Safety Evaluation of Orifice Plate in Natural Gas Pipeline using Computer Aided Engineering (CAE): A Step Towards Food Security

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Abstract

Understanding the potential causes and consequences of orifice plate failure is essential for maintaining accurate flow measurement and preventing operational disturbances. In certain cases, Fluid Structure Interaction (FSI) problem is bound to occur overtime due to fluid pressure such as buckling failure can occur in orifice plates, leading to inaccurate flow measurements and potential safety hazards. orifice plates can easily fail leading to partial or complete shutdown of the entire line which in some cases could be a major line, leading to slow output from the industry. Therefore, this study focuses on the evaluation of orifice plate performance and safety in natural gas pipelines utilizing computer-aided engineering (CAE). The orifices were modeled with Solidworks and simulated with Midas NFX using two ways FSI interface of the software. The investigation was conducted for 10,800 seconds in CFD component and 100 seconds for 60 steps in FEA component of the FSI. The buckling load factor of the orifice plates were 1.1317, 0.5056 and 0.200 for 101.6 mm, 127 mm and 152.4 mm orifice plates respectively and a predicted service life of 501 days, 235 days and 195 days for the orifice plates, respectively, The validation with data from the real plant show that the prediction was about 90% accurate.

Keywords: Orifice, buckling, fluid structure interaction, buckling load factor, deformation.

1.0 Introduction

Orifice plates play a crucial role in fluid dynamics, allowing for precise measurement and control of fluid flow rates across a wide range of industries. However, like any mechanical component, orifice plates can fail over time or under certain conditions. Understanding the potential causes and consequences of orifice plate failure is essential for maintaining accurate flow measurement and preventing operational disturbances [1]. In certain cases, Fluid-Structure Interaction (FSI) problems are bound to occur over time due to fluid pressure, such as buckling failure, which can lead to inaccurate flow measurements and potential safety hazards. This paper aims to perform a performance and safety evaluation in relation to buckling failure in orifice plates and proposes mitigation strategies to prevent such failures. The FSI interface of Midas NFX software was used for the performance and safety evaluation to check the structural integrity and deformation over time.

The failure of orifice plates due to buckling has become an increasingly concerning issue in various industries where accurate flow measurement is critical. Buckling occurs when external forces cause the plate to deform and collapse, which can lead to inaccurate readings, reduced performance, and potential safety risks [2]. The causes of orifice plate buckling are complex and multifaceted. They can result from a combination of factors including excessive pressure differentials, temperature fluctuations, fluid properties, improper installation, and insufficient support. Additionally, variations in manufacturing techniques, material selection, and design specifications add further complexity to the problem, making it difficult to implement a one-size-fits-all solution [3].

The orifice plate had failed several times, leading to a partial or complete shutdown of the entire line, which in some cases is a major line, leading to slow output from the industry until it is replaced with a foreign one. The natural gas flow consists of three (3) lines of flow, namely lines A, B, and C, with volumetric flow rates of 30 MMSCF/d (8.6 kg/s), 80 MMSCF/d (22.90 kg/s), and 250 MMSCF/d (71.541 kg/s) respectively.

The failure of orifice plates due to buckling has increasingly become a concerning issue in various industries where flow measurement is critical. Buckling occurs when external forces cause the plate to deform and collapse, leading to inaccurate readings, decreased performance, and potential safety risks [4]. Therefore, understanding the causes of orifice plate buckling and developing effective mitigation strategies are imperative to ensure reliable and efficient flow measurement operations.

Taheri et al. in 2021 studied the optimized multi-hole orifices using FSI software and they concluded that a multi-hole orifice plate is better than a single orifice plate in terms of performance [2]. In their investigations,

buckling was not studied but flows through orifice plates. Guangdong Yang et al. in their work published in 2023 investigated the blast resistance of orifice targets subjected to underwater explosions through field tests and numerical simulations [5]. They investigated and validated parameters such as blast pressure, structural deformation, and damages. Parameters like explosive mass, detonation location, orifice plate, steel reinforcement, and concrete strength on the resistance of the orifice targets were also studied. However, their work was not on natural gas pipeline buckling failure of orifice plates.

Syed et al. in 2023 modeled the dynamics of the human cardiovascular system using fluid-structure interaction models to simulate blood circulation in the human body [6]. According to them, this will help in treatment plans for patients. The use of FSI has been applied not only in the field of engineering but also in medicine for human treatment. In an independent work, Lars Davidson in 2022 provided insights into modeling turbulence in CFD, which is very much useful in this investigation involving natural gas flow, as gas flows are naturally turbulent [7].

Sravani and Santhosh in 2022 studied the dynamics of flow measurement, effects caused on the measurement due to variation in a physical dimension of the orifice like thickness of orifice plate, orifice-hole diameter, number of holes, fluids type, position, and type of plate using FSI but not in relation to buckling in gas flow [8].

In the work of Tukiman et al. in 2017, commercial Computational Fluid Dynamics (CFD) was used to predict the flow features in the orifice flow meter [3]. The center point of the research work was the visualization of the velocity and pressure profiles for that particular pipe flow and also the location of the vena-contracta. Their studies were said to be in agreement with the published data in terms of flow pattern, velocity profiles, and pressure profile. It is believed that flow physics, such as the location of the vena contracta and characteristic length and velocity scales in orifice flow, are very interesting for researchers and engineers in the study of flow metering, particularly the effects of the ratio on these flow physics.

It is also concluded that the CFD technique can be used as an alternative and cost-effective tool towards the replacement of experiments required for estimating discharge coefficient, empirically [9]. In some other cases, such as ours where the concentric Orifice plate is being used to control the flow of natural gas into an equipment, there is a need to monitor the orifice plate to know when it starts failing for immediate replacement to avoid complete failure, which will cause more damages. The orifice plate had failed several times, leading to the shutdown of the entire line, which in some cases is a major line, leading to slow output from the industry until it is replaced with a foreign one. The orifice was fabricated locally, and there is a need for us to determine the deformation for a period of time and predict when it will likely fail with the aid of Computational Fluid Dynamics (CFD) software. The use of Computer-Aided Engineering (CAE) is a disposable tool in the hands of engineers for design, simulation, and analysis before hitting the ground for manufacturing. Virtual manufacturing laboratory works have been proven to be over 80% accurate and thereby reduce design time, eliminate waste of material, and ultimately save costs as confirmed by other researchers in the field [2]. However, David Ferras et al. in 2018 argued that Fluid–Structure Interaction is a case-dependent problem; there is no general solution or numerical model capable of describing and simulating any pipe setup [10]. Some setups have been predicted to about 80% accuracy by modern CFD software using RANS-based models. Experiences and a good knowledge of the fluid governing equations or theories will go a long way in getting a close-to-reality setup.

In 2015, Karthik et al. used ANSYS fluent, a commercial CFD software, to calculate the discharge coefficient (Cd) of orifice plates of different thicknesses ranging from 3 mm, 5 mm, 10 mm, and 15 mm, and they concluded that the results were in agreement with experimentally measured ones [11]. Similarly, Manu et al. in 2019, in their work on the orifice using CFD software, calculated the discharge coefficient (Cd) and pressure loss coefficient (Cl) among other parameters which they concluded to be well-compared with experimentally determined values [12]. These further prove the efficiency of CFD software in process industries involving flows.

In a separate research work, Nathan da Costa Maidana and Eugênio Spanó Rosa in 2017 experimentally studied the pressure drop induced by an orifice plate on multiphase (air and water) flow in a horizontal pipe in the slug regime [13]. Their work pointed out that, like a single-phase flow, there is a fluctuating pressure drop about a mean value which is confirmed by the nature of the pressure–time plot from CFD studies. Multiphase flows in a pipe have been studied using CFD software but with respect to orifice plate studies. In the same year, Dhumal et al. in 2017 investigated the key factors affecting Multi-hole Orifice throttle or flow control characteristics with CFD and developed a general multi-hole orifice design method and applied this procedure in throttle experiments [14]. They conducted a series of throttle tests in water flow to investigate the effect of various geometric features on the pressure loss characteristics of multi-hole orifice plates. They concluded that the five (5)-hole multi-hole orifice gave the best results in terms of pressure drop measurements.

One type of failure is buckling, meaning sudden lateral deformation of a slender structure when subjected to excessive axial compressive stress or a plate subjected to pressure loading. Buckling analysis is used to determine the critical load factors of a structure and their corresponding buckling mode shapes. However, buckling of an orifice plate in a fluid flow pipe is subjected to pressure from the fluid along the direction of its flow and also loads (pressure) from the swirling back of some fluid elements in the flow fields as it passes through the orifice. In this work, various hole diameters and flow rates were investigated.

2.0 Materials and Methods

The materials, equipment and instruments employed for experimental investigation are shown in the Table 1. The methodology involves the component: experiment (data acquisition), modeling and simulation and optimization,

Table 1: List of materials/equipment, manufacturer/model and their sources

Materials/Equipment	Manufacturer/Model	Source
(Restriction Orifice Plate) RO	Fischer Connectors/ Fischer Sintoflow S40S-001	DPR
Flow meter	Omega Engineering Inc./ Omega FMA-A203	DPR
Pressure Gauge	Ashcroft Inc./Ashcroft 1179G-30-R-P-B	DPR
Differential Pressure Gauge	Ashcroft Inc./Ashcroft E2HP200S-020	DPR
HPC (High-Performance Computing)	Dell Technologies/ Dell PowerEdge C4140	NEDDI-NASENI
Solidworks Software	Dassault Systemes/Solidworks 2022	NEDDI-NASENI
Midas NFX Software	Midas I.T. Co. ltd (South Korea)/ 2022	FAZSAL Nigeria ltd

2.1 Modelling

The required data for the investigation, validation and optimization with the aid of Computer Aided Engineering (CAE) was obtained from the plant. The data were read and recorded by the assistance of an operator from three different lines identified as line A, B and C with different flow conditions in terms of flow rates, pressure drop and restriction orifice plates of diameter 101.4 mm, 127 mm and 152.4 mm respectively but with the same buckling problem. The data are shown in the table2.

Table 2: Plant data about the orifice plate

	Line A	Line B	Line C
Fluid	Natural Gas	Natural Gas	Natural Gas
Orifice	4 in (101.6 mm)	5 in (127 mm)	6 in (152.4 mm)
ΔP	22, 660 Pa (3.23 PSI)	36, 750 Pa (5.33 PSI)	41,682 Pa (6.05 PSI)
Flow Rate	30 MMSCF/d (8.585 kg/s)	80 MMSCF/d (22.90kg/s)	250 MMSCF/d (71.541 mm)
Max. Deflection	0.952 mm	0.5948 mm	0.5622 mm
Pipe ID	300 mm	300 mm	300 mm
Plate Material	Stainless steel	Stainless steel	Stainless steel
Outer Cover	Teflon	Teflon	Teflon

The concentric orifice was modeled with a hole at the center and simulated with Midas NFX, and it is fitted in between two pipes where the Natural gas flows. The concentric orifices have central hole diameters of 4 inches (101.6 mm), 5 inches (127 mm), and 6 inches (152.4 mm) and with Natural gas volumetric flows of 30 MMSCF/d (8.585 kg/s), 80 MMSCF/d (22.90 kg/s), and 250 MMSCF/d (71.541 kg/s) respectively. The orifices were of the same thickness (2 mm) and external diameter except for the central hole diameter that differs. The simulation involves two major operations, i.e., Fluid Flow (Computational Fluid Dynamics (CFD) and nonlinear Buckling Analysis with the help of Fluid Structure Interface (FSI)). The flow rate was the input for the CFD, while the resulting pressure from the CFD serves as the input to the Buckling Analysis. The FSI is a two-way interaction with the approach of partition in which both the effect of the fluid on the structure and that of the deformed structure on the fluid are investigated simultaneously. Nonlinear Quasi-Static analysis was used as the analysis type with one hundred (100) seconds as time duration and 60 steps, which amount to one minute, forty-second investigation. The fluid flow investigation was a transient type. The pressure from the fluid flow served as the load on the orifice to investigate its buckling possibility with the aid of Fluid Structure Interaction (FSI) with Midas NFX. The material (stainless steel) for the orifice plate analysis was used to compare the resistance or reluctance to deformations due to the pressures. The outer part, which is made of Teflon, was connected with the plate, which is a metallic alloy, using auto-connect and auto-contact (welded contact) so as to make it a component for the analysis. The geometry was analyzed along the plane of symmetry for better results and to save computing time. The most ideal model for compressible fluids (natural gas) was chosen as the k-ϵ model [12]. The outer wall type was selected to be no-slip. The pressures were tapped at a distance of D upstream and D/2 downstream in accordance with ISO – 5167 standards as shown in Fig. 3. The fluid composition used is presented in Table 3.2

below. The analysis was however preceded by conducting a Grid Independency Test (GIT) to determine the minimum mesh density for accurate results.

Figure 1: (a) Plan picture of the concentric orifice plate, (b) Side picture of the concentric orifice plate
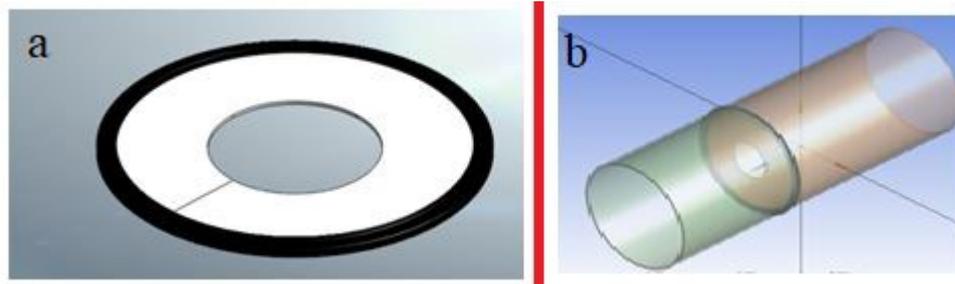

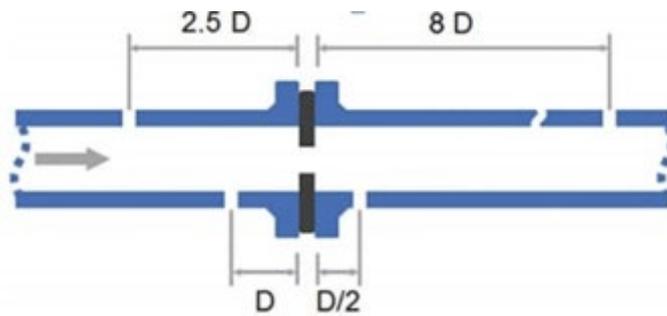Figure 2: **(a)** Model of the concentric orifice plate, (b) Model of the concentric orifice plate in the pipe

Figure 3: Location of plate and tapping location

2.2 Grid Independent Test (GIT)

Grid Independency test is very good to ensure accurate results from simulations. Several GITs were performed on computational fluid Domains containing the orifice plate. It was found that a minimum of 11,929 nodes and 58,585 tetrahedral and prism elements were sufficient to provide accurate results.
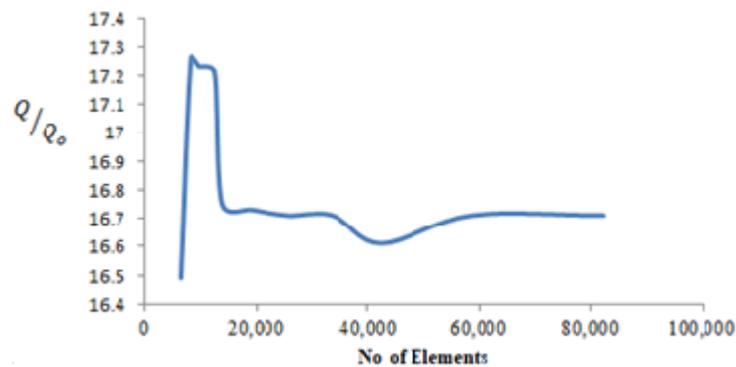

Figure 4: Grid independency test

The analysis was first carried out with the plate original design and dimension to study the flow and failure mode.
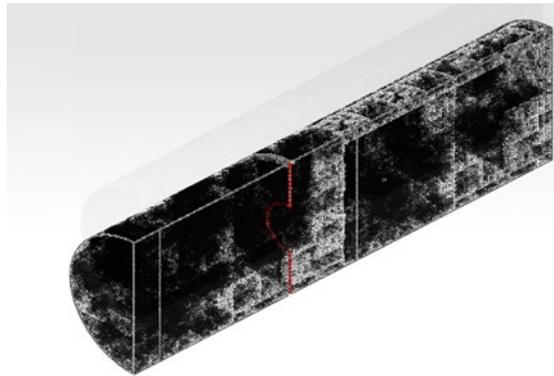

Figure 5: Mesh Density over the CAD domain

The grid independency test is necessary to strike a balance between cost (Computing time, space requirement, and hardware) and good results.

2.3 Governing Equations

The basis of CFD is rooted in the solution to the Navier-Stoke Equation (NSE) within the physical geometry and context. With the assumptions that fluids are Newtonian, incompressible and isothermal.

$$\varrho\left(\frac{\partial u}{\partial t} + (u.\nabla)u\right) = -\nabla p + \mu\nabla^2 u + F \qquad (1)$$

where ϱ – density, u --- fluid velocity, p – pressure, μ – fluid dynamic viscosity, F – external forces.

Equation 1 above mean that inertia forces = Pressure forces + Viscous forces + External forces. The equation can be defined for a compressible and incompressible flow and the negative sign indicate that the fluid flow in the direction of pressure drop (Notebook).

The FEA use a number of equations for the evaluation of the deformation, stress distribution etc. Such equation include the Hooke's law F=Ku   (2)

Other equations include the basic equations for stress and strain calculations using von-mises model.

$$\text{Stress } (\delta) = \left(\frac{F}{A_o}\right) \qquad (3)$$

$$\text{Strain } (\epsilon) = \left(\frac{\Delta L}{L_O}\right) \qquad (4)$$

In nonlinear analysis case, the load can be divided in several load steps and the equation 5 is used for each load step to find displacement.

$$\Delta F = [Kx][\Delta U] \qquad (5)$$

3.0 Results and Discussion

Table 3: Comparison of The Plant data against Simulated Results

	Design/Operating Conditions			Simulated Result		
	FLOW Rate (MMSCF/d)	ΔP (Pa)	Max. Deflection/ Buckling (mm)	ΔP (Pa)	Deviation	% Error
4 inches (101.6 mm)	30	22,660 (3.3 psi)	0.952	24,300 (3.5 psi)	-1,640	-7.2374
5 inches (127 mm)	80	36,750 (5.33 psi)	0.5948	33,700 (4.9 psi)	3,050	8.2993
6 inches (152.4 mm)	250	41,682 (6 psi)	0.5622	40,600 (5.9 psi)	1,082	2.5958

The analysis was first carried out with the data from the plant about the orifice plate and process conditions to make a validation and also to investigate the failure of the orifice plates due to buckling. Table 3 shows the comparison of the data obtained from the plant and the simulated results from Midas NFX. The three orifice

plates were investigated independently using the FSI interface of Midas NFX with the flow rate as the input. The pressure drop across the plates from the simulated work is compared to that of the plant where the 101.4 mm orifice plate with a flow rate of 30 MMSCF/d showed a pressure drop of 24,300 Pa compared to that from the plant which is 22,660 Pa, representing a -7.237% deviation. The 127 mm orifice plate with a flow of 80 MMSCF/d returned a pressure drop of 33,700 Pa compared to 36,750 Pa from the plant, which is an 8.29% deviation from the real-life scenario, and the 6-inch orifice plate with the flow of 250 MMSCF/d with a simulated pressure drop of 40,600 Pa as against the plant's pressure drop of 41,680 Pa, representing a deviation of 2.59% from the real-life scenario. With less than 10% deviation, this proves that the simulated work is very close to reality and can predict the FSI behaviors of the plant to over 90% accuracy.

Table 4: Results of the Analysis for Plates under various flow conditions

Stainless Steel			
	101.4 mm Hole Diameter	127 mm Hole Diameter	152.4 mm Hole Diameter
Max deflection (mm)	0.952	0.5948	0.5622
Pressure Drop (ΔP) (Pa)	22,660	36,750	41,682
Stress (Pa)	102.154	180.008	335.074
Strain	4.1510×10^{-10}	7.3146×10^{-10}	1.3616×10^{-9}
Simulated Pressure Drop (MPa)	24,300	33,700	40,600
Deflection (mm)	2.6634×10^{-7}	3.3172×10^{-7}	3.5779×10^{-7}
Rate of Deflection (mm/s)	2.1974×10^{-8}	2.9301×10^{-8}	3.3370×10^{-8}
BLF	1.1317	0.5056	0.200
Expected service life (Days)	501	235	195

The investigation using FSI for 10,800 sec (3 hours) under various flow rates for the 101.4 mm, 127 mm and 152.4 mm orifice plates maximum deformation/deflection of 2.6634×10^{-7} mm, 3.3172×10^{-7} mm and 3.5779×10^{-7} mm respectively for the period as shown in table 4. The plate with 6 inch orifice shows the maximum deformation over same time. This is not unconnected to its flow condition being the highest with a value of 250 MMSCF/d and also recording the highest stress and strain with value of 335.074 Pa and 1.3616×10^{-9} while the 4 inch have the least stress and strain value as shown in the table 3.2 above.

The buckling load factor which is the ratio of critical load to applied load show the level of instability of the orifice plates with the value of 1.1317, 0.5056 and 0.200 for 101.4 mm, 127 mm and 152.4 mm orifice plates respectively. The value of 1.1317 for the 101.4 mm show that the critical load is just equal to the applied load confirming its instability and easily fail with a little surge in pressure. The 101.4 mm and 152.4 mm have 0.5 and 0.2 BLF which can easily fail and need constant monitoring.

The results from Midas NFX FSI model were to predict service life of 501 days, 235 days and 195 days for the 101.4 mm, 127 mm and 152.4 mm orifice plate respectively. This is to help the operators in constant monitoring and replacement to avoid shutdown of any line or even the entire for failure and to eliminate the potential hazards it constitutes to both staffs and environment in the case of sudden failure. The Fig 6a and b shows the BLF and expected service life for the orifice plates.
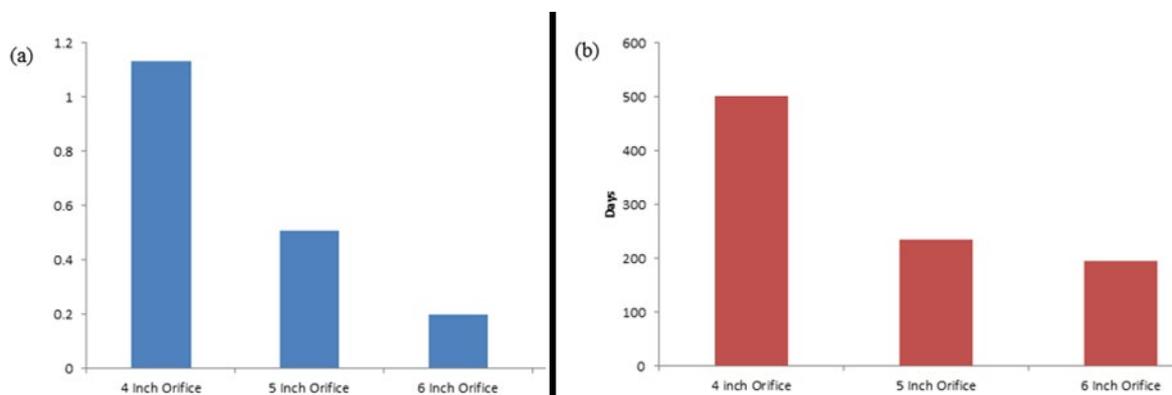

Figure 6: (a) BLF comparison chart; (b) Expected service life of the orifice plates

The deformed velocity profile has consequences on its precision as a little deformation on the plate will correspondingly alter the location of the vena contracta whose position is pivotal to measuring accuracy and targeted pressure drop when used for measurement. The position of vena contracta is so important that pressure sensors are always positioned there for accurate and precise measurement. It can be observed from the studies that the orifice plate is very sensitive to deflection/ deformation even when it occurs in a Nano scale which further confirms the indispensability of computer aided engineering as disposable tools to investigate such a small changes.
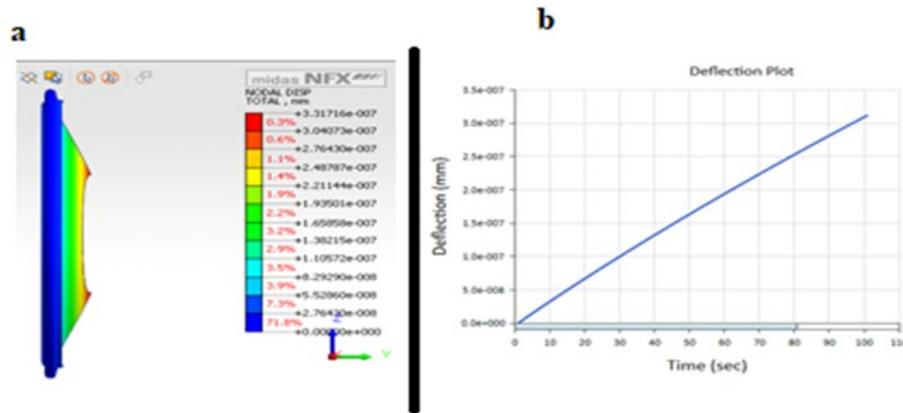

Figure 7: (a) Deformed 101.4 mm orifice, (b) Deflection – time plot for 101.4 mm orifice plate
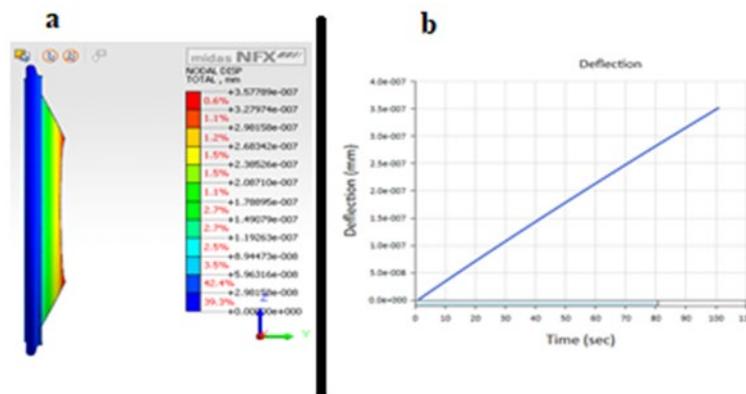

Figure 8: (a) Deformed 127 mm orifice plate, (b) Deflection – time plot for 127 mm orifice plate
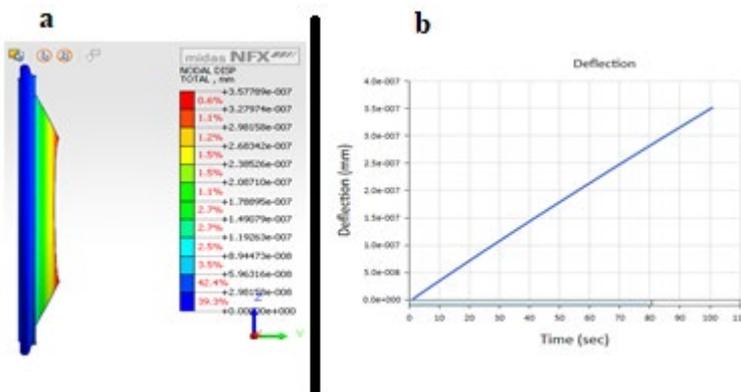

Figure 9: (a) Deformed 152.4 mm Orifice, (b) Deflection – Time Plot for 152.4 mm Orifice Plate

The structural deformation was accounted for by the Finite Element Analysis on the plate continuous deformation with time which shown in Fig7b, 8b and 9b respectively while fig 8a. 9a and 10a show the maximum deformation at the end of the analysis with percentage of the total surface area of the plate affected by the deformation. The 101.4 mm show the least deformation of value 2.6634×10^{-7} mm affecting 21.60% of the surface area of the plate, while the 127 mm orifice plate has a deformation of 3.3172×10^{-7} mm covering 18.80% of the orifice plate total surface area and the 152.4 mm orifice plate deformed by 3.5779×10^{-7} mm affecting 18.30% of the plate surface area.

4.0 Conclusion

This study comprehensively evaluates orifice plates' performance and safety under various flow conditions, meticulously finding that simulated pressure drops remarkably match real-life data with less than 10% deviation, thereby validating the accuracy of the simulation model, and larger diameter plates experience more pronounced deformation and stress due to increased flow rates, while all plates are inherently prone to failure, with smaller plates being more critically unstable due to their buckling load factors, and the service life of plates is predictively modeled, highlighting the paramount importance of precise measurement and advanced computer-aided engineering in orifice plate design, development, and continuous monitoring to ensure optimal performance and prevent potential failures.

The study advances knowledge by proposing a two-ways fluid-structure interaction (FSI) software in performance, Safety and Failure Evaluation of process equipment in Industries to improve simulation accuracy while reducing computational cost. The study addresses key factors in industrial problem investigations relating to buckling such as the estimation of buckling load factors for orifice plates in Natural gas pipelines to serve as guide to operators/ designers for effective and efficient operations and estimation of orifice plates service life to serve as a guide for replacement or maintenance to avoid total failure which can be very disastrous. The buckling load factor (BLF) of the orifice plates were 1.1317, 0.5056 and 0.200 for 4- inch, 5- inch and 6- inch orifice plates respectively and a predicted service life of 501 days, 235 days and 195 days for the 4- inch, 5- inch and 6- inch orifice plate respectively serving as a perfect guide to its replacement before failure.

The results from the investigation when compared with real life scenario from the existing plant achieving less than 10 % deviations. The optimized plate boosts the plates performance by increasing the critical buckling pressure by 5%. The traditional design relies on trial-and-error; this is the first systematic FSI- based optimization for orifice plates to prevent catastrophic failures and gas pipelines thereby ensuring safety and saving cost.

This work also contributes to the fundamental knowledge in orifice plates fabrication by suggestion of other materials with high corrosion resistance and high yield strength as an alternative to commonly used stainless steel for orifice plate fabrication coupled with an ideal plate thickness of 5 mm for this particular case to avoid choking condition.

Suggestion of an alarming system or real time monitoring devices to help know when an orifice plate under investigation is about to fail for quick attention as it is always out of sight.

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