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Expansion Analysis of Subsea Pipe-In-Pipe Due to High Temperature and High Pressure Product

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고온 고압 수송용 해저 이중배관의 팽창해석

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KEY WORDS: Pipe-in-pipe 이중배관, Pipe Expansion 배관의 팽창, Flowline Pipe 수송배관, Casing Pipe 케이스배관

요 약: *본 논문은 고온 고압의 유류 수송용 이중배관의 팽창에 대한 해석적 방법에 대한 결과고찰과 해석, 그리고 설계시 응용이 가능한 현상에 대해 논하였다. 고온의 유류수송시 온도를 유지할 목적으로 내부의 수송 배관과 외부의 케이싱 배관사이에, 절연체가 쓰여진다. 이런 이중배관의 팽창을 조사할 수 있는 간단한 해석적 방법이 개발되었다. 본 논문에서는 온도의 분포, 입력, 토질의 저항, 수송배관과 케이싱배관과의 상호작용 등이 고려되어졌으며, 이 해석적 방법은 심해의 이중배관 해석에 적합하게 개발되었다. 계산의 결과 분석에서 고온의 영향이 고압보다 현저한 것이 밝혀졌다.*

1. Introduction

This paper presents an analytical method, investigation results, and application of expansion of subsea, insulated, pipe-in-pipe (PIP) systems due to high temperature and high pressure product (Figs. 1 and 2). Subsea pipelines, such as flowlines from the subsea wells, are often operated with high temperature and high pressure (HT/HP). To avoid wax or hydrate problems, the fluid temperature in a flowline must frequently be maintained within a desired temperature range. Heat loss from the flowline can be prevented by applying insulation between the flowline pipe and casing pipe using the pipe-in-pipe design concept. Additionally, the oil or gas production may be associated with high internal pressure. Both temperature and pressure result in pipeline expansion defined by temperature, thermal expansion coefficient, internal pressure, interaction force between the flowline pipe and casing pipe, and the pipeline restraint condition on the seabed.

A pipeline, buried or unburied, has both an active portion and fully-restrained portion. A buried pipeline has a much larger contact area with seabed and, consequently, thepipeline is restrained by the combined effect of soil pressure and friction. However, most of the deepwater pipeline are unburied. An unburied pipeline's relatively low contact area with the seabed increases its mobility on the seabed.

Expansion analysis of a single wall pipeline were presented by AGA (1987), Choi (1995), Hobbs et al. (1989), and Palmer et al (1981). Choi (1995) introduced an iterative method to solve the interaction of subsea pipeline and the restraint at the end of the pipeline. Lateral deviation and self-limiting stabilization of a single wall pipeline under axial compressive load on a resistive soil medium was introduced by Kershenbaum et al (1996). Kershenbaum et al utilized an energy variational method to investigate subsea pipeline lateral deviation with plastic and elastic soil resistance.

A primary objective of this paper is a development of a simple analytical method of expansion of pipe-in-pipe systems. A conventional approach with a structurally -coupled flowline and a casing pipe was considered. Temperate distribution, pressure, soil resistance, and interaction force between the flowline pipe and the casing pipe are considered. The new analysis method can be applied to the deepwater pipe-in-pipe systems. By implementing a more realistic analytical model into the design, installation, and operation of offshore pipe-in-pipe systems, offshore pipeline construction cost may be reduced significantly without pipeline expansion loops or expansion absorption joints.

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2. Pipe-in-Pipe System

A typical pipe-in-pipe arrangement is presented in Fig. 1. Hot and high pressure product is flowing in the carrier pipe whose wall thickness and material grade are determined by the maximum operating pressure. Insulation material is applied between the flowline pipe and casing pipe to prevent heat loss. The outer casing pipe protects the insulation and flowline pipe. The casing pipe's wall thickness and material grade are determined by the collapse criteria due to installation bending and external pressure. The flowline pipe and casing pipe have structural connections through the bulkhead at each end of the pipeline as shown in Fig. 1. In addition, centralizers are used to prevent contact of the flowline pipe and casing pipe. A typical deepwater pipeline consists of a subsea tie-in (subsea sled) on the one end and a steel catenary riser (SCR) at the other end of pipeline as shown in Fig. 2.

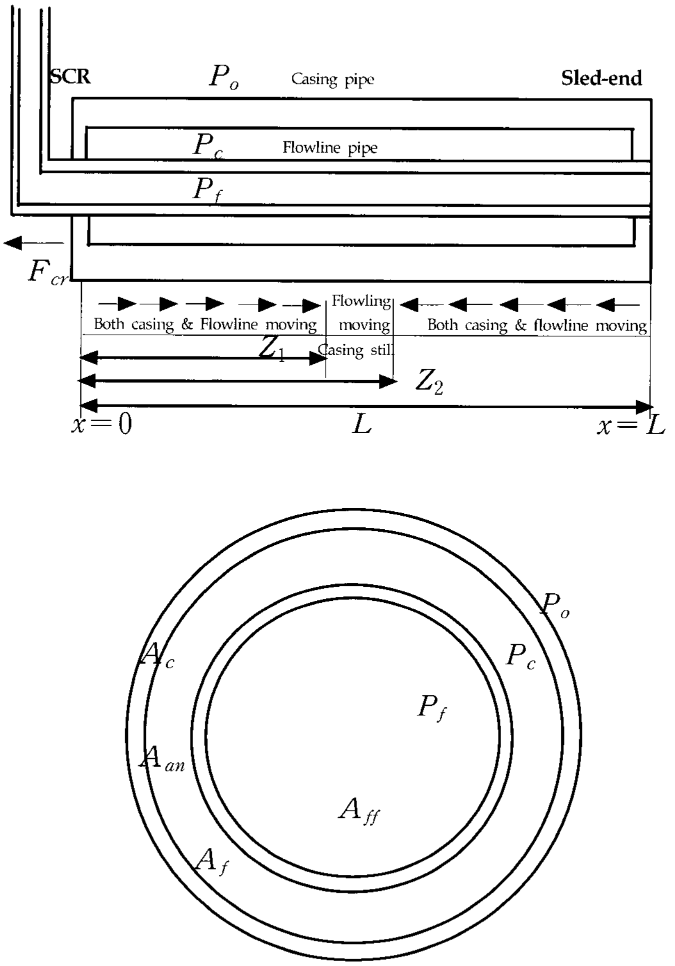

Fig. 1 typical pipe-in-pipe system

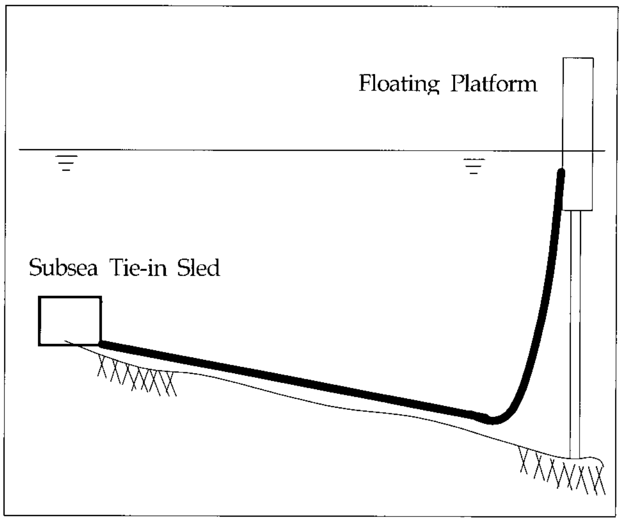

Fig. 2 Sketch of a PIP pipeline system

3. Expansion of Pipe-in-Pipe

3.1 Axial Forces

Axial force in the flowline pipe is due to internal pressure (P_f), external hydrostatic pressure (P_o), and force imparted to the casing pipe(Q) by rigid bulkheads:

$$F_f = F_{pf} - Q \tag{1}$$

$$F_{pf} = P_f A_{ff} - P_o \cdot (A_f + A_{ff}) \tag{2}$$

where,

P_f = Flowline internal pressure

A_{ff} = Flowline flow area

P_o = External hydrostatic pressure

A_f = Flowline steel section area

Axial force in casing pipe (F_c) is due to internal pressure (P_c), soil friction, horizontal tension from steel catenary riser(F_{cr}), and interaction force (Q) imparted by the flowline pipe.

$$\begin{aligned} F_c &= F_{pc} + Q + F_\mu + F_{cr} && \text{for } x \le Z_1 && \text{Region 1} \\ &= 0 && \text{for } Z_1 \le x \le Z_2 && \text{Region 3} \\ &= F_{pc} + Q + F_\mu && \text{for } Z_2 \le x \le L && \text{Region 2} \end{aligned} \tag{3}$$

$$F_{pc} = P_c A_{an} - P_o (A_{an} + A_c) \tag{4}$$

$$F_\mu = -\mu \cdot W \cdot x \tag{5}$$

where, F_{cr} = Horizontal force due to SCR

L = Total pipeline length

P_c = Casing internal pressure

A_{an} = Annular area

A_c = Casing steel sectio area
μ = Soil pipe friction coefficient
W = Pipeline submerged weight per unit length

3.2 Strain and Expansions

Pipe strain in the flowline pipe is:

$$\varepsilon_f = \frac{1}{EA_f} \cdot (F_{pfc} + F_{tf} - Q) \tag{6}$$

$$F_{pfc} = F_{pf} - A_f \cdot \nu \cdot \sigma_f \tag{7}$$

$$F_{tf} = E \cdot A_f \cdot \alpha \cdot \Delta T \tag{8}$$

where,

E = Young's modulus of steel
ν = Poisson's ratio of pipe steel
σ_f = Hoop stress in flow line
α = Thermal expension coefficient of steel
$\triangle T$ = Temperature change in flowline

Then, the expansion in the flowline pipe is:

$$\Delta L_f = \varepsilon_f \cdot L \tag{9}$$

Pipe strain in the casing pipe is:

$$\varepsilon_c = \frac{F_c}{EA_c} - \frac{\nu \cdot \sigma_c}{E} \tag{10}$$

In region 1, the Eq. (10) becomes:

$$\varepsilon_{c1} = \frac{1}{EA_c} \cdot (F_{c1e} + F_\mu) \tag{11}$$

where,

$$F_{c1e} = F_{pc} - A_c \cdot \nu \cdot \sigma_c + Q + F_{cr} \tag{12}$$

$$Z_1 = \frac{F_{c1e}}{(\mu \cdot W)} \tag{13}$$

In region 2, the Eq. (10) becomes:

$$\varepsilon_{c2} = \frac{1}{EA_c} \cdot (F_{c2e} - F_\mu) \tag{14}$$

where,

$$F_{c2e} = F_{pc} - A_c \cdot \nu \cdot \sigma_c + Q + F_\mu \tag{15}$$

$$Z_2 = -\frac{F_{c2e}}{(\mu \cdot W)} \tag{16}$$

In region 3, the casing pipe has zero strain. Pipe expansion in casing pipe in region 1 is:

$$\Delta L_{c1} = \int_0^{Z_1} \varepsilon_{c1} dx = \frac{Z_1}{E \cdot A_c}(F_{c1e} - \frac{\mu W Z_1}{2}) \tag{17}$$

Pipe expansion in casing pipe in region2 is:

$$\Delta L_{c2} = \int_{Z_2}^{L} \varepsilon_{c2} dx$$

$$= \frac{L}{E \cdot A_c}(F_{c2e} + \frac{\mu W L}{2}) - \frac{Z_2}{E \cdot A_c}(F_{c2e} + \frac{\mu W Z_2}{2}) \tag{18}$$

Total expansion of the pipeline is,

$$\Delta L_c = \Delta L_{c1} + \Delta L_{c2} \tag{19}$$

The unknown value of interaction force (Q) can be obtained:

$$\Delta L_f = \Delta L_c \tag{20}$$

The detailed calculation of Q is presented in Appendix A.

4. Calculation and Discussion

Example calculations were performed for the following pipe-in-pipe system.

- Flowline pipe: 6.625-in x 0.719-in API 5L X-60
- Casing pipe: 10.75-in x 0.5-in API 5L X-60
- Total length of pipeline: 7012 m (23000 ft)
- Water depth: 1000 m (3280 ft)
- Operating temperature difference: 60 deg C
- Operating pressure at surface: 5000 psi
- Soil friction coefficient: 0.12

A detail of sample input and output of the computer calculation is attached in Appendix B.

Fig. 3 depicts pipe expansion at the sled end and the effect of the temperature variation at constant operation pressure of 5000 psi. As the temperature increases, the expansion at the sled end increases significantly.

Fig. 4 presents the pipe expansion at the sled end and the effect of pressure variation at constant operation temperature difference of 60 deg C. The variation of the expansion lengths are not very sensitive to the pressure variation. Fig. 5 shows the pipe expansion at the sled end and the effect of the soil friction variation at the constant operation pressure of 5000 psi and temperature difference of 60 degree C. The soil friction coefficient yield the linear variation of the end force, but the expansion length has a maximum near the 0.1 for the given PIP system.

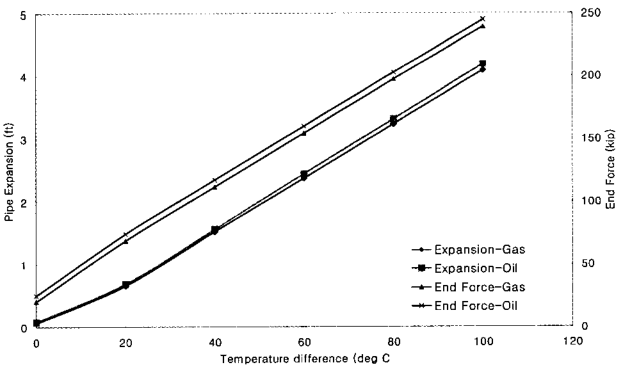

Fig 3 Effect of temperature at constant pressur5000psi

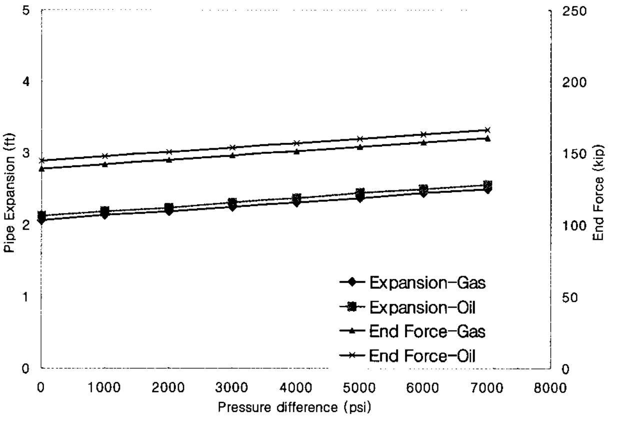

Fig. 4 Effect of temperature at constant temperature 60 deg C

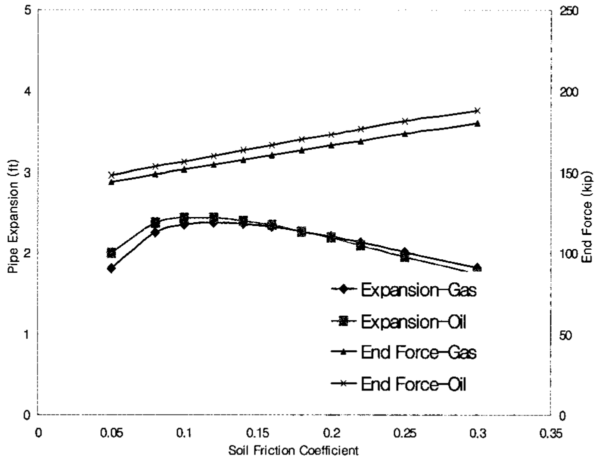

Fig. 5 Effect of soil friction coefficient at P = 5000 psi $\triangle T$ = 60 deg C

5. Concluding Remarks

1. A simple anlaytic method was developed to estimate the expansion lengths of a pipe-in-pipe system and can be applied design of subsea pipeline tie-in systems.
2. Pipe-in-pipe systems yield less longitudinal expansion compare to single wall pipe systems.
3. Pipe-in-pipe systems may be able to avoid installation of unnecessary expansion absorption devices.
4. The effect of high temperature on the expansion is more significant than the effect of high pressure

Acknowledgements

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Appendix A : Calculation of Q

From Eqs. (13) and (17), and rearrange for Q,

$$\triangle L_{c1} = \frac{(F^*_{pc}+Q+F_{cr})^2}{2\nu WEA_c}$$

$$= \frac{(F^*_{pc}+F_{cr})^2}{2\mu^*} + \frac{F^*_{pc}+F_{cr}}{\mu^*}\cdot Q + \frac{Q^2}{2\mu^*} \qquad \text{(A1)}$$

where,

$$F^*_{pc} = F_{pc} - A_c\,\nu\,\sigma_c$$

$$\mu^* = \mu\, WEA_c$$

From Eqs. (16) and (18), and rearrange for Q

$$\triangle L_{c2} = \frac{(F^*_{pc})^2}{2\mu^*} + \frac{F^*_{pc}}{\mu^*}\cdot Q + \frac{Q^2}{2\mu^*} \qquad \text{(A2)}$$

From $\triangle L_f = \triangle L_{c1} + \triangle L_{c2}$

$$A\cdot Q^2 + BQ + C = 0 \qquad \text{(A3)}$$

where,

$$A = \frac{1}{\mu\, WA_c}$$

$$B = \frac{2F^*_{pc}+F_{cr}}{\mu\, WA_c} + \frac{L}{A_f}$$

$$C = \frac{(F^*_{pc})^2 + (F^*_{pc}+F_{cr})^2}{2\mu\, WA_c} - \frac{F^*_{pf}+F_{tf}}{A_f}\cdot L$$

$$F^{*}_{pf} = F_{pf} - A_{f}\nu\sigma_{f}$$

Solving the Eq. (A3), we can obtain;

$$Q_{12} = \frac{-B \pm \sqrt{B^2 - 4AC}}{2A} \tag{A4}$$

Appendix B : Sample Calculation sion of Pipe-in-Pipe

Simbol	Description	Unit	Gas Line	Oil Line
Dc	Casing outside diameter	in	10.75	10.75
tc	Casing wall thickness	in	0.5	0.5
Df	Flowline outside diameter	in	6.625	6.625
tf	Flowline wall thickness	in	0.542	0.542
L	Pipe length (total)	ft	23000	23000
Wd	Submerged weight (empty)	lb/ft	63	63
h	Water depth	ft	3280	3280
T	Flowline temperature	deg C	81.7	81.7
Ta	Ambient temperature	deg C	21.7	21.7
DT	Temperature difference	deg C	60	60
a	Coefficient of thermal expansion	1/C	1.17E-05	1.17E-05
E	Young's modulus	ksi	29000	29000
n	Poisson's ratio	#	0.3	0.3
W	Submerged weight (product)	lb/ft	63.8	71.7
po	Ambient pressure	psi	0	0
pc	Casing internal pressure	psi	0	0
pf	Flowline internal pressure	psi	5114	6184
Fcr	Tension due to SCR	lbf	33000	33000
Aef	Flowline ending area	in^2	24.1	24.1
Af	Flowline section area	in^2	10.4	10.4
Ac	Casing section area	in^2	16.1	16.1
Aan	Annular area	in^2	40.2	40.2
sqf	Hoop stress on flowline	psi	31254.2	37797.0
sqc	Hoop stress on casing	psi	0	0
Ftf		lb	210864	210864
Fpf	Force on flowline due to pressure	lb	123315	149131
Fpf*		lb	26198	31683
Fpc	Force on casing due to pressure	lb	0	0
Fpc*		lb	0	0
Case 1	Z1<Z2			
A			0.008	0.007
B			2488.107	2458.741
C			-5.22E+08	-5.35E+08
Q1		lb	143083	150744
Q2		lb	-449963	-491390
Fcl*1		lb	176083	183744
Fcl*2		lb	-416963	-458390
Fcl*1>0 ?			Yes	Yes
Fcl*2>0 ?			No	No
Fcl*		lb	176083	183744
Fcll*		lb	-33108	-47170
Q		lb	143083	150744
Z1	Anchor point, riser end	ft	22986	21353
Z2	Anchor point, sled end	ft	4322	5482
Z1<Z2?			No	No
DLf	Expansion on flowline	ft	7.20	7.03
DLcl	Expansion on casing, riser end	ft	4.33	4.20
DLcll	Expansion on casing, sled end	ft	2.86	2.83
DLc	Total expansion on casing	ft	7.20	7.03
Fflowline	Force on flowline	lb	-19768	-1613
Fcl	Max. force on case section I	lb	176083	183744
Fcll	Max. force on case section II	lb	143083	150744
Case 2	Z1>=Z2			
Z		ft	13654	13418
Q		lb	154438	159968
Fcl*		lb	187438	192968
Fcll*		lb	-21753	-37946
DLf	Expansion on flowline	ft	6.33	6.32
DLcl	Expansion on casing, riser end	ft	3.95	3.89
DLcll	Expansion on casing, sled end	ft	2.37	2.44
DLc	Total expansion on casing	ft	6.33	6.32
Fflowline	Force on flowline	lb	-31122	-10837
Fcl	Max. force on case section I	lb	187438	192968
Fcll	Max. force on case section II	lb	154438	159968

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