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Integrated Expansion Analysis of Pipe-In-Pipe Systems

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KEY WORDS: Pipe-in-pipe, Flowline, Casing pipe, Pipe expansion, Bulkhead, Water stop, Expansion loop

ABSTRACT: *This paper presents an analytical method, application of expansion, mechanical design, and integrated expansion design of subsea insulated pipe-in-pipe (PIP) systems. PIP system consists of a flowline and a casing pipe for the transport of high temperature and high pressure product from the subsea wells. To prevent heat loss from the flowline, insulation material is applied between the pipes. The flowline pipe and the casing pipe have mechanical connections through steel ring plate (water stops) and bulkheads. Pipeline expansion is defined by temperature, internal pressure, soil resistance, and interaction force between the flowline and the casing pipe. The results of the expansion analysis, the mechanical design of connection system of the two pipes and tie-in spool design are integrated for the whole PIP system.*

1. Introduction

High pressure and high temperature (HP/HT) reservoirs in subsea field are being developed as part of subsea tie-backs to existing or new platforms. There is a need to insulate the flowlines to transport the product without wax and hydrate formation (Choi, 2002).

To prevent wax and hydrate formation, the pipe-in-pipe (PIP) system is the best configuration so far to insulate the flowline. In addition, the pipe-in-pipe system provides a good protection of the HP/HT flowlines. Heat loss from the flowline can be prevented by applying insulation between the flowline (carrier) pipe and the casing pipe using the pipe-in-pipe design concept as shown in Fig. 1.

The pipe-in-pipe system approach with a structurally-coupled flowline pipe and a casing pipe was considered. Temperature, pressure, soil resistance, and interaction force between the flowline pipe and the casing pipe are considered (Choi, 1995; Choi, 1999; Harrison et al., 1997; Kershenbaum et al., 1996; Palmer and Ling, 1981).

The primary objective of this study is to develop a complete procedure of an integrated expansion design of the pipe-in-pipe systems. For this purpose, the expansion analysis, the mechanical design of connection system between the two pipes and the tie-in spool design are integrated for the whole PIP system. Currently, no design code specifies any analytical method (Bai, 2001).

2. Pipe-In-Pipe System

A typical cross sectional arrangement of a pipe-in-pipe system is presented in Fig. 1. Hot and high pressure product is flowing in the flowline whose wall thickness and material grade are determined by the maximum operating pressure (Bai, 2001). Insulation material is applied between the pipes. The casing pipe protects the insulation material and the 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 the casing pipe have mechanical connections through water stops and bulkheads. In addition, spacers are placed at specified intervals to maintain the annulus gap of the two pipes.

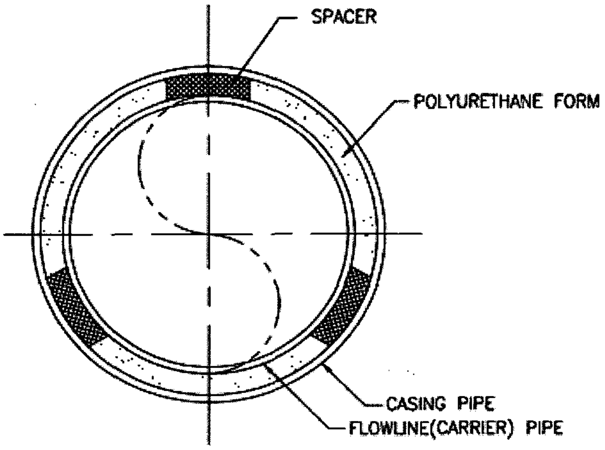

Fig. 1 Typical cross section of a pipe-in-pipe system

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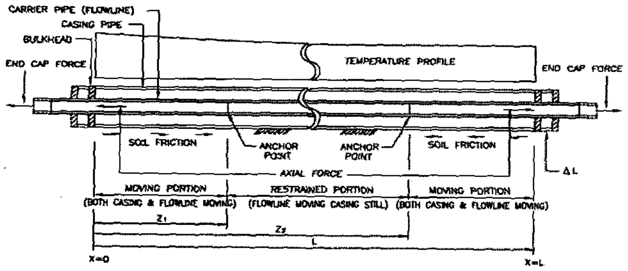

Fig. 2 Expansion mechanism of pipe-in-pipe system

3. Expansion Analysis

A typical configuration with expansion mechanism of the pipe-in-pipe system is presented in Fig.2.

3.1 Axial forces in the pipes

Axial force in the flowline pipe (F_f) 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, A_{ff} = Flowline flow area

P_o = External hydrostatic pressure

A_f = Flowline pipe steel section area

Axial force in casing pipe (F_c) is due to internal pressure (P_c), soil friction, and interaction force (Q) imparted by the flowline pipe:

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

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

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

where, A_{an} = Annular area

A_c = Casing pipe steel section area

μ = Soil friction coefficient

W_{sub} = Pipeline submerged weight/unit length

x = Pipeline length

L = Total pipeline length

3.2 Strain and expansions in the pipes

Pipe strain in the flowline pipe is:

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

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

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

where, E = Young's modulus of pipe steel

ν = Poisson's ratio of pipe steel

σ_f = Hoop stress in flowline pipe

α = Thermal expansion coefficient of steel

ΔT = Temperature change in flowline

Then, the expansion in the flowline pipe is:

$$\Delta L_f = \frac{1}{EA_f} \cdot \left(F_{pfc} + F_{tf} - Q\right) \cdot L \tag{9}$$

Pipe strain in the casing pipe is:

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

In region 1, the equation (10) becomes:

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

where, $F_{c1e} = F_{pc} - A_c \cdot \nu \cdot \sigma_c + Q$ (12)

$$Z_1 = \frac{F_{c1e}}{\mu \cdot W_{sub}} \quad \text{(Anchor point)} \tag{13}$$

In region 2, the equation (10) becomes:

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

where, $F_{c2e} = F_{pc} - A_c \cdot \nu \cdot \sigma_c + Q - \mu \cdot W_{sub} \cdot L$ (15)

$$Z_2 = -\frac{F_{c2e}}{\mu \cdot W_{sub}} \quad \text{(Anchor point)} \tag{16}$$

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

$$\Delta L_{c1} = \int_0^{Z_1} \varepsilon_{c1} \cdot dx = \int_0^{Z_1} \frac{1}{E \cdot A_c} (F_{c1e} + F_\mu) dx \tag{17}$$

Pipe expansion in casing pipe in region 2 is:

$$\Delta L_{c2} = \int_{Z_2}^{L} \varepsilon_{c2} \cdot dx = \int_{Z_2}^{L} \frac{1}{E \cdot A_c}(F_{c2e} - F_{\mu})dx \qquad (18)$$

Total expansion of the casing pipeline is:

$$\Delta L_c = \Delta L_{c1} + \Delta L_{c2} \qquad (19)$$

3.3 Interaction force between the pipes

Interaction force (Q) can be obtained from:

$$\Delta L_f = \Delta L_c \qquad (20)$$

$$(\varepsilon_{tf} + \varepsilon_{pf} + \varepsilon_{cf}) \cdot \frac{L_f}{2} - \frac{Q \cdot \frac{L_f}{2}}{A_f \cdot E} = (\varepsilon_{pc} + \varepsilon_{cc}) \cdot L_{anch} + \frac{Q \cdot L_{anch}}{A_c \cdot E} \qquad (21)$$

where, $L_{anch} = \dfrac{A_c \cdot E(\varepsilon_{pc} + \varepsilon_{cc} + \frac{Q}{A_c \cdot E})}{Fr_c}$ (22)

$$\varepsilon_{pc} = -\frac{\nu \cdot OD_c \cdot \Delta P_c}{2 \cdot t_c \cdot E} \qquad (23)$$

$$\varepsilon_{cc} = \frac{1}{A_c \cdot E}(P_c \cdot A_{an} - P_o \cdot \frac{\pi \cdot {OD_c}^2}{4}) \qquad (24)$$

3.4 Calculation and discussion

An example calculation was performed based on the following a pipe-in-pipe system.

1) Flowline pipe:

Outside diameter, OD_f = 24 in

Wall thickness, t_f = 0.374 in

Design (inlet) temperature (at LAT), T_f = 85°C

Content density, $\rho_{content}$ = 900 kg/m^3

Internal pressure (at LAT), P_{in} = 46.2 barg (670 psi)

2) Casing pipe:

Outside diameter, OD_c = 28 in

Wall thickness, t_c = 0.5 in WT

Design temperature, $T_c = T_o$ = 16°C (Seawater temp.)

Internal pressure, P_c = 0 barg

Concrete coating thickness, t_{conc} = 35 mm

Concrete coating density, ρ_{conc} = 3040 kg/m^3

3) Other data:

API 5L X-52, *SMYS* = 359 N/mm^2

Young's modulus, E = 207000 MPa (N/mm^2)

Poisson coefficient, ν = 0.3

Steel density, ρ_{steel} = 7850 kg/m^3

Thermal coefficient, α = 11.7 x 10-6 /°C

Insulation form thickness, t_{form} = 1.5 in

Effective insulation form density, ρ_{form} = 96.1 kg/m^3

Total length of pipeline, $L_f = L_c$ = 17400 m

Seabed soil density, ρ_{soil} = 5000 kg/m^3

Soil friction coefficient, μ_{soil} = 0.5

4) Result of calculation:

Q = 3.259 x 106 kg·m/sec^2 (Interaction Force)

L_{anch} = 959.615 m (Anchor Length)

$\Delta L_f = \Delta L_c$ = 532.256 mm

3.5 Review of effective factors in PIP expansion

Figure 3 depicts pipe expansion at the pipeline end manifold (PLEM) and the effect of the temperature variation at constant operation pressure of 670 psi. As the temperature increases, the expansion at the PLEM increases significantly.

Figure 4 presents the pipe expansion at the PLEM and the effect of pressure variation at constant operation temperature difference of 69°C. The variation of the expansion lengths are not very sensitive to the pressure variation.

Figure 5 shows the pipe expansion at the PLEM and the effect of the soil friction variation at the constant operation pressure of 670 psi and temperature difference of 69°C. The soil friction coefficient yields almost linear variation of the end force, when it is greater than 0.3 for the given PIP system.

4. Mechanical Design

The pipe-in-pipe system, i.e., the flowline pipe and the casing pipe have mechanical connections through the water stops and the bulkheads. The former is evenly distributed along the pipeline and the latter will be located at both ends of the pipeline.

The finite element (FE) analysis program ANSYS 9.0 has

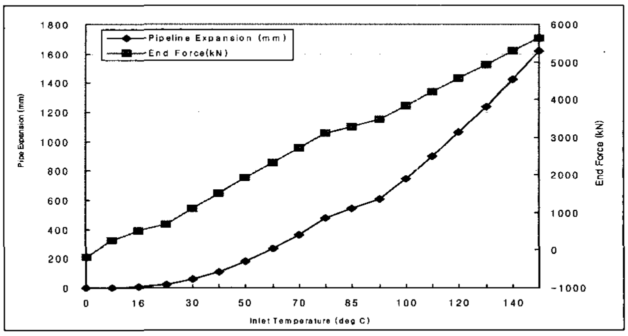

Fig. 3 Effect of temperature at constant *P*=670 psi

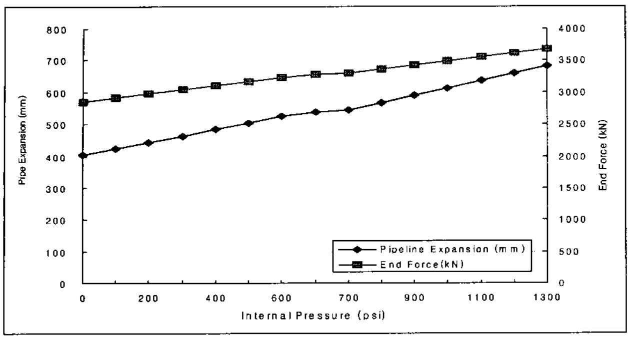

Fig. 4 Effect of pressure at constant $\Delta T = 69°C$

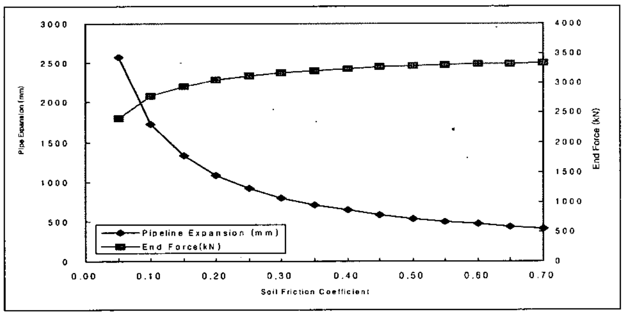

Fig. 5 Effect of soil friction coefficient

been used in the analysis of the bulkheads and water stops. Dimensions were established and a detailed FE analysis was conducted to capture local stresses within the bulkhead and water stop under the design loads.

4.1 General assumptions and input data

General assumption:

- The actual solid model FE analysis assumes perfect joint alignment between the pipes.
- The maximum operational pressure and temperature have been used.
- The flow line and the bulkhead pipe are assumed to be fully corroded.

Mechanical data for the flowline pipe and the casing pipe are the same with Sec. 3.4 except the following:

1) Bulkhead pipe:

Outside diameter, $OD_f = 24$ in

Wall thickness, $t_f = 0.5$ in

$t_f = 0.374$ in (Fully corroded condition)

Material grade, $SMYS = 359$ N/mm^2 (API 5L X-52)

2) Bulkhead plate:

ASTM A572 Gr.50, Plate 9mm, $SMYS = 345$ N/mm^2

3) Water stop plate:

ASTM A572 Gr.50, Plate 6mm, $SMYS = 345$ N/mm^2

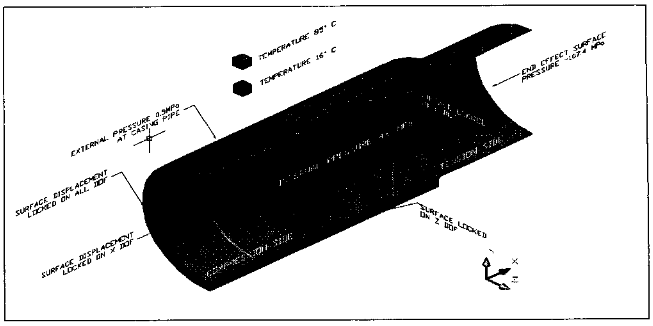

Fig. 6 Bulkhead model and loading

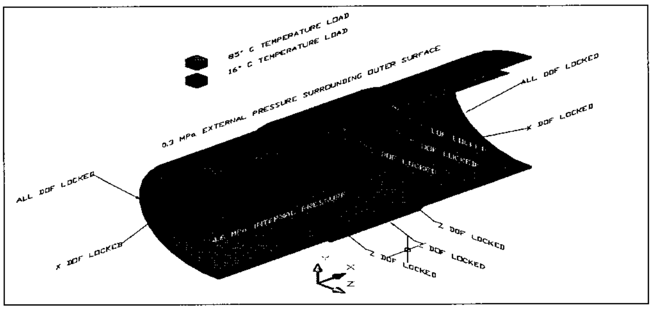

Fig. 7 Water stop model and loading

4.2 Model and loading conditions

The models and applied loads considered in the analyses are presented in Fig. 6 for the bulkheads and Fig. 7 for the water stops.

The structural loads imposed upon the bulkhead / water stop due to thermal expansion when operating at maximum pressure and temperature are considered in the analysis.

The bulkhead and water stop geometry and dimensions have been established on the following considerations:

- Adequate plate thickness, especially nib to flange thickness for end bulkheads
- Avoidance of high stress concentrations at transitions by using appropriate fillets instead of sharp corners.

4.3 Result of analysis

Some standard checks have been performed to confirm that the model is responding correctly to the applied loadings and boundary conditions.

- The full set of boundary conditions is visually examined to confirm them prior to analysis.
- The displaced shapes have been visually examined to confirm that the structure displaces in a justifiable manner
- The stress contour plots have been examined to identify discontinuities, or any irregular flow, of the stress contour
- The averaged stresses will be plotted for the selected range of elements being considered.

Tables 1 and 2 summarize the calculated stresses (von

Mises equivalent) for the various components of the bulkhead and water stop. Figures 8 and 9 present the distributed maximum von Mises equivalent stresses. The final dimensions of the bulkheads and water stops are optimally selected so that calculated stresses are below the allowable stresses specified in the design codes.

The bulkhead is composed of the two ring plates and connected plates. This bulkhead is very simple to fabricate and very effective to share the interaction forces between the inner pipe and outside pipe. It has a unique shape compared to the other existing bulkheads.

5. Integrated Expansion Design

The spool piece (expansion loop) method is probably the most popular method of subsea tie-in for pipeline and next platform. The connection can be made by either flanges or welding.

From the design point of view, should there be large expansion of pipeline, then this can also be accommodated by incorporating a dog leg in the spool. This will permit expansion of the pipe without transmitting high loads into the adjacent pipe and/or platform.

5.1 Expansion loop model and input data

The pipeline expansion loop is modeled using AutoPIPE

Table 1 Summary of bulkhead stress

Component	Max. equivalent von Mises stress	Allowable stress	Unity check
	(MPa)		
Casing pipe	227.2	323.1	0.70
Flowline pipe	225.2	323.1	0.70
Bulkhead	249.9	310.5	0.80
Stiffener plate	218.0	310.5	0.70
Wing plate	257.2	310.5	0.83
Bulkhead pipe	210.7	323.1	0.65

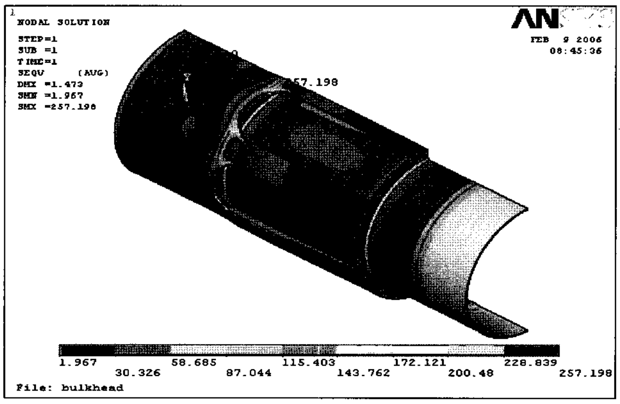

Fig. 8 Max. von Mises equivalent stress - bulkhead

Table 2 Summary of water stop stress

Component	Max. equivalent von Mises stress	Allowable stress	Unity check
	(MPa)		
Flowline pipe	317.3	323.1	0.98
Water stop	257.2	310.5	0.83
Casing pipe	203.2	323.1	0.63
Pipe sleeve	174.4	323.1	0.54

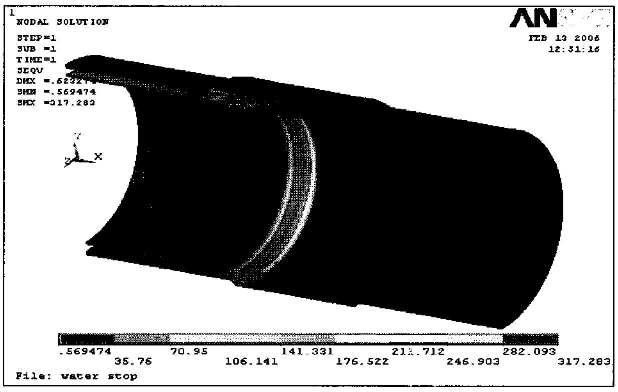

Fig. 9 Max. von Mises equivalent stress - water stop

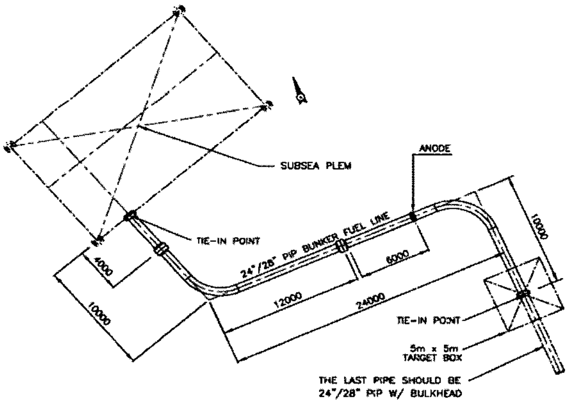

Fig. 10 Tie-in spool (expansion loop) detail

Table 3 Summary of maximum stress allowable checks

Load	Stress category	Stress (MPa)	Allowable (MPa)	Unity check	Node no.
	Stress criteria				
Operation	Longitudinal	250	287.2	0.87	A67
Operation	Equivalent	244	323.1	0.76	A67
Hydrotest	Longitudinal	146	287.2	0.51	A55
Hydrotest	Equivalent	216	344.64	0.63	A55

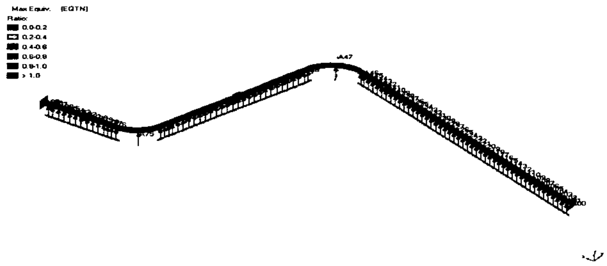

Fig. 11 Max. equivalent stress profile

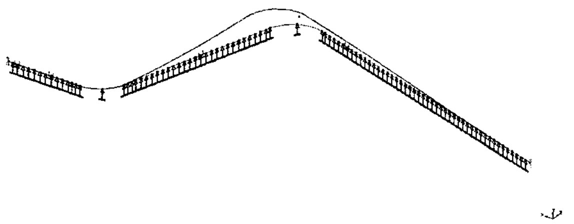

Fig. 12 Tie-in spool displacement profile

Version 6.2, a FE analysis program for the evaluation of the loadings on the pipeline system as presented in Fig. 10.

The PIP loop geometry has been taken from the below and model as a single pipe with equivalent steel density and stiffness to represents the PIP system. The model does not include PLEM piping and equipment to eliminate any imposed loads from PLEM. It is assumed that the anchor position is 1 meter from the interface flange of PLEM.

Static stress analyses were carried out for the hydrostatic and operation conditions.

Basic data and mechanical data for the flowline pipe and the casing pipe are the same as in section 3.4. The calculated thermal displacement due to the expansion of the pipeline has been considered in the model.

5.2 Result of analysis

Table 3 summarizes the calculated stresses for the different operation modes. The final dimensions of the tie-in system was optimally selected so that calculated stresses are below the allowable longitudinal and equivalent (von Mises) stresses. Figure 11 shows the maximum equivalent stress distribution along the tie-in spool system and adjacent pipes. Figure 12 shows the displaced profile of the tie-in system under the design condition specified in section 3.4 The displacement of the tie-in spool is the main major portion of the absorption of the pipeline expansion.

6. Conclusions

(1) A simple analytical method was developed to estimate the expansion length of a pipe-in-pipe system which can be applied to the design of subsea pipeline tie-in systems.

(2) Pipe-in-pipe systems yield less longitudinal expansion when compared to single wall pipe systems.

(3) The effect of high temperature on the expansion is more significant than the effect of high pressure.

(4) Once the expansion is obtained, an optimum design of mechanical connection (bulkhead/waterstop) can be done through FE analysis.

(5) Once the expansion analysis and the mechanical connection design is obtained, the optimum dimension of the tie-in spool can be determined.

(6) A complete procedure of an integrated expansion analysis was established.

Acknowledgements

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