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THERMAL MANAGEMENT OF FLOW ASSURANCE CHALLENGES IN OFFSHORE FIELDS-A REVIEW

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ABSTRACT

Hydrocarbon transport system in oil and gas industry faces major challenges of flow blockage resulting from hydrates formation and wax depositions. To ensure efficient and economical hydrocarbons transport from wellhead to processing facilities, flow assurance is important in planning and designing of flow transport system. Flow assurance challenges in offshores increase with water-depth because of the surrounding low temperature. Flow assurance thermal management techniques include insulation, pipe burial, electrical heating, and hot fluid circulation. A survey on thermal management techniques employed in oil and gas industry with their various comparative advantages and disadvantages focused on achieving economic pipeline design was conducted. The review showed that the most cost effective method of thermal management technique is pipeline burial and thermal insulation but less effective down deepwater. Electrical heating is effective at all length and at various ambient conditions but expensive. Hot fluid circulation is economical and maintenance friendly with less technical risk but less effective when compared with electrical heating.

Keywords: thermal management, flow assurance, insulation, passive heating, active heating, heat retention.

INTRODUCTION

Flow assurance studies play a significant role in the identification, quantification, prevention/mitigation of severe fluid flow issues in oil production/transportation systems in the offshore oil and gas industry. Flow assurance is a major technical challenge which results due to the appearance of wax and formation of hydrates at temperatures below the wax appearance temperature and hydrate formation temperature in flowlines, respectively. In some cases, asphaltene precipitate are formed in heavy crude oil and deposited on the pipe wall, thus restricting the flow. Flow assurance techniques are designed to optimize oil recovery and enhance oil production from wells over the full range of the oil field's life. It is a key factor in the developmental planning of any exploration site (Esaklul *et al.* 2003). Several techniques are available for flow assurance in the oil and gas industries which include chemical inhibitors, thermal management and thermo-chemical management. The chemical inhibitors may be in the form of hydrate inhibitors employed in the control of hydrate formation or pour-point-depressants used for wax deposition control. For long flowlines, the economics and viability of chemical inhibitors becomes questionable (Thant and Maung, 2012), (Thant *et al.* 2011). The use of chemical inhibitors alone has been reported by PETROBRAS to be of unfavorable in terms of cost-benefit (Rocha *et al.* 2009), (Cardoso *et al.* 2003), (Marques *et al.* 2003), (Minami *et al.* 1999), (Khalil *et al.* 1994). Thermal management is an alternative solution to chemical injection in the management of hydrate formation and wax appearance. Thermal management is a technique of heat containment in a flowline to control the temperature of the flowing hydrocarbons. Thermal management system comprises of thermal insulation and active heating. Thermal insulation uses materials with relatively low thermal conductivity to reduce heat loss from flowing hydrocarbon to the surrounding while active heating is the addition of heat from external source to the flowline and the flowing fluid. To sustain the heat in flowing fluid and control heat loss from the flowing fluid in pipeline, thermal insulation is the commonly employed technique (Goodlad, 2013), (Dixon, 2013), (Wang *et al.* 2009), (Rubel *et al.* 1994).

From the survey of Thant et al. (2011), comparison of flow assurance mitigation techniques using active heating inferred that a combination of two or more thermal management techniques are used to effectively manage wax deposition and hydrate formation. Therefore, this paper reviews thermal management techniques of flow assurance, identifies the challenges and recommends suitable combination of the cost effective techniques.

THERMAL MANAGEMENT SYSTEM

Thermal management technique of flow assurance is heat containment method of maintaining the temperature of the hydrocarbon flowing through flowline at a temperature above wax appearance and hydrate formation temperatures. In flowline designs thermal management is considered very important in flow assurance development because of its cost-effectiveness, however with some technical limitations. Thermal management techniques can be classified into passive mechanism and active mechanism.

PASSIVE MECHANISM

The passive mechanism of thermal management is the insulation of flowlines with materials of low thermal conductivity such as polyurethane, polyurethane foam (Hansen, 1999), rockwool, rubber, glass reinforced plastic and silica sphere slurries (Nelson *et al.* 1993) to minimize and control heat loss from production fluid to the surrounding. Some of the insulation methods include wet and dry insulations, pipeline burial, pipe-in-pipe, vacuum insulated pipe, thin film insulation, and hybrid riser tower.

Wet insulation systems employ materials such as polyurethane, polypropylene, rubber or glass reinforced plastic which have low heat transfer coefficients (U-values) of approximately 2 W/m2K (Lee, 2002). On the other hand, materials for dry insulations include polyurethane foam and rockwool which have U-value of approximately 1 W/m2K (Lee, 2002) and are mostly employed for shallow water and onshore flowline insulations. Insulation reduces the heat loss from the flowline to the ambient. When a flowline is insulated to an optimum insulation thickness, the technique is of lower cost compared to other flow assurance techniques but the increase in the thickness of the insulation incurs higher cost while contact with water deteriorates the performance of the dry insulation (Thant *et al.* 2011), (Hansen and Delesalle, 2000), (Woodyard, 1978). Going deep down the sea, buoyancy effects limit the overall insulation thickness for flowlines. Following the setbacks of the use of insulation as thermal management techniques in the offshore flowlines, Pipe-In-Pipe (PiP) system was introduced to prevent water ingress to the insulation layer and to give better insulation performance. The main features of a PiP system are a concentric insulated inner flowline and a protective outer pipe (Sriskandarajah, 2000), (Inglis *et al.* 1996), (Bokaian, 2004), (Harrison *et al.* 1997). Between the inner pipe and the protective outer pipe is an annular space for insulation of the inner pipe to avoid thermal losses from the flowing fluid (Tough *et al.* 2001). A PiP system can be designed with the inclusion of partial vacuum in the insulation to reduce the U-value to about 0.5 W/m2K (Lee, 2002), (Easton and Sathananthan, 2002), thus making the system more effective for fluid flow heat containment.

The PiP systems have gained popularity in flow assurance for offshore transport of oil/gas, hence designs, operations, and thermal studies were reported by various researchers (Harrison *et al.* 1997), (Tough *et al.* 2001), (Easton and Sathananthan, 2002), (Mollison, 1991), (Suman and Karpathy, 1993), (Guijt, 1999), (Fyrileiv and Venås, 1998), (Ghoi, 1995), (Eigbe *et al.* 2006). PiP flowlines can be installed either in conventional lay barge or by reeling operations (Tough *et al.* 2001), (Mollison, 1991). The thermal expansion of PiP flowlines has been investigated analytically and numerically by various researchers (Harrison *et al.* 1997), (Suman and Karpathy, 1993), (Guijt, 1999), (Fyrileiv and Venås, 1998). The effects of thermal gradients and restraining forces in pipeline was studied by Han (Ghoi, 1995) with focus on providing accurate pipeline design criteria. (O'Grady *et al.* 2008) developed an engineering tool for the prediction of installation response of pipe-in-pipe systems in offshore. Remedial and operational repairs in PiP was presented by (Jukes *et al.* 2008), (Eigbe et al. 2006), (Gilchrist, 2001). The cost of designing a PiP flowline was estimated to be about 1.27 ±25% the cost of single insulated pipeline of same materials and insulation thickness (C-Core, 2000).

In the quest to improve heat retention, Vacuum insulated Tubing (VIT) was introduced. VIT is an improved design of PiP system with thin annulus maintained at vacuum condition to reduce heat transfer from the fluid to the ambient (Feeney, 1997). VIT is characterized by low heat transfer coefficient of 0.008 to 0.36 W/m2K (Feeney, 1997), (Bunton, 1999). In the Gulf of Mexico deepwater fields, VITs were successfully used to prevent wax deposition and hydrate plugging and handle annular pressure buildup during crude transport process (Bunton, 1999), (Azzola *et al.* 2007). VITs were also used to manage flow assurance challenges in Norman Well fields (Purdy *et al.* 1991) and Alaska (Singh *et al.* 2007), (Singh *et al.* 2006), (Feeney, 1999). VITs have no specific insulation value (U-value) rather the insulation losses are associated to the boundary conditions such as coupling insulation and the surrounding thermal conditions (Azzola *et al.* 2004). Vacuum insulated tubing is considered expensive when compared to other thermal insulation methods of flow assurance (Wang *et al.* 2009), (Feeney, 1997), (Purdy *et al.* 1991), (Davalath and Barker, 1995) but may be of advantage in places where the cloud point temperature of the crude is high such as Gulf of Mexico (Bunton, 1999).

Pipelines burial is one of the most cost effective thermal management techniques in flow assurance (Lee, 2002) which finds applications in both onshore and shallow water sites. It is a form of thermal insulation where the pipelines are buried in excavated trench in the soil, backfill trench or have rocks dumped over them below the mudline. In offshore, pipeline burial depends on the pressure, viscosity and temperature characteristic of the site, soil properties, topography geohazards and infrastructures (Thant *et al.* 2011). The rationale for pipeline burial is on the advantage of utilization of the good heat capacity of the soil as both heat storage and heat sink. Heat capacity of insulated buried pipelines can be higher than a PiP while the cost of an insulated and buried pipeline is approximately between 35-50 % that of a PiP system (Bai and Bai, 2012), (Bai and Bai, 2005). Buried pipelines has as much as four times longer heat retention than PiP system during the shutdown period before gelling process of wax and hydrates occur (Thant *et al.* 2011). Some analytical and numerical models of the thermal process in partially and fully buried pipelines have been developed (Zakarian *et al.* 2012), (Ovuworie, 2010), (Morud and Simonsen, 2007), (King *et al.* 2011). (Oh *et al.* 2014) conducted laboratory experiments to validate some of the analytical and numerical models.

ACTIVE HEATING

The active heating mechanism is a thermal heating process where external heat is added to the flowline/production fluid through circulated hot fluid or electrical heat source (Fleyfel *et al.* 2004). It is an effective and economical solution for flowline thermal management systems especially in deep water fields where flowlines (subsea tieback field concept) and riser lengths are such as to span large temperature and pressure differences (Thant and Maung, 2012), (Thant *et al.* 2011), (Chin and Bomba, 1999), (Chin and Kvaerner, 2003). Active heating of flowlines are employed for warming up

the flowline and to maintain or increase temperature for a flowing fluid, thus keep hydrocarbons temperature above the wax and hydrates formation temperatures over longer distances compared to a passively insulated pipeline. The use of active heating reduce dependence on flowline pigging for wax deposition control (Esaklul *et al.* 2003).

Electrical heating is one of the effective heat containment flow assurance techniques for long flowline systems (Lervik *et al.* 1998), (Lenes *et al.* 2005), (Von Flatern, 2001). It can be employed to flowlines to compensate for the heat loss to the surrounding in the course of fluid flow or to heat up flowline and dissolve plugs when flow lines were allowed to cool below desirable temperature or when plugs obstructs the flow pipe (Mares, 1959). It has been successfully applied in Statoil Asgard in the North Sea (Helland *et al.* 2001), (Dretvik and Bornes, 2001), (Knudsen *et al.* 2001) and in DeepStar in the Gulf of Mexico (Hansen, 1999).

The hot fluid circulation method is a flow assurance technique where the hydrocarbon is heated by convection and conduction from hot water or another suitable fluid which is circulated in a relatively small heating pipe in a tube bundle. The hot fluid is generated at the subsea wellhead or by a heater situated above-surface processing facility. The use of hot fluid circulation has found application in Statoil's Gullfak and ConocoPhillips' Britannia fields (both in the North Sea) and BP's King in Gulf of Mexico (Fleyfel *et al.* 2004) . A hot water heated bundle of 15 km subsea Britannia project, UK North Sea, design and implementation was reported by (Brown *et al.* 1999) and the operation kept transported fluid above its hydrate formation temperature. (Zhang *et al.* 2002) analyzed the factors affecting performance of hot fluid active heating pipeline system and reported that hot fluid flow rate, hot fluid temperature, pressure, and heat generation system capacity must be properly determined with respect to transport flowline length and the surrounding condition for the pipeline to meet the expected performance. The authors reported that direct and indirect hot fluid heating are effective but direct hot fluid heating has more efficient heat exchange between the heating fluid and the heated fluids than indirect hot fluid heating. On the heat loss, it was reported that indirect heating loses less heat to the ambient than the direct heating. On cost relationship, the indirect heating bundle is smaller than the direct heating bundle in size, thereby lower in cost of manufacture. The indirect active heating technique was also reported to have more flexibility for modification, maintenance and repairs than the direct heating system. (Rouillon, 2002) presented the report on the installation of production bundle in West Africa, which has stringent operating requirements for flexibility with the length of the production bundles varies from 700 m to 3000 m and showed that indirect heating system was suitable for the required flexibility. (Esaklul *et al.* 2003) describes the flow assurance challenges encountered in the development of a multi-well of about 27 km transport bundle length and how a 30 wt % aqueous ethylene glycol solution as heating fluid was used to solve problem of wax deposition. The report concluded that indirect active heating using hot fluid is more cost effective for long distance transport but requires exterior insulations using PiP. (Fleyfel *et al.* 2004) evaluated the cost effectiveness of conventional PIP insulation, non-jacketed insulated pipeline and two configurations of hot fluid active heating options for the transportation of waxy crude oil for 16.1 km pipeline at offshore Africa. They reported that the non-jacketed pipe option is not thermally efficient while the PiP insulation can keep the crude oil warm during normal flow but at low temperature, it could not meet the expected temperature requirement for waxy crude. It was reported that the bundled pipeline configurations maintain the crude oil temperature above the WAT thus avoiding waxing and gelling during both steady state flow and restart operations.

Secher *et al.* (2002) describe an Integrated Production Bundle (IPB), which is an integration of the hot fluid active system with electrical heating technology. They concluded that both electrical and hot fluid active heating approaches have advantages where the hot water circulation is considered cheapest, followed by the integrated electrical and hot fluid circulation system while the electrical system was the most expensive but any selection between them would depend on the specific circumstances.

COMPARISON OF FLOW ASSURANCE TECHNIQUES

Based on the various thermal management methods currently practiced in the oil and gas industry, a comparison of their effectiveness, cost and flexibility is presented in Table-1.

CONCLUSIONS

Proper flow assurance strategy is important in the planning and development of any exploration site for the management and mitigation of hydrate formation and wax deposition in the production fluid transport system. A good flow assurance strategy will prevent flowline restriction which may result from solid depositions, reduce downtime during operation and prevent product loss and the related economic loss and environmental degradation.

This study reviewed the current thermal management operation techniques for flow assurance challenges mitigations. It highlighted the different techniques applicability and limitations. In the review, pipeline burial was found to be most cost effective with good heat retention capacity but limited to shallow waters. Conventional insulation process was also found to have good thermal retention capability but when employed for offshore under high pressure might get soaked and lose the proper insulation quality leading to excessive heat loss from the flowline. The PiP system and the VIT-PiP system are effective in heat retention, control of leakage to the surrounding and pressure management but of higher cost compare to conventional insulation. The passive thermal management techniques are not suitable for long distance waxy crude transport in low temperature surrounding and

will require other supporting flow assurance techniques to effectively transport the crude with low down time.

Table-1. Comparison of thermal management methods with their effectiveness, cost and flexibility.

Technique	Effectiveness	Technical/Cost Limitations
Conventional Insulation	➢ Simple construction ➢ Low construction costs ➢ Low life cycle costs ➢ Higher inspection reliability	➢ May not be able to maintain the product temperature above wax appearance temperature for long pipeline. ➢ When there is product leak, it leaks into the environment
PiP Insulation	➢ It has operation and maintenance flexibility ➢ Proper containment of a product from leaking ➢ Environmental safety due to containment of oil in the event of an inner pipe failure ➢ Easy monitoring of the annulus for evidence of a leak or pipe degradation ➢ The failure probability or leak in both pipes at the same time is very low ➢ Lower risk of product release to the environment than a single wall pipe	➢ The design and construction is more complex than insulated single wall pipe. ➢ It has monitoring difficulties associated with spacers and bulkheads or shear rings. ➢ Limited capability to inspect and monitor the condition of the outer protective pipe ➢ Repair costs of PiP for a total containment failure would be about 25% higher than similar case of insulated single wall pipe ➢ The VIT-PiP is expensive and not suitable where other PiP can be used as a replacement
Pipeline Burial	➢ High heat containment period ➢ Simple construction and laying ➢ Low construction costs ➢ Low life cycle costs	➢ When there is product leak, the products leaks into the environment and cause degradation ➢ When wax is formed, external heat or chemical inhibitors are required.
Electrical Heating	➢ Melting and dispersing the solid particles instantaneously ➢ Maintain flowline temperature at desirable operating temperature ➢ Control spillage when insulated with PiP ➢ Less downtime in relation to flow blockage	➢ Required extensive facility and not cost effective
Hot Fluid Heating	➢ Melting and dispersing the solid particles instantaneously ➢ Maintain flowline temperature at desirable operating temperature ➢ Control spillage as the production pipe is completely isolated from the surrounding ➢ Cost of heating the heat transport fluid is cheaper than the cost of using electrical heating	➢ Limited to the temperature of the heating fluid. ➢ May not be able to dissolve the deposit effectively due to limitation of maximum temperature requirement at the location of interest. ➢ Required extensive facility and is more expensive when compared to insulation and pipe burial

Active heating methods on their own without the support of the passive technique – insulation will be impracticable because of the excessive heat loss that the system will be prone to. Considering the two forms of active heating, it was shown that hot fluid circulation is more cost effective compared to electrical heating. For the hot water circulation, indirect heating is more cost effective compared to direct water circulation while the indirect heating method is less effective because the heat transfer mode between the dedicated heating tube and the production pipes is by convective heat transfer but for the direct, the heat fluid has direct contact with the production pipe which transports the products, thus higher heat transfer effect.

A combination of two or more thermal management techniques was found to be common in the management of flow assurance challenges in the industry. It was found that flow assurance technique is site sensitive and production fluid characteristics will determine the thermal requirement.

With thermal management techniques, the uses of conventional chemical injection of hydrate inhibitors such as glycol and pour point depressant can be avoided. For high performance, high efficiency and operational

flexibility, active heating is most practicable, economical and viable solution compared to passive techniques in the management of various flow assurance challenges in offshore fields. Following the above comparison, it can be inferred that hot fluid active heating with PiP insulated outer wall is most cost effective combination of thermal management techniques.

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REFERENCES

[1] Azzola, J.H., Pattillo, P.D., Richey, J.F., Segreto, S.J. (2004). The Heat Transfer Characteristics of Vacuum Insulated Tubing. In Proc. of the SPE Annual Technical Conference and Exhibition; Houston, Texas. SPE:90151 pp.1-8. doi: http://dx.doi.org/10.2118/90151-MS

[2] Azzola, J., Tselepidakis, D., Pattillo, P.D., Richey, J.F., Tinker, S.J., Miller, R.A. (2007). Application of Vacuum Insulated Tubing to Mitigate Annular Pressure Buildup. SPE Drilling & Completion, 22(01):pp.46-51. doi: http://dx.doi.org/10.2118/90232-PA

[3] Bai, Y., Bai, Q. (2012). Subsea Engineering Handbook: Gulf Professional Publishing.

[4] Bai, Y., Bai, Q. (2005). Subsea pipelines and risers: Elsevier Science.

[5] Bokaian, A. (2004). Thermal expansion of pipe-in-pipe systems. Marine Structures. 17(6): pp.475-500.

[6] Brown, L.D., Clapham, J., Belmear, C., Harris, R., Loudon, A., Maxwell, S. (1999). Design of Britannia's Subsea Heated Bundle for a 25 Year Service Life. In Proc. of the Offshore Technology Conference; Houston, Texas. OTC:11017 pp.1-17. doi: http://dx.doi.org/10.4043/11017-MS

[7] Bunton, M.A. (1999). Vacuum Jacketed Tubing: Past, Present, and Future. In Proc. of the SPE Western Regional Meeting; Anchorage, Alaska. SPE: 55994 pp.1-8. doi: http://dx.doi.org/10.2118/55994-MS

[8] Cardoso, C.B., Alves, I.N., Ribeiro, G.S. (2003). Management of Flow Assurance Constraints. In proc. of the Offshore Technology Conference, Houston, Texas. OTC: 15222 pp.1-9.doi: http://dx.doi.org/10.4043/15222-MS

[9] C-CORE, (2000). An Engineering Assessment of Double Wall Versus Single Wall Designs for Offshore Pipelines in an Arctic Environment. USA: Final Report for Minerals Management Service, US Dept. of Interior.

[10] Chin, Y.D., Bomba, J.G. (1999). Structural and Thermal Optimization of Cased Insulated Flowlines. In Proc. of the Offshore Technology Conference; Houston, Texas. OTC:11041 pp.1-9.doi: http://dx.doi.org/10.4043/11042-MS

[11] Chin, Y.D., Kvaerner, A. (2004). Cool-Down-Temperature Overshoot Phenomenon in Subsea Flowline and Riser Systems. In proc. of the Offshore Technology Conference; Houston, Texas. OTC:15253 pp.1-11. doi: http://dx.doi.org/10.4043/15253-MS

[12] Davalath, J., Barker, J.W. (1995). Hydrate Inhibition Design for Deepwater Completions. SPE Drilling & Completion.10(02):pp.115-21. doi: http://dx.doi.org/10.2118/26532-PA

[13] Dixon, M. (2013). Pipe-in-Pipe: Thermal Management for Effective Flow Assurance. In Proc. of the Offshore Technology Conference, Houston, Texas. OTC:24122 pp.1-9. doi: http://dx.doi.org/10.4043/24122-MS

[14] Dretvik, S., Bornes, A.H. (2001). Direct Heated Flowlines In the Asgard Field. In Proc. of The Eleventh International Offshore and Polar Engineering Conference, Stavanger, Norway. pp.730-735.

[15] Easton, S., Sathananthan, R. (2002). Enhanced flow assurance by active heating within towed production systems. Offshore. 62(1):46.

[16] Eigbe, U., Fletcher, M., Hensley, M., Ling, D., Routh, C. (2006). Free-Span Remediation Studies for the K2 Pipe-In-Pipe Flowlines. In Proc. of the Offshore Technology Conference; Houston, Texas. OTC:18382 pp.1-12.doi: http://dx.doi.org/10.4043/18312-MS

[17] Esaklul, K.A., Fung, G., Harrison, G., Perego, R. (2003). Active Heating for Flow-Assurance Control in Deepwater Flowlines. In Proc. of the Offshore Technology Conference, Houston, Texas. OTC: 15188 pp.1-8. doi: http://dx.doi.org/10.4043/15188-MS

[18] Feeney, S. (1997). Flow assurance: Vacuum-Insulated Tubing for Subsea Completions. Journal of Petroleum Technology; 49(08):802-3.

[19] Feeney, S. (1999) Vacuum Insulated Tubing: Project Case Histories, Future Applications. Offshore. 59(10).

[20] Fleyfel, F., Hernandez, O., Sturgis, R., Meng, W. (2004). Evaluation of Pipeline Configurations with

Active Heating for Export of Waxy Crude Oil. In proc. of the SPE Annual Technical Conference and Exhibition, Houston, Texas. SPE: 90054 pp.1-6. doi: http://dx.doi.org/10.2118/90054-MS

[21] Fyrileiv, O., Venås, A. (1998). Finite element analysis of pipeline bundles on uneven seabed. In Proc. of the Eighth International Offshore and Polar Engineering Conference, Canada. pp. 46-52.

[22] Ghoi, H.S. (1995). Expansion Analysis of Offshore Pipelines Close to Restraints. In Proc. of the Fifth International Offshore and Polar Engineering Conference; The Hague, the Netherlands. pp. 81-88.

[23] Gilchrist, R. (2001). Repair of the Macaroni 10 x 6 in. Pipe-in-Pipe Flowline. In Proc. of the Offshore Technology Conference, Houston, Texas. OTC: 13015 pp.1-10. doi: http://dx.doi.org/10.4043/13015-MS

[24] Goodlad, M. (2013). Bundle Technology for the Future. In Proc. of the SPE Offshore Europe Oil and Gas Conference and Exhibition, Aberdeen, UK. SPE-166561-MS pp.1-21.

[25] Guijt, W. (1999). Design considerations of high-temperature pipelines. In Proc. of The Ninth International Offshore and Polar Engineering Conference, p.683.

[26] Hansen, A.B., Clasen, T.L., Bass, R.M. (1999). Direct Impedance Heating of Deepwater Flowlines. In Proc. of the Offshore Technology Conference, Houston, Texas. OTC: 11037 pp.1-11. doi: http://dx.doi.org/10.4043/11037-MS

[27] Harrison, G.E., Kershenbaum, N.Y., Choi, H.S. (1997). Expansion Analysis of Subsea Pipe-in-Pipe Flowline. In Proc. of the Seventh International Offshore and Polar Engineering Conference; Honolulu, Hawaii. pp.293-298.

[28] Hansen, A.B., Delesalle, A. (2000). Cost-Effective Thermal Insulation Systems for Deepwater West Africa in Combination with Direct Heating. In Proc. of the Offshore West Africa Conference, Abidjan, pp.1-8.

[29] Helland, A.I., Ohm, A., Johannessen, A. (2001). Åsgard Transport Pipeline -- Onshore Section. In Proc. of the Eleventh International Offshore and Polar Engineering Conference; Stavanger, Norway. p.26.

[30] Inglis, B., Morrison, A. (1996). Analysing pipe-in-pipe solutions for HP/HT conditions. In Proc. of the Offshore Pipelines Conference, London. pp. 1-32.

[31] Jukes, P., Wang, S., Wang, J. (2008). The Sequential Reeling and Lateral Buckling Simulation of Pipe-in-Pipe Flowlines Using Finite Element Analysis for Deepwater Applications. In Proc. of the Eighteenth International Offshore and Polar Engineering Conference; Vancouver, Canada. p.181.

[32] Khalil, C.N., Neumann, L.F., Linard, C.A., Santos, I.G. (1994). Thermochemical Process To Remove Paraffin Deposits In Subsea Production Lines. In Proc. of the Offshore Technology Conference, Houston, Texas. OTC: 7575 pp.573-79. doi:http://dx.doi.org/10.4043/7575-MS

[33] King, T., Phillips, R., Johansen, C. (2011). Pipeline Routing and Burial Depth Analysis Using GIS Software. In Proc. of the Arctic Technology Conference, Houston, Texas, USA. OTC: 22085 pp.1-11. doi: http://dx.doi.org/10.4043/22085-MS

[34] Knudsen, B., Leite, B.A., Mjoen, S.A. (2001). Turret Operations in the North Sea: Experience from Norne and Asgard A. In Proc. of the Eleventh International Offshore and Polar Engineering Conference; Stavanger, Norway. pp.328-335.

[35] Lee, J. (2002). Design and Installation of Deepwater Petroleum Pipelines. In Proc. of the World Congress of Korean and Korean Ethnic Scientists and Engineers. Seoul, Korea.

[36] Lenes, A., Lervik, J.K., Kulbotten, H., Nysveen, A., Børnes, A.H. (2005). Hydrate Prevention on Long Pipelines by Direct Electrical Heating. In Proc. of the Fifteenth International Offshore and Polar Engineering Conference; Seoul, Korea. pp. 24-30.

[37] Lervik, J.K., Ahlbeck, M., Raphael, H., Lauvdal, T., Holen, P. (1998). Direct Electrical Heating of Pipelines As a Method of Preventing Hydrate And Wax Plugs. In Proc. of the Eighth International Offshore and Polar Engineering Conference; Montreal, Canada. pp. 1-7.

[38] Mares, C.F. (1959). Electrical Heating of Pipelines Carrying Viscous Products. In Proc. of 5th World Petroleum Congress; New York, USA.

[39] Marques, L.C.C., Pedroso, C.A., Paixão, L.C.A. (2003). New Flow Assurance Solutions to Work Out Hydrate and Paraffin Blockage Problems in Deepwaters. Offshore Technology Conference, Houston, Texas. OTC: 15190 pp.1-7. doi: http://dx.doi.org/10.4043/15190-MS

[40] Minami, K., Kurban, A.P.A., Khalil, C.N., Kuchpil, C. (1999). Ensuring Flow and Production in Deepwater Environments. In Proc. of Offshore Technology Conference, Houston, Texas. OTC: 110356 pp. 1-9. doi: http://dx.doi.org/10.4043/11035-

MS

[41] Mollison, M.I. (1991). Reel Installation of Pipe-in-Pipe Insulated Pipelines. American Society of Mechanical Engineers. pp. 137-44.

[42] Morud, J., Simonsen, A. (2007). Heat transfer from partially buried pipes. In Proc. of 16th Australasian Fluid Mechanics Conference, Gold Coast, Australia.

[43] Nelson, D.O., Wozniak, T., Colquhoun, R. (1993). New Thermal Insulations for CDTM Bundles: Foamed Polyurethane and Silica Sphere Slurries. In Proc. of the Offshore Technology Conference; Houston, Texas. OTC 7313 pp. 505-516.doi: http://dx.doi.org/10.4043/7313-MS

[44] Oh, D-W, Park, J.M., Lee, K.H., Zakarian, E., Lee, J. (2014). Effect of Buried Depth on Steady-State Heat-Transfer Characteristics for Pipeline-Flow Assurance. SPE Journal. 19(06) pp.1162-1168.

[45] Ovuworie, C. (2010). Steady-State Heat Transfer Models for Fully and Partially Buried Pipelines. In Proc. of the CPS/SPE International Oil and Gas Conference and Exhibition in China; Beijing, China. SPE: 13137 pp.1-27. doi: http://dx.doi.org/10.2118/131137-MS

[46] Purdy, I.L., Cheyne, A.J. (1991). Evaluation of Vacuum-Insulated Tubing for Paraffin Control at Norman Wells. In Proc. of the International Arctic Technology Conference; Anchorage, Alaska. SPE:22102 pp.387-392.doi: http://dx.doi.org/10.2118/22102-MS

[47] Rocha, N.O., Khalil, C.N., Leite, L.F., Goja, A.M. (2009). Thermochemical Process to Remove Sludge from Storage Tanks. SPE Projects, Facilities and Construction, pp. 97-102.

[48] Rouillon, J. (2002). Girassol - The Umbilicals and Flowlines - Presentation and challenges. In Proc. of the Offshore Technology Conference; Houston, Texas. OTC: 14171 pp.1-12. doi: http://dx.doi.org/10.4043/14171-MS

[49] Rubel, M.T., Broussard, D.H. (1994). Flowline Insulation Thermal Requirements for Deepwater Subsea Pipelines. In Proc. of the SPE 69th Annual Technical Conference and Exhibition, New Orleans, Louisiana. SPE: 28481 pp.193-201. doi: http://dx.doi.org/10.2118/28481-MS

[50] Secher, P., Felix, A., Secher, H. (2002). Thermal Performances of the Flexible Bundled Risers. In Proc. of the Offshore Technology Conference, Houston, Texas. OTC: 14322 pp.1-9. doi: http://dx.doi.org/10.4043/14322-MS

[51] Singh, P., Walker, J., Lee, H.S., Gharfeh, S., Thomason, B., Blumer, D. (2006). An Application of Vacuum Insulation Tubing (VIT) for Wax Control in an Arctic Environment. In Proc. of the Offshore Technology Conference; Houston, Texas. OTC: 18316 pp.1-10. doi: http://dx.doi.org/10.4043/18316-MS

[52] Singh, P., Walker, J.A., Lee, H.S., Gharfeh, S.G., Thomason, W., Blumer, D. (2007). An Application of Vacuum Insulation Tubing for Wax Control in an Arctic Environment. In Proc. of the SPE Drilling & Completion, 22(02):pp.127-136. doi: http://dx.doi.org/10.2118/111006-PA

[53] Sriskandarajah, T., Ragupathy, P., Anurudran, G. (2000). Challenges in the design of HP/HT pipelines. In Proc. of the 23rd Annual Offshore Pipeline Technology Conference, Oslo. pp. 1-33.

[54] Suman, J., Karpathy, S. (1993). Design method addresses subsea pipeline thermal stresses. Oil and Gas Journal, 91(35).

[55] Thant, M.M.M. (2012). Experimental investigation of natural convection heat transfer in bundle pipeline: Ph.D. Thesis, Imperial College London.

[56] Thant, M.M.M, Sallehud-Din, M.T.M., Hewitt. G., Hale, C., Quarini, J. (2011). Mitigating Flow Assurance Challenges in Deepwater Fields using Active Heating Methods. SPE Middle East Oil and Gas Show and Conference, Manama, Bahrain. SPE-140997 pp.1-10. doi: http://dx.doi.org/10.2118/140997-MS

[57] Tough, G., Denniel, S., Al Sharif, M., Hutchison, J., editors. (2001). Nile-Design and Qualification of Reeled Pipe in Pipe for Deepwater. In Proc. of the Offshore Technology Conference, Houston, Texas. OTC: 13257 pp.1-9. doi: http://dx.doi.org/10.4043/13257-MS

[58] Von Flatern, R. (2001). Serrano charged up for hydrates bartle. Offshore Engineer, 23.

[59] Wang, X., Qu, Q., Javora, P.H., Pearcy, R.G. (2009). New Trend in Oilfield Flow-Assurance Management: A Review of Thermal Insulating Fluids. SPE Production & Operations. 24(01): pp. 35-42.

[60] Woodyard, A.H. (1978). An Insulated Offshore Oil Pipeline for Deep Water. In Proc. of the 10th Annual Offshore Technology Conference; Houston, Texas. OTC: 3070 pp. 199-206. doi: http://dx.doi.org/10.4043/3070-MS

[61] Zakarian, E., Holbeach, J., Morgan, J.E.P. (2012). A Holistic Approach to Steady-State Heat Transfer from

Partially and Fully Buried Pipelines. In Proc. of the Offshore Technology Conference, Houston, Texas. OTC: 23033 pp.1-5. doi: http://dx.doi.org/10.4043/23033-MS

[62] Zhang, J.J., Chen, M.J., Wang, X., Chacko, J. (2002). Thermal Analysis and Design of Hot Water Heated Production Flowline Bundles. In Proc. of the Offshore Technology Conference; Houston, Texas. OTC: 14015 pp.1-11. doi: http://dx.doi.org/10.4043/14015-MS