Effect of Cyclic Pressure on Sealing Behaviour of Spiral Wound Gasket in Flange Joint

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1 Introduction

With increase in the demand for oxygen in health care application and hydrogen usage as fuel, many chemical industries have been installed. These comprises of pressure vessel for generation and piping system for transferring these gases. Gasketed flange joints are vital in pressure vessel and piping systems, acting as a common type of sealing node. They are provided with gasket interfacing element between the flange mating surfaces. These systems, in many cases are not subjected to constant load. The pressure of the internal fluid in the system varies with time due to start-up or shut down condition, varying working cycle and water hammer, in addition to surges due to uncertain conditions. In medium or high-pressure applications at elevated temperature, these systems are employed with spiral wound gaskets (SWG). It is a semi-metallic gasket with metallic spiral ring and soft filler material. The sealing behaviour of these joints, depends mainly on the compressive stress distribution in gasket under loading and unloading cycles.

The pressure fluctuations in a pipeline can occur because of fluctuations in operating pressure, temperature cycling, vibrations in pipeline, water hammer, fluctuations in fluid flow and external load. The distribution of thermal loads in the tubes causes expansion and contraction of tubes. This further causes local cyclic loading. The localized area subjected to higher temperature experiences compression, whilst the localized area subjected to lower temperature experiences tension [1]. The pressure vessel or pipeline containing gaseous hydrogen are subjected to pressure cycles which lead to fatigue loading. They are subjected to frequent fluctuation of pressure having several occasions on a day and >10,000 occasions in the

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lifetime [2]. The gaseous hydrogen is observed to reduce the fracture resistance and fatigue behaviour of the material. The gaseous products like oxygen or hydrogen are externally compressed for proper channelling and transportation via tubes. On using reciprocating compressor for high compression ratio, it is also accompanied with considerable amount of inherent pressure fluctuations. These fluctuations usually result from forward and backward motion of the piston in the cylinder. This fluctuation may lead to ignition, explosion, or even damage of the entire system [3]. Gas-fired generators are used to balance the intermittency caused in wind generation. This causes the pressure fluctuation in the gas transmission pipelines between minimum delivery pressure and the max allowed pressure based on the material behaviour. Whenever the pressure drops below the threshold value, external compressor is used to pressurize the gaseous hydrogen which might cause large fluctuations [4]. This process can create challenges to pipelines and their reliability. Recently, American Society of Mechanical Engineers (ASME) has incorporated the methodology for accommodating the effect of hydrogen crack growth rate [5].

Water hammer also known as surge flow occurs in pipeline, with rapid change in the fluid flow causing the pressure to vary. The pressure hikes may also go to 5 to 10 times the operating pressure, in addition to high support reactions, flow reversal, bursting of pipes and leakage of joint. The sampling of pressure fluctuation data also has impact on corrosion behaviour and fatigue crack growth [6]. In order to extract the small undulations in pressure fluctuations, the experiments were performed for very small sampling interval. The procedure established using Supervisory control and data acquisition (SCADA) data generation process, misses both the minor load cycles and underload data, yielding very conservative results for liquid pipelines [7]. The effect of flow velocity and wall roughness on noise level was analysed using large eddy theory and subgrid theory [8]. The turbulency in pressure is observed to increase with increase in flow velocity and wall roughness.

In the present study, flange joint with gasket is analysed under varying internal pressure load. The effect of gasket nonlinear behaviour is modelled, including the hysteresis characteristics under loading and unloading. During assembly stage, the gasket undergoes plastic deformation, in order to get squeezed into the surface irregularities in the flange surfaces. To include this effect, the elasto-plastic behaviour of individual constituents in the gasket is considered. In operating condition, the internal pressure exerted on the inner circumference of the flange walls is of pulsating in nature under many occasions. The fluctuation in the pressure causes loading and unloading of the gasket material. Its effect on the sealing performance of the flange joint is analysed in the present work using finite element analysis. The main mode of failure is leakage through the interfacial area. The stress distribution in the gasket material is obtained and the sealing performance is predicted using the minimum residual stress retained in gasket, as recommended by ASME.

Fig. 1 Damage in pipeline due to pressure fluctuation [10]

2 Background

The pressure fluctuations in a pipeline can occur because of fluctuations in operating pressure, temperature cycling, vibrations in pipeline, water hammer, fluctuations in fluid flow and external load. The major contribution of pressure fluctuation will be due to the working cycle of the pressure vessel components for specific work output. In order to obtain the desired work output the pressure inside the vessel will be varied [9]. Apart from this reason, all the other causes for pressure fluctuations are undesirable. Pressure variation also occurs in long pipelines, due to thermal deformation of the component. Another major contribution comes from the water hammer (i.e.) sudden stoppage or opening of pressurized fluid causes loud banging noise. Water hammer is usually accompanied with loud noise, similar to banging a pipeline with hammer. This can be of single cycle or multiple cycle in nature, which happens when the pressurized fluid is controlled. These can cause erosion of inner walls of pipe, leakage and catastrophic failure of pipeline (Fig. 1).

3 Micromechanical Modelling of SWG

In pressure vessels and piping system, flange joints with spiral wound gasket (SWG) are used in medium and high-pressure applications. These spiral wound gasket possess high non-linearities and hysteresis during loading and unloading. Usually, in a flange joint, the gasket will be loaded during assembly stage via bolt preload and unloaded during pressurization stage via internal pressure and thermal loads from fluid. The spiral wound gasket is a semi-metallic gasket with both metallic entity and non-metallic entity. The metallic component is preformed into 'V' shape with open end of the V aligned towards the inner diameter. This preformed 'V' shape helps in spring back effect, during unloading of the gasket entity. The common metallic material used are SS 304, SS 316, Monel, etc., which have good strength and spring back effect. The non-metallic component used in SWG is usually soft and binds

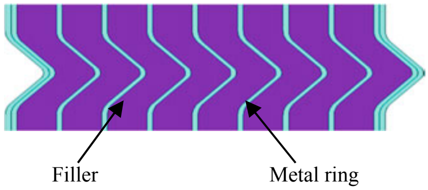


Fig. 2 Individual constituents in the micromechanical model of spiral wound gasket

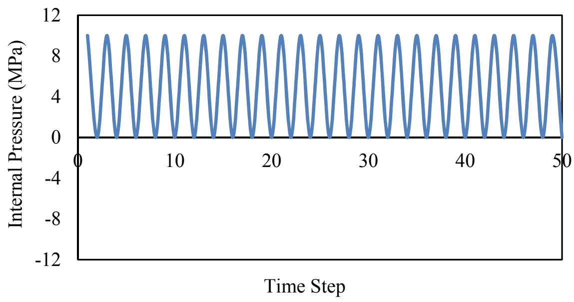
well with the metallic component. The common non-metallic filler material used are graphite, Teflon and rubber based on the fluid used. Here, metal rings provide stability and filler material provides seal ability for the gasket.

In spiral wound gasket (SWG) the minor leakage path is through the gasket internal structure and the major leakage path is through the contact surfaces between gasket and flange surfaces. The minor leakage path in SWG is included in the analysis by modelling the individual components in the gasket (i.e.) metal rings and filler materials separately and establishing contacts between them. In our previous work [11], the micromechanical model of SWG is established, considering the representative volume element (RVE) including the metal ring and filler material is chosen based on the volume fraction. The robustness of the model in obtaining the gasket stress along the radial and circumferential direction is also investigated. The micromechanical model of the spiral wound gasket used is shown in Fig. 2.

3.1 Cyclic Loading in Pipeline

In pressure vessels and pipeline, the internal fluid is pressurized to a value well above the atmospheric condition. During operating condition, these components are subjected to varying pressure load due to various reasons. Basically, these components operate in cyclic nature with cyclic loading conditions, which keeps repeated from the time of starting stage to any stoppages. The cyclic loading nature occurs for both temperature and pressure because of working cycle, thermal expansion, vibration and water hammer. This pressure fluctuation causes the material to experience residual effect, if the deformation enters into plastic region. In a flange joint, the only component designed to deform plastically is gasket material for filling the surface irregularities on sealing surfaces. Moreover, the gasket has high hysteresis behaviour under loading and unloading the material. Since, the plastic deformation cannot be recovered upon unloading, some amount of residual or permanent deformation will remain in the gasket, which affect the contact stress distribution. The sealing behaviour of the flange joint is usually, defined based on the contact stress distribution in gasket. Thus, analysing the effect of cyclic loads on gasket is very important for designing a safe joint. The nature of pressure fluctuation [12, 13] experienced in pressure vessel against time is shown in Fig. 3.

Fig. 3 Pressure load variation in a pipeline



4 Methodology

The pressure fluctuations in pipelines carrying fluids with flange joints is inevitable. The performance of the flange joint, both structural integrity and the sealing performance depends the nature of loads acting on it. The sealing performance is a function of stress distribution in gasket material. The residual stress in gasket material varies based on the internal fluid pressure and its nature. During assembly stage, the gasket material gets compressed; whereas under pressurization, the gasket material gets relaxed.

Finite element analysis is carried out in flange joint with gasket, considering the individual constituents in it. The metal rings and filler tape in the SWG are modelled separately considering the individual behaviour under elastic and plastic regions. The contact stress response from the gasket is validated with the previous work of author [11]. The analysis is performed in flange joints with gasket under varying internal pressure loads and the variation in stress distribution is obtained.

5 Material Model

The flange joint is composed of weld-neck flanges, interface gasket, bolt and nut connector. The weld-neck flange is characterized using SA195 material; whereas bolt-nut connector using SA193B7 material. The flange and bolt materials are characterized considering isotropic material behaviour using Young's modulus of elasticity and Poisson's ratio. The individual entities of the gasket material, both metal rings and filler tape are characterized using elasto-plastic material behaviour. The metal rings are characterized using bilinear material model shown in Table 1. The linear elastic region is characterized using Young's modulus of elasticity and Poisson's ratio; whereas linear plastic region beyond yield stress is characterized using Tangent modulus. The filler tape is characterized using linear elastic region and nonlinear plastic region, to include the more realistic plastic behaviour. The nonlinear plastic region is characterized using unidirectional stress strain curve beyond the yield strength of the material as shown in Fig. 4.

Table 1 Material properties of joint members

	Parameters	SA195	SA193B7	SS304
Elastic property	Young's modulus (GPa)	195	203	197
	Poisson's ratio	0.3	0.3	0.29
Plastic property	Yield stress (MPa)			340
	Tangent modulus (MPa)			6850

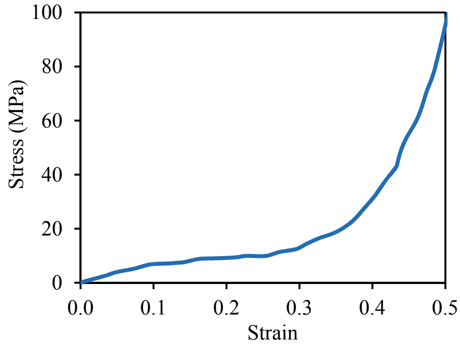


Fig. 4 Uniaxial compressive behaviour of graphite material [11]

5.1 FE Model

Finite Element (FE) model of the flange joint is developed using a commercial finite element analysis (FEA) software, ANSYS v18.1. An 80 Nominal Pipe Size (NPS) 80 schedule flange joint is considered for the study. The FE model is developed with symmetric weld-neck flange, bolt-nut connector and SWG of 4.5 mm thickness. Considering the rotational symmetry, 22.5° of the flange joint is modelled with half segment of bolt region and half segment of web region. Since symmetric flange joint is considered, upper flange with half portion of the bolt in axial direction and gasket with half thickness is taken for the study.

The flange member is discretized using lower order-8 noded brick element, SOLID185; whereas bolt-nut connector using higher order-16 noded brick element, SOLID186. The pretension in the bolt is applied using PRETS179 element, by creating the master node and slave nodes along a plane. The preload applied is transferred to the slave nodes from the master node. The contact is established between flange-bolt interfaces and flange gasket interfaces. The contact is established with TARGE170 and CONTAC173 elements. In gasket, the metal rings are discretized using SOLID185 elements and filler tape using SOLID186 elements [14]. The higher order elements will be capable of capturing the discontinuity and nonlinearity in a better way (Fig. 5).

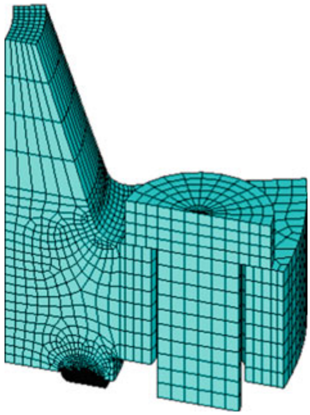


Fig. 5 FE Model of flange joint

5.2 Boundary Condition

Considering the rotational and axial symmetry of the joint, symmetric boundary condition is applied on 0° and 22.5° faces of the joint including flange surface, gasket surface, bolt and nut surface. The flange joint is constrained along the axial direction by applying symmetric boundary condition in the bottom surface of the gasket.

During assembly stage, pretension is applied on the bolt shank region. The bolt pretension applied is transferred to other connected members in the joint. Upon application of pretension, the bolt is subjected to tension and other members are subjected to compression. The gasket gets compressed and fills the irregularities in the sealing surfaces. Upon application of internal pressure, the flanges are pushed away from each other. This causes relaxation in gasket and other joint members, but bolt is subjected to additional tensile load. The nature of the internal pressure load is cyclic with repeated loading.

6 Results and Discussion

Finite Element Analysis (FEA) is carried out in flange joint with gasket considering the individual constituents. The analysis is performed in two stages, namely, assembly and pressurization stage.

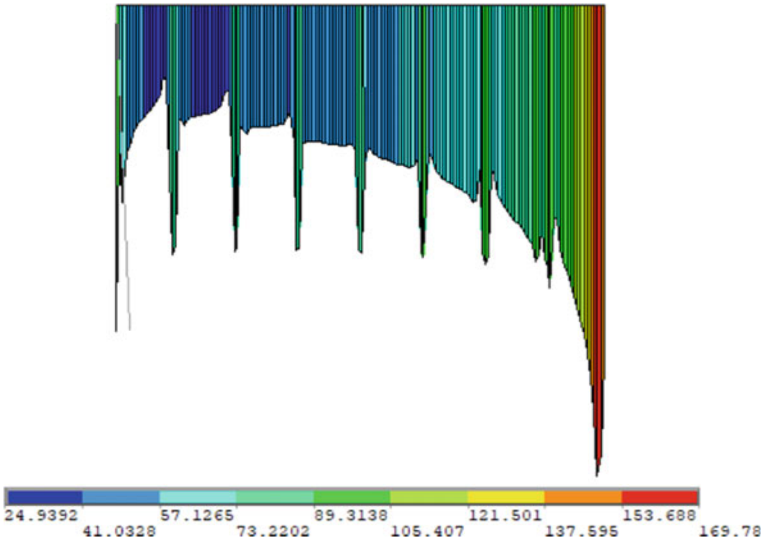


Fig. 6 Distribution of contact stress (MPa) in gasket on 0° face of flange joint under assembly stage

6.1 Assembly Stage

During assembly stage the pre-tightening torque is applied to the bolt in terms of bolt pretension. A bolt preload value of 30 kN is applied on each bolt. Upon applying the bolt preload, the bolt member gets elongated and other members of the joint gets compressed. The bolt member will be subjected to tensile stress; whereas other joint members are subjected to compressive stress. The contact gets established between the flange-bolt interface and flange gasket interfaces, so the bolt load gets transferred to the gasket. The contact stress in gasket obtained under application of bolt preload is shown in Fig. 6. The gasket contact stress varies along the radial direction from inner to outer circumference. The contact pressure is higher upon closeness towards bolt-nut connector.

6.2 Pressurization Stage

During pressurization stage, the fluid load is applied in the flange joint. The internal fluid load (i.e.) pressure is applied on the inner walls of the flange joint. The hydrostatic force components acting on the cross-sectional areas are calculated and applied on the respective areas. Upon applying the internal pressure, the flanges move away from each other. This causes increase in the bolt tensile stress and increases the bolt axial load, based on the proportion of the internal pressure load taken by the bolt.

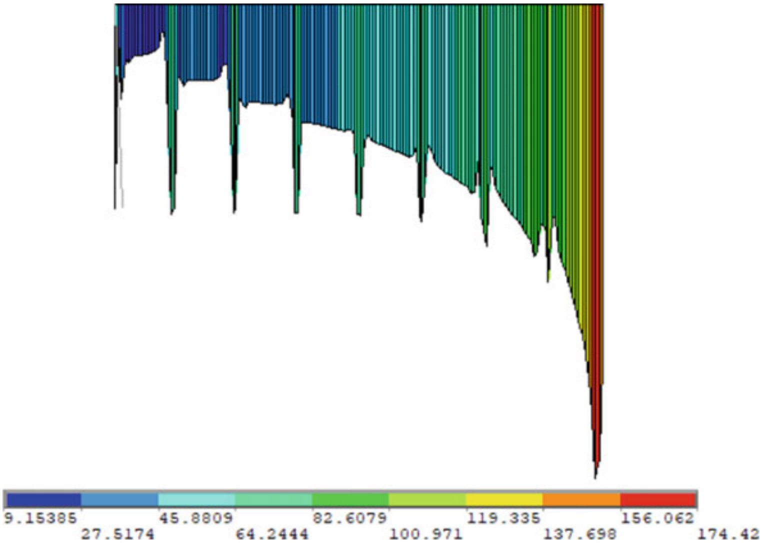


Fig. 7 Distribution of contact stress (MPa) in gasket on 0° face of flange joint under pressurization stage

Consequently, the compressive stress in the connected members reduces, resulting in reduction of gasket contact stress. Simultaneously, the compressive deformation in the gasket also reduces, leaving some part of deformation in it. The gasket contact stress distribution under internal pressure of 10 MPa is shown in Fig. 7.

6.3 *Under Cyclic Internal Pressure*

As discussed in Sect. 1, the pressure vessels and pipeline are subjected to fluctuating pressure during working condition. The cyclic pressure variation considered for the study is shown in Fig. 3. The analysis is done separately for assembly stage as a separate load step and pressurization stage as a separate load step. The nature of load applied is repeated loading with actual pressure applied under normal pressurization stage as maximum and 0 MPa as minimum. Upon applying the cyclic pressure loading, the gasket contact stress obtained is also of similar nature with values getting attenuated. The attenuation happens because of accumulation of plastic deformation in the gasket material under each cycle. At first cycle, the minimum gasket contact stress is 21.91 MPa, which reduces to 19.56 MPa after 50 loading cycles is shown in Fig. 8.

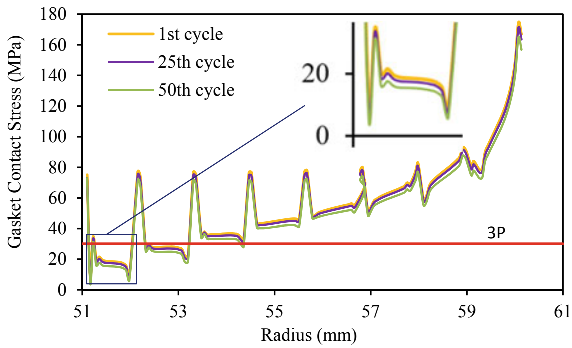


Fig. 8 Variation in contact stress in gasket for cyclic loading

6.4 Sealing Characteristics

The sealing behaviour of the flange joint depends on the residual gasket stress in the gasket material. The minimum residual stress in gasket is provided by Eq. (1) based on internal pressure (P), defined by ASME.

$$\text{Residual Stress Line} = 3P \quad (1)$$

Under cyclic pressure loading, the ability of the flange joint to have better sealability reduces with the cycles it is subjected. Figure 8 shows the variation in sealing characteristics of flange joint subjected to repeated cyclic pressure loading after 1 cycle, 25 cycles and 50 cycles, respectively. Therefore, whilst designing the flange joint, the nature of loading should also be taken into account. The nature of loading should also be considered as an uncertainty.

7 Conclusions

The flange joint used in pressure vessel and pipeline are subjected to fluctuating pressure loading inevitably. These pressure fluctuations may be due to local thermal cycles, water hammer, vibrations and working cycles. Compared to structural integrity, the sealing characteristics of the flange joint gets affected due to fluctuating pressure.

- Due to high hysteresis, the gasket material will be subjected to both elastic and plastic deformation.
- Under cyclic pressure loading, the plastic deformation in the gasket material gets accumulated based on the cycles of operation.
- The sealing ability of the flange joint reduces with cyclic pressure loading. The nature of loading should be included to design a safe joint considering the sealability of the joint.

References

1. Pang L, Yi S, Duan L, Li W, Yang Y (2019) Thermal stress and cyclic stress analysis of a vertical water-cooled wall at a utility boiler under flexible operation. Energies 12:1170
2. Marchi C, Dedrick DE, Van Blarigan P, Somerday BP, Nibur KA, Pressure cycling of type 1 pressure vessels with gaseous hydrogen
3. Rahman M, Lee GH, Utomo TS, Jeong HM, Chung HS (2009) A Study on gas pressure fluctuation characteristics inside the snubber and pipe of hydrogen. Adv Mech Eng 2009:138708
4. Chertkov M, Fisher M, Backhaus S, Bent R, Misra S, Pressure fluctuation in natural gas networks caused by gas-electric coupling
5. Boiler and Pressure Vessel Code (2004) Section VIII, Division I. American Society of Mechanical Engineers, New York
6. Zhao J, Chen W, Chevil K, Been J, Boven GV, Keane S, Kania R (2017) Effect of pressure sampling method on pipeline integrity analysis. J Pipeline Syst Eng Pract 04017016:1–13
7. Dzierwa P (2018) New start-up curves for a 200MW steam boiler with natural circulation. MATEC Web Confer 240:05007
8. Qu D, Zhang Z, Lou J, Dai Q (2016) Numerical simulation of fluctuation pressure with liquid-filled pipes based on large eddy simulation method. Vibroeng Proc 10:2345–2533
9. Cheng S, Chenlong D, Yuemin Z, Liang D, Zhenfu L (2018) Analysis and evaluation on pressure fluctuations in air dense medium fluidized bed. Int J Min Sci Technol 28:461–467
10. Aboshoufa ME, Alkanshi AA (2016) Transient oil flow study—Waha oil pipeline. Thesis Submitted to University of Tripoli, Libiya
11. Nelson NR (2021) Effective modelling of spiral wound gasket with graphite filler in gasketed flange joint subjected to bending loads. Mater Today Proc 44(1):2199–2204
12. Sutton A, Hubert Y, Textor S, Haider S (2014) Allowable pressure cycling limits for liquid pipelines. In: 14th international pipeline conference, Canada, September 2014, V002T06A058
13. Li, Y, Yu Z, Ye Q, Yang J, Hayat S (2021) Analysis of pressure fluctuation for oil-gas two-phase flow in a horizontal pipe using the bubble number density equation. Chem Eng Commun https://doi.org/10.1080/00986445.2020.1869950
14. ANSYS 18.1, User's Manual. ANSYS Inc. Canonsburg, USA (2015)