Chemical Engineering Science 192 (2018) 477–487

Contents lists available at ScienceDirect

Chemical Engineering Science

journal homepage: www.elsevier.com/locate/ces

Investigation on the mechanical properties and mechanical stabilities of pipewall hydrate deposition by modelling and numerical simulation

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HIGHLIGHTS

- A structural model for pipewall hydrate deposition is established.
- Mechanical parameters of pipewall hydrate deposition are calculated.
- Mechanical properties and stabilities of pipewall hydrate deposition are simulated.
- Influences of flow rate, deposition thickness and deposition length are investigated.

ARTICLE INFO

Article history:
Received 4 April 2018
Received in revised form 18 June 2018
Accepted 26 July 2018
Available online 27 July 2018

Keywords:
Pipewall hydrate deposition
Mechanical properties
Mechanical stabilities
Modelling
Numerical simulation

ABSTRACT

The mechanical properties and mechanical stabilities of pipewall hydrate deposition are of great importance to the prevention and removal of pipeline hydrate plugging. In this paper, the mechanical properties and mechanical stabilities of pipewall hydrate deposition are quantitatively investigated by modelling and numerical simulation. First, a structural model for pipewall hydrate deposition is established based on particle packing theory. Using this structural model, the main mechanical parameters of pipewall hydrate deposition can be calculated. Then, numerical simulations using finite element method and ANSYS Mechanical APDL 14.5 are conducted based on the calculated mechanical parameters. Through the simulations, the structure deformation, internal stress distribution and failure of pipewall hydrate deposition when it is under the action of external forces are studied and the influences of flow rate, deposition thickness and deposition length are investigated. The results of this paper can provide guidance for pipeline flow assurance.

1. Introduction

Natural gas hydrates (NGH) are crystalline solids composed of water and gas molecules such as methane, ethane, propane, and carbon dioxide (Sloan et al., 2003). NGH are easy to form when the ambient temperature is relatively low and the ambient pressure relatively high (Sloan et al., 2010). Since the first explicit hydrate plugging incident was identified in 1934 (Hammerschmidt, 1934), NGH have always been found in oil production systems (Wang et al., 2017; Song et al., 2018). In addition, with the development tendency of oil industry moving towards deep sea and ultra-deep sea, hazards caused by hydrate plugging are now posing a severe threat to the subsea flow assurance (Sloan et al., 1998; Song et al., 2017a). Generally, once hydrate plugs form, the remediation of them may require weeks of operating downtime and the consequent economic losses caused by production break and hydrates removal can be quite huge (Jassim et al., 2010).

Hydrate deposition on the pipewall is identified to be an important reason that could lead to pipeline hydrate plugging (Grasso, 2015; Song et al., 2017b). Many researches have been carried out to investigate the formation mechanisms and formation characteristics of pipewall hydrate deposition. According to the experimental researches published in recent years, pipewall hydrate depositions can form mainly by hydrate particle bedding, hydrate film growth and hydrate-wall adhesion. High hydrate concentration, large hydrate particle size and low fluid velocity together lead to hydrate particle bedding (Hernandez et al., 2006; Jassim et al., 2010; Joshi et al., 2012). When there is a temperature gradient between the pipe wall and the bulk phase, gas molecules or water molecules tend to diffuse to the cooler pipe wall to form film growth hydrate deposition (Nicholas et al., 2008; Rao et al., 2013; Grasso et al., 2015). The capillary liquid bridge force and

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https://doi.org/10.1016/j.ces.2018.07.055
0009-2509/© 2018 Published by Elsevier Ltd.

the van der Waals force between hydrate particles and the pipe wall could count for hydrate-wall adhesion deposition (Taylor et al., 2006; Aspenes et al., 2010; Aman et al., 2013). Subcooling, flow rate, wall heat flux, internal cooling and fluid properties are the main factors that could affect the process of hydrate deposition (Straume et al., 2018). Once hydrate deposition forms in the pipeline, it would lead to the decrease of flow cross section and the increase of flow pressure drop, which could finally results in pipeline hydrate plugging.

Recent years, many researchers have found that the deposition of hydrates on the pipewall is always accompanied by sloughing or washing out (Sloan et al., 2010), which occurs as a result of the combination of flow impact force, flow shear force and gravity. The sloughing or washing out of pipewall hydrate deposition could lead to the fluctuation of pressure drop (Song et al., 2017b; Chen et al., 2015) and could result in the accumulation of hydrate debrises downstream of the pipeline. The accumulation of hydrate debrises downstream of the pipeline would then accelerate hydrate plugging and thereby poses a great threat to pipeline flow assurance. Whether sloughing or washing out could happen depends heavily on the mechanical properties and mechanical stabilities of pipewall hydrate deposition. In addition, the removal of pipewall hydrate deposition in the downtime is also closely related to its mechanical properties and mechanical stabilities. Therefore, the study on the mechanical properties and mechanical stabilities of pipewall hydrate deposition is of great importance to the prevention and removal of pipeline hydrate plugging. Through experimental researches, Aman et al. (2016), Grasso et al. (2015) and Song et al. (2017b) found that pipewall hydrate depositions had a certain mechanical stability. Usually, at the initial formation stage of pipewall hydrate deposition, the high liquid content and high porosity of the deposition will result in a low mechanical stability. Under these circumstances, sloughing or washing out is easy to happen on pipewall hydrate depositions. The researches of Aman et al. (2016); Rao et al. (2013) and Song et al. (2017b) also indicated that annealing could happen on pipewall hydrate depositions and the mechanical stabilities of pipewall hydrate deposition would increase a lot after annealing. By doing flowloop experiments, Aman et al. (2016) found that pipewall hydrate depositions formed at large subcoolings were more stable and were harder to fall off from the pipewall. Through flowloop experiments, Ding et al. (2017) found that flow rate could strength the process of hydrate deposition by accelerating mas transfer. They also found that sloughing would happen when a critical shear rate was reached. By doing experiments in a rocking cell, Straume et al. (2018) pointed out the stochastic nature of hydrate sloughing and the potential existence of an operational window for conditions without sloughing. Using permittivity probes, Sa et al. (2018) quantitatively studied the thickness, wetness, and porosity of hydrate depositions formed in deadlegs. Chen et al. (2017) investigated the sloughing critical flow rates of different pipewall hydrate depositions using a high pressure water tunnel. Lorenzo et al. (2018) proposed a model for hydrate deposition and sloughing in gas dominated systems based on flowloop experimental data. Liu (2017) established a theoretical model to estimate the mechanical properties of pipewall hydrate deposition. However, according to the literatures above, till now studies on the sloughing or washing out of pipewall hydrate deposition almost focus on the qualitative analyses of the experimental phenomena. Literatures on the mechanical properties and mechanical stabilities of pipewall hydrate deposition are even rarer. Consequently, quantitatively researches on the mechanical properties and mechanical stabilities of pipeline hydrate deposition are quite in need.

In this paper, the mechanical properties and mechanical stabilities of pipewall hydrate deposition are quantitatively investigated by modelling and numerical simulation. First, a structural model for pipewall hydrate deposition is established based on particle packing theory. Using this structural model, the mechanical parameters of pipewall hydrate deposition can be calculated. Then, numerical simulations are conducted based on the calculated mechanical parameters to further study the mechanical properties and mechanical stabilities of pipewall hydrate deposition when it is under the action of external forces. The results of this paper can provide guidance for pipeline flow assurance.

2. Modelling

2.1. Hydrate deposition modelling

In this section, a structural model for pipewall hydrate deposition is established based on particle packing theory and is then used to analyze the mechanical properties and mechanical stabilities of hydrate deposition. Particle packing theory is a discipline focuses on the packing regularities and packing characteristics of a large number of particles in a finite space (Xu et al., 2013; Mohammed et al., 2013). Till now, particle packing theory has been widely used in the fields of materials and mineral processing. In particle packing theory, a large number of particles accumulate in a finite space to form a packing structure. A packing structure has several packing parameters, such as porosity, porosity distribution, packing fraction, coordination number and specific surface area. The strength, density, heat value and many other properties of the packing structure are greatly influenced by the packing parameters. Usually, the packing parameters of a packing structure are directly related to the packing pattern of the inside particles. When the inside particles are equal-diameter spheres, there are mainly five kinds of regularly packing patterns for a packing structure: simple cubic packing, orthorhombic packing, rhombohedral packing, tetrahedral packing and pyramid packing. In this paper, pipewall hydrate deposition is taken as a special packing structure in order to establish a structural model for it and the following assumptions are made: (1) Pipewall hydrate deposition is composed of water and equal-diameter spherical hydrate particles. (2) The bulk of pipewall hydrate deposition is formed by the regularly packing of several hydrate particle layers. Water is filled in the voids between hydrate particles. (3) Pipewall hydrate deposition is isotropic. Based on particle packing theory and the assumptions above, the structural model for pipewall hydrate deposition can be established, as seen in Fig. 1. In Fig. 1, pipewall hydrate deposition is also divided into five kinds and the packing arrangement of hydrate particles for each kind is given. Using the structural model in Fig. 1, the packing parameters of pipewall hydrate deposition can be calculated. In all the packing parameters, porosity, packing fraction and coordination number have the greatest influence on the mechanical properties and mechanical stabilities of pipewall hydrate deposition. Therefore, only these three packing parameters are briefly introduced in this paper.

Porosity is defined as the volume fraction of the voids between hydrate particles in the deposition. Porosity can be calculated by:

$$\varepsilon = \frac{V_v}{V_d} = \frac{V_d - V_h}{V_d} \tag{1}$$

where ε is porosity, V_d, V_h and V_v are the volume of hydrate deposition, hydrate particles and voids between hydrate particles, respectively.

Packing fraction refers to the volume fraction of hydrate particles in the deposition and is defined as:

$$\lambda = \frac{V_h}{V_d} = 1 - \varepsilon \tag{2}$$

where λ is packing fraction.