A MULTI-OBJECTIVE OPTIMIZATION OF ACTIVE HEATING IN PIPE-IN-PIPE SYSTEMS WITH MULTIPLE INSULATING LAYERS

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Abstrat *Pipe-in-Pipe (PIP) systems received increasing interest during the past years, due to new applications in oil and natural gas production in deep water. This type of system is used in situations where there is a need to guarantee the flow for submarine production of oil and natural gas. In this work, a cross section of a PIP system was simulated taking into account one or two layers of insulators as well as several active electrical heaters. It was considered the most critical situation, where the flow was stopped for a long maintenance period. Thus, the objective was to maintain the oil above some critical temperature with the lowest operation and installation costs possible. The optimization task was conducted by using the Multi Objective Game Theory (MOGT), Multi Objective Simulated Annealing Algorithm (MOSA) and An Efficient Multi-Objetctive Genetic Algorith (ARMOGA) Methods provided by the modeFRONTIER® software, where the thicknesses of the insulating layer and the position and the intensity of the electrical resistances were optimized in order to minimize the operation and installation costs and to maximize the temperature of the oil, preventing gas hydrate formation and wax deposition. As a final result, the Pareto frontier for all non-dominated solutions is presented, where the final decision can be made considering the appropriate scenarios.*

Keywords: *Multi-Objective Optimization, Pipe-in-Pipe, Active heating*

1. INTRODUCTION

Active heating in ducts for oil and gas production has been intensively studied over the past years, mainly due to the increasing production of such products in deep water. The main technological issue related to the extraction of oil and gas in deep water is related to the hydrate and paraffin formation inside the pipelines. Paraffin is commonly present in the vast majority of crude oils and, depending on its characteristics, may capture water, sand or oil, creating deposits that obstruct the pipeline (Creek *et al*., 1999). On the other hand, hydrates have aspect similar to ice and are composed of natural gas, sulfidric gas or carbon dioxide in contact with water. They have higher density than the oil and might obstruct the pipelines. Hydrates are created at low temperatures and high pressures, which are typical conditions encountered in pipelines in deep water. At very high depths, the sea water can have temperature as low as 4^{o} C. Thus, in the event of an emergency shutdown or, during a long maintenance period, the oil inside the pipelines can reach the hydrate formation zone and damage the entire pipeline (Mokhatab *et al*., 2007).

The hydrate formation can be suppressed through the injection of inhibitors, lowering the pressure or heating the pipe (Boatman and Peterson, 2000). The heat losses from the duct are usually controlled by using some sort of insulators or, more recently, through the use of Pipe-in-Pipe (PIP) systems. PIP systems are formed by two concentric metal pipes, where the space between them is filled by one or more insulating materials (Mollison, 1992). The oil flows through the inner pipe and the sea water flows outside the outer pipe. In many times, active heating is used in PIP systems in order to extend their applications to long distances and to long periods of maintenance situations (Gomes *et al*., 1996).

Su and Estefen (2001) studied a PIP system during its heating and cooling. They analyzed the transient heat transfer in a sandwiched pipeline with active electrical heating, considering a lumped approach for the heat conduction within the solid and a finite difference method to the fluid flow inside the inner duct. Laouir and Denniel (2001) presented a proposal for a PIP system with active heating, where they used resistances capable to generate 100 W/m in a distance up to 3 km. Two prototypes were constructed, considering a system with active heating and the other one without active heating. Two types of insulating materials were used. The authors showed that for a system with a good thermal insulation, the energy dissipated by the active heaters is very low and a control system can be used to activate the resistances only at certain time intervals. Su *et al*. (2002) analyzed the heat conduction in an infinite multilayer duct with active heating. They considered only the steady-state case and two types of heating systems, given by hot water and electrical resistances. They analyzed also the possibility of segmented electrical heaters along the pipeline. Su *et al*. (2003) studied the active heating in a pipeline 27 km long and with 6 in. of internal diameter. The electrical heaters were made of four cupper bars symmetrically disposed along the outer surface of the inner tube. Kullmann (2006) presented an automatic heating procedure for PIP systems, composed of segmented electrical resistances, which were activated independently and with variable heat generation. Su *et al*. (2005) presented a transient heat transfer analysis in a cross section of a PIP system with active heating. Three configurations were studied, using polypropylene as insulating material. They concluded that, although the insulators were capable to maintain the oil temperature above the hydrate formation zone, the active heating was needed during the maintenance periods were the production was stopped. Tough *et al*. (2001) presented some results of a PIP system used in the Nile production camp, located at 85 miles south of New Orleans. The water was 1 km depth and three types of thermal insulators were used: polypropylene, mineral wool and a porous material. They also discussed some issues related to the air-gap needed between the outer duct and the insulators in order to provide space to mechanical deformations of the system. Hansen and Rydin (2002) presented a PIP system with polypropylene as a thermal insulator and described some test of this system, which was installed in the Mexican Gulf. Esaklul *et al*. (2003) describe some results of a PIP system and compared the use of an active heating system with the use of chemical inhibitors to control the hydrate and paraffin deposition in such systems. Urdahl *et al*. (2003) used an electrical heating system in a system to transport gas, in order to avoid the deposition of hydrates during the production stops. The gas duct had 16 km of length and the results were very good. Nuttal and Rogers (1998) analyzed a cross section of a PIP system using air as a fluid. Silva and Colaço (2007) and Silva (2008) emphasized the need for the active heating in pipes during the shutdown and maintenance processes. The thickness of the insulating layer and the location of the active heaters were obtained using the Multi Objective Game Theory Method (MOGT).

In this work we used three different optimization methods provided by the modeFrontier® software to optimize the thickness of the insulating layers, as well as the position and intensity of the electric heaters that minimizes the cost of installation (CI) and the cost of operation (CO), and maximize the temperature of the fluid with intention to prevent the hydrate formation and paraffin deposition in the pipes. The methods used were the Multi Objective Game Theory – MOGT - (Clarich *et al*., 2003), Multi Objective Simulated Annealing Algorithm – MOSA - (Rigoni, 2003) and An Efficient Multi-Objetctive Genetic Algorith – ARMOGA - (Sasaki, 2003). The final result obtained through this multi-objective optimization process is a set of non-dominated solutions, known as Pareto frontier (Deb, 2002), where the final decision can be made considering appropriate scenarios.

2. PHYSICAL PROBLEM

The physical problem considered in this work consists of a cross section of a PIP formed by two concentric steel pipes where the space between them is filled by one or more insulating materials. The internal pipe is filled with oil and the external pipe is exposed to sea water at a very low temperature. Each layer is composed of a homogeneous and isotropic material, with constant thermal properties. It is assumed perfect thermal contact among the layers. Five electrical heaters are placed on the external surface of the metal duct that is in contact with the fluid, as shown in Fig. 1. At the external part of the system there is sea water exchanging heat with the PIP system. The variation of the temperature of the oil during a deactivation period (e.g. eight hours) of the production was analyzed. During this period, the oil (which was initially at a high temperature) exchanges heat with the external water through the several layers and it becomes more inclined to form paraffin and hydrates. The objective was, then, finds the appropriate location and intensities of the heaters, as well as the best thickness of each insulator material that was able to prevent the formation of hydrates with the lowest costs of installation and operation.

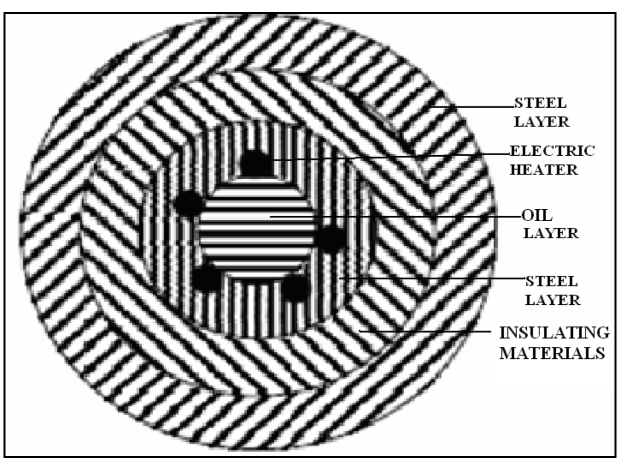

Figure 1. A Multilayered Pipe-in-Pipe with electrical heating

2.1. MATHEMATICAL MODELING

In this work, a cross section of a PIP system consisting of N concentrically cylindrical layers, as shown in Fig. 1, has been considered. Each layer was assumed to be homogeneous, isotropic, and with constant thermal properties. The layers are assumed to be in perfect thermal contact among them. The mathematical formulation of such two-dimensional heat conduction problem is given as

$$\frac{\partial^2 T_i(r,\theta,t)}{\partial r^2}+\frac{1}{r^2}\frac{\partial^2 T_i(r,\theta,t)}{\partial \theta^2}+\frac{1}{r}\frac{\partial T_i(r,\theta,t)}{\partial r}+\frac{g_i(\theta)}{k_i}=\frac{1}{\alpha}\frac{\partial T_i(r,\theta,t)}{\partial t} \quad \text{in } r_i < r < r_{i+1}, \quad i=0,\ldots,N \tag{1}$$

where T_i is the temperature, α_i is thermal diffusivity and k_i is the thermal conduction of the *i-th* layer. The inner and outer radiuses of the *i-th* layer are r_i and r_{i+1}, respectively.

Equation (1) is subjected to the following boundary conditions, as well as temperature and flux continuity conditions at each interface

$$\frac{\partial T}{\partial r}=0 \qquad \text{at } r=0 \tag{2.a}$$

$$k_i\frac{\partial T}{\partial r}+hT=hT_\infty \qquad \text{at } i=N \text{ and } r=r_N \tag{2.b}$$

$$T_i=T_{i+1}, \qquad k_i\frac{\partial T_i}{\partial r}=k_{i+1}\frac{\partial T_{i+1}}{\partial r} \qquad \text{at } r=r_i,\ i=1,..,N-1 \tag{3}$$

In this work, T_∞ was taken as 4°C, which is the temperature of the sea water at a very high depth and h was takes as 1000 W/m^{2}K. The initial condition was assumed constant over all layers, and it is given as

$$T=60^\circ\text{C} \qquad \text{for } t=0, \text{ at } r_i < r < r_{i+1},\ i=0,\ldots,N \tag{4}$$

The physical problem given by Eqs. (1)-(4) was solved using the implicit finite difference method (Tannehill *et al.*, 1984).

In this work, two types of costs were considered, namely: the cost of installation and the cost of operation. The objective, thus, was to minimize such costs, while maintaining the flow above certain temperature level, which was capable to avoid the formation of hydrates and paraffin. The expression for the cost of installation is given as

$$\text{CI}=L*[\pi(r_{ext}^2-r_{in}^2)]*(\text{price per each m}^2 \text{ of the insulating material}) \tag{5}$$

where r_{ext} and r_{int} are the external and internal radius of the *i-th* insulator layer and L is the length of the duct, which was considered equal to 5 km (3.11 miles). The price per square meter of polypropylene was assumed to be equal to 18 for 0.025 m^2 of area and 55.10 for 0.1 m^2 of area. For mineral wool, the price was taken as 13.24 for 0.025 m^2 of area and 52 for 0.1 m^2 of area. A linear interpolation was used to obtain values within such range of areas. Notice that only the cost associated with the purchase of the insulator was considered. Thus, depending on the thickness of the insulator, the cost of installation will vary. Due to the very long duct (5 km), such cost can be very high.

The expression for the cost of operation was taken as

$$\text{CO}=(q_1+q_2+q_3+q_4+q_5)*(\text{price per watts/hours})*8 \text{ hours} \tag{6}$$

where q_i is the intensity of each one of the 5 heaters being considered. Such cost represents the amount of energy used to activate the 5 electrical resistances during a period of 8 hours. As a first approximation, it was considered that the heaters are always turned on. However, in a future, a time depending expression for q_i should be used. In Eq. (6), the cost per Watts/hours was taken equal to 0.00032.

4. RESULTS AND DISCUSSION

The implicit finite differences method was used for the numerical solution of the heat conduction problem proposed in this work, in cylindrical coordinates. For the validation of the problem composed of N layers, a comparison against an analytical solution (Özisik, 1980) was performed (Silva and Colaço, 2007; Silva, 2008).

Due to the lack of more realistic pipeline and production data, hypothetical conditions were applied for sandwiched pipelines with inner diameter of 6 in. (0.1524 m). The pipelines considered in this work had internal and external pipes made of steel. Polypropylene and a combination of polypropylene with mineral wool were used as thermal insulation materials, whose thickness were optimized in order to reduce the costs of installation and operation, as well as maximize the minimum value of temperature within the oil. The thicknesses of the inner and outer pipes were considered equal to 3.175 mm and the total length of the pipeline was equal to 5 km. All electrical heaters considered in this work have dimensions equal to 3.175 mm *x* 50 mm. The thickness of the insulator layer, which was one of the variables being optimized, varied from 25 mm to 100 mm and the outer duct diameter varied according to this variable. The oil temperature before the shutdown was considered equal to 60°C and the sea temperature equals to 4°C. The heat transfer coefficient at the surface of the outer duct was taken as 1000 W/m^{2}K. During the optimization process, the minimum temperature within the oil could not be less than 30°C. Table 1 shows the thermophysical properties of the materials used in this work.

Table 1 - Thermophysical properties of the Pipe-in-Pipe

Material	α (m^2/s)	K (W/m °C)
Stainless Steel	1.41×10^{-5}	54.0
Polypropylene	1.0×10^{-7}	0.17
Mineral wool	1.0×10^{-7}	0.05

Using single-objective optimization methods, it is possible to deal with problems with only one objective function. However, real life problems usually demand more than one objective function. As an example, one might want to maximize the power of a gas turbine, while at the same time minimizing the fuel consumption in the combustion chamber.

It is thus necessary to analyze simultaneously various objective functions, according to their relative priorities. In order to deal with such situations, there are several approaches. One technique is to optimize a multi-objective problem by means of scalar methods. These methods are based on a combination of the individual objective functions into a single function. In other words, the original objective functions $f_1, f_2, \ldots, f_k$ are combined into a generic function f as $f = G(f_1, f_2, \ldots, f_k)$, where G is a linear or non-linear combination of the original functions. The resultant function f can be minimized using the traditional single-objective optimization techniques. Thus, the final result is a single value, corresponding to the optimum values of the variables of the generic function f. The technique of combining different objective functions allows one to define individual weights to each one of the original functions, according to their relative importance.

Although easy to implement, the technique described above has some disadvantages. The combination of all individual objective functions into a single function does not allow the designer to evaluate globally the relative importance of the functions. In order to offer to the designer a wider knowledge of the problem at hand, the new paradigm for multi-objective optimization no longer combines all functions into a single one. A better solution is to deal with the original functions, leading to a set of all possible solutions, where the optimum values are located. Such set of solutions is called a 'Pareto front' or 'Pareto set' (Deb, 2001), and will be briefly discussed next.

To better understand the role of the Pareto front, it is necessary to define the concepts of dominated and non-dominated solutions. A solution S_1 is defined as dominated, when there is another solution S_2 such that, for all objective functions, the solution S_1 is worse than the solution S_2. On the other hand, a solution S_1 is defined as non-dominated, when there is no such solution S_2 for which all its objective function values are better than S_1. An alternative definition for a non-dominated solution is the following: a non-dominated solution is one, for which an improvement in one of the objective functions cannot be performed without deterioration in one or more of the other objective function values.

The set of all non-dominated solutions is called Pareto front. The so-called best solution, taken from the Pareto front, is obtained through additional decision criteria (economic, technical, political, or other, based on some specific scenario for the application). The choice of the appropriate decision criteria is left to the designer.

In this work we intend to minimize the sum of the costs of operation and installation, and maximize the minimum value of the temperature within the oil. The variables are the thickness of each one of the insulation layers (up to two), the intensities and angular locations of each one of the five thermal heaters.

Figure 2 shows the result of the optimization of a PIP system with polypropylene as the insulating material using three different optimization methods: ARMOGA, MOSA and MOGT. In this figure, the ordinate axis shows the sum of the operation and installation costs (MinCICO) while the abscissa shows the minimum value of the temperature within the oil (tmin).

For the MOGT, the optimizer solved Eqs. (1)-(4) 980 times, which took 66 hours and 45 minutes, in order to find the Pareto front. The power required to activate the heaters varied from 669 kW to 965 kW to heat a pipeline with 5 km of length. In a similar work, Su *et al*. (2005) found a power equals to 1.38 MW. The results obtained through the use of the MOSA optimization method are dominated by the ones obtained with the MOGT at low values of T_{min} and dominate them at high values of T_{min} as one can see from the inspection of Fig. 2. The MOSA optimizer required the solution of Eqs. (1)-(4) 2484 times in order to find the Pareto frontier. Such effort took 169 hours and 11 minutes, and the required heating power for the 5 km of pipes varied from 493 kW to 771 kW. Finally, one can inspect, from the analysis of Fig. 2 that the ARMOGA optimizer could obtain a Pareto front that dominates all other solutions obtained by the other two optimizers. In order to find such results, the ARMOGA optimizer required the solution of Eqs. (1)-(4) 1648 times at a computational cost of 112 hours. The required heating power obtained through the use of the ARMOGA optimizer varied from 770 kW to 982 kW. From the analysis of the Pareto front, the ARMOGA optimizer obtained the best solutions, when compared with the other two optimizers. The average thickness of the insulator obtained was equal to 0.064 m, 0.068 m and 0.067 for the MOGT, MOSA and ARMOGA methods, respectively. This thickness is lower than the one obtained by Su *et al*. (2005), who obtained a value equals to 0.076 m. Also, the encountered average heating power was equal to 856 kW, 681 kW and 885 kW for the MOGT, MOSA and ARMOGA methods, respectively.

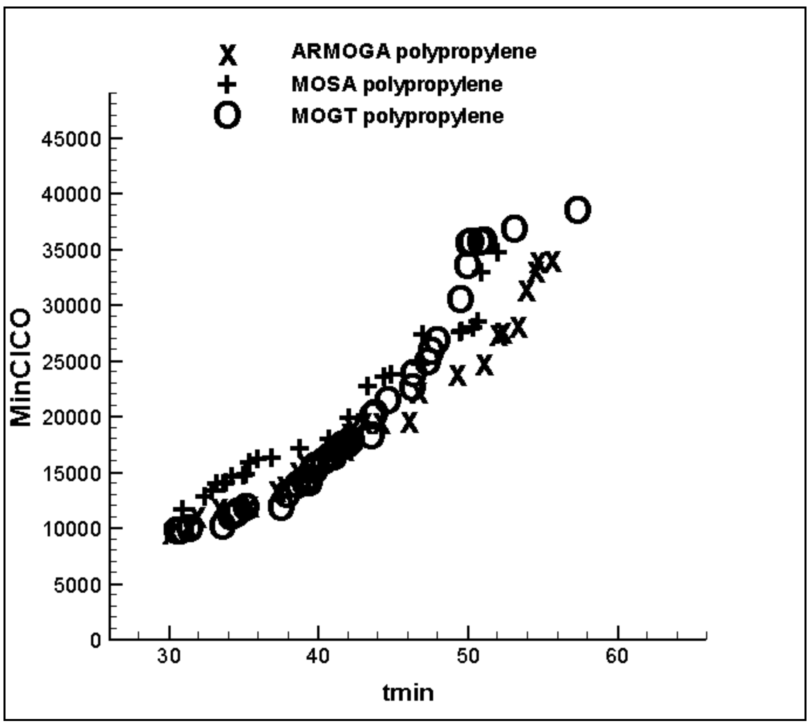

Figure 2. Comparison among the optimization methods using polypropylene as thermal insulator

As an attempt to reduce the costs associated with the thermal insulator, a PIP system with two layers of insulators was analyzed. For this system, polypropylene and mineral wool were employed. The objective thus was to obtain the optimum thickness of each insulator, as well as the intensity and location of the electrical resistances in order to minimize the installation and operation costs and maximize the temperature of the oil. Figure 3 shows the results obtained for this test case. For this case, the ARMOGA and MOSA methods obtained the best results, where all point in the Pareto front were non-dominated. It is worth to note that, while the ARMOGA method was able to obtain the lower portion of the Pareto front, the MOSA method was able to capture its upper part. This indicates that perhaps a combination of the two methods would be able to capture all Pareto front. The MOGT method obtained the worst result. The MOGT method required the solution of Eqs. (1)-(4) 1025 times, with a CPU time equals to 70 hours. The results obtained with this method indicate a heating power varying from 18 kW to 545 kW for 5 km of pipeline. The MOSA method required 1728 times the solution of Eqs. (1)-(4), with a total of 118 hours of CPU time. The required heating power obtained through the use of the MOSA method varied from 455 kW to 815 kW. It is interesting to note that, even having a worst solution, the MOGT method was able to generate more points in the Pareto front than the MOSA method. While the MOSA captured the upper part of the Pareto front, the ARMOGA, which need 1710 solutions of Eqs. (1)-(4), was able to capture the lower part of it. The ARMOGA method took 117 hours of CPU time to obtain its final results. The average thickness of the mineral wool obtained was equal to 0.035 m, 0.049 m and 0.028 m for the MOGT, MOSA and ARMOGA methods, respectively. The average thickness of the polypropylene obtained was equal to 0.036 m, 0.048 m and 0.027 m for the MOGT, MOSA and ARMOGA methods, respectively. Finally, the required heating power obtained was equal to 248 kW, 665 kW and 595 kW for the MOGT, MOSA and ARMOGA methods, respectively.

It is interesting to note that the values of the required heating power for a combination of the polypropylene and mineral wool are lower than the ones obtained when only the polypropylene was used as a thermal insulator material. Also, due to the high cost associated with the polypropylene, the overall costs are lower when a combination of the two materials is used, as one can see from the inspection of Figs. 2 and 3.

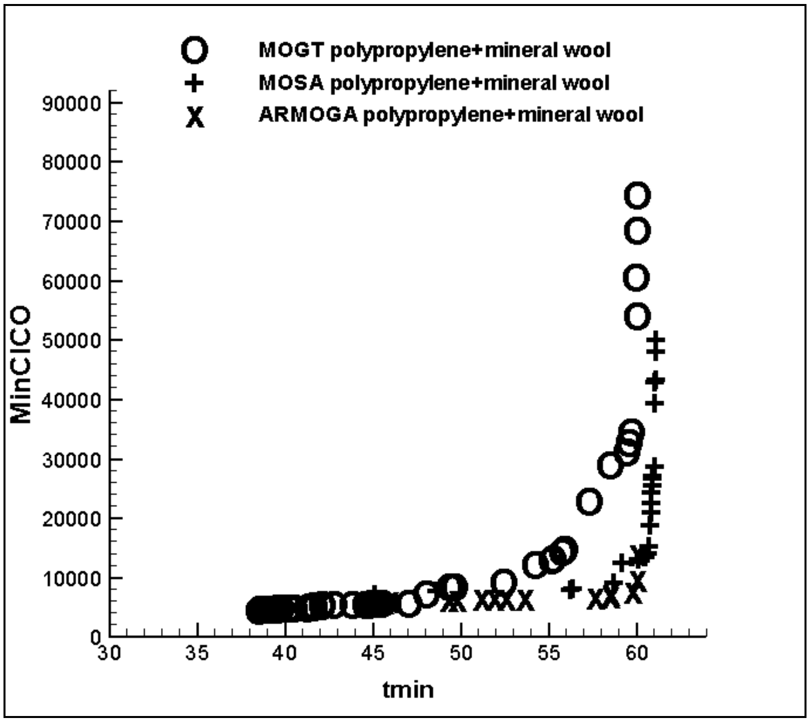

Figure 3. Comparison among the optimization methods using a combination of polypropylene and mineral wool as thermal insulators

5. CONCLUSIONS

In this work, three different multi-optimization methods – MOGT, MOSA and ARMOGA – were applied to the optimization of a cross-section of a Pipe-in-Pipe system. The objectives were to minimize the sum of the costs of operation and installation, and maximize the minimum value of the temperature within the oil. The variables were the thickness of each one of the insulation layers (up to two), the intensities and angular locations of five thermal heaters. All three methods were able to obtain a Pareto front for non-dominated solutions, where the final decision can be made considering the appropriate scenarios. However, the MOGT method presented the worst results among them.

Two test cases were analyzed: the first one considered only polypropylene as insulator material and the second one considered a combination of polypropylene and mineral wool. The second test case gave a Pareto front with lower costs and lower power heating than the case with only polypropylene. The results show that a multi-objective optimization of a PIP system could reduce significantly the costs associated with its installation and operation.

The CPU time required to accomplish the optimization task was, in general, too high and response surface methods shall be used in the future. Also, the fluid flow within the duct and the air-gap between the insulator and the outer duct must be included in future works.

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