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Performance and Failure Evaluation of Orifice Plate in Natural Gas Pipeline using Computer Aided Engineering (CAE)

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Abstract

The knowledge of the potential causes and consequences of orifice plate failure is essential for maintaing accurate flow measurement and preventing operational disturbances. In some cases, Fluid Structure Interaction (FSI) problem is bound to occur overtime due to fluid pressure such as buckling failure do occur in orifice plates, leading to inaccurate flow measurements and potential safety hazards. The orifice plate had failed several times leading to partial or complete shutdown of the entire line which in some cases is a major line, leading to slow output from the industry till it is replaced with foreign one. 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 shows that the prediction was about 90% accurate.

Keywords: Orifice Plate, Buckling, Fluid Structure Interaction, Buckling Load Factor, Safety Evaluation

1.1 Introduction

Orifice plates play a crucial role in fluid dynamics, allowing for precise measurement and control of fluid flow rates in pipelines used across a wide range of industries. However, like any mechanical component, orifice plates can fail over time or under certain conditions. Knowledge of the potential causes and consequences of orifice plate failure is essential for maintaining accurate flow measurement and preventing operational disturbances (M. D. Shel 2020). In some 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. This paper aims to do 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.

1.2 Problem Statement

The idea of this work stemmed from a Port Harcourt based client who sought for assistance on the design, evaluation and prediction of the likely failure time and equally fabricate an orifice plate locally for a natural gas plant lines as the foreign ones keep failing within short period of service life.

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The failure in orifice plates due to buckling has increasingly become a major problem 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 (Burkhardt, 2018). Therefore, understanding the causes of orifice plate buckling and developing effective mitigation strategies are imperative to ensure reliable and efficient flow measurement operations.

1.3 Related Works

Karthik *et al.,(2015)* used ANSYS fluent, a commercial CFD software to calculate the discharge coefficient (C_d) of orifice plates of different thicknesses ranging from 3 mm, 5 mm, 10 mm, and 15 mm and concluded that the results was in agreement with the ones experimentally measured.

Nathan and Eugênio,(2017) experimentally studied the pressure drop induced by an orifice plate on multiphase (air and water) flow in a horizontal pipe in slug regime. The work showed that as a single phase flow there is a fluctuating pressure drop about a mean value which is confirmed by the nature of pressure – time plot from CFD studies. Multiphase flows in a pipe have been studied using CFD software but with respect to orifice plate studies.

Dhumal et al,(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. Series of throttle tests were conducted in water flow to investigate the effect of various geometric features on the pressure loss characteristics of multi hole orifice plates. The conclusion was that Five(5)hole of multi-hole orifice gave the best results in terms in terms of pressure drop measurements.

Tukiman et al., (2017) used commercial Computational Fluid Dynamics (CFD) to predict the flow features in the orifice flow meter. The center point of the research work was the visualization of the velocity, pressure profiles for that particular pipe flow and also the location of the vena-contracta. The studies were in tandem 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 the flow physics.

It is also concluded that the CFD technique can be used as an alternative and cost-effective tool towards replacement of experiments required for estimating discharge coefficient, empirically (Karthik et al.,2018). In some other cases such as this where the concentric Orifice plate was used to control flow of natural gas into an equipment, and the need to monitor the orifice plate to know when it starts failing for immediate replacement to avoid complete failure which would cause more damages. The orifice plate had failed several times leading to shutdown of the entire line which in some cases was a major line, leading to slow output from the industry till replacement with foreign one. The orifice was fabricated locally and the need 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) as a disposable tool in the hands of engineers for design, simulation, and analysis before hitting ground for manufacturing. Virtual manufacturing laboratory works had 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.

David et al (2018) argued that Fluid–Structure Interaction was a case-dependent problem; there was no general solution or numerical model capable of describing and simulating any pipe setup.

Some setups have been predicted to about 80% accuracy by the 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 get a close to reality set up.

Manu B. V. et al., (2019), work on orifice using CFD software calculated the discharge coefficient (Cd) and pressure loss coefficient (Cl) among other parameters, and concluded to be well compared with experimentally determined values. These further proved the efficiency of CFD software in process industries involving flows.

Taheri et al (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. In their investigations, buckling was not studied but flows through orifice plates.

Faiz S. et al.,(2022) modeled the dynamics of human cardiovascular system using fluid structure interaction models to simulate the blood circulation in human body. The results obtained could be applied in treatment plans for patients. The use of FSI has been applied not only in field of engineering but also in medicines for human treatment.

Lars Davidson, (2022) provided insights in modeling turbulence in CFD which was very much useful in the investigation involving Natural gas flow as gas flows are naturally turbulent

Sravani and Santhosh (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 in relation to buckling in gas flow.

Guangdong. et al (2023) investigated the blast resistance of orifice targets subjected to under water explosions through field tests and numerical simulations. They investigated and validated parameters such as blast pressure, structural deformation and damages. Parameters like explosive mass, detonation location, orifice plate, steel reinforcement and contrite strength on the resistance of the orifice targets were also studied. However, the work was not natural gas pipeline buckling failure of orifice plate.

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

2.0 Material and Method

2.1 Materials

The materials, equipment and instruments employed for experimental investigation are shown in the table 1 below.

Table1: List of Materials/Equipment, Manufacturer/Model and their Source

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

The methodology involve the component: experiment (data acquisition), modeling and simulation and optimization

2.2: Experiment (data acquisition)

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 Table 2 below.

Table2: 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

2.1 Simulation Set up and Boundary (Methodology)

The concentric orifice was modeled with hole at the center and simulated with Midas NFX and it was fitted in between two pipes where the Natural gas flows. The concentric orifices have central holes 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 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 was 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 were 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 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 to compare the resistant or reluctant to deformations due to the pressures. The outer part made of Teflon connected with the plate which is 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 plane of symmetry for better results, and to save computing time. The most ideal model for compressible fluids (natural gas) was chosen k- ϵ model. 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 to ISO – 5167 standards as shown in Fig3.5 below. The fluid composition used is presented in Table 2.2 below. However, the analysis preceded conducting Grid Independency test (GIT) to determine the minimum mesh density for accurate results.

Fig 1: (a)Picture of the Concentric Orifice Plate, (b) Side Picture of the Concentric Orifice Plate

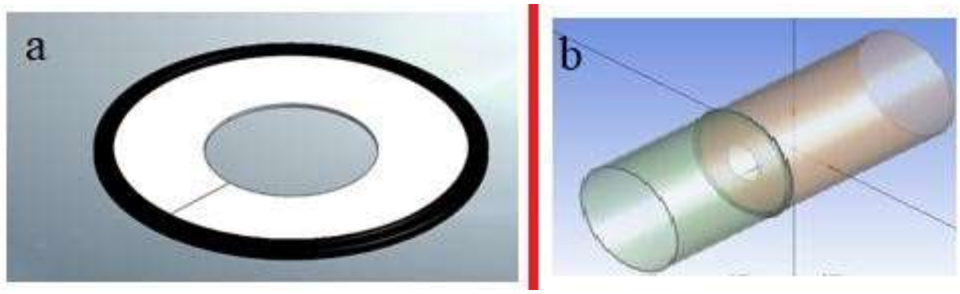

Fig2: **(a)** Model of the Concentric Orifice Plate, (b) Model of the Concentric Orifice Plate in the pipe

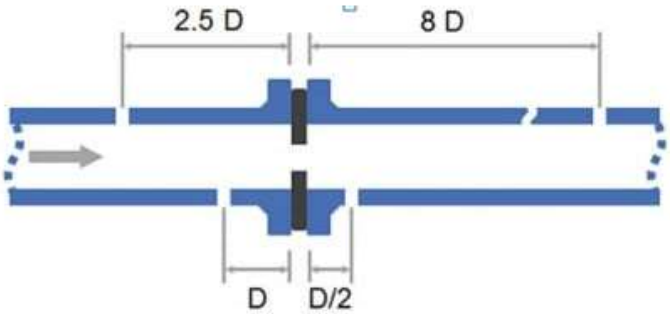

Fig 3: Location of plate and tapping location

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.

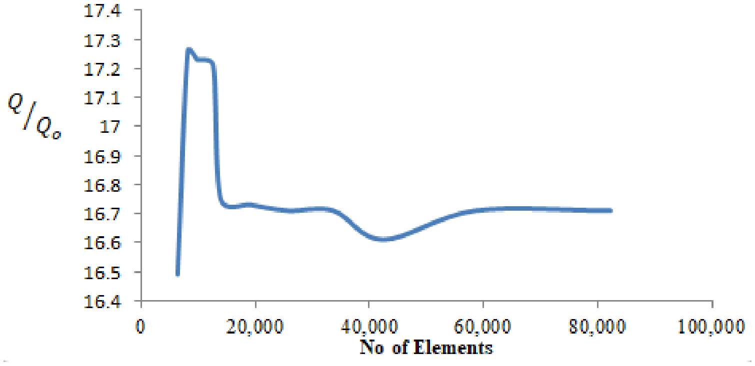

Fig4: Grid Independency Test

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

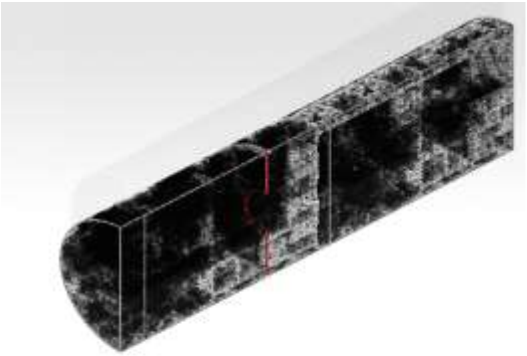

Fig5: Mesh Density over the CAD domain

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.

$$\rho(\frac{\partial u}{\partial t} + (\mathrm{u},\nabla)u) = -\nabla\rho + \mu\nabla^2 u + F \qquad (1)$$

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.

$$\text{Stress } (\delta) = ({}^{F}/_{A_0}) \tag{3}$$

$$\text{Strain } (\varepsilon) = ({}^{\Delta l}/_{L_o}) \tag{4}$$

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.

$$\Delta F = [Kx][\Delta U] \tag{5}$$

3.0 DISCUSSION OF RESULTS

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 validation and as well as to investigate the failure of the orifice plates due to buckling. Table 3 above show the comparison of the data obtained from the plant and the simulated results from midas NFX. The three orifice plates were investigated independently using FSI interface of midas NFX with the flow rate as the input and 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 flow rate 30 MMSCF/d show a pressure drop of 24,300 Pa compared to that from the plant was 22,660Pa representing -7.237% deviation, the 127mm orifice plate with flow of 80MMSCF/d returned a pressure drop of 33,700 Pa compared to 36,750 Pa from the plant which was 8.29% deviation from real life scenario and the 6 inch orifice plate with the flow of 250MMSCF/d with a simulated pressure drop of 40,600Pa 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 proves that the simulated work was very close to the reality and could predict the FSI behaviours 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 period. The plate with 6 inch orifice shows the maximum deformation over the 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 4 above.

The buckling load factor which was 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 was 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 a sudden failure. The Fig 6a and b below show the BLF and expected service life for the orifice plates

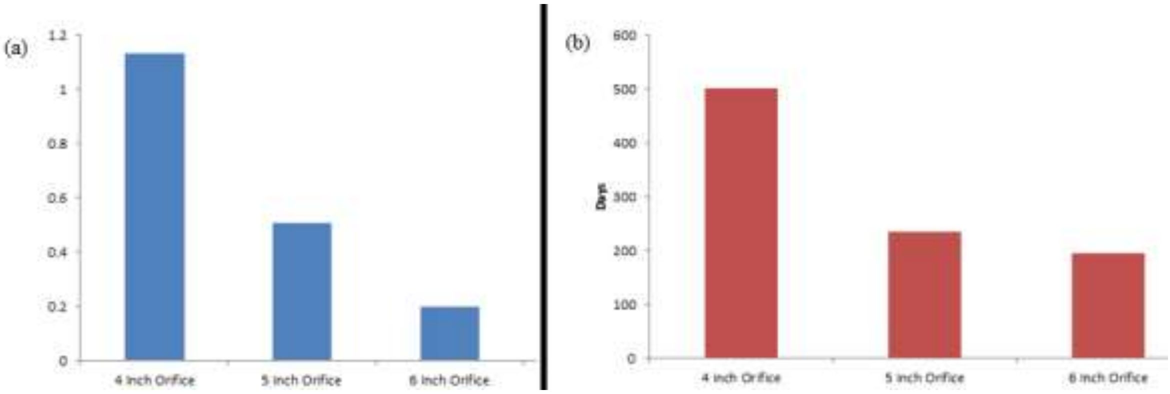

Fig 7: (a) BLF comparison chart; (b) Expected Service life of the Orifice Plates

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 was 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 was 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.

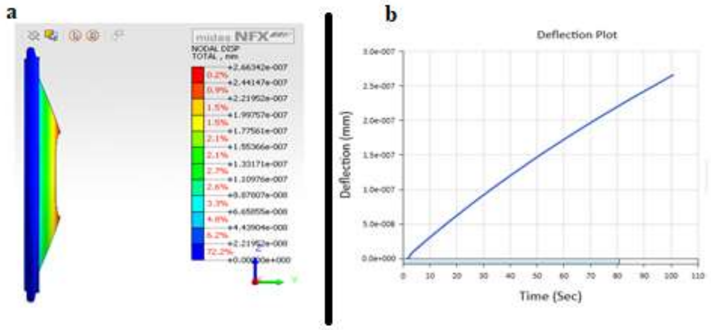

Fig8: (a) Deformed 101.4 mm Orifice, (b) Deflection – Time Plot for 101.4 mm Orifice Plate

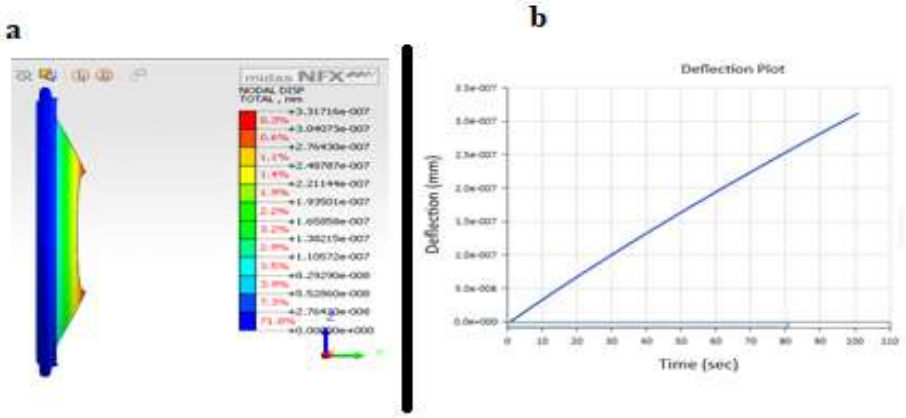

Fig9: (a) Deformed 127 mm Orifice Plate, (b) Deflection – Time Plot for 127 mm Orifice Plate

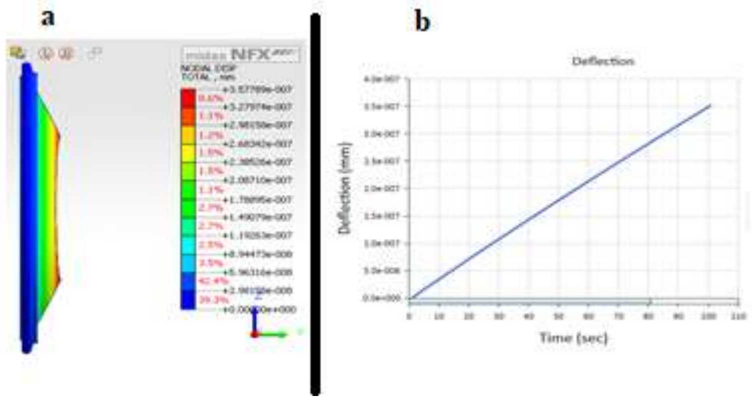

Fig10: (a) Deformed 152.4 mm Orifice, (b) Deflection – Time Plot for 152.4 mm Orifice Plate

The structural deformation was accounted for by the Finite Element Analysis on the plate continuous deformation with time as shown in Fig8b, 9b and 10b 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 x 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 x 10^{-7} mm covering 18.80% of the orifice plate total surface area and the 152.4 mm orifice plate deformed by 3.5779 x 10^{-7} mm affecting 18.30% of the plate surface area.

Conclusion

Performance and safety evaluation of the orifice plate were carried out using the various process flow conditions for the lines A, B and C with orifice plates 101.4 mm, 127 mm and 152.4 mm respectively. The three orifice plates were investigated independently using FSI interface of midas NFX with the flow rate as the input and 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 flow rate 30 MMSCF/d show a pressure drop of 24,300 Pa compared to that from the plant which is 22,660Pa representing -7.237% deviation, the 127 mm orifice plate with flow of 80 MMSCF/d returned a pressure drop of 33,700Pa compared to 36,750Pa from the plant which is 8.29% deviation from real life scenario and the 152.4 mm orifice plate with the flow of 250 MMSCF/d with a simulated pressure drop of 40,600Pa as against the plant's pressure drop of 41,680Pa representing a deviation of 2.59% from the real life scenario. Less than 10% deviation proves that the simulated work is very close to the reality and can predict the FSI behaviours of the plant to over 90% accuracy.

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 with maximum deformation/deflection of 2.6634 x 10^{-7} mm, 3.3172 x 10^{-7} mm and 3.5779 x 10^{-7} mm respectively for the period of investigation. The plate with 152.4 mm orifice shows the maximum deformation over the 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 335.074Pa and 1.3616 x10^{-9} while the 101.4 mm had the least stress and strain value

The buckling load factor 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 can easily fail with a little surge in pressure. The 127 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 predict the service life of 501 days, 235 days and 195 days for the 101.4 mm, 127 mm and 152.4 mm orifice plate respectively.

Physical observation of the velocity profiles shows that the 101.4 mm orifice plate had more swirl flows compared to others.

The swirls take place around the vena contracta of the orifice plates. The vena contracta which fall immediately after the orifice plates represented the region with maximum velocity, high kinetic energy and minimum pressure which create permanent pressure drop across orifice plates. The pressure differential is least in 101.4 mm plate compared to the remaining two plates that can be attributed to a number of factors including the small throat diameter of the plate.

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 the measuring accuracy. The position of vena contracta is so important that pressure sensors are always positioned there for accurate and precise measurement. It was 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. Future work need to make the orifice plate smart by showing information like deformation and alerting the operator with an alarm when the deformation or deflection is about to exceed maximum allowable value. This is necessary as orifice plates are always out of sight and as such can easily be forgotten until a failure happen.

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