MATHEMATICAL MODELING AND EXPERIMENTAL STUDY OF OIL AND DENSE GAS TWO-PHASE FLOW UNDER THE EFFECT OF A LEAK

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Abstract *Leak detection in oil and gas offshore pipelines is crucial for preventing accidents that compromise safety, environment and production. This research aims to provide insight into the transient effects of a leak in the hydrodynamics of oil and dense gas two-phase flow. These effects shall be studied by means of phenomenological modeling based on the fundamental physical laws of conservation of mass and momentum and of experiments that simulate leaks in controlled conditions. Databases of experimental and simulated data should be generated, which are expected to contribute to the improvement of the accuracy of the machine learning based leak detection system used in the Brazilian oil and gas industry. Appropriate data processing techniques shall be applied in order to reveal the speed of propagation and attenuation rate of a leak pulse at different flow and leak conditions.*

Keywords*: Two-phase flow. Dense gas. Leak. Numerical simulation. Experimental study.*

1. INTRODUCTION

In offshore oil and gas pipelines operating at high pressures, efficient and effective leak detection is essential to preserve integrity and safety of critical industrial structures, minimizing environment and safety risks and unnecessary production stoppages with high associated costs. In the oil and gas Brazilian industry, the machine learning based classifier applied for leak detection has the limitation of distinguishing only the presence or absence of a leak. It is unable to pinpoint the exact location and classify the magnitude of a leak and yields recurring false positives related to routine operational transients. The training of the model to address such gaps requires validated database on oil and gas leaks composed of real, experimental and simulated data (Sestito *et al*., 2022; Vieira *et al*., 2023).

Therefore, as part of a project intended to generate an experimental database on leaks, this research aims to contribute to the improvement of the accuracy of the classifier by means of phenomenological modeling and experimental study of the effect of a leak on oil and dense gas two-phase flow. Results are expected to reveal valuable insight on characteristics of transient hydrodynamic effects of a leak in the flow and allow the formulation of appropriate criteria for classification of leaks into small, medium and large.

2. METHODOLOGY

2.1. Phenomenological modeling

The occurrence of a leak results in an instantaneous local pressure drop which propagates upstream and downstream in form of a wave pulse. These effects of the leak are being modeled mathematically according to the fundamental physical laws of conservation of mass (Eq. (1)) and linear momentum (Eq. (2)) applied to each phase k of the flow (Hetsroni, 1982; Rodriguez, 2010). Appropriate hypotheses and simplifications are applied and the resulting system of equations is solved by numerical simulation. The model is transient and one-dimensional along the axis of the pipeline, evaluating pressure, velocity and volumetric fraction of both phases in function of the axial coordinate z and time t. Oil flow is considered incompressible and the dense gas is modeled as an ideal gas. Preliminary calculations show that these flow hypotheses are sufficiently accurate.

A two-fluid model is proposed for flow patterns with predictable interface such as stratified and annular flow. A mixture model is proposed for flow patterns with chaotic interface such as intermittent and dispersed bubbles flow. Initially, the model simulates the condition with no leak, which represents normal operation in steady flow. Later, it simulates the condition with a leak, which takes as reference the equilibrium state given by the condition with no leak to quantify fluctuations of pressure, velocity and volumetric fraction caused by the leak pulse propagation.

$$\frac{\partial}{\partial t}\left(\rho_k \alpha_k\right) + \frac{\partial}{\partial z}\left(\rho_k v_k \alpha_k\right) = 0 \tag{1}$$

$$\frac{\partial}{\partial t}\left(\rho_k v_k \alpha_k\right) + \frac{\partial}{\partial z}\left(\rho_k v_k^2 \alpha_k\right) = -\,\alpha_k \frac{\partial p_k}{\partial z} - \frac{\partial}{\partial z}\left(\tau_{kn}\alpha_k\right) - \rho_k \alpha_k g \cos\theta \pm \frac{\tau_{ki} S_i}{A} - \frac{\tau_{kp} S_{kp}}{A} \qquad (2)$$

2.2. Experimental study

The experiments will be made on LEMI's multiphase-flow inclinable test platform (Fig. 1), which was properly adapted to make viable the simulation of leaks in controlled conditions. The main pipeline used in the experiments has an internal diameter of 2" and the newly installed leak pipeline has an internal diameter of 1". The fluids used are the Turbina X-22 mineral oil as liquid, with a density of 867 kg/m^3, and sulfur hexafluoride (SF_6) as dense gas, with a density of approximately 100 kg/m^3 in the experimental conditions commonly observed. Pressures shall be consistently kept close to 12 bar at the main flowline and 9 bar at the leak flowline. The experimental matrix, while still under discussion and elaboration, shall include variations in flow pattern, leak size, leak position and other operational transients.

Measurements are currently being validated and calibrated with preliminary tests on the new installation. The collected data will consist in temporal series of pressure, temperature, flow rate and volumetric fraction measured since shortly before the controlled induction of the leak until a given time after it, depending on the expected time of flow stabilization.

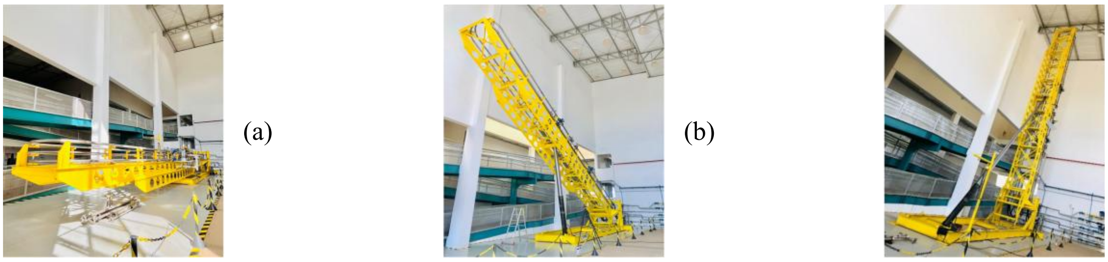
(a) (b) (c)

Figure 1. Inclinable multiphase flow platform of LEMI at (a) 0°, (b) 45° and (c) 90° inclinations, Ruiz-Diaz (2024).

3. EXPECTED RESULTS

The new database obtained from leak simulations and measurements is expected to contain information about the speed of propagation and the rate of attenuation of the transient signal generated by the leak on oil and dense gas flow. Knowledge on the speed of propagation of the leak pulse allows for pinpointing the precise location of the leak along the pipeline based on the time gap of detection of the pulse by two or more distinct sensors installed at known positions. The attenuation rate describes how fast the amplitude of a leak pulse diminishes due to irreversible energy dissipation. They are important to predict how far from the location of the leak that the pulse is yet detectable by sensors. The application of adequate statistical and time-frequency domain data processing techniques should give deeper insight also on how leak pulse characteristics depend on flow conditions.

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6. RESPONSIBILITY NOTICE

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