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Study on Sebsea Pipeline Thermal Expansion
해저송유관의 열팽창 고찰

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Abstract □ Nearshore and offshore pipelines are often applied to carry oil, gas, water and combined products. The thermal and pressure gradients of the fluid inside pipeline cause pipeline expansion. This expansion produces stress to connecting structures with pipeline. Should this stress exceeds the yield strength of connecting components or the allowable displacement of the system, a damage can occur. As most pipelines contain hazardous and toxic fluids, the damage usually leads to fatal accidents involving great economic loss as well. Even subsea pipelines can be easily applied to transport liquid type fluid without time and space constraint, they should be designed and maintained carefully to be functional safely during design lifetime. In this paper, various theories estimating pipeline thermal expansion are investigated and the effects of pipe components to expansion are studied.

Kdywords : offshore pipeline, thermal expansion, virtual anchor point, strain

要　旨 : 해안 및 해양에 설치되어 있는 해저관로는 원유, 가스, 물과 이들의 혼합된 유체들을 전달하기 위한 수단으로 사용되고 있다. 관로 내부 유체의 열과 압력 차이는 해저관로의 팽창을 야기 시킨다. 해저관로 팽창은 관로와 연결되는 구조물들에 응력을 유발시킨다. 작용 응력이 연결 부재의 항복점을 초과하거나 전체 시스템의 허용변형을 초과할 경우 구조물에 손상이 발생된다. 해안 및 해양에 설치되는 해저관로는 주로 위험 물질이나 유독 유체를 포함하기 때문에 만약 이런 유체의 유출이 발생될 경우 인명 피해는 물론 큰 경제적 손실을 가져온다. 비록 해저관로는 시간적/공간적 제약 없이 유체를 전달할 수 있지만, 이런 관로 설계 시 안전하게 그 기능을 수행할 수 있도록 고려 되야 한다. 본 논문에서는 해저관로의 열변형 해석에 사용되는 여러 개의 이론을 조사하였고, 관로의 요소들이 관로 팽창에 미치는 영향에 대해 조사하였다.

핵심용어 : 해양 관로, 열팽창, 가상 지지점, 변형

1. INTRODUCTION

Subsea pipelines installed in offshore and near shore are quite often used to transport oil, gas, water and combined product. If there is a fluid with a certain temperature and pressure running through pipelines, it creates the temperature and pressure gradients which cause expansion or contraction of pipeline. Usually, offshore pipelines are subjected to expansion since the inside fluid has higher temperature than outside. Offshore and near shore pipeline ends are generally connected to offshore structures such as platform, SPM (Single Point Mooring) system, PLEM (Pipe Line End Manifold) and etc. The expansion of pipeline results in a stress concentration at tie-in point of connecting structures. Whatever the structure types are, the connecting structures with pipeline should be designed to sustain the strain occurred to pipeline ends (ASME,

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1992a; ASME, 1992b). As offshore and near shore pipelines are connected to large offshore and onshore facilities carrying extremely flammable and toxic fluid and products, any damage to pipelines can lead to fatal accidents involving great economic loss as well. Even subsea pipelines can be easily applied to transport liquid type fluid without time and space constraint, they should be designed and maintained carefully to be functional safely during design lifetime.

A fluid with high temperature and pressure causes mainly an axial expansion of pipeline. As the fluid travels along pipeline, it losses heat and the friction between pipeline and seabed restrains the expansion. To predict the expansion of pipeline, it is important to understand the temperature gradient along the pipeline from the inlet to outlet. Also the relationship between friction restraint and expansion is to be investigated. The expansion of pipeline is an important input in the design of connecting structures such as riser, clamps, PLEM etc. The connecting component with pipeline end should be designed to absorb the expansion.

The API (1993) codes and standards are generally used in the analysis of pipeline expansion. But being known that API codes tend to over-predict the expansion, different methods have been developed by engineering companies and software industries. A popular software has introduced a method predicting pipeline expansion. Subsea structure engineering companies also produced their own codes to estimate the expansion. In this study, three methods predicting pipeline expansion have been investigated and compared. The effects of each component of pipeline such as concrete coating, wall thickness, pipeline length, input temperature are investigated.

2. PIPELINE EXPANSION THEORY

2.1 Strain Due to Temperature

The inlet temperature contributes most in the pipeline expansion. The temperature at upstream reaches the highest and decreases as the axial distance increases. The lowest temperature is detected at the downstream of pipeline. The pipeline expansion at the upstream is the largest and at a certain distance it becomes zero. From that point, it maintains no expansion all the way up to the downstream. The inside fluid temperature decreases as it travels along the pipeline. As the inside temperature goes down, the strain of pipeline also decreases. The temperature decreasing rate can be defined by two distributions; exponential distribution and logarithmic distribution as shown:

$$T_{(x)} = T_w + (T_i - T_w)\exp(-\beta x/L) \tag{1}$$

$$T_{(x)} = T_w + (T_i - T_w) \times 10^{-\beta x/L} \tag{2}$$

where x is the distance from the upstream, $T(x)$ temperature at x point and T_i the temperature at the upstream. The expansion rate due to temperature can be obtained with an assumption that the strain changes linearly at a certain point along the pipeline with a coefficient of thermal expansion, a. (McAllister, 1993).

$$e_T = \alpha(T_{(x)} - T_w) \tag{3}$$

2.2 Strain Due to Pressure

It is usually assumed that the circumferential strain is neglected and only axial stain is considered in the estimation of pipeline strain due to pressure. The pressure gradient also contributes on pipeline expansion as the temperature does. The pressure effects both to longitudinal and circumferential stresses of pipeline. However, only the longitudinal stress effects on pipeline axial strain. If the internal pressure is greater than outside pressure, the pipeline expands circumferentially and also longitudinally at the Poisson's rate, v.

$$e_P = e_L - ve_H \tag{4}$$

2.3 Strain Due to Friction

The friction force created from the contact of pipeline to seabed works against pipeline expansion due to the thermal and pressure gradients. The friction force is determined by the submerged weight of pipeline and the type of soil on seabed. The submerged weight of pipeline is very important to secure the vertical and horizontal stabilities against current and wave forces. The strain by friction increases at a certain rate along the axial distance. The friction strain can be estimated with application of the longitudinal expansion friction factor between pipeline and soil.

$$e_f = -fw_s x / EA_{st} \quad (5)$$

2.4 Total Strain

Combining three strains by temperature, pressure and friction, the total expansion of pipeline is obtained. The strain rate due to temperature gradient decreases along the axial distance and become zero at a certain location. The strain rate from pressure maintains constant from inlet to outlet. The strain rate by friction starts zero at inlet and increases along the distance. The total strain rate reaches the maximum at inlet and gradually decreases with distance and finally becomes zero at the virtual anchor point (Jorgensen and Braestrup, 1986).

$$e_{tot} = e_T + e_p + e_f \quad (6)$$

The virtual anchor point represents a certain location at where the total strain becomes zero.

$$e_{tot} = 0 \quad (7)$$

However, should the e_f is larger than the sum of e_T and e_p, the expansion does not occur.

2.5 Total Expansion

The total expansion can be estimated by integrating the total strain rate up to the virtual anchor point. The expansion should be within the allowable stress range at the boundary with connecting structures such as risers and pipelines.

$$\delta = \int_0^x e_{tot}\, dx \quad (8)$$

3. NUMERICAL APPROACH

3.1 Heat Transfer Coefficient

The heat transfer coefficients in inside and outside are different being dependent on fluid type, velocity and thermal conductivity. The inside heat transfer coefficient is expressed as Eq. (9).

$$h_i = 0.023\left(\frac{k_l}{D_i}\right)\left(\rho_l \frac{VD_i}{\mu_l}\right)^{0.8}\left(1000C_{pl}\frac{\mu_l}{k_l}\right)^{0.33} \quad (9)$$

The outside heat transfer coefficient is estimated from the below equation:

$$h_o = 0.53\,(K_w/D_o)\,(Gr \times Pr)^{0.25} \quad (10)$$

where

$$G_r = \rho_w^2 gB(T_p - T_w)\frac{D_o^3}{\mu_w^2} \quad (11)$$

and

$$P_r = 1000C_{pw}\frac{\mu_w}{k_w} \quad (12)$$

3.2 Thermal Resistance

The thermal resistance varies with type of material and component thickness of the pipeline and can be expressed with the following relation.

Fluid to Pipe : $R_i = 1/hi$ (13)

Steel Pipe : $R_{st} = r_i \times \ln(r_1/r_i)/K_{st}$ (14)

Coating : $R_{coa} = r_i \times \ln(r_2/r_1)/K_{coa}$ (15)

Concrete : $R_{con} = r_i \times \ln(r_0/r_2)/K_{con}$ (16)

Pipe to Water : $R_w = r_i/(r_0 h_o)$ (17)

Adding all terms, the total thermal resistance can be obtained.

$$R_{tot} = R_i + R_{st} + R_{coa} + R_{con} + R_w \quad (18)$$

The overall heat transfer coefficient can be expressed as

$$U = 1/R_{tot} \quad (19)$$

3.3 Temperature Decay Constant

From the overall heat transfer coefficient, the temperature decay constant can be estimated. This coefficient determines the temperature variation of fluid inside the pipeline.

$$\beta = \pi D_i UL / C_p m \quad (20)$$

4. THEORY COMPARISON

The pipeline data used in the study is shown in

Table 1. Applied pipeline data.

Item	Notation (Unit)	Data
Length of Pipeline	L (m)	28230
Outside Diameter of Pipe	D_o (m)	0.457
Thickness of Pipe	t (m)	0.0113
Density of Pipe	ρ_l(kg/m^3)	7850
Young's Modules of Steel	E (MN/m^2)	200000
Poissons Ratio of Steel	v	0.3
Thermal Expansion Coefficient of Steel	α (^{o}C^{-1})	0.0000116
Thickness of Coating	t_{coa} (m)	0.00475
Density of Coating	ρ_{coa} (kg/m^3)	1400
Thickness of Concrete	t_{con} (m)	0.035
Density of Concrete	ρ_{con} (kg/m^3)	3044
Design Internal Pressure	P_i (MN/m^2)	10.99
Design Temperature	T_i (^{o}C)	80
Density of Contents	ρ_l (kg/m^3)	95.575
Temperature of Sea Water	T_w (^{o}C)	22.8
Water Depth	d (m)	62.8
Density of Sea Water	ρ_w (kg/m^3)	1030
Pipeline/Soil Friction Factor for longitudinal Expansion	f	0.5
Volumetric Flow Rate	Q (m^3/s)	0.292
Thermal Conductivity of Contents	K_l (W/m^{o}C)	0.03
Absolute Viscosity of Contents	μ_l (Ns/m^2)	0.00002
Absolute Viscosity of Sea Water	μ_w (Ns/m^2)	0.00156
Specific Heat of Contents	C_{pl} (kJ/kg^{o}C)	2.1
Thermal Conductivity of Sea Water	K_w (W/m^{o}C)	0.6
Coefficient of Sea Water Cubical Expansion	B (^{o}C^{-1})	0.000036
Temperature of Outer Surface of Pipe	T_p (^{o}C)	80
Specific Heat of Sea Water	C_{pw} (kJ/kg^{o}C)	3.94
Thermal Conductivity of Steel	K_{st} (W/m^{o}C)	55
Thermal Conductivity of Coating	K_{coa} (W/m^{o}C)	0.75
Thermal Conductivity of Concrete	K_{con} (W/m^{o}C)	2.45

Table 2. Comparison of various theories.

	Method 1	Method 2 (Andrew, 1988)	API (API, 1993)
Strain Due to Tem. e_T	$\alpha(T_{in}-T_w)\exp(-x\,\beta/L)$	$\alpha(T_{in}-T_w)\exp(-x\,\beta/L)$	$\alpha(T_{in}-T_w)\exp(-x\,\beta/L)$
Strain Due to Pressure e_p	$(P_iD_i^2-P_oD_o^2)/4E(D_o-t)t$ $-v(P_i-P_o)D_o/2Et$	$P_iA_i/EA_{st}-v(P_iD_i-P_oD_o)/2Et$	$P_iD_o/4Et-vP_iD_o/2Et$
Strain Due to Friction e_f	$-fw_sx/\pi E(D_o-t)t$	$-fw_sx/EA_{st}$	$-fw_sX/EA_{st}$
Virtual Anchor Point X (m)	2074.0	2308.0	2334.0
Thermal Expansion δ (m)	0.68751	0.79568	0.80760

Table 1. Applying the actual pipeline data in Table 1, three theories are investigated and compared. As summarized in Table 2, the equation for the strain due to temperature are all the same in all theories. However the pressure strain is calculated differently in the theories. The method 1 is the equation widely used in the engineering companies to predict the pipeline expansion. As API (1993) neglects the external pressure, it predicts the largest strain. Also it predicts the largest expansion having the longest virtual anchor point. In method 1, by substituting D_i by D_o, it estimates the smallest strain by pressure causing the smallest expansion. It is noticed that the method 2 (Andrew Palmer and Associates, 1988) predicts in

between the method 1 and the API. Figs. 1 to 4 illustrate the differences of the predicted values from three approaches.

5. CONTRIBUTING FACTORS

The factors contributing to pipeline expansion are investigated such as pipeline length, inlet temperature, concrete coating and wall thickness. The pipeline length concerned in the expansion is referred up to the virtual anchor point. After this point, the length does not affect on the expansion. Fig. 1 shows the thermal expansion versus pipeline length of 2500 meter where the virtual anchor point located. It is noticed that as the virtual anchor point is longer the thermal expansion is also larger. The inlet temperature is the most contributing factor in the thermal expansion of pipeline. The inlet temperatures ranging from 60 degree to 100 degree are applied to investigate of the thermal expansion due to inlet temperature. As shown in Fig. 2, the inlet temperature influences directly on the thermal expansion. The role of concrete coating is to satisfy the lateral and vertical stabilities of pipeline against external force and to protect from external impact. As the concrete thickness increases, the submerged weight increases which also cause to increases the friction force. Therefore, the concrete restraints the expansion of pipeline as illustrated in Fig. 3. Fig. 3 shows the thermal expansion with change of concrete thickness

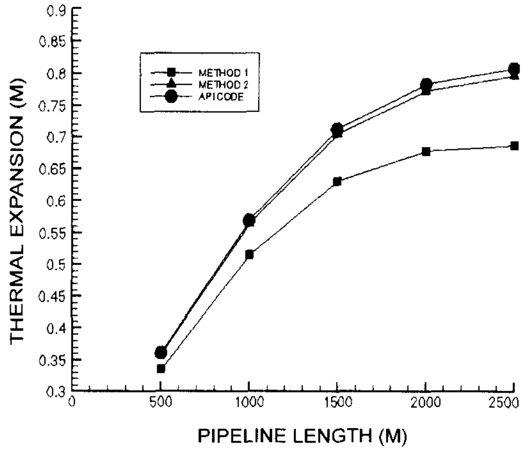

Fig. 1. Pipeline length vs. thermal expansion.

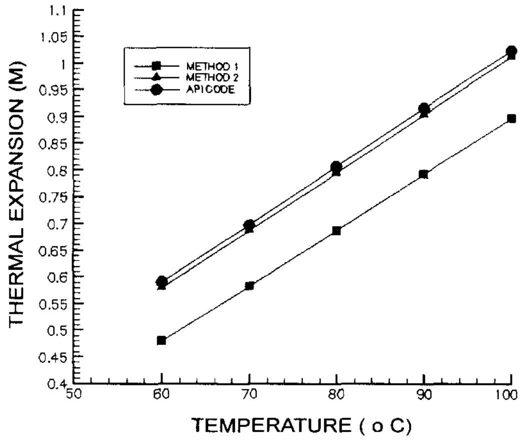

Fig. 2. Inlet temperature vs. thermal expansion.

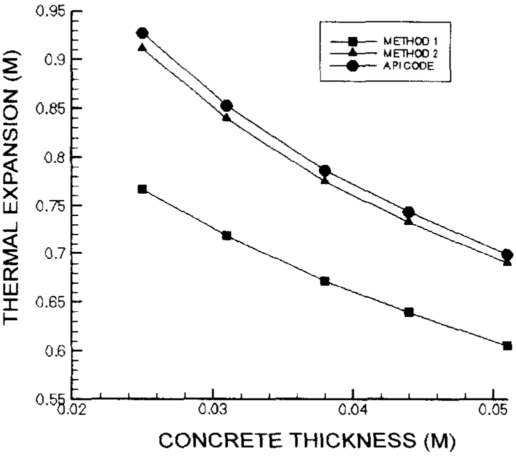

Fig. 3. Concrete coating thickness vs. thermal expansion.

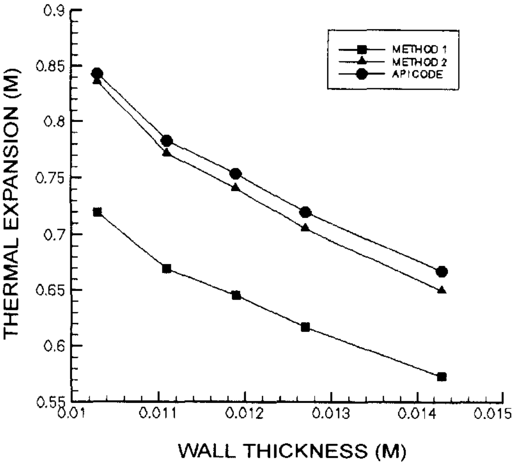

Fig. 4. Wall thickness vs. thermal expansion.

from 1 inch to 2 inch. The wall thickness acts against the pipeline expansion since it decreases the strain from pressure. The area of material becomes larger with increase of wall thickness. The thicker wall means the heavier pipe which produces a larger friction force. Fig. 4 indicates the effects of wall thickness to the pipeline expansion.

6. CONCLUSION

From the investigation of three methods predicting pipeline strain and expansion, API theory estimates the largest value having the longest virtual anchor point. As the method 1 estimates the shortest virtual anchor point, the smallest expansion is calculated. This is due to a different approach for the pressure strain. It is observed that the pressure does not affect on the strain of pipeline as much as temperature. The friction between pipeline and seabed restraints the expansion. The expansion of pipeline becomes larger as the virtual anchor point distance and inlet temperature increase. It is noticed that the increase of wall thickness and concrete thickness works against pipeline expansion. In the offshore facility design in connection with subsea pipelines, it is very important to have a clear understanding of pipeline expansion theories and the effect of components.

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