1. Introduction

In recent years, the pressure in pipelines for natural gas transmission is getting higher and higher. High-pressure pipelines are in modern trend, which is expected to offer great cost advantage. However, as the pressure increases, the stored energy of inner-gas increases and once the crack initiated, the crack may run in the manner of ductile fracture, \(i.e.\) the propagating shear fracture. This running fracture may lead to the catastrophic failure of the pipelines. So, it can be said that the fracture safety of such high-pressure pipelines is now one of the urgent problems to be solved.

The propagating shear fracture is controlled by the conflict between the crack velocity of the running fracture and the decompression velocity of inner-gas during the fracture. So, this propagating shear fracture may be arrested in a short length in the case that the gas decompression velocity is much greater than the crack velocity, but it may not be arrested and could be a disaster in the case that the crack velocity is greater than the gas decompression velocity. Therefore, in order to predict this phenomenon for the fracture safety of natural gas transmission, precisely prediction of both the crack velocity and the gas decompression velocity is needed.

This paper offers the analysis in the natural gas decompression behavior in pipelines as one of the important items for predicting the fracture safety of latest high-pressure natural gas transmission. By combining “British Gas Theoretical Model of Rich Gas Decompression” and “BWRS Equation of State”, authors successfully developed the computational program, which can calculate dual-phase decompression curves of the natural gases. In the calculated results, the phenomenon of the “plateau” in the dual-phase decompression curve has been confirmed. Authors also numerically simulated the natural gas decompression behavior in pipelines and analyzed the fracture initiation process. It was shown that the initiation period is too short to influence the gas decompression curves.

KEY WORDS: natural gas decompression behavior; high-pressure natural gas transmission; dual-phase decompression curve; fracture initiation process.
theory for the ideal gas can’t predict the dual-phase gas decompression behavior, more complete equation of state is needed to predict the decompression behavior of such rich gases.

3. Theoretical Model for Dual-phase Gas Decompression

Under the condition of some assumptions, dual-phase gas decompression behavior can be solved theoretically. In this section, the natural gas decompression behavior in pipelines is predicted by “British Gas Theoretical Model of Rich Gas Decompression.”

From four assumptions described in the following, this theoretical model can be defined as a one-dimensional isentropic homogeneous equilibrium approach.

Assumptions are:

1) The flow is one-dimensional through a “full-bore” opening. In the case of running shear fractures, this is usually the case, except a short period of the initiation process where the full-bore opening is not yet formed.

2) The flow is adiabatic. This implies that the heat addition and the frictional effects are negligible. These assumptions have been used in the theory for dry gas and have been found to be a good approximation.

3) Thermodynamic equilibrium exists everywhere in the flow. Thus, liquid is assumed to condense immediately on reaching the dew line with the amount increasing as the isentrope is followed into the dual-phase gas region. This implies that there is no supersaturation of the gas.

4) Gas and liquid flow together out of the pipe at equal velocity. This assumption is justified if any liquid is carried along in the gas in the form of a mist. There is obviously a limit to the amount of liquid, which can be effectively carried in this way. But usually, the amount of liquid is small enough where the homogeneous assumption holds.

The three continuity equations of mass, momentum and energy, as applied to horizontal one-dimensional flow without heat transfer or friction can be written as:

\[ \frac{\partial p}{\partial t} + \frac{\partial }{\partial x} (p u) = 0 \] ..................(1)
\[ \frac{\partial p}{\partial t} (p u) + \frac{\partial }{\partial x} (p u^2) + \frac{\partial p}{\partial x} = 0 \] ..................(2)

\[ \frac{\partial p}{\partial t} \rho \left( h + \frac{1}{2} u^2 \right) + \frac{\partial }{\partial x} \rho u \left( h + \frac{1}{2} u^2 \right) - \frac{\partial p}{\partial x} = 0 \] ........................(3)

where \( \rho \) is the density, \( u \) the gas velocity, \( h \) the enthalpy and \( p \) the pressure.

The equilibrium velocity of sound in the mixture “a” is defined as:

\[ a^2 = \frac{dp}{dx} \] ..................................(4)

These can be solved to give

\[ \frac{du}{dp} = \pm \frac{1}{\rho a} \] ..................................(5)

Equations (4) and (5) are used to calculate the gas velocity “u” as a function of the pressure “p”. The boundary condition is \( u=0, a=a_0 \) at \( p=p_0 \). Then, if \( p_0, \rho_n \) and \( p_{n+1}, \rho_{n+1} \) are two successive points on a line of constant entropy passing through the initial conditions, then the following finite difference forms are used for the numerical calculation:

\[ \left( a_{n+1} \right)^2 = \frac{p_n - p_{n+1}}{\rho_n - \rho_{n+1}} \] ..................(6)
\[ u_{n+1} = u_n + \frac{1}{2} \frac{p_n - p_{n+1}}{a_n} \left( \frac{1}{\rho_n} + \frac{1}{\rho_{n+1}} \right) \] ...........................(7)

When a pipeline ruptures, gas can escape from the full cross section area, i.e. the full-bore opening. The decompression disturbance travels back into the pipe, with each pressure level “p” propagating at a fixed velocity “a” given by the difference between the local velocity of sound “a” and the corresponding exit velocity of the gas “u”, i.e.

\[ w_{n+1} = a_{n+1} - u_{n+1} \] ...........................(8)

In order to calculate the decompression curve precisely using this British Gas’s theoretical model, accurate properties of the gas are needed. Gas properties are calculated on the basis of following BWRS (Benedict Webb Rubin modified by Staring) equation of state.3,6

\[ p = \rho RT + \left( B_p RT - A_p - \frac{C_0}{T^2} + \frac{D_0}{T^3} - \frac{E_0}{T^4} \right) \rho^2 \]

\[ + \left( bRT - a - \frac{d}{T} \right) \rho^3 + \alpha \left( a + \frac{d}{T} \right) \rho^6 \]

\[ + \frac{\kappa p^3}{T^2} \left( 1 + \gamma p^2 \right) \exp \left( -\gamma p^2 \right) \] ...........................(9)

where \( R \) is the gas constant, \( T \) the absolute temperature and \( A_p, \ B_p, \ C_0, \ D_0, \ E_0, \ \gamma, \ a, \ b, \ c, \ d, \ \alpha \) the equation parameters. The prediction method of the equation parameters from gas compositions can be found in Ref. 3.

By combining the above mentioned two methods, “British Gas Theoretical Model of Rich Gas Decompression” and “BWRS Equation of State”, authors successfully developed the computational program which can cal-
calculate dual-phase decompression curves of the natural gases.

The calculation was carried out on a natural gas called “C2 gas,” which was used in one of the full-scale burst tests carried out by HLP (High Strength Line Pipe) Committee.\(^5\)

The compositions of “C2 gas” are shown in Table 1.

The procedure for calculation of the dual-phase decompression curve is shown in Fig. 2. Figure 2(a) shows the phase envelope of the gas and the isentropic line through the fracture initial point. In this case of Fig. 2, fracture initial point is assumed 20 MPa in pressure and \(-10^\circ\text{C}\) in temperature. Figures 2(b), 2(c), and 2(d) show the change of the density, the change of the sonic velocity and the change of the escaping gas velocity during the fracture, respectively. The velocity of the decompression wave can be given by the difference between the local sonic velocity and the local escaping gas velocity as shown in Fig. 2(e), and this curve is called the “decompression curve”.

The fluid outflow velocity is continuous, but because of the discontinuity of the acoustic velocity of the fluid at the two-phase boundary, there is a “plateau” in the dual-phase decompression curve as shown in Fig. 2(e), which features the dual-phase decompression.

Examples of the calculated decompression curves are shown in Fig. 3 with varied initial pressure. As the initial pressure increases, the plateau grows wide. The sonic velocity, which is shown at the initial point in the figures, grows higher and higher as the initial pressure increase, and the pressure ratio of the plateau to the initial pressure goes lower, which results in the shift of the decompression curve to the higher velocity.

### Table 1. Compositions of C2 gas (mol%).

| CH4 | C2H6 | C3H8 | iC4H10 | nC4H10 | iC4H12 | nC4H12 | nC6H14 | nC6H16 | nC8H20 | N2 | CO2 |
|-----|------|------|--------|--------|--------|--------|--------|--------|--------|----|-----|
| 89.57 | 4.70 | 3.47 | 0.24   | 0.56   | 0.106  | 0.075  | 0.033  | 0.017  | 0.008  | 0.001 | 0.50 | 0.72 |

Fig. 2. Procedure for calculation of the dual-phase decompression curve.

Fig. 3. Calculated decompression curves.

4. Numerical Simulation for Natural Gas Decompression Behavior in Full-bore Opened Pipe

In this section, the natural gas decompression behavior in pipeline is numerically simulated. The merit of the numerical simulation, in spite of our successful calculation in dual-phase decompression curves by theoretical model in the previous section, is that the numerical simulation makes it possible to change the assumptions or the boundary conditions for future works.

In this study, the gas decompression behavior in the full-bore opened pipe is numerically simulated on the following
assumption.
(1) Pipe diameter is constant and straight.
(2) There is no branch and junction.
(3) The pipe is laid horizontally, and inner-gas flows to horizontal direction.
(4) The pipe heat capacity is very small. Thus the heat exchange between natural gas and pipe wall is negligible.
(5) Pipe wall is smooth enough. Thus wall friction is negligible.
(6) Pipe is full-bore opened as shown in Fig. 4 schematically.
(7) The flow of natural gas is uniform in the pipe radius direction. The flow is one-dimensional to the axial direction, and the gas and the mist flow together.

The governing equations are one-dimensional compressible Euler equations same as Eqs. (1) to (3) and the equations are solved by FDS (Flux Difference Splitting) scheme. To complete this system, BWRS equation of state, shown as Eq. (9), is used for natural gas. It is assumed that condensation process is in equilibrium state by using this equation.

The numerically simulated results of C2 gas decompression behavior are shown in Fig. 5, where the gas decompression is shown at various seconds from the formation of the full-bore opening. In this case of Fig. 5, initial gas pressure is assumed to be 15 MPa, initial temperature is 0°C, and the environmental pressure is kept at 1.5 MPa, which is the convenient value instead of the atmospheric pressure because of the calculation convergence. In the decompression process, the natural gas flows in pipeline toward the full-bore opening and the pressure becomes lower gradually. The plateau is observed where natural gas changes from the gas single phase to the dual phase of gas and mist.

The comparison between the pressure distribution of C2 gas and pure methane at seconds is shown in Fig. 6. As shown in Fig. 6, the appearance of the plateau in dual-phase decompression curve results in higher pressure in the decompression process. It can make the shear fracture propagate long. The points on the plateau correspond to the dual-phase boundary. The natural gas is in single phase at the upstream of the plateau and is in dual-phase at the downstream of the plateau.

When the natural gas changes from single phase to dual-phase, the speed of the expansion wave, so called the decompression velocity, decreases because of the drop of the acoustic velocity, in which jumping of the decompression velocity is observed. This difference of acoustic velocity between single phase and dual-phase induces the plateau.

As shown in Fig. 7, reasonable agreement, except the difference in the low-pressure area caused from the difference in the environmental pressure, between the theoretical model in the previous section and the numerical simulation in this section is obtained.
5. Numerical Simulation for Natural Gas Decompression Behavior in Partially Opened Pipe

In the previous section, the pipe is assumed to be full-bore opened and the application of the numerically simulation method to the present problem is shown to give a reliable result as the theoretical model. In this section, the natural gas decompression behavior in partially opened pipe is numerically simulated. The partially opened pipe is simulated by the pipe with an orifice shaped end of some cross section ratio as shown in Fig. 8 schematically.

In this case, the governing equation is given as

\[
\frac{\partial Q}{\partial t} + \frac{\partial E}{\partial x} + H = 0 \tag{10}
\]

where

\[
Q = \left( \begin{array}{c} \rho \\ \rho u \\ e \\ \end{array} \right) A_0, \quad E = \left( \begin{array}{c} \rho u \\ \rho u^2 + p \\ (e + p)u \\ \end{array} \right) A_0
\]

\[
H = \left( \begin{array}{c} 0 \\ -\rho \frac{\partial}{\partial x} \left( \frac{A}{A_0} \right) \\ 0 \\ \end{array} \right) \tag{11}
\]

The total energy “e” is given as

\[
e = \rho h + \frac{1}{2} \rho u^2 - p \tag{12}
\]

and \(A/A_0\) is the ratio of the local cross section area to the main cross section area.

The pressure distribution at seconds is shown in Fig. 9. The flow is blocked with orifice, which prevents inner-gas to flow out from the pipe. For this reason, the smaller open area ratio results in the higher pressure. Every 25% decrease in the open area ratio brings about 25 to 30% increases in the pressure at the pipe end.

6. Two-dimensional Fluid–Structure Interaction Simulation

The studies of the decompression behavior in pipelines are usually done with the assumption of full-bore opening. Strictly speaking, this full-bore opening corresponds to the case where the fractured pipe wall has opened fully, and apparently is not a good approximation during the fracture initiation process. The numerical simulations of the gas decompression behavior in the partially opened pipe in the previous section indicate that the orifice influences the gas decompression behavior widely if the open area ratio at the pipe-end is kept a constant low value. However, the experimental observations suggest that this initiation effect is negligible because the propagating shear fracture is very rapid phenomenon and the pipe is ruptured very rapidly and also said that the time span of this initiation process is only about 20 to 30 ms.

In this section, in order to confirm the propriety in this assumption of full-bore opening, the two-dimensional fluid–structure interaction simulation of the pipe fracture and inner gas decompression is carried out. The decompression of methane gas is simulated using two-dimensional compressible Euler equations. In this study, it is assumed that methane gas is the ideal gas and the BWRS equation of state is not used here. The equations are solved by Hertedn-Yee’s upwind TVD scheme. The deformation of the pipe wall is simulated by two-dimensional dynamic elasto-plastic finite element method using von Mises yield criterion, its associated flow rule and Prager flow rule. The young’s modulus is assumed to be 20 000 kgf/mm², the yield stress 60 kgf/mm² and the stress at 10% strain 70 kgf/mm². These values are corresponding to the high-grade pipe. In this two-dimensional model, the through-thickness crack is formed instantaneously and natural gas flows out from the inside as shown in Fig. 10 schematically. Fluid analysis and structure analysis give each other’s boundary conditions. Fluid analysis gives pressure at the pipe wall to structure analysis and structure analysis gives velocity and position of the pipe wall to fluid analysis.
The numerically simulated results of the pressure distribution and the pipe deformation are shown in Figs. 11 and 12. In the case of Fig. 11 the initial inner gas pressure is 15 MPa and initial outer pressure is 5 MPa. The initial inner gas pressure is 10 MPa and initial outer pressure is 5 MPa in the case of Fig. 12.

The pipe wall moves outside, inner gas flows out and the inner pressure becomes lower. The pipe wall continues to deform even after the inner pressure becomes equal to the outer one. The inner-gas pressure becomes equal to outer one in about 5 ms, but the deformation ends in 19 ms in both cases. This time span of about 20 ms in the fracture initiation process is very small and also agrees well with the past experimental observations. Judging from these results, it can be said that a detailed consideration on the fracture process is not necessary in predicting the natural gas decompression behavior of pipelines and the full-bore opening assumption in one-dimensional simulation is regarded as reasonable.

In the process of deformation the inner pressure becomes lower than outer one because the deformation is very fast and the expansion of the inner space is rapid enough. All
the results suggest that the pipe wall is deformed mainly by initial inertia force of the wall itself, and not by inner gas pressure distribution during the fracture. In the high-pressure pipeline fracture, the initial pressure ratio is more important factor than instantaneous pressure distribution because the inertia force of the pipe wall is obtained from high-pressurized inner gas in the beginning of fracture. The effect of inertia force is observed by comparison of the final formations at 19 ms between Fig. 11 and 12. In the case of 15 MPa initial inner gas pressure in Fig. 11, the pipe wall has larger inertia force and deforms greater than in the case of 10 MPa initial inner-gas pressure in Fig. 12.

7. Conclusions

In this paper, the natural gas decompression behaviors in high-pressure pipelines are analyzed by one-dimensional theoretical model, one-dimensional numerical simulation and two-dimensional fluid–structure interaction simulation. The following are conclusions.

1) By combining two methods, “British Gas Theoretical Model of Rich Gas Decompression” and “BWRS Equation of State”, authors successfully developed the computational program, which can calculate dual-phase decompression curves of any kind of natural gases. In this calculation of one-dimensional theoretical model, the phenomenon of the “plateau” in the dual-phase decompression curve has been confirmed. This “plateau” in the dual-phase decompression curve is caused from the discontinuity in the acoustic velocity of the fluid at the two-phase boundary.

2) Authors also numerically simulated the natural gas decompression behavior in pipelines. In the case of the full-bore opening approximation, reasonable agreement between the theoretical calculation and the numerical simulation is obtained.

3) The numerical simulation of decompression behavior through the orifice is carried out. The numerical results of orifice model show that small open area ratio results in high pressure as expected. Every 25% decrease in the open area ratio brings about 25 to 30% increases in the pressure at the pipe end.

4) The two-dimensional fluid–structure interaction simulation between the pipe fracture and inner gas decompression is carried out. In this simulation, the pipe wall keeps being deformed even after the inner pressure becomes equal to the outer one. This indicates that the pipe wall is deformed mainly by initial inertia force of the pipe wall itself, which is obtained from high-pressure inner gas in the beginning of fracture, and not by the gas pressure distribution during fracture process.

5) The two-dimensional fluid–structure interaction simulation shows that the time span of the initiation process before the flaps have opened fully is only about 20 ms and this time span agrees with past experimental observations. It indicates that the effect of fracture initiation process is negligible in predicting the natural gas decompression behavior of pipelines and full-bore opening assumption in one-dimensional simulation is regarded as reasonable.

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