Korean J. Chem. Eng., 39(5), 1158-1164 (2022)
DOI: 10.1007/s11814-021-1033-8

pISSN: 0256-1115
eISSN: 1975-7220

Safety distance analysis to prevent pipeline chain accidents

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(*Received 18 October 2021 • Revised 29 November 2021 • Accepted 2 December 2021*)

Abstract−A framework for analyzing the safety distance between pipes is proposed in this study. To calculate the probability of a chain accident, the limit state function of reliability-based design and assessment is applied, and the reliability target is obtained using the risk criteria and the consequence model. As a result of analyzing these two results to calculate the safety distance between pipes, it is found that a greater safety distance should be kept in cases of the higher the pipe pressure, the larger impact force of the transport fluid, and the more dangerous fluid which has the greater consequence. The proposed study can serve as a systematic framework for recommending a safety distance, which allows for efficient and safe pipe management.

Keywords: Probability of a Chain Accident, Reliability Target, Safety Distance Analysis

INTRODUCTION

Pipelines have been used for a long time as they are the most effective method for transporting fluids. Given the significance of pipeline safety, many studies have been conducted on its design and management to ensure the safety. The service life of a pipe is extended by preventing external corrosion through the pipe coating [1]. Rimkevicius et al. [2] proposed a methodology to increase the reliability of pipeline energy systems by improving system integrity. Considerable effort and methods have been applied to conduct reliability assessment [3-6] and analysis of the safety distance [7-10].

Many studies, such as quantifying pipe safety and predicting lifespan, are based on reliability-based design and assessment (RBDA), a probabilistic method using the inherent probability distribution of variables. RBDA was studied to complement the shortcomings of traditional methodology. Traditional methods use simple statistics from historical data, such as average lifespan and accident frequency. The disadvantage of these methods is that all pipes are managed equally. For example, pipelines buried in corrosive soil have a high probability of accidents and require strict management. Pipelines buried in areas with high population density also require strict management compared to those buried in areas with low population density. However, the traditional methodology has a limitation in that it does not reflect these characteristics. So, RBDA was developed by introducing a probabilistic methodology that can be managed differently for each pipe [11-14]. With RBDA, the probability of failure (PoF) can be calculated and reliability assessment can be performed for each pipe. As such, it has the advantage of being able to manage each pipe according to the characteristics of the pipe, but there is no methodology to analyze the effect between the pipe and the pipe. For instance, when a failure occurs in the pipe, it is not indicated how much it affects the adjacent pipe and how much the probability of a chain accident is.

A study on the safe distance of people or properties from the pipeline was developed with the concept of potential impact radius. In addition, many countries designate a safety distance between natural gas pipelines and other utilities, and related studies have been conducted [15,16]. In Korea, the Korea Gas Safety (KGS) Code FP451 and KGS Code FU551 also suggest a safety distance between the gas pipeline and other utilities. In KGS Code FP112, a high pressure gas pipeline is required to maintain a distance of 1.5 m from buildings and 0.3 m from other underground facilities. Lee and Jo [17] show the technical basis of the KGS code, which regulates the minimum separation distance between high-pressure natural gas pipelines installed on the ground and buildings. However, these studies only suggest a safety distance between pipeline and other utilities, but do not perform safety distance analysis between pipelines. The safety distance between high pressure gas pipelines is applied with a safety distance from other facilities, but the technical basis is not clear.

As such, a methodology for the probability of a chain accident in the pipeline is not presented, and there is no clear basis for the safety distance between the pipes to prevent a chain accident. If the distance between the pipes is close, the probability of a chain accident is expected to increase, which may cause safety problems. However, if the distance between the pipes is too great, efficient use of space within a limited space becomes impossible. Therefore, it is necessary to safely and efficiently manage the pipeline by suggesting the optimal safety distance.

In this paper, a framework for analyzing the safety distance between high-pressure gas pipelines is proposed. The outline of the system is shown in Fig. 1, and the main flow of this paper is summarized in Fig. 2. The system to perform reliability assessment is two gas pipelines that exist in parallel. The diameter of the pipe is 200 mm, the wall thickness is 8 mm, and the hole size is 200 mm,

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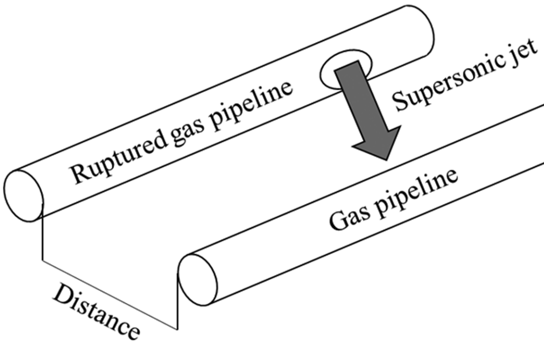

Fig. 1. Outline of the system.

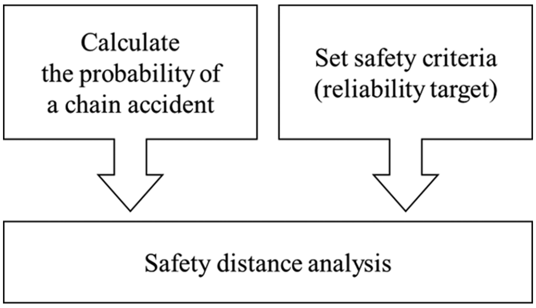

Fig. 2. The simplified procedure of reliability assessment.

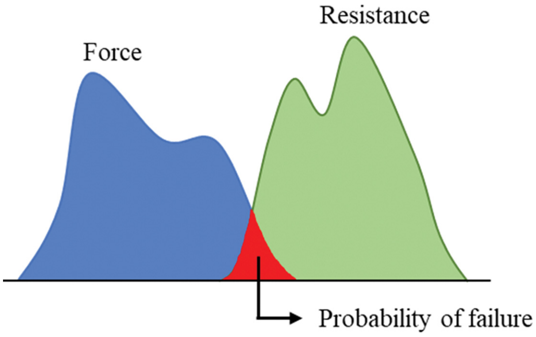

Fig. 3. Examples of probability distributions of force and resistance and probability of failure.

which is the same as the system analyzed in Eo et al. [18]. When a rupture occurs in pipe, the probability of a chain accident in the adjacent pipe is calculated, and a safety distance is proposed to prevent a chain accident. First, based on the CFD simulation results conducted in Eo et al. [18], the limit state function of RBDA is applied to calculate the probability of a chain accident in the pipeline. After that, the reliability target is obtained and reliability assessment is performed to analyze the safety distance.

PROBABILITY OF A CHAIN ACCIDENT

In RBDA, there is a function that calculates the probability that an event such as corrosion or equipment impact will lead to an accident. This function, called a limit state function, exists variously according to the cause of the accident. Limit state function is a concept that an accident occurs when the force (F) applied to the pipe is greater than the resistance (R) of the pipe. That is, an accident occurs when $R-F<0$. R and F are equations consisting of the characteristics of the pipe, such as the diameter and thickness of the pipe, and the characteristics of the cause of the accident. Among these variables, there are variables that follow a unique probability distribution. Therefore, R and F have a probability distribution, and PoF can be calculated as shown in Fig. 3.

According to Chen and Nessim [19], Fuglem et al. [20], Nessim and Zhou [21], and Stephens and Nessim [11], the equations for calculating PoF when equipment impact is applied to pipe are given by the following relationship:

$$R=C_1\left[1.17-0.0029\frac{D}{t}\right](L+w)t\sigma_u+C_2 \tag{1}$$

$$F=16{,}500W_E^{0.6919}QF_1QF_2 \tag{2}$$

All parameters used in Eqs. (1) and (2) are summarized in Table 1, and according to Stephens and Nessim [11], L, σ_u, W_E, C_2 and QF_1 follow their own probability distributions.

Eq. (1) is a semi-empirical model representing the puncture resistance of the pipe from the external force. Equipment impact and impact from a supersonic jet or shockwave are different impact sources, but both are physical impacts transmitted from the outside to the pipe. Therefore, under the assumption that accidents caused by equipment impact, shockwave and supersonic jet are similar

Table 1. Parameters used in Eq. (1) and (2)

Symbol	Definition	Unit	Probability distribution
D	Pipe diameter	mm	–
t	Pipe wall thickness	mm	–
L	Indenter length	mm	Uniform distribution
w	Indenter width	mm	–
σ_u	Ultimate tensile strength	MPa	Normal distribution
W_E	Excavator weight	tone	Gamma distribution
C_1	Multiplicative components of the model error	–	–
C_2	Additive components of the model error	–	Normal distribution
QF_1	Impact angle factor	–	Uniform distribution
QF_2	Dynamic impact factor	–	–

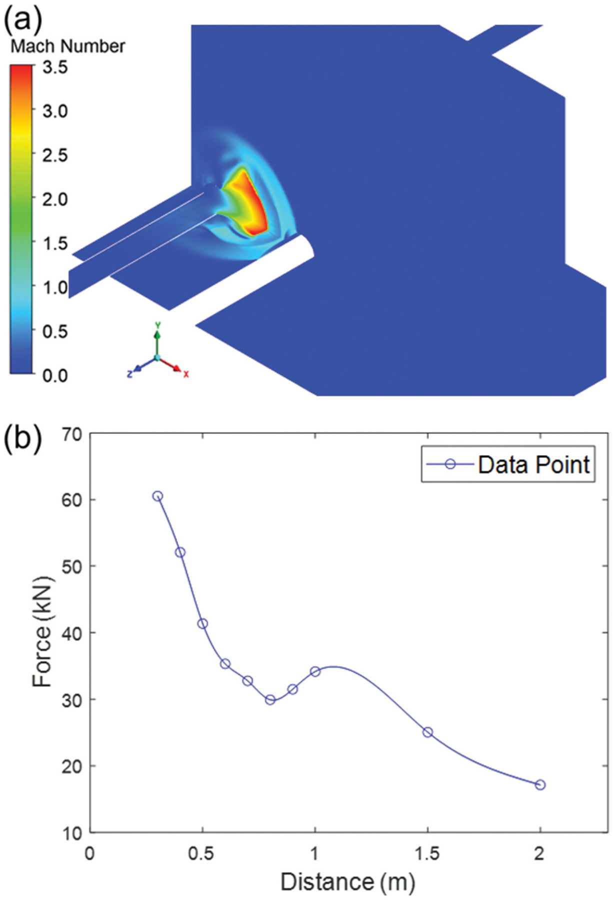

Fig. 4. CFD results in H_2/20 bar case, (a) Mach number contour in case of 0.5 m distance, (b) impact force along the pipe distance.

concepts, F is to be replaced by impact force caused by shockwave or supersonic jet. Previously, in Eo et al. [18], the amount of impact applied to the adjacent pipe when a rupture occurs in the pipe was calculated through CFD simulation. So, Eq. (1) is used as the resistance of the pipe, and the CFD results from Eo et al. [18] are used as the force applied to the pipe to replace Eq. (2). The CFD results of a total of 120 cases are used, and shows the result of H_2/20 bar case taken as the base case among them. Fig. 4(a) shows the Mach number contour around the rupture point when the maximum impact force is applied after rupture occurs in the case where the distance is 0.5 m, and Fig. 4(b) shows the maximum impact force according to the distance.

Monte Carlo simulations are performed to obtain the probability of a chain accident using R and F. The probability of a chain accident is calculated based on the number of times that $R-F<0$ is found among a total of 10^{11} Monte Carlo simulations. The results by transport fluid and distance are shown in Fig. 5.

Points at which the probability of a chain accident is calculated to be zero are not indicated. For all transport fluids, the probability of a chain accident tends to decrease with increasing distance. In addition, it can be seen that it is higher in the case of H_2 than in the case of N_2 and O_2 because the amount of impact applied to the pipe is larger. These results will be used to calculate the safety distance in section 4.

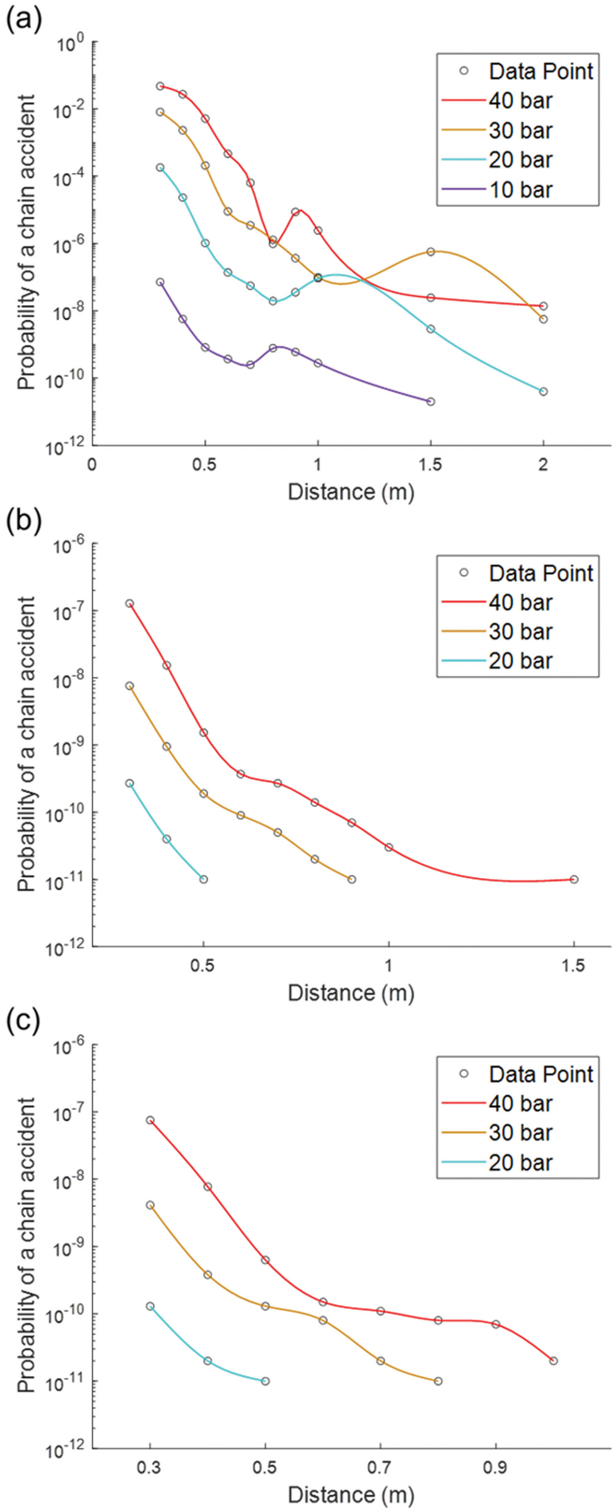

Fig. 5. Probability of a chain accident, (a) H_2 case, (b) N_2 case, (c) O_2 case.

RELIABILITY TARGET

Before calculating the safety distance between pipes, safety criterion called reliability target to keep PoF below a certain level should be found first.

1. Risk-based Reliability Target

A risk-based reliability target is used to define the maximum allowable failure probability of a pipe. The basic definition of risk r is as follows.

$$r=p\times c \tag{3}$$

p is PoF of pipe and c is the failure consequence. Based on Eq. (3), the maximum allowable probability of failure p_{max} can be defined as

$$p_{max}=r_{max}/c \tag{4}$$

where r_{max} is the maximum tolerable level of risk.

Since the reliability target R_T is the annual probability that the pipe will not fail, it can be defined as

$$R_T=1-p_{max}=1-r_{max}/c \tag{5}$$

Eq. (5) indicates that R_T is a function of r_{max} and c. Therefore, to set R_T, an appropriate consequence model and risk criteria should be used.

2. Tolerable Risk

Since several complex issues are involved in quantifying risk, several measures have been used in the industry. These risk measures are divided into two main categories: individual risk (IR) and social risk (SR). IR is the annual risk of death or serious injury to which specific individuals are exposed. It is used for sparsely populated areas with low expected number of fatalities. Values suggested by HSE and MIACC are used as IR criteria, and the tolerable risk level is 10^{-4} in Class 1, 10^{-5} in Class 2, and 10^{-6} in Class 3 and 4.

SR, which is the risk measured from the perspective of the community, is usually considered more important than IR for potentially hazardous pipelines. According to Nessim et al. [22], there are two approaches to defining SR. The first, called SR with fixed expectation, directly measures the consequence as the expected number of fatalities. The second, called SR with risk aversion, calculates the expected number of fatalities using the F/N curve.

Referring to Nessim et al. [22], in the process of calculating r_{max} using SR, it is necessary to calculate PoF of various failure modes using information on numerous actual pipes. In this paper, since actual pipe information could not be obtained; only r_{max} calculation using IR was performed.

3. Consequence of IR

For a given accident, consequence c of IR is given by

$$\begin{aligned} c&=p_i\, L_{ir} \text{ (for flammable gas)}\\ &=L_{ir} \text{ (for non-flammable gas)} \end{aligned} \tag{6}$$

where p_i is the probability of ignition and L_{ir} is the interaction length assumed to be the diameter of the hazard area a_h.

The hazard area is assumed to be a circular area with the hazard distance as the radius, and is calculated as follows considering the hazard distance corresponding to 0% and 100% fatality.

$$\begin{aligned} a_h=\pi[&p_{in}\{0.25(h_{0\%}^2-h_{100\%}^2)+h_{100\%}^2\}\\ &+p_{out}\{0.5(h_{0\%}^2-h_{100\%}^2)+h_{100\%}^2\}] \end{aligned} \tag{7}$$

p_{in} and p_{out} are the proportion of time spent indoor and outdoor, respectively. The probability of fatality is assumed to be 25% for indoor exposure and 50% for outdoor exposure. As shown in Fig. 6, $h_{0\%}$ and $h_{100\%}$ are the hazard distances corresponding to 0% and 100% fatality, respectively.

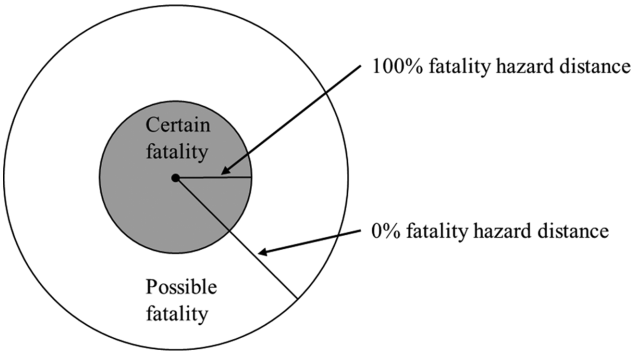

Fig. 6. Illustration of the hazard distance.

According to Baker [9,10] and Stephens [8], the hazard distance h can be expressed in the following form:

$$h=A\,(PD^2)^B \tag{8}$$

where P is the maximum operating pressure and A and B are coefficients depending on the substance. If the fatality probability is different even for one substance, A and B values will be different. That is, the coefficients corresponding to $h_{0\%}$ and the coefficients corresponding to $h_{100\%}$ are different.

It is known that the probability of ignition for rupture can be assumed as a linear function of pipe diameter:

$$p_i=4.92\times10^{-4}D \tag{9}$$

4. Reliability Target Calculation

Reliability target R_T is calculated using the consequence and risk mentioned in sections 3.2 and 3.3. Since the consequence is obtained in three ways using IR, SR with fixed expectation, and SR with risk aversion, a total of three graphs are produced. Among them, if a conservative value is selected, R_T as in Fig. 7 can be obtained. Since the r_{max} calculation using SR could not be performed,

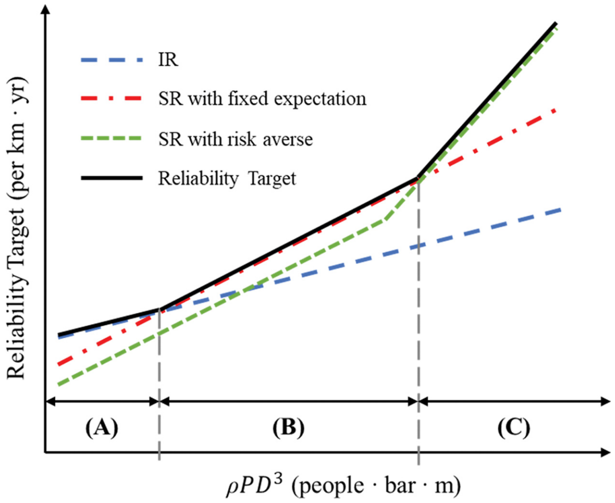

Fig. 7. Reliability targets from all three criteria considered.

Table 2. The results of reliability target calculation

Case		r_{max}	$R_T=1-p_{max}$
H_2	10 bar	10^{-4}	$1-8.00\times10^{-6}$
	20 bar		$1-5.61\times10^{-6}$
	30 bar		$1-4.54\times10^{-6}$
	40 bar		$1-3.91\times10^{-6}$
N_2	10 bar	10^{-6}	$1-1.28\times10^{-5}$
	20 bar		$1-6.87\times10^{-7}$
	30 bar		$1-1.24\times10^{-7}$
	40 bar		$1-3.68\times10^{-8}$
O_2	10 bar	10^{-}	$1-2.64\times10^{-5}$
	20 bar		$1-1.21\times10^{-6}$
	30 bar		$1-1.99\times10^{-7}$
	40 bar		$1-5.53\times10^{-8}$

the numerical value is not indicated and only the graph shape is shown. In section (A), IR is dominant over SR. Section (B) is the range in which SR dominates over IR because the risk to the pipe increases as the population density, pressure, and diameter of pipe increase. In section (C), the risk to pipe is very high, so the pipeline must be managed more strictly.

R_T is calculated using Eq. (5)-(8), and p_{in} and p_{out} are assumed to be 0.9 and 0.1, respectively. In addition, values presented in KOR. KETEP [23] are used for A and B in Eq. (8). In the case of H_2, r_{max} is set to 10^{-4} and in the cases of N_2 and O_2, r_{max} is set to 10^{-6}. The reason for using different r_{max} value for each case is to obtain a meaningful safety distance analysis result. In the cases of N_2 and O_2, the force applied to the adjacent pipe is smaller than that of H_2. As a result, the probability of a chain accident is low, so if r_{max} is set to 10^{-4}, it is always safe in the distance range in which simulation is performed. Therefore, safety distance analysis is performed by using strict risk criteria only for N_2 and O_2 cases. The results are summarized in Table 2.

SAFETY DISTANCE ANALYSIS

Although it is not possible to calculate R_T using the three risk criteria, safety distance analysis is performed using R_T, which is obtained using only IR as risk criteria. If R_T is obtained like Fig. 7 using actual pipe information, set R_T through ρPD^3 of the pipe to perform safety distance analysis.

For safety, the pipe must have a lower PoF than the safety criteria, so PoF of pipe must be lower than p_{max}. The value obtained in section 2 is the probability of a chain accident, not the total PoF. Thus, it is necessary to obtain the PoF considering all failure modes of the pipe including the chain accident. Since the previously used PoF is calculated as the sum of the probabilities of a small leak, large leak, and rupture, total PoF p_{total} considering a chain accident can be defined as follows:

$$p_{total}=p_{sl}+p_{ll}+p_{rup}+p_{ca} \tag{10}$$

p_{sl}, p_{ll}, p_{rup} and p_{ca} are probability of small leak, large leak, rupture, and chain accident, respectively. p_{sl}, p_{ll} and p_{rup} should be calculated using actual pipe information, but these values could not be obtained

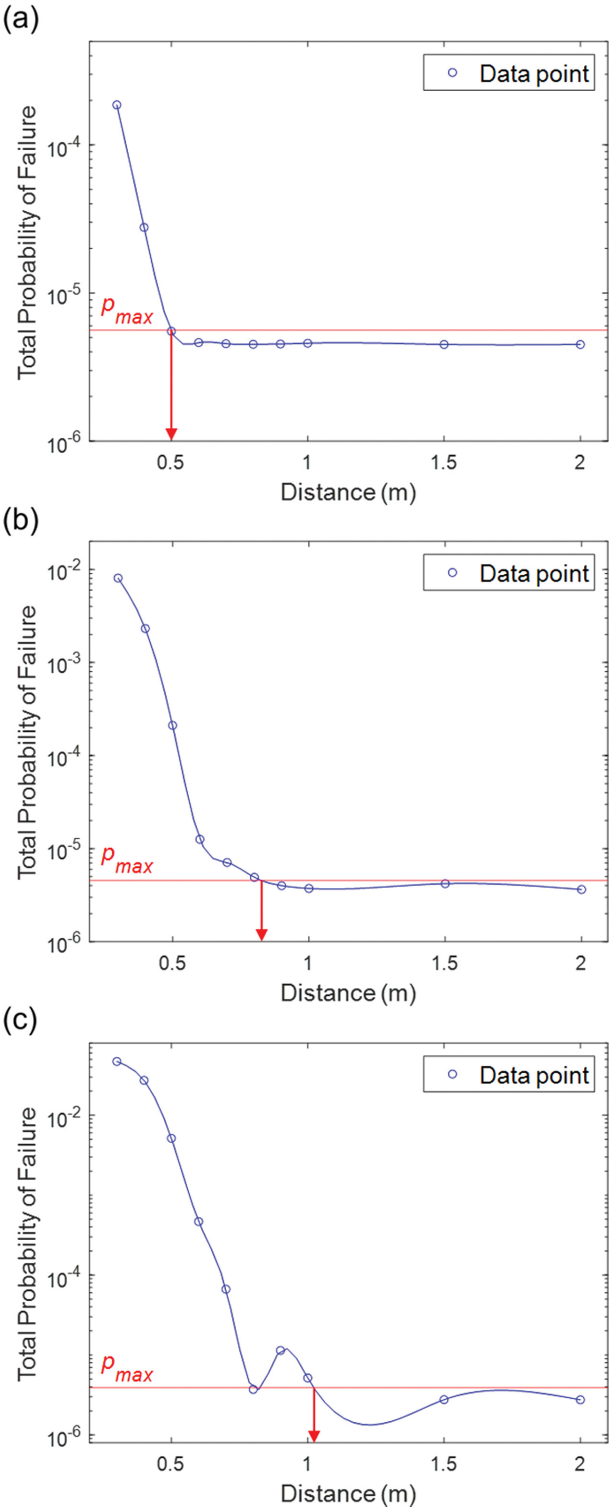

Fig. 8. Total probability of failure and p_{max} in H_2 case, (a) 20 bar, (b) 30 bar, (c) 40 bar.

in this paper due to insufficient pipe information. Therefore, the sum of p_{sl}, p_{ll} and p_{rup} was assumed to be 80% of p_{max}, assuming that the pipe complied with the safety criteria.

The results of p_{max} and p_{total} according to distance are shown in Fig. 8. The result in the case of 10 bar is not shown as the p_{total} does not exceed p_{max} at a distance of 0.3 m or more.

p_{total} increases as the distance between pipes decreases. Conversely, as the distance increases, p_{total} decreases, which satisfies the safety criteria. Thus, if a point satisfies that p_{total} is less than p_{max} in all sections where the distance is greater than that point, the point can be regarded as a safety distance. For example, in Fig. 8(c), the safety distance is 1.1 m because p_{total} is less than p_{max} at a distance after 1.1 m. However, if p_{total} becomes larger than p_{max} near 1.7 m and there is a meeting point, a distance greater than 1.7 m should be suggested as the safety distance. For safety, it would be better to increase the distance between pipelines as much as possible. But, in order to efficiently install pipes in a limited space, the distance between pipes should be close. From this point of view, the optimal safety distance is about 0.5 m in the case of H_2/20 bar, 0.9 m in 30 bar, and 1.1 m in 40 bar. As the pressure of the pipe increases, the risk of the pipe increases, so the safety distance tends to increase.

The results for N_2 and O_2/40 bar cases are shown in Fig. 9. The results for N_2 and O_2/10-30 bar are not shown, as the p_{total} does not exceed p_{max} at a distance of 0.3 m or more. The optimal safety distance is about 0.5 m in the case of N_2/40 bar, and 0.4 m in O_2/40 bar. In spite of applying strict risk criteria to the cases of N_2 and O_2, the safety distance is larger in the case of H_2. Thus, it can be seen that the greater the risk of transport fluid, the greater the safety distance should be presented.

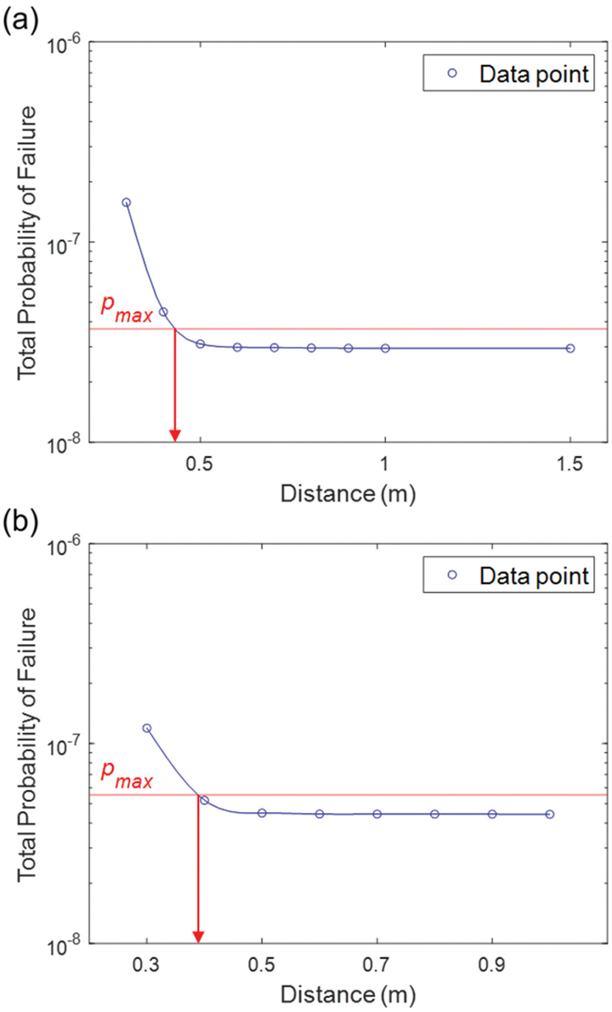

Fig. 9. Total probability of failure and p_{max}, (a) N_2/40 bar case, (b) O_2/40 bar case.

CONCLUSION

A framework for analyzing the safety distance between pipes is proposed. To calculate the probability of a chain accident, the limit state function of RBDA is applied, and the force applied to the adjacent pipe in the event of a pipe rupture is replaced with the CFD result. Reliability target, which is considered as a safety criterion, is obtained using three risk criteria and a consequence model. After that, the safety distance can be proposed by comparing the probability of a chain accident and the reliability target according to the distance. As a result of the safety distance analysis, it is found that a greater safety distance should be kept in cases of the higher the pipe pressure, the larger impact force of the transport fluid, and the more dangerous fluid which has the greater consequence.

Accurate analysis is not carried out due to insufficiency of actual pipe information, and the resulting safety distance is only a safety distance as an example, not an actual safety distance for pipes. However, if a safety distance is proposed through this process, efficient and safe pipe management will be achieved. Also, it is natural that the probability of failure decreases as the distance increases, but only in the case of H_2; there are some sections where the probability of failure increases even if the distance increases. This is considered to be related to the impact force curve according to the distance, but the reason could not be identified. If the impact force can be expressed as a function of distance, operating pressure, and material, the root cause can be identified, and more accurate safety distance analysis will be possible.

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