Influence of Loading Rate on Deformation Behaviour and Sealing Performance of Spiral Wound Gasket in Flange Joint

N. Rino Nelson, N. Siva Prasad and A.S. Sekhar

Abstract Owing to increase in the demand for power, a number of power plants have been installed in the recent past. One of the vital components in these plants is gasketed flange joint. The behaviour of gasketed flange joint is highly dependent on the deformation characteristics of gasket material. In the present study, the deformation characteristic of spiral wound gasket along thickness direction is determined experimentally for different loading rates. Gasket has high nonlinearity under both loading and unloading, with hysteresis. Based on its characteristics, the flange joint is analysed to study its performance and leakage behaviour under static condition. 3D finite element model of flange joint is developed by considering the gasket as interface entity. Finite element analysis of flange joint is performed by including the nonlinear hysteretic behaviour of gasket, under different loading rate and frictional contact between joint members. The influence of different loading and unloading rates is emphasized on the sealing performance of flange joint using leakage pressure. The gasket deforms more when loaded at low rate. This phenomenon also affects the ability to withstand internal fluid without leakage. The maximum safe pressure without leakage increases, when gasket is loaded and unloaded at low rate.

Nomenclature

F	Total bolt preload
H_D and H_T	Hydrostatic end forces
m	Gasket maintenance factor
P	Internal fluid pressure

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ANSI	American National Standards Institute
FEA	Finite element analysis
RSL	Residual stress line
RVE	Representative volume element
SWG	Spiral wound gasket
SS	Stainless steel

1 Introduction

In recent years, many power plants have been installed, due to high demand for power generation. Flange joints are widely used in power plants for connecting long pipelines, head and shell portion in heat exchangers, nozzles and man holes. Gasket is primarily provided in the flange interface, to overcome surface imperfections. For high pressure and temperature operation, spiral wound gaskets (SWG) with soft fillers are preferred due to its stability. It is a semi-metallic gasket with stainless steel ring and flexible graphite ring wounded under radial compression. A section of spiral wound gasket is shown in Fig. 1, with inner and outer rings. The deformation characteristic of sealing ring is nonlinear, due to both material behaviour and geometric configuration.

Mathan and Siva Prasad [1] evaluated the properties of SWG considering representative volume element (RVE) by homogenisation method. RVE is subjected to various loading conditions to determine its averaged elastic and Hill's model responses. Nelson et al. [2] characterized the deformation behaviour of gasket by incorporating the individual component behaviour in SWG, treating them as separate entity. A six degree polynomial equation is used by Fukuoka and Takaki [3] to characterize both loading and unloading gasket behaviour. The influence of internal pressure in gasket load drop is analytically proposed by Nagy [4], using piecewise linear model for gasket characterization. The load drop in gasket is determined by the loosening coefficient, which is a function of gasket material and geometry. Nassar et al. [5] investigated the effect of loading history in gasket and bolt tightening patterns. When star or sequential tightening pattern is followed, all the other bolts get loosened other than the tightening bolt, resulting in local loading and

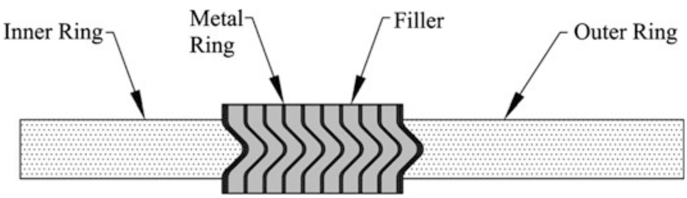

Fig. 1 A section of spiral wound gasket

unloading of gasket. The scatter in bolt load is observed to be more in flange joint with SWG. This scatter gets reduced on applying multiple tightening pass for above said patterns. The compression of gasket during assembly stage is a key factor for safe operation of flange joint, which in turn depends on its stiffness. In addition to stiffness, joint's leakage resistance also depends on the clamping force, joint rigidity, resistance to creep and surface texture of mating faces [6].

The primary failure in flange joint is leakage of internal fluid. The behaviour of flange joint is studied by Estrada [7] using contact finite element analysis (FEA). The accurate evaluation of gasket stress is very important to study the interaction between joint members. Bouzid and Galai [8] proposed an analytical model to predict the joint tightness along with flange rotation and relaxation in bolt load, based on flexibility of the joint and member interaction. In many cases, the gasket member alone fails in flange joint. Jenco and Hunt [9] revealed the common issues of gasket failure due to insufficient compression, gasket buckling and crushing. The limiting size for clearance between gasket and groove is provided by Roos et al. [10], which ranges between 1.0 and 1.5 mm. In general, gasket is observed to fail due to inward buckling/collapse, when it is provided without support rings. The buckling of gasket results in unwinding of sealing rings due to turbulence of internal fluid [11]. During compression, the distribution of stress becomes non-uniform in buckled gaskets, which is highly prone to leakage on pressurization. Nassar and Alkelani [12] investigated the effect of tightening speed on stress distribution in joint. The clamp load in soft gasket reduces with increase in tightening speed and vice versa in hard gasket.

SWG is observed to have high nonlinearity and hysteresis during loading and unloading [2]. It also has considerable amount of permanent deformation in gasket even after unloading the gasket. This viscos behaviour of gasket is very important for material characterization. In literature, this effect due to varying loading rate is not investigated, which might have higher influence on performance of flange joint.

In the present study, deformation characteristics of SWG under different loading rates are determined. Uniaxial compression testing is performed to determine the characteristics for 200, 500 and 1000 N/s loading rate. A 3D finite element model of flange joint is developed considering these deformation characteristics and contact between joint members. The effect of loading rate on sealing behaviour of flange joint is also analyzed for different bolt preload under internal fluid pressure.

2 Experimental Procedure

The behaviour of flange joint depends on deformation characteristics of gasket material. Spiral wound gasket is a semi metallic gasket with stainless steel (SS) windings and graphite filler. The behaviour of gasket along thickness direction is more important compared to other two directions. The deformation characteristics of this gasket are determined from uniaxial compression testing. The test set-up used for the present study is shown in Fig. 2. Here, vertical universal testing

Fig. 2 Experimental set up for uniaxial compression of gasket specimen

machine is used to apply the axial compressive load on specimen. This machine is self-built with extensometer and other sensors to measure the deformation in specimen, during application and removal of load. It also has the ability to control loading and unloading rate of specimen. The entire machine is controlled using a control system, through which the rate of loading and maximum compressive load is pre-set. The data acquisition system is used to retrieve the output data from experiment, both stress and deformation in the specimen.

The gasket specimen is subjected to gradual compressive load from 0 to 15 tonnes, based on specific loading rate. After loading the gasket to 15 tonnes, the load is reduced gradually to zero, defining the unloading characteristics of material. The initial (before loading) and final (after unloading) specimen thicknesses are measured, to determine the permanent deformation (plastic deformation) in gasket on application of load. The same procedure is repeated for 30 tonnes, in order to obtain another unloading curve. The loading and unloading of specimen is carried out at controlled load rate viz., 200, 500 and 1000 N/s. The specimen is kept in the loaded position for 10 min at the maximum load (15 or 30 tonnes), before relaxing the load. It is done on specimen to reach stabilization. Both loading and unloading is carried out at the same controlled rate.

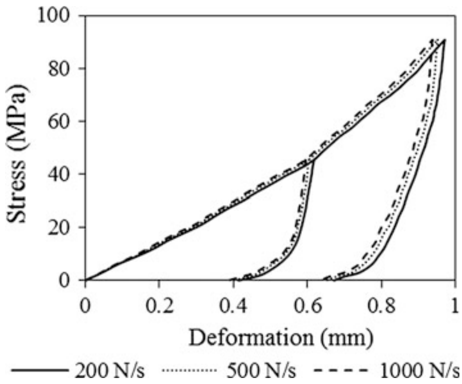

Fig. 3 Stress displacement relation of SWG for different loading rates

3 Gasket Characteristics at Different Loading Rate

Generally, the gasket materials used in flange joint are comparatively softer than other joint members. They possess high nonlinear characteristics and strong hysteresis. The leakage behaviour of flange joint is highly dependent on this characteristic i.e., deformation along thickness direction. The experiments are conducted on gasket specimen, by applying compressive load at different loading and unloading rates. The gasket material used is semi-metallic spiral wound gasket, with stainless steel (metal) rings and soft graphite (non-metallic) filler material. Usually, spiral wound gaskets are provided with inner and outer supporting rings. The sealing ring is composed of radially wounded SS and graphite rings, which helps to prevent leakage. The deformation of gasket is concentrated on sealing ring because, the inner and outer supporting rings are provided for stability purpose to prevent over compression. The thickness of gasket sealing ring is 4.5 mm; whereas supporting ring is 3 mm. So, on application of compressive load, the sealing ring alone gets compressed first. The deformation behaviour of gasket for different loading rates is shown in Fig. 3, against the corresponding stress values. The gasket material shows strong hysteresis and viscoplastic behaviour. On loading, gasket is subjected to both elastic and plastic deformation; whereas on unloading, only elastic deformation is recovered. The gasket deformation increases with decrease in loading rate. This might be due to increase in material flowability, when loaded at a low rate.

4 Flange Joint with Gasket

In this study, ANSI B16.5 Class 600, 80 mm NPS flange with weld neck and raised face is considered. Flange and bolt materials are carbon steel and high chromium steel respectively. The properties used to characterize the flange joint members are shown in Table 1. Except gasket, the other joint members are characterized using linear elastic material model to include only their elastic material behaviour.

Table 1 Material properties of joint members

Member	Young's modulus (GPa)	Poisson's ratio
Flange	195	0.3
Bolt	203	0.3

4.1 FE Model of Flange Joint

Finite element model of flange joint is developed and analyzed using Ansys v14.5. The flange geometry is discretized using SOLID185, 3D 8-noded element with 3 DOFs at each node [13]; whereas bolt by SOLID90. These solid elements have translation along three perpendicular directions as its DOF. The bolt and flange members are modelled as separate entity and contact is established between their interfaces. The bolt-nut connector is modelled as a single entity without considering threads. For FE modelling, the hexagonal bolt head and nut are modelled as cylindrical entity.

The contact behaviour is modelled using CONTA174 and TARGE170. Surface to surface contact with 0.2 friction coefficient is established in flange-bolt interface. Here, comparatively stronger member, flange is taken as target and bolt as contact region. The primary component in gasketed flange joint, gasket is modelled and discretized using interface elements, INTER195. It has a unique characteristic of having one element along thickness direction between the mating surfaces, which controls its deformation behaviour. Pretension applied to the bolt during assembly

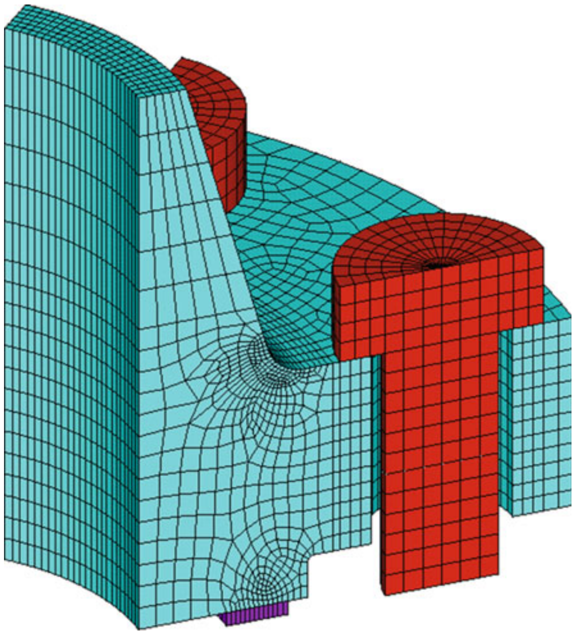

Fig. 4 FE model of flange joint

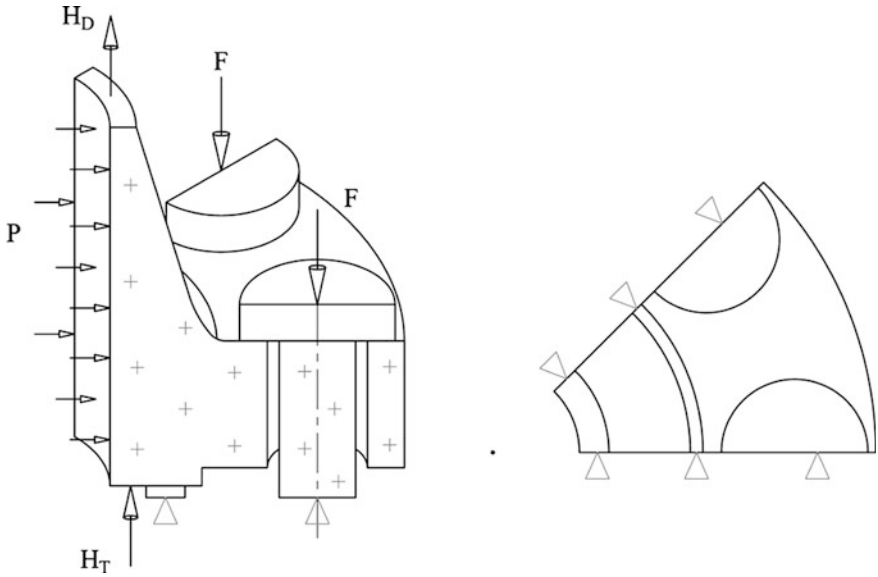

Fig. 5 Boundary condition

stage, for holding flanges together is simulated using a special element, PRETS179. A node on the specified plane is taken as pretension node and all other nodes on same plane of the entity are connected to it. The pretension load is directly applied on to the pretention node. Figure 4 shows the meshed FE model of the flange joint.

Flange joint is a cyclic symmetric component, due to which 45° segment of it is considered, covering two half bolt region and ligament region between them. One of the flanges and gasket with half thickness are modelled, considering the longitudinal symmetry. The bolt preload (*F*) is applied on each bolt during assembly stage and internal fluid pressure (*P*) is applied on pressurization stage. The hydrostatic end forces H_D and H_T [10], due to internal fluid pressure are also considered. The circumferential displacement is constrained on 0° and 45° surfaces of flange joint, in order to specify the cyclic symmetric condition. The bottom surface of the gasket is restrained along longitudinal direction (see in Fig. 5), to specify the longitudinal symmetry.

5 Gasket Behaviour

The deformation behaviour of sealing ring alone decides the sealing performance of flange joint. The flexible graphite filler used in gasket helps in sealing the mating surfaces, while SS ring provides stability to the sealing ring. The SS rings preformed in V-grooved shape, to provide the spring back effect in gasket during unloading. These V-grooves are placed in such a way that the opened end of 'V' is along the inner circumference. During assembly stage, the compressive load makes the graphite filler to squeeze into the irregularities in mating surface and SS ring also gets compressed. When internal pressure is applied, the flanges tend to move away from each other. This flange opening results in reduction of compressive load in gasket. When the flanges open, the compressed V-shaped metal (SS) rings produce partial spring back effect, along with graphite filler. The compressive stress remaining in sealing ring after spring back, is termed as residual stress in gasket. The leakage occurs, when the spring back effect of gasket sealing ring is not enough to retain the internal fluid at operating pressure.

5.1 Gasket Contact Stress Distribution

During assembly stage, the compressive stress in gasket follows the loading curve in Fig. 3; whereas during pressurization stage it depends on the unloading characteristics of the gasket material. The distribution of gasket stress along the radial width of the gasket varies from inner to outer diameter. This variation is due to the eccentric transfer of bolt load from bolt to gasket via flange member. The gasket stress is more along the outer circumference compared to inner edge, due to proximity towards bolt region.

On application of internal pressure, the gasket compression stress relaxes due to opening of flange joint. The internal fluid pressure tends to move the mating surfaces apart from each other. The hydrostatic end force acting on the area between flange and gasket inner diameter, results in more relaxation along the inner circumference of gasket compared to the radial width. The variation in gasket stress distribution along radial width of gasket at 2 and 10 MPa internal pressure and 120 kN total bolt preload for different loading rate is shown in Fig. 6. The variation in gasket stress along radial width increases with increase in loading rate and internal fluid pressure.

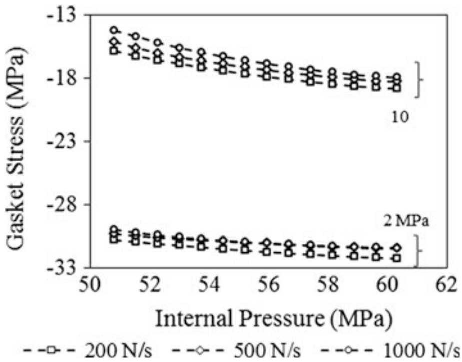

Fig. 6 Radial distribution of gasket stress for 120 kN total bolt preload

5.2 Sealing Performance

The sealing performance of flange joint is determined based on the gasket contact stress distribution. Leakage in gasketed joint depends on the gasket stress along inner circumference of gasket. The residual stress line given by Eq. (1) defines the minimum required compressive stress to be present on the gasket material as a residue, even after application of fluid pressure. While designing, the residual stress required to be on gasket depends on the internal pressure, which the flange joint should withstand. The gasket factor, m [14] for spiral wound gasket with graphite filler is 3. The residual stress line is a function of gasket material and fluid pressure.

The variation of gasket stress with internal pressure for different loading rates is shown in Fig. 7 for 120 kN bolt load. The intersection point for gasket stress variation line with residual stress line Eq. (1), is the minimum compressive gasket stress required on gasket and the corresponding internal fluid pressure is the safe value without leakage. The compressive stress on gasket increases with decrease in loading rate, i.e., the gasket gets more compressed, when loaded slowly. For 6 MPa internal pressure, the gasket stress at 200 N/s is −22.54 MPa, which reduces to −21.38 MPa at 1000 N/s. Thus, the safe internal pressure without leakage also reduces with increase in loading rate. The gasket stress during bolt up stage is almost same for different loading rate. The variation in the compressive stress increases with internal pressure. The safe internal fluid pressure for 200 N/s loading rate at 120 kN total bolt preload is 6.95 MPa and the same for 1000 N/s is 6.75 MPa (see Fig. 7).

$$Residual\,Stress\,Line\,(RSL) = mP \quad (1)$$

The analysis is carried out for different total bolt preloads viz., 120, 140 and 160 kN. The minimum leakage pressure for 80 mm NPS Class 600 flange joint under different bolt preload and varying loading rate is given in Table 2, along with percentage reduction in leakage pressure between 200 and 1000 N/s loading rate.

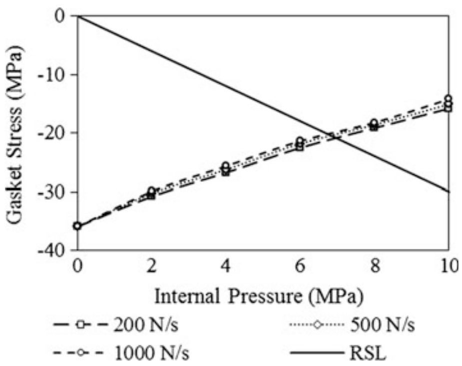

Fig. 7 Gasket stress distribution for different loading rate at 120 kN total bolt preload

Table 2 Leakage pressure for different loading rates and different bolt preload

Total bolt preload (kN)	Leakage pressure (MPa) at loading rates			% reduction between 200 and 1000 N/s
	200 N/s	500 N/s	1000 N/s	
120	6.95	6.82	6.75	2.96
140	8.20	8.00	7.95	3.14
160	9.30	9.11	9.00	3.33

At a particular bolt preload, the minimum leakage pressure decreases with increase in loading rate. For instance at 160 kN total bolt preload, the safe internal pressure is 9.30 MPa for 200 N/s loading rate, which reduces to 9.11 and 9.00 MPa for 500 and 1000 N/s loading rates respectively. The percentage reduction in safe internal pressure, between lower and higher loading rate increases with bolt preload, making the influence of loading rate more critical at higher bolt preload.

After gasket performance, more emphasis is given on the flange behaviour while designing flange joint. The flange behaviour is determined in terms of stress in flange ring, hub and fillet region between them. The stress in flange member depends on the stiffness of the joint, which in turn depends on gasket stiffness. The variation in flange stress is not substantial for different loading rate (deformation) of gasket, making it negligible.

6 Conclusions

Spiral wound gasket is tested under compression at different loading rates, to determine its deformation behaviour during loading and unloading. Substantial variation in deformation is observed, with comparatively higher deformation at lower loading rate. FE analysis is performed on flange joint including the gasket nonlinear characteristics at different loading rate. Based on the gasket contact stress variation, the leakage pressure is predicted in flange joint. The important observations are as following:

- The variation in gasket deformation behavior under compressive load is within 4% for the loading rates considered.
- The gasket compressive stress in flange joint is comparatively more at low loading rate. This results in withstanding higher internal fluid pressure for lower loading rate.
- The percentage reduction in safe internal pressure, due to different loading rate increases with bolt preload.
- The variation in flange stress is not significant for different loading rates of gasket.

The influence of gasket loading rate in sealing performance of the flange joint is highlighted. It has significant effect on the leakage pressure, due to variation in its compression behaviour with different loading rates.

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