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Behavior of Subsea Pipelines Expansion under High Pressure and Temperature Design

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ABSTRACT

In offshore operation, Crude oil is transported by means of pipeline system from oil well to platform at High Pressure and High Temperature. The pipeline will experience expansion and multi stresses due to internal pressure and operating temperature that the material properties of pipe tend to deformation which affect to the durability of pipeline. This phenomenon should be considered in the design process of pipeline and to estimate the expansion is under limit of pipeline strength otherwise the pipeline will be failure cause of catastrophic.

KEY WORDS: *Pipeline Expansion; High Pressure; High Temperature; Axial Force.*

NOMENCLATURE

API	American Petroleum Institute
ΔT	Temperature Difference in and out
F_T	Thermal Expansion
L_A	Anchor Length
ΔL	Expansion
F_P	Pressure Force
F_F	Friction Force
ε_{sd}	Design Compressive Strain
ε_c	Critical Strain

1.0 INTRODUCTION

Increasing of pipeline trend to deep water will compel operating condition at high pressure and temperature. in this circumstances, the pipeline construction challenges will move into strain base design using the lateral buckling design approach. Strain-based design allows the pipelines expand laterally at designated location to relieve thermal expansion rather than being restrained. the lateral buckling design requires the correct initiation method to provide low critical buckling forces at the designated location. The main issues of offshore pipeline operations are expansion induce movement due to internal pressure and high temperature. The operation of High Pressure High Temperature (HPHT) pipelines are susceptible to move such as lateral buckling and axial creeping. There is some interaction in the movement of pipelines between pipe and seabed soil or other connection that is always to be a problem in the design pipeline moreover the complexities of pipeline interaction to the extreme seabed condition. Understanding and solving, the pipeline embedment to estimate the reliable pipe soil interaction on the HPHT pipeline is to be crucial aspect in the implementation of the pipeline design in deep water.

2.0 MECHANICAL PROPERTIES OF PIPE

The grade designation comes from API Spec 5L specification for pipeline. Stronger grades have designation X followed by the specified minimum yield strength of the pipe steel. Table 2.1 shows the SMYS (Specific Minimum Yield Strength) and SMTS (Specific Minimum Tensile Strength) of pipeline based on the material grade.

Table.1 SMYS and SMTS

API Grade	SMYS	SMTS
	MPa	MPa
X42	289	413
X46	317	434
X52	358	455
X56	386	489
X60	413	517
X65	448	530
X70	482	565
X80	551	620

2.1 Strain by DNV Regulation

$$\varepsilon_{sd} \leq \varepsilon_{Rd} = \frac{\varepsilon_c(t_2, p_{min} - p_e)}{\gamma_\varepsilon} \quad (1)$$

where,
ε_{sd} = design compressive strain
$\varepsilon_c(t_2, p_{min})$

$$p_e = 0.78\left(\frac{t}{D} - 0.01\right).\left(1 + 5.75.\frac{p_{min} - p_e}{p_b(t)}\right).\alpha_h^{-1.5}.\alpha_{gw} \quad (2)$$

p_{min} = minimum internal pressure
p_e= external pressure, ρgh. (3)

$$\alpha_h = \left(\frac{R_{t\,0.5}}{R_m}\right)_{max} \quad (4)$$

$$\left(\frac{R_{t\,0.5}}{R_m}\right)_{max} = 0.93$$

3.0 PRINCIPLE THEORY

3.1 Axial Force

a) Pressure Force Expansion

$$F_{P1} = PA_i\left[1 - \frac{2v(D-t)}{(D-2t)}\right] \quad (5)$$

b) Friction Force

$$F_{F1} = fW_S x_1 \quad (6)$$

3.2 Exponential Temperature End Expansion Theory

a) Thermal Expansion Force

$$F_{T1} = EA_S\alpha\Delta T(x_1) \quad (7)$$

$$\Delta T(x_1) = \Delta T_1 \exp\left(-\frac{x_1}{\lambda}\right)$$

Combine equation, thermal expansion force become:

$$F_{T1} = EA_S\alpha\,\Delta T_1 \exp\left(-\frac{x_1}{\lambda}\right) \quad (8)$$

b) Anchor length (long pipe)

$$PA_i\left[1 - \frac{2v(D-t)}{(D-2t)}\right] + EA_S\alpha\Delta T_2 \exp\left(\frac{L_{A2}}{\lambda}\right) = fW_S L_{A2} \quad (9)$$

c) Anchor length (short pipe)

$$L_{A1} = (EA_S\alpha\left[\Delta T_1 \exp\left(\frac{-L_{A1}}{\lambda}\right) - \Delta T_2 \exp\left\{\frac{L_T - L_{A1}}{\lambda}\right\}\right] + fW_S L_T)/(2fW_s) \quad (10)$$

d) Expansion

$$\Delta L_1 = \frac{L_{A1}}{EA_S}\left(F_{P1} - \frac{fW_S L_{A1}}{2}\right) + \alpha\lambda\Delta T_1[1 - \exp\left(-\frac{L_{A1}}{\lambda}\right) \quad (11)$$

3.3 Linear Temperature End Expansion Theory

a) Thermal Expansion Force (F_{T1}):

$$F_{T1} = EA_S\alpha\Delta T_1 + EA_S\alpha M_1 L_{A1} \quad (12)$$

b) Anchor length (long pipe)

$$L_{A1} = \frac{PA_i\left[1 - \frac{2v(D-t)}{(D-2t)}\right] + EA_S\alpha\Delta T_1}{fW_s - EA_S\alpha M_1} \quad (13)$$

c) Anchor length (short pipe)

$$(2L_{A1} - L_T) = \frac{EA_S\alpha(\Delta T_1 - \Delta T_2)}{fW_S - EA_S\alpha M_1} \quad (14)$$

d) End expansion

$$\Delta L_1 = \frac{L_{A1}}{EA_S}\left[F_{P1} + EA_S\alpha\Delta T_1 + \frac{L_{A1}}{2}(EA_S\alpha M_1 - \quad fW_S)\right] \quad (15)$$

3.4 Uniform Temperature End Expansion Theory

a) Thermal expansion force

$$F_T = EA_S\alpha\Delta T \quad (16)$$

b) Anchor length (long pipe)

$$L_A = \frac{\left[PA_i\left[1 - \frac{2v(D-t)}{(D-2t)}\right] + EA_S\alpha\Delta T\right]}{(fW_S)} \quad (17)$$

c) Anchor length (short pipe)

$$L_A = \frac{L_T}{2} \quad (18)$$

d) End Expansion

$$\Delta L = \frac{L_A}{EA_S}\left[F_P + EA_S\alpha\Delta T - \frac{fW_S L_A}{2}\right] \quad (19)$$

3.5 Design Burst Pressure

$P_t \leq f_d . f_e . f_t . P_b$
$P_d \leq 0.80P_t$
$P_a \leq 0.90P_t$
f_d= internal pressure burst design factor, 0.90 for pipeline and 0.75 for riser
f_e= weld joint factor
f_t= Temperature, derating factor, 1.0 for temperature less than 121 ^{0}C.
P_b=Specified Minimum Burst Pressure
P_d=Pipeline Design pressure
P_t= Hydrostatic test pressure

$$P_b = 0.90(SMYS + SMTS)\left(\frac{t}{D - t}\right)$$

where, D = outside diameter note the formula for the burst pressure are for $D/t = 15$
Substituting the pressure test:

$$P_d =\leq 0.80 f_a f_e f_t P_b P_d =\leq 0.80 f_a f_e f_t 0.90(SMYS + SMTS)(\frac{t}{D-t}) \quad (20)$$

3.6 Allowable Pressure

Allowable external pressure of subsea pipeline:

$$P_{allow} = \frac{2E}{3(1-v^2)}(t/D)^3 \quad (21)$$

where, E = modulus elasticity, t = thickness, D = outside diameter, v= poisson's ration

If the allowable external pressure is smaller than the design external pressure, either the pipe thickness is increased or stiffening rings are applied to increase the allowable pressure. When the un-stiffened pipe segment is short, the buckling may occur with two or more lobes depending on the diameter, thickness, and length.
The allowable compressive stress:

$$S_{allowable} = \frac{0.125}{2}E(t/R) \quad (22)$$

R= outside radius

3.7 Hoop Stress

$$\sigma_h = (P_i - P_e)\frac{D-t}{2t} \leq \eta(SMYS - f_{y.temp}) \quad (23)$$

$f_{y.temp}$ = Derating value due to Temperature

η = usage factor $\frac{2\alpha_u}{\sqrt{3}.\gamma_m.\gamma_{sc}.\gamma_{inc}}$

α_u= material strength factor
γ_m= material resistance factor
γ_{sc}= safety class factor
γ_{inc}= incidental to design pressure ratio

4.0 SIMULATION AND DISCUSSION

4.1 Operating Data

Table.2 Pipe Data

PIPE DATA	
Outside Diameter (mm)	762
Corrosion Coating Thickness (mm)	5
Concrete Coating Thickness (mm)	40
Pipe Density (kg/m^3)	7850
Corrosion Coating Density (kg/m^3)	1280
Concrete Coating Density (kg/m^3)	3040
Young modulus	2.07x10^11
Thermal Coefficient	1.17x10^-5
Poisson Ratio	0.3
Overall pipeline length (m)	27.00

Table.3 Environment Condition

Environment Condition	
Sea Water Density	1025 kg/m^3
Friction Factor	0.4
Seabed Temperature	21^{0}C

Table.4 Operating Condition

Operating Condition	
Internal Pressure	9.38 MPa
Outlet Temperature	27^{0}C
Inlet Temperature	55^{0}C

Table.5 End Expansion

Pipeline Case	End Expansion Programming Results		End Expansion site results	
	Inlet (m)	Outlet (m)	Inlet (m)	Outlet (m)
Exponential temperature-long pipe	2.2781	0.4801	2.2781	0.4802
Exponential temperature-short pipe	0.1403	0.0465	0.1403	0.0465
Linear temperature-long pipe	0.4126	0.0558	0.4126	0.0558
Linear temperature-short pipe	0.6014	0.1324	0.6015	0.1324
Uniform temperature-long pipe	0.1859	0.1859	0.1860	0.1860
Uniform temperature-short pipe	0.8144	0.8144	0.8145	0.8145

Comparison between simulation results and company data shows that the small different value about 0.02 % from actual value. The different come from round off decimal number to nearest value. Figure.1 shows the inlet region has greater expansion compare to outlet region. This program identifies the limit of pipeline pressure and strain design complies with the DNV regulation. Strain design should be lower than rule strain. In the design of pipeline, strain will not be the concern problem to comply with DNV regulation but it can effect to fixed riser fatigue. Stress and strain Criteria tested by this programming in line with DNV regulation in which no specific formula for calculation of end expansion. The length of pipeline expansions can be determined to consider the mode of buckling but the magnitude of displacement will be estimated based on the value of pipeline end expansion.

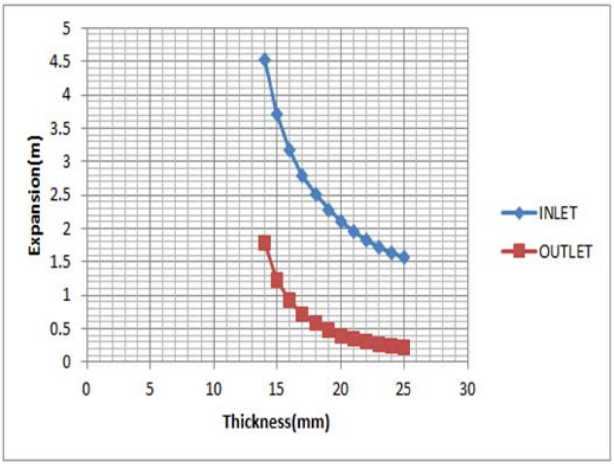
The parameter of pipeline design will be set in this programming such as stress, strain and pressure to remind the designer that the conditions are either under limit or exceed the limit of pipeline strength.

Comparing empirical formula and DNV regulation in this programming showed that empirical formula only used the general data of carbon steel. In the DNV has specific grade of material value like specific minimum yield strength (SMYS) and specific minimum tensile strength (SMTS).

Table.6 Thickness and Expansion

Thickness (mm)	Inlet Expansion (m)	Outlet Expansion (m)
14	4.52	1.79
15	3.72	1.23
16	3.19	0.92
17	2.80	0.72
18	2.51	0.58
19	2.29	0.48
20	2.10	0.40
21	1.96	0.35
22	1.83	0.31
23	1.73	0.27
24	1.64	0.24
25	1.56	0.21

Figure.1 Result plotted of end expansion against thickness



5.0 CONCLUSION

In this programming result the parameter design of pipeline work at high pressure and temperature induce end expansion that should be consider to avoid failure. The end expansion bring the stress and strain to the pipe line when interact with soil of seabed. The operating data by programming makes the result by limitation of several parameters.

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