temperature load of the fluid-solid boundary was loaded and converted in the Steady-State Thermal module to obtain the finite element analysis of the
valve body temperature field and thermal flux field. Secondly, in the Static Structural module, the crude oil pressure and seawater pressure were loaded on the inner and outer walls of the valve body respectively. At the same time, the temperature field calculated in the Steady-State Thermal module was also loaded into the valve body area, and the corresponding constraints were set to obtain the stress and strain of the valve body. The operation process of valve thermal fluid-solid-coupling simulation was shown in Figure 4.

4.2.1. Structure temperature field and heat flux field

The temperature of the valve body simulated in Fluent was loaded into the Steady-State Thermal module to obtain the temperature field and heat flux field of the valve body analyzed by finite element method, as shown in Figure 5 and Figure 6.

Figure 5. Finite element analysis of valve external surface: (a) Temperature field (b) Heat flux field

Figure 6. Finite element analysis of valve internal surface: (a) Temperature field (b) Heat flux field

It can be seen from Figure 5 and Figure 6 that the temperature distribution on the inner and outer surfaces of the valve body is consistent with the temperature field obtained in Fluent. The flange and the valve cover are far away from each other and the temperature gradient changes greatly. The maximum heat flux on the surface of the valve body is 93188 W/m², and the heat flux at the junction of the flange and the valve body is relatively intense.
4.2.2. Structural stress field
In order to study the influence of fluid pressure, temperature and their combination on gate valve, the following calculation was carried out separately.

(1) Only considering temperature field
In the Static Structural module, the temperature field was applied to the inner and outer walls of the valve body, and the corresponding constraints were set to calculate the displacement, stress and strain of the valve body (without considering the pressure field), as shown in Figure 7 and Figure 8.

(2) The combined effect of temperature field and pressure field
Under 3000m sea depth, the seawater pressure is about 30MPa, and the crude oil pressure in the valve can reach 25MPa. Therefore, in the Static Structural module, the seawater pressure load, crude oil pressure load and temperature field load were simultaneously applied to the inner and outer walls of the valve. The one-way fluid-solid-heat coupling calculation was performed on it, and the constraint conditions were the same as the above. The stress and total deformation of the valve body were calculated, as shown in Figure 9 and Figure 10.
Figure 10. Deformation of the inter surface of the valve body under temperature and pressure load: (a) Total deformation; (b) Equivalent elastic strain

3) Comparison of results

According to the finite element analysis, the stress and total deformation of the valve body under the action of only the temperature field load and the pressure and the temperature field load were compared, as shown in Table 3.

|                      | Only the temperature field | The joint effect of sea water, crude oil pressure and temperature field |
|----------------------|---------------------------|---------------------------------------------------------------|
| Maximum equivalent  | 94.02                     | 85.43                                                         |
| stress /MPa          |                           |                                                               |
| Total deformation /mm| 0.2165                    | 0.2125                                                        |
| Maximum equivalent   | 4.3053                    | 4.2167                                                        |
| elastic strain /m    |                           |                                                               |

It can be seen that under the action of only temperature load, the maximum equivalent stress of the valve body is 94.02 MPa, which appears at the corner of the bottom of the valve seat, where the expansion of the structure is limited after being heated, which is prone to stress concentration. When the fluid pressure and temperature load act together, the equivalent stress of the valve body decreases, which is 85.43 MPa. At the same time, the total deformation and the maximum equivalent elastic strain of the valve body are also reduced, and the deformation caused by heat is larger.

5. Conclusions

(1) When the underwater valve works, due to the large temperature difference of the fluid medium inside and outside the valve body, the heat exchange will occur between the valve body and the outside surface when the fluid flows, thus producing thermal stress.

(2) The individual force (thermal stress) of the thermal stress generated by the heat exchange on the valve body is greater than the equivalent stress (thermal stress + medium pressure) generated by the thermo-mechanical load. Therefore, the thermal stress has a great influence on the structural strength of the valve body.

(3) The simulation can provide a reference for the design of underwater valve, and the force of thermal effect on the valve should be considered in the design.

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