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Overall performance optimization of a spiral pipe type heater by fluid- structure interaction modeling and partitioning screening method

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ABSTRACT

A spiral pipe type heater is applied to the natural gas transportation system to inhibit gas hydrate, but fracture failure often happens at the joint of a coil pipe and a gathering pipe. To understand the mechanical behavior of the spiral pipe heater, a mechanical model of the coil pipe acted by the gas fluid is constructed, and the mechanical characteristics of the fracture point are obtained by numerical calculation. Then, the relation between angle parameters and the axial force, shear force, bending moment as well as stress of the structure is gotten. Comparison calculations of heat exchange before and after structural adjustment are done to get the optimized structure parameters of better mechanical properties and high heating rate. From this study, it is found that although the mechanical properties are improved, when increasing an angle parameter, the heat transfer performance is decreased. A coordination method is used for resolving the contradiction between heat transfer performance and mechanical properties to get an overall performance optimization. The provided partitioning screening method can improve the heating efficiency and mechanical properties of the heater obviously and conveniently.

1. Introduction

Because the pipeline of offshore natural gas transportation system is very long, and there is a high pressure in the pipe, a low temperature outside the pipe and a big temperature gradient in the natural gas, it is easy to form gas hydrate in the pipeline [1]. Gas hydrate is a kind of enveloped crystal similar to dense ice or snow which is formed by the combination of gas or volatile liquid with water at a certain temperature and pressure [2]. Gas hydrate may cause pipeline blockage, which would threaten the normal operation of the pipeline system and even cause serious accidents [3]. So, it is a major challenge for flow assurance [4]. Methods for inhibiting gas hydrate include heating, chemical reagent suppression, and mechanical cleaning, among which heating method is used commonly [5–7].

To suppress the formation of gas hydrate by heating during the transporting of natural gas, a spiral pipe heater is used. The heater is installed beside the submarine natural gas wellhead, which mainly comprises a heating furnace cavity, two gathering pipes and several sets of coil pipes. Heating furnace cavity is a sealed container cavity, which is filled with heating liquid. To keep a constant temperature, the heating liquid is heated by an electric stove wire. Gathering pipe is the passage of the natural gas into or out of the heater, and coil pipe is the main heat exchange structure. The coil pipe is a spiral structure with a diameter of R, which is coiled by a steel pipe with an outer diameter of d and a thickness of b (See Fig.s 1 and 2). The connection way for a coil pipe and a gathering pipe

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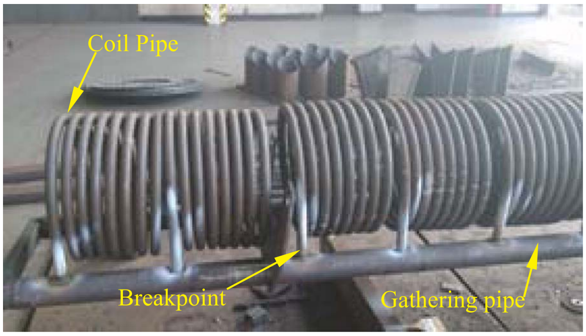

Fig. 1. Heater pipes.

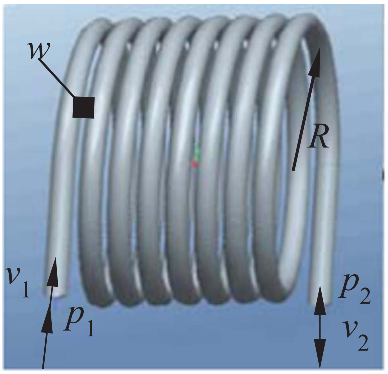

Fig. 2. Coil pipe model.

is shown in Fig. 1. As the coil pipes are surrounded by heating liquid, natural gas in the coil pipe can exchange heat with the heating liquid through the wall of the coil pipe. So, it can ensure the natural gas flowing in the transportation system with a higher temperature to prevent the condensation of gas hydrate. In engineering, accidents of fracture at the joint of a coil pipe and a gathering pipe occurred (See Fig. 1). To find out the causes and solutions of fracture failure, a mechanical model is established to analyze the stress characteristics of the coil pipe. Heat transfer calculating is also done to provide some parameters for the optimization.

Fluid solid coupling is a common and complicated problem in many engineering fields, such as turbine mechanical design, coastal marine engineering, high-rise building engineering, fluid pipeline transportation and human artery flow. Fluid solid coupling problem is an important factor that can't be ignored in the safety work of pipeline system. Engineers and scientists have never stopped the research on this problem.

A physical model featuring the combined phenomena of fluid–structure interaction and vaporous cavitation is presented by Tijsseling et al. [8]. Ferràs et al. [9] got stress–strain states of a coiled pipe by hydraulic transient experiments and provided a simplified version of the stress–strain equations to facilitate fluid–structure interaction implementation in the hydraulic transient model. Messahel et al. [10] presented a numerical methodology to solve three-dimensional complex industrial problems through the combination of homogeneous equilibrium model, arbitrary lagrangian eulerian formulation and fluid structure interaction. Benyahia et al. [11] examined the viscous incompressible newtonian fluid in a cylindrical compliant tube numerically and solved the coupled flow-structure problem.

Other works also provided the modeling method of fluid acting on the heater. Marušić-Paloka et al. [12] studied the flow of a heat-conducting incompressible Newtonian fluid through a helical pipe with cooling. Tharayil et al. [13] modeled a miniature loop heat pipe theoretically and compared the thermal performance and entropy generation with the predicted results and the experimental results. Alammar [14] constructed a three-equation average turbulence model to study the heat transfer characteristics of the flow acting on the pipe. Ferras et al. [15] analyzed the fluid–structure interaction occurring during hydraulic transients in pipe coils by means of a four-equation model to understand and describe the effect of the coil movement on the transient wave.

Scholars have conducted extensive studies on the oil/gas heater including flow assurance method, heat exchange and heat transfer modeling, especially, a lot of research works about heat transfer performances have been done to find a good method to improve heating efficiency. Yi et al. [16] studied the heat transfer characteristics and the flow patterns of the evaporator section using small diameter coiled pipes in a looped heat pipe. Ji et al. [17] analyzed the flow and heat transfer performances of horizontal spiral-coil pipes of circular and elliptical cross-sections. Zohir et al. [18] enhanced the heat transfer coefficient by inserting coiled wire around the outer surface of the inner tube of the double-pipe heat exchanger. Inaba et al. [19] investigated the reduction characteristic of turbulent drag and heat transfer of drag reduction surfactant solution flowing in a helically coiled pipe.

However, there is no systematic study report about the optimization of natural gas heater considering both the mechanical