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Effects of different loads on structure stress of "L"-type large-diameter buried pipe network based on fluid-structure-heat coupling

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ABSTRACT

Large-diameter buried pipeline is widely used because of its energy-saving advantage and high efficiency. In this paper, "L"-type heat pipe network was taken as the research object, which was studied using the flow–heat–solid coupling method. The ANSYS Workbench platform was used to simulate heat transfer and the flow of the medium in the pipe network. The pressure and temperature of the flow field and the temperature, equivalent stress of the solid structure under different conditions were calculated, and the force characteristics of pipe network and elbow under coupled and non-coupled loads were compared. Results show the maximum equivalent stress was located at inner wall surface of the short-arm anchor end. The equivalent stress of the inner wall was larger than that of the outer wall at the same position. The stress of the straight pipe of the pipe network was mainly affected by the temperature of the fluid, whereas the stress of elbow was mainly affected by the pressure. The stress distribution of the pipe network was influenced by the temperature and pressure loads coupled and the coupling effect was stronger with the higher pressure and temperature of the medium, but the coupling effect had its limit.

1. Introduction

Directly buried installation, a kind of underground pipeline laying method, has been developed in the recent years because of its advantages of convenience, short construction time, and less construction cost [1–3]. Directly buried heating pipeline has been widely applied in district heating pipe networks in Sweden, Finland, Denmark, Germany, and other countries [4–5]. The heating pipeline load increases with the population. In addition, the pressure and diameter of buried pipelines also increase. In China, the heating pipe network pressures of some municipal main lines work to reach 2.5 MPa, the operating temperature of 150 °C, and diameter of DN1400 mm [6–8]. Several failure forms appear because of the flow–heat–solid coupling phenomenon in network systems, such as infinite plastic flow, cyclic plastic deformation, fatigue failure, and overall instability. Pipeline steering parts (elbow, tee, taper pipe) bear larger pressure in fluid three-dimensional turbulent flow at high temperature and pressure, and they also increase the overall structure deformation [9–11].

Fluid structure interaction mechanics is a branch of fluid and solid mechanics that is mainly concerned with the behavior of solids in the flow field and the influence of solid deformation on flow field [12–13]. If the flow field, temperature field, and structure are solved separately, the computational results of structural deformation caused by the heat transfer and fluid pressure of the pipe network will deviate from the actual situation. Meanwhile, flow–heat–solid coupling analysis method can accurately reflect the interaction of fluid and structure deformation. Flow–heat–solid coupling analysis method has been receiving increasing attention in engineering practice [14–15]. In directly buried heating pipe systems, the tube body is mostly made of stainless steel, and deformation of the structure system is generally smaller under the flow field action, but the stress is high. Stress concentration is more common in the most unfavorable conditions (anchorage segment) and the weakest link of the whole system. Further thermal stress changes the stiffness of the structure, induces structural deformation, and thus affects the stability and dynamic response of the structure, shortens the life of the system, and increases security risks. Therefore, thermal stress has important significance in pipe network system architecture analysis and research [16–17].

At present, many research related to heat transfer and the mechanical behavior of large-diameter buried pipe networks have been conducted, but studies on the flow–heat–solid coupling of pipe networks are limited [18]. In this paper, the coupled flow and heat transfer inside the pipe wall at high temperature and pressure were simulated in three dimensions using the Computational Fluid Dynamics CFD Fluent

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software [19–21]. The pressure load on the pipe wall was determined from the fluid of high temperature and pressure based on the fluid calculation results. The transition from the fluid temperature and the pressure load to the structure of the model was achieved through the Workbench platform [22–26]. Subsequently, the unidirectional flow–heat–solid coupling of the large-diameter buried pipe was solved. The stress distribution of the pipe network and elbow were comparatively analyzed under different fluid pressures and temperatures or combined load actions. The analysis results could provide a basis for the structural strength design of large-diameter buried pipe networks.

2. Fundamental theory

2.1. Fluid theory

Continuity equation:

$$div(\overline{\boldsymbol{U}}) = 0 \tag{1}$$

"N-S" equation:

$$\rho\overline{\boldsymbol{U}}\, grad\, \overline{\boldsymbol{U}} = \text{-gradP} + \mu\, \text{div}\cdot grad\, \overline{\boldsymbol{U}} + \rho\overline{F} \tag{2}$$

"*k*-ε" equation:

k equation

$$div(\rho\overline{\boldsymbol{U}}k) = div\left[\left(\eta + \frac{\eta_t}{\sigma_k}\right)gradk\right] + \eta_t G_k - \rho\varepsilon \tag{3}$$

ε equation

$$div(\rho\overline{\boldsymbol{U}}\varepsilon) = div\left[\left(\eta + \frac{\eta_t}{\sigma_\varepsilon}\right)grad\varepsilon\right] + c_1\eta_t G_k\frac{\varepsilon}{k} - c_2\rho\frac{\varepsilon^2}{k} \tag{4}$$

$$G_k = \frac{\partial u_i}{\partial x_j}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) \tag{5}$$

where G_k represents a shear generation term.

Energy conservation equation:

$$div(\rho\overline{\boldsymbol{U}}h) = div\left[\left(\eta + \frac{\eta_t}{\sigma_t}\right)gradh\right] - q \tag{6}$$

where $\overline{\boldsymbol{U}}$ is the fluid velocity vector; $\overline{F}$ is the volumetric force, N; ρ is the fluid density,$kg\cdot m^{-3}$; P is the fluid pressure, Pa; μ is the dynamic viscosity, $N\cdot s\cdot m^{-2}$; k is the turbulent kinetic energy, J; ε is the turbulent dissipation rate, %; c_1 and c_2 are constants; σ_k and σ_ε are the K and ε equations of the Prandtl number, respectively; η and η_t are the dynamic and turbulent viscosity coefficients, Pa·s; h is the fluid enthalpy, $J\cdot kg^{-1}$; and q is source terms, including chemical reaction heat and other volume internal heat sources, J.

2.2. Solid theory

Based on the Hamilton principle of classical mechanics theory, the motion equation of the whole structure is established as follows:

$$M\overline{Z} + C\overline{Y} + K\overline{X} = F(t) \tag{7}$$

where M is the mass matrix, C is the damping matrix, K is the stiffness coefficient matrix, $\overline{X}$ is the displacement vector, $\overline{Y}$ is the velocity vector, $\overline{Z}$ is the acceleration vector, and F is the force vector, including its own gravity, centrifugal force, and flow field pressure.

The following assumptions should be met in the analysis: the K matrix must be continuous and the corresponding material should satisfy the linear elastic and small deformation theory. The F matrix is a static load, and the influences of the time variation of the load and inertia (such as mass and damping) were not considered.

Thermal coupled heat conduction equation:

$$\sigma D = div(KgradT_i) \tag{8}$$

$$-(KgradT_i)\cdot n\mid_\Gamma = \mu[T_i - T_\alpha(t)]_\Gamma \tag{9}$$

where $\sigma$is the displacement matrix, D is the heat capacity matrix, i is used to distinguish the different items of different media, Γ is used to study the outer boundary of the area, μ is the heat transfer coefficient, n is the outer normal vector, $T_0(x)$ is the distribution of the initial temperature of the system, and $T_\alpha(t)$ is a function of the time to interact with the external environment of the system.

Stress–strain constitutive relation:

$$\sigma_{ij} = \frac{E}{1+\upsilon}\varepsilon_{ij} + \frac{\upsilon E}{(1+\upsilon)(1-2\upsilon)}\theta\delta_{ij} \tag{10}$$

where $\theta = \varepsilon_{kk}$, θ is the first strain invariant, E is the elastic modulus, and υ is the Poisson ratio.

Force balance equation:

$$\frac{\partial\sigma_x}{\partial x} + \frac{\partial\tau_{xy}}{\partial y} + \frac{\partial\tau_{xz}}{\partial z} + F_x = 0 \tag{11}$$

$$\frac{\partial\sigma_y}{\partial y} + \frac{\partial\tau_{yx}}{\partial x} + \frac{\partial\tau_{yz}}{\partial z} + F_y = 0 \tag{12}$$

$$\frac{\partial\tau_{zx}}{\partial x} + \frac{\partial\tau_{zy}}{\partial y} + \frac{\partial\sigma_z}{\partial z} + F_z = 0 \tag{13}$$

where $\sigma_i(i = x,y,z)$ is the normal stress, $\tau_i(i = xy,yz,zx)$ is the shear stress, and $F_i(i = x,y,z)$ is the volume force.

3. Numerical simulation

The solid model of the directly buried heating pipe network system was established using the Inventor software [23] and then imported into the Workbench analysis platform. The fluid region was established by the filling function in mechanics (fill). Internal flow is a three-dimensional, viscous, and turbulent flow, and the movement law conforms to the N-S equation of the three-dimensional Reynolds average. The calculation process included the energy, mass, and momentum conservation equations to obtain the temperature field inside the pipe network.

Fluent (flow field calculation software) was used to calculate the pressure and temperature fields in the flow field under different temperature conditions. The total pressure inlet, mass flow outlet, and temperature of the inlet medium were set in the calculation process. The temperature load of the pressure field in the flow field can be applied to the solid field when data transmission is established between the flow field analysis module (Fluent) and the thermal stress analysis module (Thermal-Stress).

The interface between the fluid and solid domains should be highly matched to guarantee that the pressure and temperature loads can be accurately transferred to specify the solid domain. Finally, the analysis of pipe network stress in the static-structure module was conducted.

3.1. Calculation model and mesh generation

DN1400 mm caliber was selected as the research object. Its numerical calculation and experiment were performed. Elbow pipe was selected as the 1.5D bend radius large-diameter and connected with the straight pipe. The design parameters are shown in Table 1, and the pipe network structure is shown in Fig. 1.

3.1.1. Grid division

The convection field was divided into 215,760 elements using the ICEM-CFD software [24]. The structure domain used the grid partition function of Workbench ANSYS software, and the pipe body was divided into 115,760 elements. The flow field, solid domain, and local enlarged drawing are shown in Fig. 2.