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Study on heat transfer process during leaks of high pressure argon through a realistic crack

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ABSTRACT

This paper proposes a method for simulating the heat transfer process of high pressure argon gas leaking through a narrow crack which causes the Joule-Thomson cooling effect (JT cooling effect). A once-through (decoupled) model was developed to firstly calculate the gas pressure drop at different crack depth, followed by the temperature drop. A MATLAB code was also developed to iteratively calculate the properties of leaking gas in a crack which was fitted as formula as boundary conditions in heat transfer simulation in COMSOL program. The simulated lowest temperature of the test plate in the vicinity of the crack is 13.8 °C after decreasing from the temperature of 30 °C with initial argon gas pressure of 91 bar. An experiment test rig designed and tested under the same conditions showed a good agreement between the simulation and experiment at the obtained lowest temperature in the test plate. The method is useful for predicting the lowest temperature in the vicinity of the crack caused by the JT cooling effect.

1. Introduction

Natural gas now plays an important strategic role in energy supply as global energy demand rises. The price and environmental advantages render natural gas as one of the most acceptable forms of energy. However, it is more difficult to transport and store gas than oil and therefore it lagged behind oil for a considerable period [2–4]. In natural gas transportation, large market reserves mainly rely on Pipelined Natural Gas (PNG) and Liquefied Natural Gas (LNG) transportation technologies. However, 30% of the discovered gas is considered "stranded" throughout the world. "Stranded" is defined as gas reservoir fractions that prevent their development or optimal production from an oil or gas field as a result of their distance from the market, lack of transport economy or conversion technology. Neither PNG nor LNG transportation technique can economically exploit these stranded gas reserves.

Compressed Natural Gas (CNG) transportation can be considered as a niche that will supplement both PNG and LNG technologies for the monetization of stranded gas. The basic idea of CNG is to compress the natural gas at pressures between 100 and 250 bar, and sometimes chill it to lower temperatures (up to −40 °C). In CNG projects, the gas is stored in high pressure piping or coils inside the CNG ships (up to 250 bar), therefore the reliability of pressure vessel and careful design of CNG transport fleets are very important.

The critical technology to maintain the integrity of pressure vessels is the concept of leak-before-break (LBB) [5–10]. The LBB technology applied in nuclear industry can be transplanted into CNG systems, although there are significant differences. For CNG system with leakage on the container wall, the temperature of leaking CNG will drop due to Joule-Thomson (JT) cooling effect when CNG passes through the crack. This will chill the vessel wall in the vicinity of the crack and reduce the fracture toughness of the wall. This may push the transition of previously stable crack propagation to become critical. Therefore, it is necessary to assess the impact of the JT cooling effect in cracks on the LBB approach and on the safety and reliability of pressure vessels.

There are very few papers on this research topic. The challenges in this study are how to develop a model to represent the JT effect in narrow and tortuous cracks and to evaluate the pressure and temperature drop of leaking gas through cracks. Many factors such as crack opening displacement, crack surface angle, crack turns, surface roughness and temperature dependent properties of the gas critically affect the process. This paper presents an acceptable crack model to calculate the temperature and heat transfer coefficient of leaking gas through a crack and then simulate the metal temperature distribution in the vicinity of the crack.

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Nomenclature

Latin characters

A	cross-section area, m^2
a_0, a_1, a_2, and a_3	empirical constants of gas property dependent
C_p	heat capacity at constant pressure, J/(kg K)
D	diameter of microchannels, m
D_e	equivalent diameter, m
dp	pressure drop per depth increment into the crack, Pa or bar
f	friction factor
H	enthalpy, J
h	heat transfer coefficient, W/(m^2 K)
L	characteristic length, m
M	molar mass, g/mol
N_u	Nusselt number
Nu_{Gn}	Gnielinski modified Nusselt number
P	wetting perimeter, m
p	pressure, Pa or bar
P_r	Prandtl number
R_e	Reynolds number
R_{eff}	effective roughness, m or μm
R_{glamp}	peak-to-trough amplitude of the global roughness contours for a sawtooth geometry, equal to four times the global roughness R_{global}, m or μm
R_{global}	global roughness, m or μm
R_{local}	local roughness, m or μm
T	temperature, K or °C
t	crack through-wall thickness (or crack depth), m or mm
t_{eff}	effective crack through-wall thickness, m or mm
v	fluid velocity, m/s
W_c	crack opening displacement (or crack width) perpendicular to the through-wall direction, m or mm
W_{ceff}	effective crack width perpendicular to the average flow direction, m or mm

Greek characters

α	crack surface angle relative to the crack direction through wall, rad
Δp	pressure loss, Pa or bar
Δp_{fric}	frictional term of pressure loss during fluid flowing through a crack, Pa or bar
Δp_{inert}	inertial term of pressure loss during fluid flowing through a crack, Pa or bar
Δp_{recirc}	recirculation term of pressure loss during fluid flowing through a crack, Pa or bar
η	dynamic viscosity, μPa s
θ	average flow direction relative to the crack direction through-wall, rad
λ	thermal conductivity, mW m^{-1} K^{-1}
λ^c	thermal conductivity critical enhancement, mW m^{-1} K^{-1}
λ^0	dilute gas thermal conductivity, mW m^{-1} K^{-1}
λ^r	residual fluid thermal conductivity, mW m^{-1} K^{-1}
μ_{JT}	Joule–Thomson coefficient, K/Pa or °C/bar
$\hat{v}$	specific volume (which is the reciprocal of density), m^3/kg
ρ	fluid density, kg/m^3

2. Summary of the experimental work

An experimental study of the JT effect reported in Ai and Ng [11] was conducted with argon gas. Argon is safer as it is inert compared to flammable methane, the major constituent of natural gas, and it possesses a similar JT coefficient to that of methane [12–16]. A pressure vessel was designed and fabricated according to ASME Boiler and Pressure Vessel Code Section VIII Division 1 and Section II Part D [17,18] and a JT test system was set up as shown in Fig. 1. The detailed dimensions of the pressure vessel are shown in Fig. 2. The key part in the experiment is the data collection of temperature in the vicinity of the crack in the test plate. The test plate is clamped between the upper and lower flanges of the pressure vessel. The thermocouple mounting locations on the test plate are shown in Fig. 3.

2.1. Fabrication of the test plate

The test plate contains an artificial, but realistic crack which is made following the procedures shown in Fig. 4. The liquid nitrogen quenching method was adopted in this research. The cracked pieces were mated and welded together into the slot machined in the test plate. The realistic crack-like leak path is shown in Fig. 5. The detailed dimensions of the test plate are shown in Fig. 6.

2.2. Experimental procedure

In the JT 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. During the test, the valves and regulators on the argon gas cylinders were fully opened to pressurize the pressure vessel. The digital pressure gauge with a relative accuracy of 1% connected to the side nozzle of the pressure vessel monitored and recorded the pressure inside the pressure vessel. Temperature in the vicinity of the crack was measured by thermocouples connected to a data logger. Once the temperature stabilized for a while, the vessel was depressurized by closing all valves of gas cylinders. The temperature and pressure data were collected until the metal temperature reached room temperature. In addition, prior to the JT experiment, 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.

2.3. Analysis of tested results

In this experiment, the maximum pressure of argon 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. 7. With regard to the tested points on the test plate, H1 is the one near the crack and H10 is the one far away from the crack. It is found that the temperature rises on the surface of the test plate at the beginning of the experiment are due to the temperature increase of the gas inside the pressure vessel. 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. The gas warming effect disappeared after the pressure inside the pressure vessel increases to maximum value. At the same time, the JT cooling effect occurred