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Design of a Heating System for Petroleum Pipelines Based on State Estimation and Optimal Control

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Deepwater operations in subsea production systems can be critically affected during transient events, such as shutdown periods, because of the formation of hydrates and/or wax deposits (see figure 1). Such formations/deposits can completely block production pipelines, thus requiring different technological solutions to restart production [1, 2]. In fact, during shutdown periods the fluid looses heat to the surrounding environment and hydrates can be formed even at relatively high temperatures, due to the high pressures involved in oil fields nowadays located around 2000 meter below sea level. A possible solution to avoid the formation of hydrates and wax deposits currently applied by the petroleum industry is to use heating protocols on subsea production systems. Typical heating protocols can be used to maintain the fluid temperature above critical levels, as well as to warm it up from the seawater temperature, or from a critical temperature, to a desired thermal profile [3].

(a) Hydrate (b) Wax

Figure 1: Typical deposits in subsea pipeline

The main focus of this paper consists in examining an optimal observer and a control approach on the design of heating systems, during shutdown simulated conditions [4]. The physical problem consists of a pipeline cross-section represented by a circular domain filled with a stagnant fluid. Figure 2 shows four points over the pipe wall, representing the simulated heating system. The fluid was considered as homogeneous, isotropic and with constant thermo-physical properties. The dimensionless mathematical formulation for this two-dimensional unsteady heat diffusion problem is given by:

$$\frac{\partial\theta(R,\emptyset,\tau)}{\partial\tau} = \frac{\partial^2\theta(R,\emptyset,\tau)}{\partial R^2} + \frac{1}{R}\frac{\partial\theta(R,\emptyset,\tau)}{\partial R} + \frac{1}{R^2}\frac{\partial^2\theta(R,\emptyset,\tau)}{\partial\emptyset^2} \quad 0 \le R < 1 , 0 \le \emptyset < 2\pi \quad \tau > 0 \tag{1.a}$$

Where $\theta(R,\emptyset,\tau)$ is the dimensionless temperature distribution into the medium. This equation was solved subjected to the following boundary and initial conditions:

$$\frac{\partial\theta(R,\emptyset,\tau)}{\partial R} + Bi\,\theta(R,\emptyset,\tau) = Q(\emptyset,\tau) \quad R = 1 ,\ 0 \le \emptyset < 2\pi \quad \tau > 0 \tag{1.b}$$

$$\theta(R,\emptyset,\tau) = 1 \quad 0 \le R < 1 ,\ \tau = 0 \tag{1.c}$$

The transient temperature field in the pipeline cross section is predicted in this paper by utilizing an optimal observer [5], from reduced measured data available on a single point at the pipeline wall (see figure 2). Figure 3 presents simulated measured temperatures containing Gaussian errors with standard deviation of 3°C. Figure 4 shows the predicted temperature distribution obtained with an optimal observer in the form of a particle filter, for a case involving a standard deviation of the evolution model errors of 1°C. For the results shown in figure 4, an optimal control approach was used to drive the predicted temperatures above a reference level. This optimal control was based on a state feedback control law [6], in which a quadratic cost functional was minimized through the solution Riccati's equation. Figure 5 presents the dimensionless heat flux obtained from the optimal control approach.

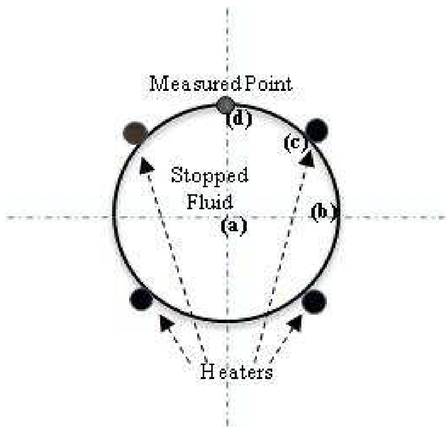

Figure 2 - Pipeline cross-section

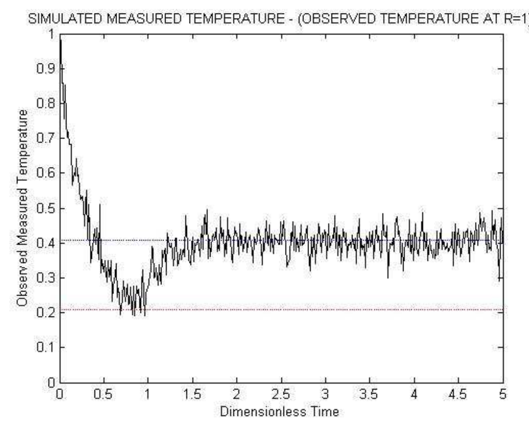

Figure 3 – Simulated temperature

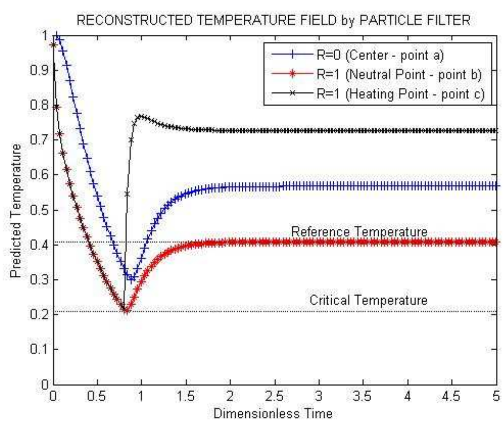

Figure 4 – Predicted temperature field

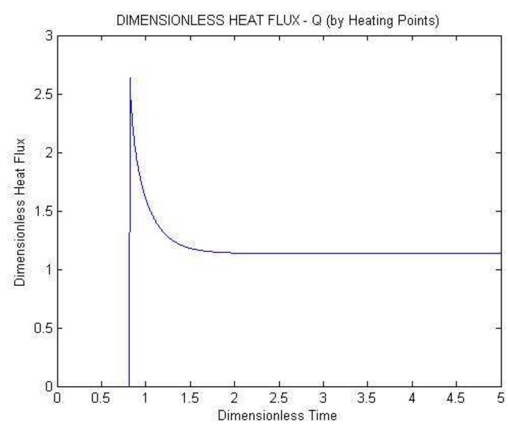

Figure 5 – Designed heat flux

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