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FAILURE ANALYSIS IN A DOWNHOLE SAFETY VALVE SUBJECTED TO TWO-PHASE PIPE FLOW

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Abstract. A study of a common down hole safety valve (DHSV) that is installed in offshore oil wells is performed, with the objective to determine whether the internal flow has a relationship with the reduced life of that structural element. A fluid-structure interaction analysis is considered, to demonstrate that the vibrations of structural elements induced by flow are more likely to occur. Particularly, whether the internal two-phase flow arranged in the intermittent flow pattern could have influence on the reliability of the DHSV. The experimental work, which will be carried out in the LEMI (from Portuguese, Laboratório de Escoamentos Multifásicos Industriais) at the University of São Paulo in Brazil, will focus on determining the structural behavior of a pipe with internal dimensions similar to those of a DHSV subjected to an internal two-phase flow dynamically similar to that that occurs in real practice. The main objective is the scaling up of the results, which should allow extrapolation to full scale in the oil industry, therefore, the development of tool to predict the occurrence of failures according to the existing flow conditions.

Keywords: DHSV, Two-phase flow, Fluid-Structure Interaction (FSI), Fluid-Induced Vibration (FIV).

1. INTRODUCTION

Safety valves installed in offshore oil wells are considered a key safety element (Lindqvist *et al.*, 1988; Rausand e Vatn, 1998), and because of it, they should perform with the highest reliability. These valves act in the event of any failure in the production conditions, for example (Alisjabana *et al.*, 2013), damage to any component or equipment that generates an explosion and/or fire; excess of pressure of the production line that generates an oil spill into the sea, etc. For this reason, these devices should automatically shut down the flow when necessary, avoiding serious environmental, economic and social consequences (Amir-Heidari e Raie, 2018).

The valves so-called Subsurface Safety Valve (SSSV) or Down Hole Safety Valve (DHSV) (Oliveira *et al.*, 2017), are classified in two types (see Figure 1): subsurface controlled for (SSCSV), and surface controlled for (SCSSV) (Purser, 1977; Alisjabana *et al.*, 2013).

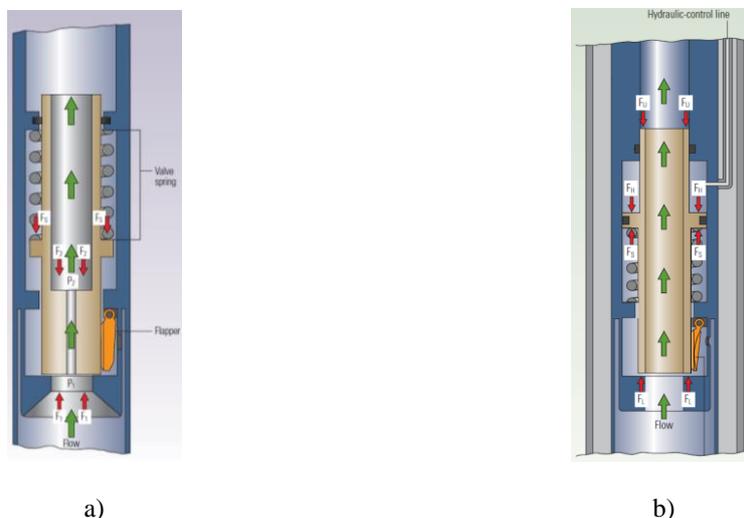


Figure 1. Safety Valve of Subsurface: a) subsurface controlled (SSCSV), b) Surface controlled (SCSSV).

Source: Garner *et al.* (2002).

The SSCSV was designed to operate with a flow variation in the production well (see Figure 1a). For this purpose, the main tube was equipped with a rigid tube that was formed by a choke that creates a pressure difference between the inlet and the outlet. However, these devices had some limitations because, in order to be activated, the flow (or pressure) variation had to be significant, which previously limited the well production to a level less than the maximum capacity. This means that, for flow conditions below the production levels defined above, the valve simply did not work (Garner *et al.*, 2002).

For this reason, and due to the high operational requirement, the need to control these valves was observed to guarantee their operation regardless of the working conditions of the well. As a consequence, SCSSVs were created (Figure 1b), which are activated through a hydraulic line controlled from the platform at the wellhead (Lindqvist *et al.*, 1988; Rausand e Vatn, 1998). Therefore, its activation does not depend on the flow nor the pressure conditions. Even its opening and closing can be manipulated to confirm the functioning status of the device.

Now, considering that the oil production process is accompanied by gas, an analysis associated to two-phase flow must be performed. This is because after processing a set of real oil well data, it was found that DHSVs failures could be related to the type of flow (see Figure 2).

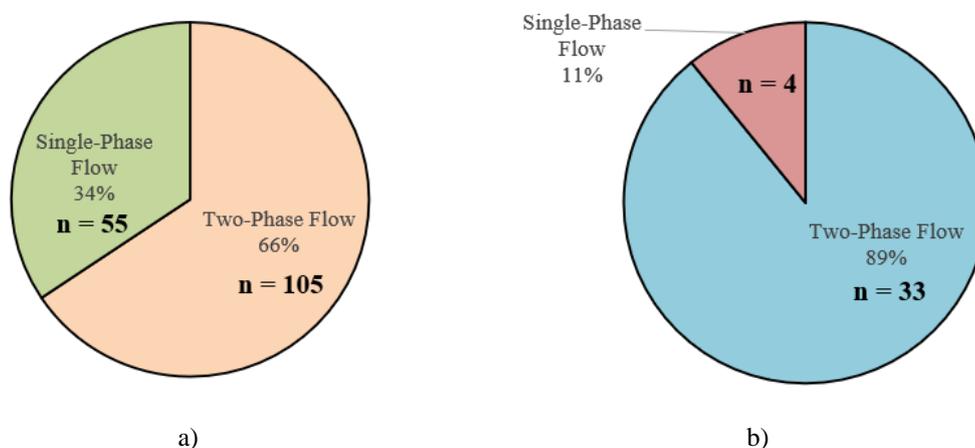


Figure 2. Real well data analysis: a) according to flow type, b) valve failures associated with flow.
Source: Own.

The presence of two-phase flow on the hydrocarbon extraction line is very likely since the reservoirs can contain oil and gas at the same time. Consequently, the joint movement of both fluids and interfaces can generate mechanical vibrations in the valve area that, projected in time, would cause failure for fatigue. This is because the fluids can adopt a particular physical configuration that could be aggressive in some situations; for example, in Slug flow pattern (see Figure 3b), since in these cases the high-density liquid moves at high velocities that are close to those of the gas flow.

Thus, researchers like Bamidele *et al.* (2019), Cabrera-Miranda e Paik (2019), Ortega *et al.* (2018) e Li *et al.* (2020) have demonstrated in recent years the importance of deepening in this area due to the evident relationship that exists between the vibrations of the structures caused by the type of flow. These problems are called *Flow-Induced Vibration* or FIV.

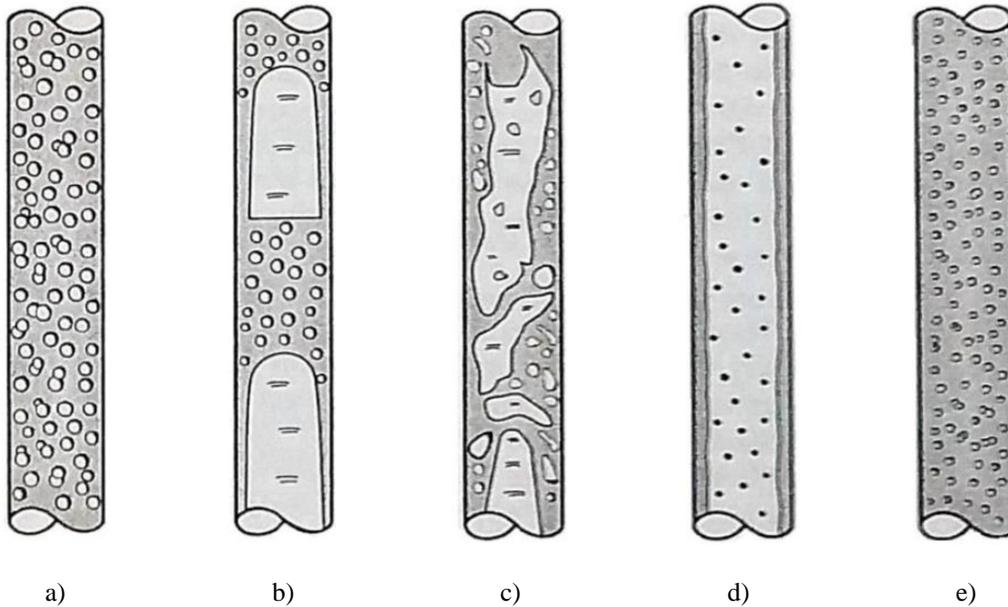


Figure 3. Vertical gas-liquid flow patterns: a) Bubble pattern, b) Slug pattern, c) Churn pattern, d) Annular pattern, e) Finely dispersed bubbles pattern.
Source: (Rocha, 2016)

2. METHODOLOGY

An experimental apparatus must be designed and subsequently built with the objective of collecting data of structural behavior of the transition similar to the valve in terms of displacement and acceleration. In this sense, instruments such as strain-gauges and accelerometers should be considered.

With respect to the fluids, it is intended to use dense gas (SF_6) and oil and the LEMI's multiphase flow loop. It must be assured that the intermittent flow pattern (slug flow) is present in situ, since in practice it has been shown that this flow pattern is more aggressive to the structures.

It is also interesting to comment that, due to the large dimensions of the valve and considering the difficulty of accessing it by the company, a study of dynamic similarity of both structure and flow is to be carried out. This with the purpose of scaling up, solving the problem using models for the structure and two-phase flow and later extrapolating the results to full scale. Therefore, Buckingham's π Theorem is used.

3. PRELIMINARY RESULTS

Some preliminary results associated with the flow dynamic similarity are shown in Table 1, where real data from oil wells were used under an operating condition considered as catastrophic, since this situation is the most critical.

Note that for the dynamic similarity to be guaranteed, the Reynolds number must be maintained for both the model and the prototype (real device), because in this way the phenomena are equally comparable. The Mach number is another one that should be considered, as compressibility effects are likely to occur as well.

Table 1. Similarity of dynamic flow for a catastrophic situation.

| Parameter | Oil Well | Dense Gas (SF_6) |
|-------------------------------------|--------------------|-----------------------------|
| Diameter (m) | 0.1270 | 0.0508 |
| Flow rate (m^3/s) | 0.1104 | 0.0044 |
| Pressure (kPa) | 27,210 | 910 |
| Temperature ($^{\circ}\text{C}$) | 50 | 27.5 |
| Density (kg/m^3) | 850 | 70 |
| Viscosity (Pa s) | 2×10^{-3} | 1.58×10^{-5} |
| Reynolds number (-) | 470,397 | 470,3397 |

On the other hand, the part related to the structural dynamic similarity is still under development, which must be consistent with the dynamic flow similarity. However, a proposal is made and presented below that considers the most important physical variables of the problem.

3.1 Proposal Dynamic Similarity Two-phase flow/Structural

The objective of this section is to present a proposal on dynamic similarity relating both structural and two-phase flow phenomena at the same time. In this context, the determination of dimensionless parameters is essential for design experimental tests that will permit to predict the behavior of a prototype from the behavior of a model. Consequently, geometric, kinematic and dynamic conditions must be guaranteed to adequately scale the problem (Çengel and Cimbala, 2006).

Thus, between the variables considered important in this problem are:

Table 2. Parameters that influence the physics of the problem.

| Variable | Nomenclature | Unit |
|------------------------|--------------|-------------------|
| Length | L | L |
| Transversal area | A_s | L^2 |
| Density of material | ρ_M | $M L^{-3}$ |
| Moment of inertia | I | L^4 |
| Modulus of elasticity | E | $M L^{-1} T^{-2}$ |
| Amplitude of vibration | A | L |
| Gravity | g | $L T^{-2}$ |
| Frequency | ω | T^{-1} |
| Damping | ξ | 1 |
| Dynamic viscosity | μ_F | $M L^{-1} T^{-1}$ |
| Density of fluid | ρ_F | $M L^{-3}$ |
| Inner diameter | D_i | L |
| Flow velocity | j_F | $L T^{-1}$ |

Table 2 shows a total of 13 variables between structural properties as well as those associated with flow. So, since there are 3 different units of measurement in this problem (mass, length and time), the total number of π parameters obtained are 10. Subsequently, the solution may be expressed how:

$$f(\pi_1, \pi_2, \pi_3, \pi_4, \pi_5, \pi_6, \pi_7, \pi_8, \pi_9, \pi_{10}) = 0, \quad (1)$$

Therefore, we have:

Table 3. π parameters resulting from dimensional analysis.

| Dimensionless Parameters | |
|--|---|
| $\pi_1 = L A_s^{-1/2}$ | $\pi_6 = \xi$ |
| $\pi_2 = I A_s^{-2}$ | $\pi_7 = \mu_F E^{-1/2} \rho_M^{-1/2} A_s^{-1/2}$ |
| $\pi_3 = A A_s^{-1/2}$ | $\pi_8 = \rho_F \rho_M^{-1}$ |
| $\pi_4 = \rho_M A_s^{1/2} g E^{-1}$ | $\pi_9 = D_i A_s^{-1/2}$ |
| $\pi_5 = \rho_M^{1/2} A_s^{1/2} E^{-1/2} \omega$ | $\pi_{10} = \rho_M^{1/2} j_F E^{-1/2}$ |

Note that, the Reynolds number did not appear among the π parameters obtained from dimensional analysis. Nevertheless, this parameter is considered extremely relevant for scale phenomena related to fluids flow. It is for this reason that, the Reynolds number is added to the π parameters presented in the Table 3 for determine the characteristics of the model, but with caution because the appearance of errors in the development of the method used is likely. Hence, it will necessary to find a point of equilibrium that allow to properly define the physical dimensions of the model and the flow conditions.

Now, considering typical conditions in oil/gas wells to perform the calculations, it follows:

Table 4. Variables of prototype.

| Variable | Quantity | Unit |
|---|-----------------------|-------------------|
| Modulus of elasticity (E) | 200 | GPa |
| Density of material (ρ_M) | 7,850 | kg/m ³ |
| External diameter (D_{ext}) | 0.1670 | m |
| Inner diameter (D_{int}) | 0.1270 | m |
| Length (L) | 6 | m |
| Density of fluids (ρ_F) | 663 | kg/m ³ |
| Dynamic viscosity of fluids (μ_F) | 1.20×10^{-3} | Pa s |
| Kinematic Viscosity of fluids (ν_F) | 1.80×10^{-6} | m ² /s |
| Flow velocity (j_F) | 0.4372 | m/s |
| Reynolds number (Re) | 30,677 | - |

To simplify the analysis, the geometry of the prototype is approximated a straight cylinder of constant length and diameter and it is assumed that the valve is constructed mainly of steel, hence the properties corresponding to the modulus of elasticity (E) and density (ρ_M) have referred to said material. Regarding the flow of fluids, the values of density, velocity, and viscosity were taken from average values of oil and gas production as previously mentioned.

According to the similarity theory, ideally all magnitudes of the dimensionless parameters must be guaranteed between the prototype and the model, however, this cannot always be covered. For example, as there is information associated with the original valve in terms of vibration, the parameters π_3 , π_5 and π_6 cannot be calculated.

In this context, the other parameters are calculated without problems since they only relate geometry and flow conditions. Nevertheless, it is important to remember that the Reynolds number will be include too for the reasons previously discussed.

In this way, utilized the equations list in the Table 3, and after to analyzing 17 different materials, the following results are reached for the copper alloy C83400 (which performs better under stated conditions):

Table 5. Results of model sizing.

| | | |
|---|-----------------------|-------------------|
| Modulus of elasticity (E) | 101 | GPa |
| Density of material (ρ_M) | 8,740 | kg/m ³ |
| External diameter (D_{ext}) | 0.0679 | m |
| Inner diameter (D_{int}) | 0.0508 | m |
| Length (L) | 2.5 | m |
| Density of fluids (ρ_F) | 738.16 | kg/m ³ |
| Dynamic viscosity of fluids (μ_F) | 3.60×10^{-4} | Pa s |
| Kinematic Viscosity of fluids (ν_F) | 4.87×10^{-7} | m ² /s |
| Flow velocity (j_F) | 0.2944 | m/s |
| Reynolds number (Re) | 30,677 | - |

Now, in the following figure (see Figure 4) a diagram of model is presented, which must be built to be mounted on the experimental bench to be able to carry out the fluid/structural tests. Note that, in this model did not be considered the flapper of the original valve (see Figure 1), however, that element will be included in the moment of construction of the model because it is believed that a rapid close test is really important for to determine the aggressivity of fluid when the valve is closed. In addition, it is interesting to mention that in the model (see Figure 4) a restriction was included to produce the acceleration of the fluid as it is done in the original valve, at instant in which the fluid enters it.

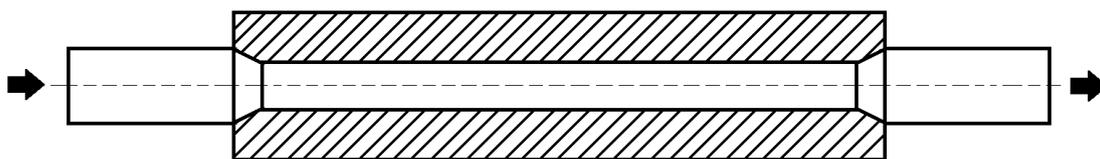


Figure 4. Valve DHSV model.

Finally, to have an idea about of errors obtained in the calculate of the sizing between prototype and model, it is important to mention that the parameter π_4 was the one that presented the greatest error with 8.14%, followed by parameter π_2 that presented an error of 5.75%. All the others had lower errors.

4. CONCLUSIONS

In this work an analysis was presented that will allow to determine in a practical way, the relationship between a two-phase flow and the mechanical vibrations produced in a safety valve (DHSV) installed in Offshore oil wells. To this end, efforts will focus on devising an experimental bench on a small scale, which will allow experiments to be carried out at the LEMI at the University of Sao Paulo, Brazil. In this context, studies of structural and flow similarity were considered to guarantee the extrapolation of results at real scale. However, it is important to understand that the calculations presented in this work are preliminary and they are subject to eventual adjustments because it will depend, among other things, on the physical reality of the experimental bench in the laboratory.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

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