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Research Paper

Influence of end side displacement load on stress and deformation of “L”-type large-diameter buried pipe network

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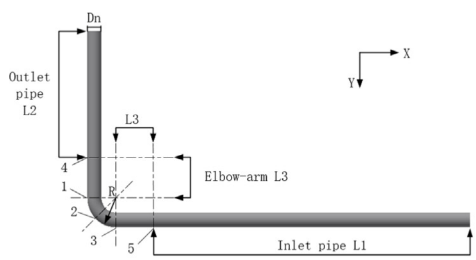
HIGHLIGHTS

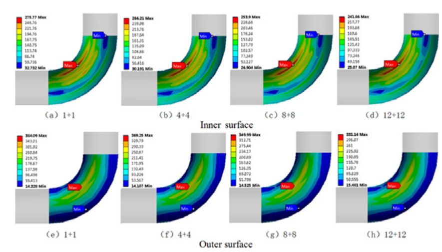
- “L”-type heat pipe network was studied using the flow-heat-solid coupling method.
- The stress and deformation under different displacement release conditions were calculated.
- The effects of unequal end-side displacement on pipeline were compared.
- The effects of end-side displacement on deformation and stress were compared.

GRAPHICAL ABSTRACT



1- Elbow outlet cross section, 2- Elbow 45°cross section, 3- Elbow inlet cross section, 4- Elbow outlet arm cross section, 5- Elbow inlet arm cross section

Schematic diagram of the pipe network structure



Equivalent stress distribution under equal end-side displacement release of elbow (inlet displacement + outlet displacement)

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ABSTRACT

Large-diameter buried pipelines are widely used because of their energy-saving advantage and high efficiency. In this study, an “L”-type heat pipe network was considered as research object and studied using flow–heat–solid coupling method. The ANSYS Workbench platform was used to simulate heat transfer and medium flow in the pipe network. The maximum equivalent stress and deformation of the pipe network under different displacement release conditions were calculated and compared with those under no-displacement release condition. The displacement release of the end sides did not change the stress and deformation distribution of the entire pipe network system but reduced the maximum equivalent stress and deformation, resulting in improved safety and stability of the pipeline. When the total amount of the displacement release of the inlet and outlet sections was defined, the influence of unequal end-side displacement on the stress and stress distribution of the pipe network can be neglected. Moreover, the maximum deformation gradually decreased with increasing displacement release in the inlet section and rapidly decreased with increasing total displacement release amount.

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

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Nomenclature

$\bar{\boldsymbol{U}}$	fluid velocity vector (m/s)
P	fluid pressure (Pa)
G_k	turbulent production term
q	total energy (J)
k	turbulent kinetic energy (J)
c_1, c_2	constants of the k-ε model
h	fluid enthalpy (J/kg)
T	temperature (K)
M	mass matrix
C	damping matrix
K	stiffness coefficient matrix
$\bar{X}$	solid displacement vector
$\bar{Y}$	solid velocity vector
$\bar{Z}$	solid acceleration vector
$\bar{F}$	force (N)
E	elastic modulus
F_i	volume force (N)
Greek symbols	
ρ	fluid density (kg/m^3)
υ	Poisson ratio
$\sigma_\varepsilon, \sigma_k$	Prandtl numbers for k-ε equations
σ_t	Prandtl number
η	dynamic viscosity coefficient (Pa·s)
ε	turbulent dissipation rate (%)
θ	first strain invariant
σ_i	normal stress (Pa)
τ_i	shear stress (Pa)
η_t	turbulent viscosity coefficient (Pa·s)
μ	dynamic viscosity (N·s/m^2)

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. 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 [14,15]. 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 and deformation have important significance in pipe network system architecture analysis and research [16,17].

Many scholars have studied the heat transfer and mechanical behavior of large-diameter buried pipe networks [18–20]. However, few studies have investigated the flow–heat–solid coupling of pipe networks. In the previous studies by our project team [21,22], the coupled flow and heat transfer inside the pipe wall at high temperature and pressure under fixed inlet and outlet sections (i.e., when the pipe network is in the anchorage section) was simulated in three dimensions by using computational fluid dynamics fluent software. The unidirectional flow–heat–solid coupling of the large-diameter buried pipe was also solved. However, the stress and deformation distributions in the pipe network and elbow have not been comparatively analyzed under different fluid pressures and temperature conditions when the inlet and outlet sections were unfixed.

When the temperature load acts on the pipe network, the change in the temperature load expands and contracts the pipe network. The thermal elongation and cold contraction of the pipe network are hindered, and the structural deformation cannot be released because of the obstruction of soil around the pipe network and the presence of fixed piers in the pipe network, resulting in the generation of structure stress. The temperature load is a part of the generalized displacement load. During actual engineering operation, the temperature load mainly loads not only the displacement load but also the end-side displacement load, a typical displacement load. According to the engineering practice, a small release of displacement greatly reduces the force of the fixed pier, thereby influencing the stress environment of the entire pipe network. Therefore, the influence of the end-side displacement load on the stress and deformation of "L"-type large-diameter buried pipe network was elucidated in this study. Different displacement loads are loaded in the inlet and outlet sections along the axial direction of "L"-type pipe network to determine the influence of release displacement on the stress and deformation of the entire pipe network. The analysis results can provide a basis for the structural strength design of large-diameter buried pipe networks.

2. Fundamental theory

Fluid theory:

Continuity equation :

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

"N-S" equation:

$$\rho\bar{\boldsymbol{U}}\mathrm{grad}\bar{\boldsymbol{U}} = -\mathrm{grad}P + \mu\mathrm{div}\cdot\mathrm{grad}\bar{\boldsymbol{U}} + \rho\bar{F} \tag{2}$$

"k-ε" equation:

k equation

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

ε equation

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

Energy conservation equation:

$$\mathrm{div}(\rho\bar{\boldsymbol{U}}h) = \mathrm{div}\left[\left(\eta + \frac{\eta_t}{\sigma_t}\right)\mathrm{grad}h\right] - q \tag{5}$$

Solid theory:

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

$$M\bar{Z} + C\bar{Y} + K\bar{X} = F(t) \tag{6}$$

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(t) 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.