MODEL BASED PIPELINE MONITORING WITH LEAK DETECTION

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Abstract: We design a leak detection system consisting of an adaptive Luenberger-type observer based on a set of two coupled one dimensional first order nonlinear hyperbolic partial differential equations governing the flow dynamics. It is assumed that measurements are only available at the inlet and outlet of the pipe, and output injection is applied in the form of boundary conditions. Heuristic update laws for adaptation of the friction coefficient and leak parameters are given, and simulations demonstrate their ability to detect, quantify and locate leaks. Particular attention is given to time-varying boundary conditions, such as during pipeline shut-down. A scenario consisting of leak detection followed by pipeline shut-down during which the leak is accurately quantified and located is successfully simulated for both liquid and gas systems.

Keywords: Partial differential equations; Observers; Adaptive systems; Pipeline leaks

1. INTRODUCTION

Transportation of fluids in pipelines requires monitoring to detect malfunctioning such as leaks. In the petroleum industry, leaks from pipelines may potentially cause environmental damage, as well as economic loss. These are motivating factors, along with requirements from environmental authorities, for developing efficient leak detection systems. While some leak detection methods are hardware-based, relying on physical equipment being installed along the pipeline, the focus of this paper is on software-based methods that work for cases with limited instrumentation. In fact, instrumentation in the petroleum industry is usually limited to the inlet and outlet of pipelines, only. This calls for sophisticated signal processing methods to obtain reliable detection of leaks. Some software-based leak detection methods perform statistical analysis on measurements (black box), while others incorporate models based on physical principles. Our method falls into the latter category, in that we will use a dynamic model of the pipe flow based on a set of two coupled hyperbolic partial differential equations.

There have been numerous studies on model based leak detection. We mention here the most relevant ones with regard to our work. Based on a discretized pipe flow model, Billman and Isermann (1987) designed an observer with friction adaptation. In the event of a leak, the outputs from the observer differs from the measurements, and this is exploited in a correlation technique that detects, quantifies and locates the leak. Verde (2001) used a bank of observers, computed by the method for fault detection and isolation developed by Hou and Müller (1994). The underlying model is a linearized, discretized pipe flow model on a grid of N nodes. The observers are designed in

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such a way that all but one will react to a leak. Which one of the N observers that does not react to the leak depends on the position of the leak, and this is the mechanism by which the leak is located. The outputs of the remaining observers are used for quantifying the leak. The bank of observers are computed using the recursive numerical procedure suggested by Hou and Müller (1994), however it was shown in Salvesen (2005) that due to the simple structure of the discretized model, the observers may be written explicitly. This is important, because it removes the need for recomputing the bank of observers when the operating point of the pipeline is changed. Verde (2004) also proposed a nonlinear version, using an extremely coarse discretization grid.

Several companies offer commercial solutions to pipeline monitoring with leak detection. Fantoft (2005) uses a transient model approach in conjunction with the commercial pipeline simulator OLGA2000, while EFA Technologies (1987, 1990, 1991) uses an event detection method that looks for signatures of no-leak to leak transitions in the measurements.

The detection method of Verde (2001) using a bank of observers, can potentially detect multiple leaks. However, multiple simultaneous leaks is an unlikely event, so the complex structure of a bank of N observers seems unnecessary. Aamo et al. (2006) instead employed ideas from adaptive control, treating the magnitude and location of a single point leak as constant unknown parameters in an adaptive Luenberger-type observer based on a set of two coupled one dimensional first order nonlinear hyperbolic partial differential equations. Heuristic update laws for adaptation of the friction coefficient, magnitude of the leak and position of the leak were suggested. In the present paper, we continue the development of our leak detection system by greatly improving the leak detection performance under time-varying boundary conditions. This is achieved by remodelling the leak. A comprehensive simulation study demonstrates the leak detection system for both liquid and gas systems.

2. MATHEMATICAL MODEL

For liquid flow in a pipe we have the mass conservation

$$\frac{\partial p}{\partial t} + u\frac{\partial p}{\partial x} + \rho c^2 \frac{\partial u}{\partial x} = 0, \tag{1}$$

and the momentum conservation (ignoring friction for now)

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + \frac{1}{\rho}\frac{\partial p}{\partial x} = 0, \tag{2}$$

for $(x,t) \in (0,L) \times (0,\infty)$, and where $u(x,t)$ is flow velocity, $p(x,t)$ is pressure, and $\rho(x,t)$ is density. The relation between pressure and density is modelled as (Nieckele et al. (2001))

$$\rho(x,t) = \rho_{ref} + \frac{p(x,t) - p_{ref}}{c^2}, \tag{3}$$

where ρ_{ref} is a reference density at reference pressure p_{ref}, and c is the speed of sound in the fluid. Equation (1)–(2) also describes gas flow in a pipe, simply by replacing (3) with the ideal gas law. Under the conditions we consider, we assume c is sufficiently large to ensure $\rho > 0$. Defining $k = c^2\rho_{ref} - p_{ref}$ and substituting (3) into (1)–(2) we obtain

$$\frac{\partial p}{\partial t} + u\frac{\partial p}{\partial x} + (k+p)\frac{\partial u}{\partial x} = 0, \tag{4}$$

$$\frac{\partial u}{\partial t} + \frac{c^2}{k+p}\frac{\partial p}{\partial x} + u\frac{\partial u}{\partial x} = 0. \tag{5}$$

The boundary conditions are

$$u(0,t) = u_0(t), \tag{6}$$

$$p(L,t) = p_L(t). \tag{7}$$

3. OBSERVER DESIGN

In reality, input signals to pipelines are usually choke openings at the inlet and outlet. Here, we instead view $u_0(t)$ and $p_L(t)$ in (6)–(7) as inputs to the process, and the remaining boundary quantities $p_0(t) = p(0,t)$ and $u_L(t) = u(L,t)$ as process measurements. Aamo et al. (2006) showed that a Luenberger-type observer consisiting of a copy of (4)–(5) and the boundary injections

$$\hat{u}(0,t) = u_0(t) + c\frac{1-k_0}{1+k_0}\ln\left(\frac{k+p_0(t)}{k+\hat{p}(0,t)}\right), \tag{8}$$

$$\hat{p}(L,t) = (k+p_L(t)) \times \exp\left(\frac{k_L - 1}{c(1+k_L)}(u_L(t) - \hat{u}(L,t))\right) - k. \tag{9}$$

has favorable convergence properties for $|k_0| \leq 1$ and $|k_L| < 1$ when compared to a plain copy of the plant, that is $\hat{u}(0,t) = u_0(t)$ and $p(L,t) = p_L(t)$. Figure 1 shows the observer error in terms of evolution in time of the $L_2(0,L)$ norm of $u(x,t) - \hat{u}(x,t)$ and $p(x,t) - \hat{p}(x,t)$ for the cases with and without output injection. Notice that when $k_0 = 1$ and $k_L = 1$, (8)–(9) reduces to the plain copy.

4. ADAPTATION OF FRICTION COEFFICIENT

Adding friction to the model (4)–(5), we have the mass balance

$$\frac{\partial p}{\partial t} + u\frac{\partial p}{\partial x} + (k+p)\frac{\partial u}{\partial x} = 0, \tag{10}$$

and momentum conservation

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + \frac{c^2}{k+p}\frac{\partial p}{\partial x} = -(1+\Delta)\frac{f}{2}\frac{|u|u}{D}, \tag{11}$$

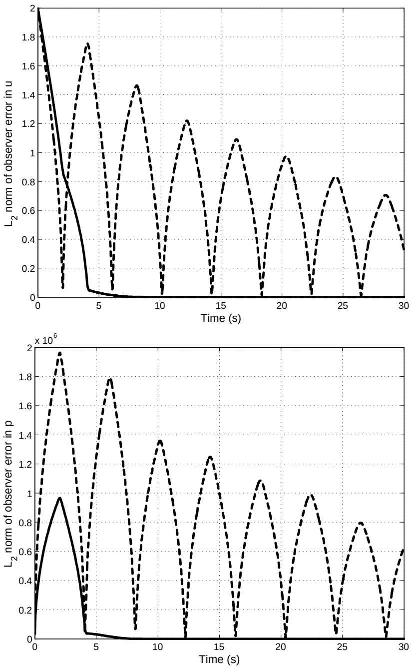

Fig. 1. Observer error with (solid) and without (dashed) output injection.

where D is the pipe diameter, and Δ is considered an unknown constant that accounts for uncertainty in the friction coefficient f, which is given by Schetz and Fuhs (1996) as

$$\frac{1}{\sqrt{f}} = -1.8\log_{10}\left[\left(\frac{\epsilon/D}{3.7}\right)^{1.11} + \frac{6.9}{\mathrm{Re}_d}\right]. \quad (12)$$

ϵ/D is the pipe relative roughness, Re_d is the Reynolds number defined as

$$\mathrm{Re}_d = \frac{\rho u D}{\mu}, \quad (13)$$

and μ is the fluid viscosity. The observer is then

$$\frac{\partial \hat{p}}{\partial t} + \hat{u}\frac{\partial \hat{p}}{\partial x} + (k+\hat{p})\frac{\partial \hat{u}}{\partial x} = 0, \quad (14)$$

$$\frac{\partial \hat{u}}{\partial t} + \hat{u}\frac{\partial \hat{u}}{\partial x} + \frac{c^2}{k+\hat{p}}\frac{\partial \hat{p}}{\partial x} = -\left(1+\hat{\Delta}\right)\frac{\hat{f}}{2}\frac{|\hat{u}|\,\hat{u}}{D}, \quad (15)$$

which incorporates an estimate $\hat{\Delta}$ of Δ, and with boundary conditions (8)–(9). Consider the heuristic parameter update law

$$\dot{\hat{\Delta}} = -\kappa_\Delta\left(\varphi_1 + \varphi_2\right), \quad (16)$$

where κ_Δ is a strictly positive constant, and

$$\varphi_1 = u(0) - \hat{u}(0) + c\,\ln\left(\frac{k+\hat{p}(0)}{k+p(0)}\right), \quad (17)$$

$$\varphi_2 = u(L) - \hat{u}(L) + c\,\ln\left(\frac{k+p(L)}{k+\hat{p}(L)}\right). \quad (18)$$

Figure 2 shows the evolution of $\Delta - \hat{\Delta}$ when the initial friction in the observer is twice that of the plant.

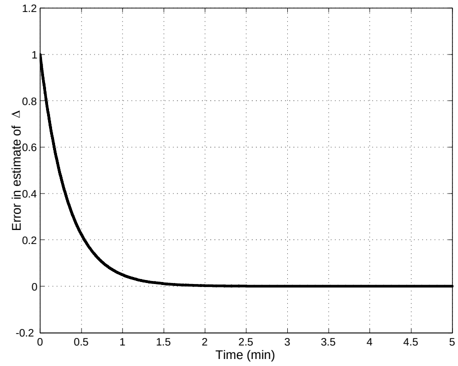

Fig. 2. Error in estimated friction factor, that is $\Delta - \hat{\Delta}$.

5. LEAK DETECTION

Adding a leak to the model (10)–(11), with $\Delta = 0$, we have the mass balance

$$\frac{\partial p}{\partial t} + u\frac{\partial p}{\partial x} + (k+p)\frac{\partial u}{\partial x} = -\frac{c^2}{A}f_l(x,t), \quad (19)$$

and the momentum conservation

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + \frac{c^2}{k+p}\frac{\partial p}{\partial x} = -\frac{f}{2}\frac{|u|\,u}{D} + \frac{1}{A}\frac{c^2}{k+p}u f_l(x,t), \quad (20)$$

where A is the pipe cross sectional area. Assuming a point leak occuring at $t = t_l$, we select $f_l(x,t)$ as

$$f_l(x,t) = w_l\,\delta(x - x_l)\,H(t - t_l), \quad (21)$$

where w_l and x_l are the magnitude of the leak and position of the leak, respectively, δ denotes the Dirac distribution, and H denotes the Heaviside step function. Aamo et al. (2006) treated w_l as a constant which led to poor leak localization performance for time-varying boundary conditions. In practice, the boundary conditions will most likely be time-varying since the logical thing to do as soon as a leak is detected, is to start shutting down the pipeline. In this case, the leak magnitude will vary during the shut-down, violating the assumption that w_l be constant. To overcome this problem, we propose to model the point leakage rate according to the valve equation

$$w_l(t) = C_v\sqrt{\rho(x_l,t)\left(p(x_l,t) - p_{amb}\right)}, \quad (22)$$

where C_v is a discharge coefficient and p_{amb} is the ambient pressure on the exterior of the pipe. While p_{amb} is assumed known, C_v is an unknown constant to be estimated by the leak detection system. The observer now becomes

$$\frac{\partial \hat{p}}{\partial t} + \hat{u}\frac{\partial \hat{p}}{\partial x} + (k+\hat{p})\frac{\partial \hat{u}}{\partial x}$$
$$= -\frac{c\hat{C}_v}{A}\sqrt{(k+\hat{p}(\hat{x}_l))\left(\hat{p}(\hat{x}_l) - p_{amb}\right)}\,\delta(x - \hat{x}_l), \quad (23)$$

$$\frac{\partial \hat{u}}{\partial t} + \hat{u}\frac{\partial \hat{u}}{\partial x} + \frac{c^2}{k+\hat{p}}\frac{\partial \hat{p}}{\partial x} = -\frac{\hat{f}}{2}\frac{|\hat{u}|\,\hat{u}}{D}$$

$$+\frac{c\hat{C}_v}{A}\hat{u}\sqrt{\frac{\hat{p}(\hat{x}_l)-p_{amb}}{k+\hat{p}(\hat{x}_l)}}\delta(x-\hat{x}_l), \quad (24)$$

which incorporates estimates of the leak discharge coefficient and position, $\hat{C}_v$, $\hat{x}_l$. We consider the heuristic parameter update laws

$$\dot{\hat{C}}_v = \kappa_C(\varphi_1 - \varphi_2), \quad (25)$$

$$\dot{\hat{x}}_l = -\kappa_x(\varphi_1+\varphi_2)|\varphi_1+\varphi_2|^{\frac{1}{\gamma}-1}, \quad (26)$$

where φ_1 and φ_2 are given in (17)–(18), and κ_C, κ_x and γ are strictly positive constants. The update laws (25)–(26) are derived from those in (Aamo et al. 2006) taking the new leakage model (22) into account.

6. SIMULATION RESULTS

A comprehensive simulation study has been carried out for a 5 km long pipeline with a diameter of 20 inches, varying the many parameters in the process model and observer. Due to page constraints, we report here on selected key results. The parameters used are summarized in Tables 1 and 3 for the oil and gas cases, respectively. Tuning parameters for the leak parameter update laws are given in Tables 2 and 4. The most probable scenario in practice, is the one where the pipeline is shut down as a consequence of detecting a leak. This leaves a limited time window for quantifying and locating the leak. A partial shut-down of the pipeline carrying oil is simulated by reducing the velocity at the inlet to 10 percent of its initial value and the pressure at the outlet to 30 percent of its initial value over a period of 3 minutes. An illustration of the performance of the leak detection system with these boundary conditions can be seen in Figure 3. The leak is very quickly detected, as shown by the steep increase in the magnitude-of-leak estimate immediately following the time when the leak occurs. An accurate estimate of the leak magnitude is obtained within a few seconds, while localization takes several minutes. Figure 4 shows the corresponding results for the gas case, where the velocity at the inlet was decreased to 10 percent of its initial value and the outlet pressure to 30 percent of its initial value over a period of 11 minutes. Due to the compressibility of gas, giving a lower speed of sound, there is a longer time-lag before the leak is detected (a few seconds). Accurate estimates of the leak magnitude and position are obtained in about a minute. The position of the leak shows some oscillatory behaviour, which is related to grid-size and tuning, and may be removed by filtering.

To further demonstrate the leak detection capabilities under time-varying boundary conditions, sinusoid perturbations were applied to both ends of the pipeline carrying oil. The sinusoids are meant to represent the varying production rate set at the inlet and the choking at the outlet. The velocity perturbation at the inlet has an amplitude of 25 percent of the initial value and a period of 3 minutes. The pressure perturbation at the outlet has an amplitude of 10 percent of the initial value and a period of 2 minutes. Figure 5 shows that leak detection and quantification performs very well under these boundary conditions, while localization suffers some oscillations at the frequency of the perturbation.

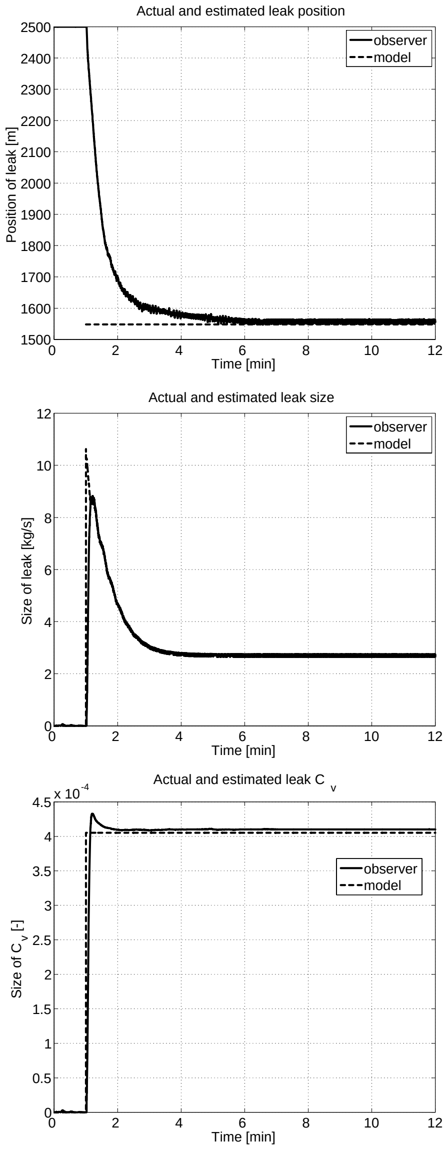

Fig. 3. **Oil, shut-down.** Estimates for a leak at 1548 m of with $C_v = 4.05 \cdot 10^{-4}$.

Finally, we present a case showing the important effect of the chosen boundary injections, that is, it compares results for $k_0 = k_L = 0$ (*with* boundary injection) with results for $k_0 = k_L = 1$ (*without* boundary injection). Here, the boundary conditions of the process model, u_0 and p_L, are assumed to vary randomly (low-pass filtered, however), while a leak occurs at 1548 m with $C_v = 2.55 \cdot 10^{-4}$. The amplitude of the input

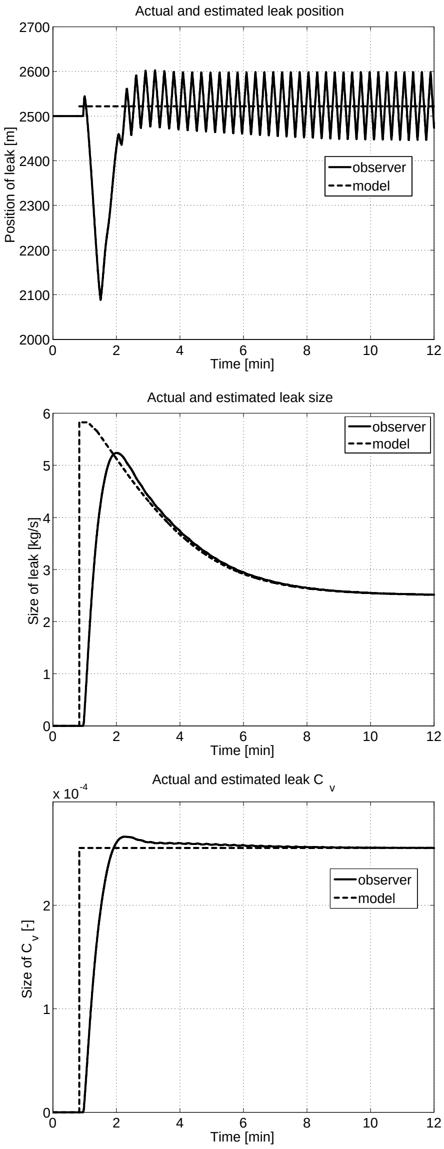

Fig. 4. **Gas, shut-down.** Estimates for a leak at 1548 m with $C_v = 2.55 \cdot 10^{-4}$.

velocity varies within 10 percent of the initial value, and the output pressure varies within 0.7 percent of the initial value. Figure 6 clearly shows the crucial effect of output injection, as well as the leak detection capability under randomly varying input.

7. CONCLUDING REMARKS

We have designed a leak detection system for pipelines consisting of an adaptive Luenberger-type observer and heuristic update laws for the parameters characterizing a point leak. The only available process information is flow velocity and pressure at the inlet and outlet of the pipe. Simulations demonstrate accurate quantification and localization of the leak under transient operation of the pipeline, such as for instance during shut-down. Current work focuses on replacing the simple model presented in this paper with a state-of-the-art fluid flow simulator and incorporating

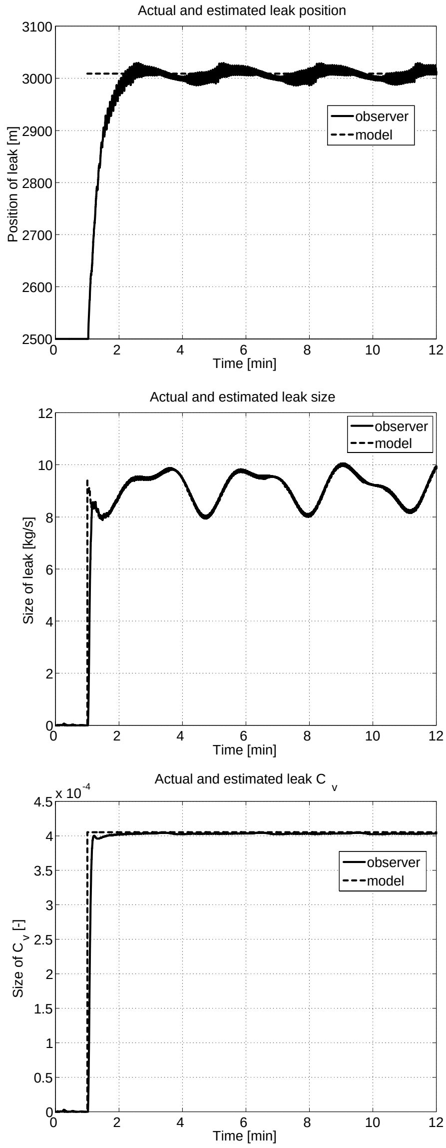

Fig. 5. **Oil, sinusoid.** Estimates for a leak at 3009 m of with $C_v = 4.05 \cdot 10^{-4}$.

Parameter	**Value**
L	5000 m
D	20 in
p_{ref}	$5 \cdot 10^5$ Pa
p_{amb}	101325 Pa
p_{initial}	101325 Pa
u_{initial}	2 m/s
$\bar{u} = u_0$	2 m/s
$\bar{p} = p_L$	$5 \cdot 10^5$ Pa
ρ_{ref}	870 kg/m^3
w_{in}	353 kg/s
μ_{ref}	$1.04 \cdot 10^{-1}$ Pa·s
c	1227 m/s
K	$1.31 \cdot 10^9$ Pa

Table 1. Pipeline and fluid parameters for oil.

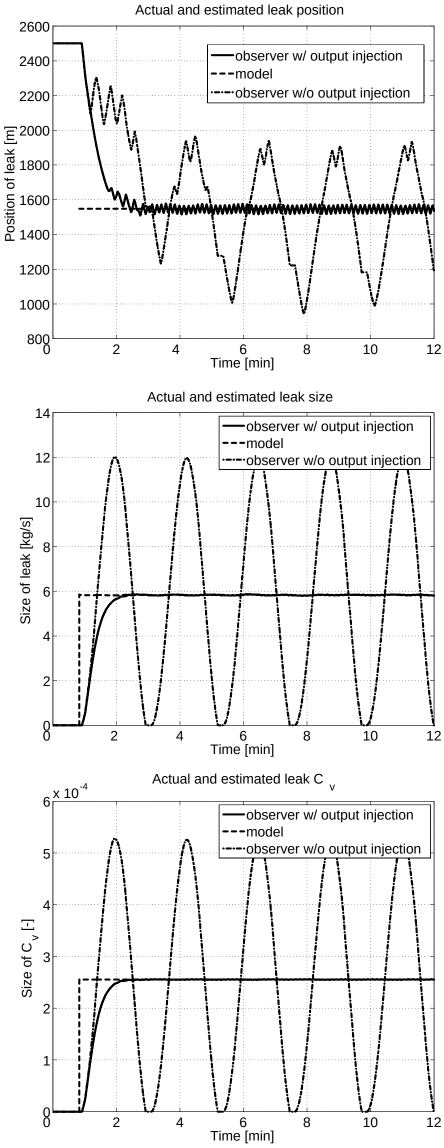

Fig. 6. **Gas, random.** Leak detection with and without output injection.

Parameter	Value
κ_c	$8.12 \cdot 10^{-4}$
κ_x	100
γ	4

Table 2. Tuning parameters for oil.

Parameter	Value
L	5000 m
D	20 in
p_{ref}	0 Pa
p_{amb}	101325 Pa
p_{initial}	5016390 Pa
u_{initial}	4 m/s
$\bar{u} = u_0$	4 m/s
$\bar{p} = p_L$	5016390 Pa
ρ_{ref}	52.67 kg/m^3
w_{in}	43 kg/s
μ_{ref}	$1.20 \cdot 10^{-5}$ Pa·s
c	308 m/s

Table 3. Pipeline and fluid parameters for gas.

Parameter	Value
κ_c	$8.12 \cdot 10^{-4}$
κ_x	35
γ	4

Table 4. Tuning parameters for gas.

the presented boundary conditions and parameter update laws into it. The increased accuracy of the flow calculations provided by such a simulator is expected to improve the leak detection capability described in this paper even further.

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