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Effect of the Joule-Thomson cooling on the leak-before-break approach

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ABSTRACT

Due to the high pressure inside compressed natural gas (CNG) containers, its safety is the first important factor to be considered. Leak-before-break (LBB) is an important methodology of maintaining the integrity of pressure vessels. However, the Joule-Thomson (JT) cooling effect occurred during a leak may impact the validity of the LBB approach. In this paper, a looping model based on MATLAB software is developed starting with the gas at room temperature and 250 bar at the entrance of the crack. From this, the pressure and JT temperature drop is calculated initially, which in turn affects the gas properties, such as viscosity, density, thermal conductivity and heat transfer coefficients. Heat transfer and FEA analysis using a 3D model of the plate with a central through-thickness crack are carried out. Under the internal pressure of 250 bar, the temperature drop and the stress intensity factor in the vicinity of the crack is 59.7 °C and 120 MPa $m^{1/2}$, respectively. The stress intensify factor obtained is higher than the fracture toughness of the material at the same low temperature. However, the structure may not experience a catastrophic failure. The reasons for this phenomenon are discussed in the paper.

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1. Introduction

Natural gas has become to the forefront of the international energy debate as it is an important environment friendly energy for decreasing pollution and maintaining a clean and healthy environment. Its applications can serve to reduce harmful pollution levels from other fossil fuels. As a result, the transport of natural gas becomes important [1]. As to the transportation of natural gas, there are only two commercially proven concepts—pipelines and LNG. However, there are many large natural gas reserves that not located near the natural-gas-demand markets. It is considered "stranded" which is defined as gas reservoir fractions that prevent their development or optimal production from an oil or gas field. Neither pipeline nor LNG transportation techniques can economically exploit these stranded gas reserves. The compressed natural gas (CNG) marine transportation concept is one of the most developed and promising natural-gas-transportation concepts that has not yet commercialized [2–4].

Due to the high pressure inside CNG containers, the most critical characteristic previously undiscovered in CNG systems with leakage is the Joule-Thomson (JT) effect. At room temperature, all gases except hydrogen, helium and neon cool upon expansion by the Joule-Thomson process [5]. For CNG system with leakage on the container wall, the temperature of leaking CNG gas will drop due to Joule-Thomson cooling effect when CNG gas passes through the crack, thus chilling the vessel wall in the vicinity of crack and reducing fracture toughness of the wall. This may push the transition of previously stable crack propagation to become critical leading to its rapid growth [6]. As shown in Fig. 1 proposed in a proposal of this research, the initial defect continues to propagate till it penetrates the wall thickness which results in a leak. According to Paris crack growth law, during this initial phase of subcritical crack growth, each advance of the crack front corresponds to loading/unloading cycles of pressurization. Two interruptions to this steady progress can occur. Firstly, the possibility of rapid unstable crack growth which occurs when the stress intensity exceeds the fracture toughness of the material, the crack will penetrate the wall thickness in an instant. Secondly, the remaining ligament of material beyond the crack front is subjected to a high tensile stress, leading to tensile yielding or plastic instability and instantaneous rupture of the ligament. Failure of the ligament can therefore occur by either fracture or plastic instability. Beyond this stage, a through-wall thickness crack is created with

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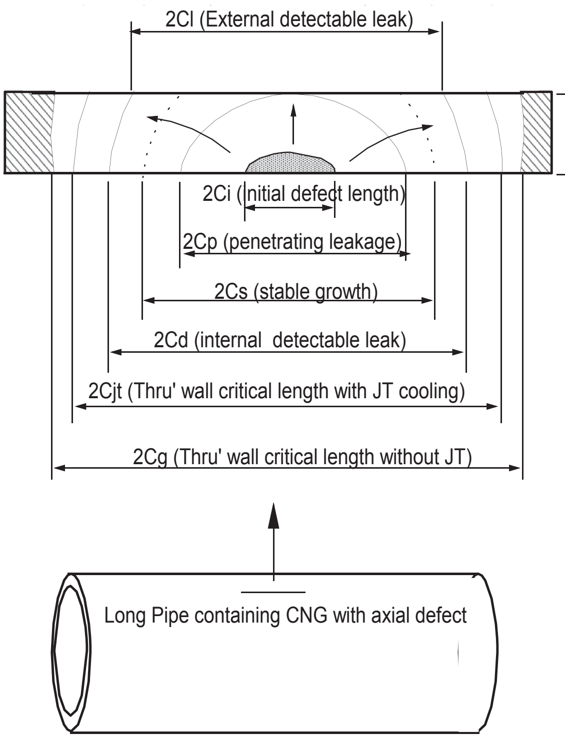

Fig. 1. Illustration of axial defect growth subjected to mainly cyclic internal pressurization and associated JT cooling.

resulting leakage of the gas. However, the small leak at this point may be too small to be detectable. The crack continues to grow in a stable mode ($2C_s$) provided its length is less than the critical crack length ($2C_g$). The internal ($2C_d$) and external crack lengths ($2C_l$) are enlarged and leakage flow rate increases to the point where it is now detectable. The main characteristic of safe LBF technology is the development of a small stable leak, which can be safely detected well before instability. The crack continues to grow outward, from $2C_d$ and approaches the critical length of $2C_g$. On reaching the critical length, unstable and rapid growth will occur causing the pipe will burst open longitudinally. However, JT cooling intervenes to reduce the temperature of the metal and its fracture toughness K_{1c} as well as the plastic yield strength. The reduction in properties reduces the critical crack length to $2C_{JT}$ which will be shorter than the critical crack length $2C_g$ without JT cooling. Hence JT cooling effect reduces the time to respond to leakage and the margin to failure. This paper aims to study whether the leak-before-break concept is safe or not safe with the JT cooling effect for a specific case.

2. Summary of experimental work

An experimental study of the JT effect was conducted by Ai et al. [7] with argon gas. A pressure vessel was designed and fabricated according to ASME Boiler and Pressure Vessel Code Section VIII Division 1 and Section II Part D [8,9] as shown in Fig. 2. The test plate containing an artificial, but realistic crack was clamped between the upper and lower flanges of the pressure vessel. The artificial crack was made by first machining a block of steel, then quenching in liquefied nitrogen before cracking in a three point bend rig as shown in Fig. 3. The cracked pieces were mated and welded together into the slot machined in the test plate. The result is tightly fitting realistic crack-like leak path as shown in Fig. 4. In the Joule-Thomson experiment, high pressure gas was allowed to leak through the crack in the test plate by tapping the high pressure gas into the pressure vessel. Temperature in the vicinity of the crack and pressure (inside the pressure vessel) were measured by thermocouples and a digital pressure gauge, respectively. The surface roughness of the surfaces of crack was measured by the surface metrology to be 38.05 μm. The crack width (i.e. the crack opening displacement) was measured by feeler gauge to be 0.25 mm.

In this experiment, the maximum pressure of argon reaches in the pressure vessel is 91 bar. The temperature changes on the outside surface of test plate (in horizontal direction to the crack line) are shown in Fig. 5. After investigation and analysis, it is found that the temperature rise on the surface of the test plate at the beginning of the experiment in Fig. 5 is caused by the temperature increase of the gas inside the pressure vessel. The reason for the temperature rise is as follows. At the beginning of the experiment, high pressure gas was tapped into the pressure vessel while the leakage was negligible due to the lower pressure inside the pressure vessel. At this time, the sharp increase of the pressure inside the pressure vessel accounts for the rise of gas temperature which can be explained by the first law of thermodynamics. The gas warming effect disappeared when the pressure inside the pressure vessel tended to be stable. At the same time, the JT cooling effect occurred during gas' leaking through the crack began to dominate to cool the surrounding metal. It is noticed that there is a significant temperature drop during this stage. During the temperature stable stage (between 160 and 400 s), the temperature of the metal increases slightly as the pressure in gas source supply containers reduces continuously. Gas supply was stopped after finishing the test, the metal temperature decreased abruptly with the sharp decreased pressure in the pressure vessel.

3. Simulation of the temperature and stress of the test plate under the pressure of 250 bar

The modelling and calculation procedures for the temperature of the test plate are similar to that described in the paper of Ai et al. [10]. The only difference is that the pressure inside pressure vessel is changed to 250 bar. Therefore, the following only shows the procedure and results which are different from it.

3.1. Evaluation of the properties of leaking argon through a crack under the pipe pressure of 250 bar

Table 1 shows crack geometry parameters and initial state parameters of argon gas inside the pressure vessel. Beck et al. [11] stated that comparison with experimental results indicates that in the absence of proper measurement, the value of $\pi/6$ for crack surface angle is reasonable. Therefore, the value of $\pi/6$is selected as the crack surface angle.

Fig. 6 shows the pressure distribution of the leaking argon along the crack depth direction. It is indicated that the pressure decreases greatly along the crack through-wall position from the inside to the outside the pressure vessel. The pressure of the leaking argon drops from 250 bar at the entrance of the crack to 26.05 bar at the exit of the crack. The total pressure drop of the leaking argon through the crack is 224 bar. The fitted pressure formula:$p = (2.5 \times 10^7)e^{-125.6z}$ (z is the crack depth direction) is used as the boundary condition on the crack surface in the structural mechanics module.

The temperature of the leaking argon along the crack depth direction is illustrated in Fig. 7. It is shown that the temperature of leaking argon falls greatly along the crack through-wall position from the inside to the outside the pressure vessel. The temperature of the leaking argon drops from 30 °C at the entrance of the crack to −48 °C at the exit of the crack. The fitted temperature formula

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