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Analysis of mechanical-fluid-thermal performance of heat pipeline system with structural deformation effects

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ABSTRACT

Energy storage and transmission are important issues in the heating and cooling systems, chemical industry and other energy fields. The long-distance transmission pipeline system security under complex underground coupling loads was judged by structural deformation, especially the mechanical-fluid-thermal performance. A representative "L"-type heating pipeline system was selected as the research object and three-dimensional model was established to figure out the heat transfer, medium flowing and the deformation of the solid structure. The influence of coupled and non-coupled loads on deformation was also compared and analyzed. Results show that the deformation was affected by pressure and temperature loads simultaneously, which was lower under the coupled loads than the sum of the pressure and temperature loads alone. Due to the soil hindering the extension of the heat pipeline, the main affection factor was precisely the opposite, but the deformation distributions of the pipeline were not the exact opposite. The coupling strength was mainly influenced by pressure load under the burying laying condition, and the influence by temperature load could be ignored, whereas the coupling strength was influenced by both pressure and temperature loads under the trench laying condition.

1. Introduction

Since the energy structure of the country is unevenly distributed and the development of various urban is uneven, energy source sites are located far away from energy demand sites [1–3]. With the dramatic global energy demand, the utilization of low-grade heat sources and renewable energy are instability and intermittency feature, energy fuels (such as oil, and natural gas) and other types of energy materials have to be transferred through large-scale pipe networks [4]. Therefore, the energy storage and transmission should be guaranteed in the heating and cooling systems, chemical industry and other energy fields [5,6]. The most important link is the safety of the pipeline network [7]. Pipelines are susceptible to leakage and rupture because of stress concentration, corrosion, and large deformation [8]. The long-distance transmission pipeline system security of wind energy, electricity, and fuel caused by underground complex coupling loads have been drawing more and more people's attention [9].

There are three design options for these complex pipeline systems, which are the overhead laying on the ground, the trench and directly burying laying conditions underground. Each laying method has its advantages [10]. For heating pipe network system, the above-ground pipeline can be easily monitored for operation, but long-term exposure to the ground has a great impact on the heat loss of the pipeline [11]. For an underground natural gas storage pipeline system, corrosion slowly but gradually reduces the resistance of mechanical components, leading to the increase in the likelihood of pipeline failure over time. The utilization of the limit above-ground space leads to the underground laying methods more popular. Also, with the increase in energy demand, the pipeline system load increases, which leads to a larger diameter pipeline system [12]. Compared with the small-diameter pipe network system, more security risks will be magnified for the larger-diameter pipeline system. For a buried heating pipeline system, there are more high-temperature and high-pressure medium flowing in the pipe network with the increase of pipe network caliber. The stress produced by the millions of tons of hot water on the

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Nomenclature

u	fluid flow velocity (m/s)
P	fluid pressure (Pa)
S_T	source term for energy equation
k	turbulent kinetic energy (m^2/s^2)
c_1, c_2	constants of the k-ε model
c_p	specific heat (J/(kg·°C))
T	temperature (K)
$\mathbf{M}$	mass matrix
$\mathbf{C}$	damping matrix
$\mathbf{K}$	stiffness coefficient matrix
$\mathbf{F}$	force matrix
$\bar{\mathbf{X}}$	solid displacement vector
$\bar{\mathbf{Y}}$	solid velocity vector
$\bar{\mathbf{Z}}$	solid acceleration vector
$\boldsymbol{\sigma}_s$	displacement matrix
$\mathbf{D}$	heat capacity matrix
$\bar{\mathbf{n}}$	outer normal vector
E	elastic modulus
F	volume force N/m^3

Greek symbols

ρ	fluid density (kg/m^3)
α	thermal conductivity (W/m·°C)
$\sigma_\varepsilon, \sigma_k$	Prandtl numbers for k-ε equations
ε	dissipation rate of turbulence energy (m^{-3} s^{-2})
μ	dynamic viscosity (kg/m·s)
μ_t	turbulent dynamic viscosity (kg/m·s)
Γ	interface between the wall and fluid
λ	heat transfer coefficient (W/(m^2·°C))
υ	Poisson ratio
σ_i	normal stress (Pa)
τ_i	shear stress (Pa)
θ	first strain invariant

Subscripts

l	liquid
s	solid

impact of the pipeline could not be neglected [13]. The flow characteristics are magnified, and the influences of temperature boundary layer and velocity boundary layer on the flow and heat transfer are also magnified [14]. The temperature difference between different locations causes great thermal stress. The failure mode becomes more and more obvious because of the mechanical-fluid-thermal interaction [15]. The deformation and stress distributions of pipeline system under different loads and laying conditions, especially the coupled loads and underground laying methods, should be deeply studied [16].

A large number of studies have been conducted on the heat and mass transfer performance and mechanical structural performances of large diameter pipes. Cao et al. [17] designed two laboratory tests of the road surface to study the influences of the shallowly-buried pipe on the permanent deformation under cyclic traffic loading. Danielewicz [18] studied the heat losses from district heating pipe system through the finite element analysis. Vitel et al. [19] studied the heat transfer between the soil and pipeline using a 3D model. Chao et al. [20] studied the heat transfer characteristics of a heat exchange system using a vertical deep-buried U-bend pipe though in-situ experiments and finite-element method. Liu et al. [21] simulated a buried pipeline as a beam on the elastic foundation to evaluate the seismic responses of buried pipe networks in a numerical simulations model. The influence deformation distribution on a pipeline system was discussed by Liu G with a CFD software to simulate the mechanical-fluid interaction [22]. Yuan et al. [23] calculated the pressure distribution of fluid field at Ansys Workbench Platform. Chen et al. [24] has simulated the pipeline and made a related experiment about depth performance under burying laying condition. Saif et al. [25] used the finite element model to study the dynamic load and static load of the buried pipe network system, and different work conditions were compared through field experiment to prove the accuracy of the numerical model. The influences of various traffic loads on buried pipelines are further analyzed by Rakitin et al. [26–28].

The previous pipeline researches mainly concentrated on the flow field, working condition, deformation distribution or structural stress individually [17–30]. However, if the above factors and the interaction between pipeline and soil are not considered simultaneously, the results of heat and mass transfer and fluid properties of the pipeline will deviate from the actual simulation. Also, there is limited research on the mechanical-fluid performance of pipeline system between the flow medium and pipe wall, and the work condition was either the trench or burying laying method, which could not accurately reflect the characteristics of the fluid region, solid region, and fluid-solid coupling interaction surfaces [31]. For the pipe network system, when the soil covered the pipe body outside, the deformation of the whole system could be hindered, and the release of concentrated stress could be hampered. Therefore, the deformation and stress distributions between the burying and trench laying heat pipelines would be very different [8]. The mechanical-fluid-thermal interaction performance of stress under different laying conditions was particularly different according to the previous research, and system deformation is another indicator to evaluate the safety of the pipeline network [9]. Moreover, there is a special relationship between the deformation and stress, which would play a very important role in the overall design of the pipe network. Therefore, in this paper, a mechanical-fluid-thermal coupling model was established to calculate the deformation characteristics. A representative "L"-type heating pipeline network was selected as an example for calculating the deformation distributions under different laying conditions using the working platform of Ansys Workbench. Different working conditions (such as flow medium parameters, laying conditions) were analyzed, meanwhile the effects of the loads coupled and non-coupled on the overall performance were compared. The conclusions of the analysis can improve the pipeline system safety and provide the basis for the structural strength design of large-diameter heating pipelines.

2. Numerical simulation

2.1. Calculation model

A representative heating pipeline network under trench and burying laying conditions is shown in Fig. 1. The buried pipeline is covered by the shadowed soil. The outer surface of trench pipeline only bears its own weight, and there is no soil pressure on it. The major system geometries are described by the inlet pipe length L1, outlet pipe length L2, elbow arm length L3, wall thickness d, elbow arm length L3, Bending radius R, pipe external diameter D,