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ESTABLISHMENT OF INDUSTRY STANDARD FLANGE SEALING EFFECTIVENESS MEASURE (LEAKAGE RATE BASED) METHODOLOGY

Przemyslaw LUTKIEWICZ[1], David ROBERTSON
Freudenberg Oil & Gas Technologies
Metal Sealing Solutions - Vector Products
Tollbugata 49
3044 Drammen (Norway)

Michael PULVINO
Freudenberg Oil & Gas Technologies
Metal Sealing Solutions - Vector Products
10035 Brookriver Drive, Suite 400
Houston, Texas 77040 US

ABSTRACT

There are currently no industry accepted methods for calculating sealing effectiveness of flange connections at the research and development phase of a project. As there are many different designs of bolted piping connectors being widely used in the oil and gas industry, operators and regulators could benefit greatly from a more accurate comparison and estimate of expected flange tightness level, based on design calculations only. This paper will propose a new methodology for sealing effectiveness estimation of bolted connections based on leak rate calculations. The methodology will combine practical simplicity and advance theory to get a simple but effective engineering/designing tool to assess the seal tightness. A new proposed method will be based on the contact stress pattern (FEA results), material properties (code specification) and surface finish/roughness (manufacture requirements) as inputs and leak rate estimation as an output. The Representative Surface Element concept will be introduced and presented. In this paper, the general methodology principles will be presented and followed by an engineering example.

Keywords: FEA, DBA, leak rate, sealing, compact flange

NOMENCLATURE

APDL	ANSYS Parametric Design Language
SPO CF	SPO Compact Flange
CFD	Computational Fluid Dynamics
DBA	Design By Analysis
DNV	Det Norske Veritas
FE	Finite Elements
FEA	Finite Elements Analysis
FFS	Fitness For Service
FO&GT	Freudenberg Oil & Gas Technologies
HPHT	High Pressure High Temperature
R&D	Research & Development
RSE	Representative Surface Element
UHV	Ultra High Vacuum
A, A_{valley}	capillary cross section area
A_s	capillary shape function
C	conductance
L	the total sealing path length
L_a	roughness (radial wave length)
L_{aL}	roughness (circumferential wave length)
P	contact pressure
P_{ave}	average capillary pressure
P_{in}	inside pressure
P_{out}	outside pressure
R_a	roughness (radial wave height)
R_{aL}	roughness (circumferential wave height)
RSE_{Ra}	R_a reduction factor
RSE_{RaL}	R_{aL} reduction factor
h_a, h_{aL}	capillary section height
p, p_{valley}	perimeter length
r	circular capillary radius
s	sealing path length parameter
α	calibration factor
γ	calibration parameter/function
η	viscosity
θ	flow throughput
δ	Kronecker delta
ϕ_{1m}	unit (1m) leak rate

[1] Contact author: przemyslaw.lutkiewicz@fogt.com

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INTRODUCTION

Theoretically, there is no connection without a degree of fugitive emissions. Even solid material is not "tight" and the "leaking" through the metal can be described by its permeability [1][2]. In practical terms the connection is tight if it fulfils the sealing criteria defined by codes, system specification, and vessel operator/client requirements.

The leak tightness is an important criterion for all kinds of connections, in any pressure system, and is a component of the connection functionality. The practical "tightness" criteria can be different for different applications and the design code used. As an example, in steady steam power applications even high leakage rates can be accepted [3]. At the other end of the spectrum, in UHV systems only negligible leaks are acceptable [4][5]. The tightness requirement depends on many factors: medium (toxic, explosive, radioactive, inflammable), design conditions (pressure, temperature, joint size), sealing materials (metal-to-metal seals, Teflon/elastomer gaskets), consequences (pollution, loss of medium, system re-tightening or connection replacement request) and legal restrictions.

During the design process the first question to answer is: What leak rate is acceptable for the project? Given the complexity of the problem, answering the question is not an easy task. Some guidance already exists and is related with the Tightness Classes concept developed for ASME type flange connections [6][7]. The original concept was defined by three Tightness Classes; Economy, Standard and Tight and was introduced to ASME standards [3][6]. Each step of tightness class represents two orders of magnitude change in leak rate. A similar approach was used in European Union for EN 13555 [8], DIN 28090 [9] [10] and KTA 3211.3 [11] standards. International standard BS EN ISO 15848-1 [12] follows the same concept for fugitive emissions leak rate requirements by introducing AH, GH and HC classes. Recently, the initial concept was extended to seven classes [7]. The new lowest leak rate Very Tight tightness class was introduced. In addition, in between classes were introduced to represent one order of magnitude change in leak rate.

By following any engineering standard, for example ASME VIII, Div. 2 [13] or European equivalents [8][9][11], not only structural capacity but also functionality (tightness) requirements need to be addressed and fulfilled by the design. As the capacity requirements are well defined and described for both, standard and non-standard components, the situation is not so clear for functionality (tightness). For standard components, based on ASME VIII, Div. 2, part 4.16 calculations, the gasket parameters M and Y are used for designing flange connections. Those parameters describe gasket tightness and related seating pressure/force needed to fulfill functionality requirements. The M and Y gasket parameters are defined by tests for many gasket materials and gasket types [8][9][11]. Unfortunately, behind the simplicity of the method, there are also high restrictions. If gasket is not standard, then method is not applicable, until the M and Y values are defined by testing. Some M and Y values can be found in literature for non-standard gaskets [14][15]; however, there is no guidance on how to predict the leak rate value using calculations only. The other problem is related to flange equations. Those are only applicable for specific flanges type and does not work for other connections. An example is the SPO CF and standardized and simplified CF version defined by the international ISO-27509 [16] standard. It has contact outside the bolt circle diameter and seal ring instead of a gasket. That type of flange connection cannot be assessed by using ASME VIII, Div. 2, part 4.16 [13] calculations.

As the calculation methods are limited, some standards use real test requirement to ensure compliance for non-standard components. For example, based on visual leak evidence or number of drops/bubbles per min/hour, connections can be assessed for riser applications based on API 16F [16],16R [18] or international ISO 13628-7 [19] standards. In addition, some suppliers have developed, through experience and/or tests, simplified design methods to ensure tightness. An example can be a rule used for establishing the CF with IX seal ring design (contact stress higher than twice the inside pressure [20]).

In addition to the existing standards, detailed leakage description for surfaces in contact have been investigated lately [21][22][23] and compared to test results for tribological devices. A good correlation to the testing was shown, but the complexity of the calculation can be too high for a standard engineering tool in relation with pressure components design. The contact surfaces are described in detail by many parameters based on real surface scan measurements and the calculations themselves are complicated and more suitable for scientific evaluation and experiment description than for a practical engineering tool.

A formula was also developed to describe leakage for UHV system connections [2]. The method was linking the contact pressure, surface roughness and leak rate by using a simple equation and it is still in use today. The methodology is based on the Hagen-Poiseuille laminar flow theory and material parameters. As the application is related with vacuum pressure range, molecular flow mechanism was added. Lately, the same approach was used by another author of leakage prediction for non-metallic gaskets [21]. The method presented for UHV systems has good potential and could be adapted for pressure component design.

In this paper, the closed method will be presented. The methodology is aimed to evaluate the leak rate at the new product development stage. The method will use some basic FEA results as input (contact pressure profile described by P(s) function). The sealing surface condition and material properties will be taken into account by using the RSE analysis (sub-modeling concept). The leak rate equations are based on Hagen-Poiseuille theory (laminar flow). As the methodology is based on the RSE concept, different sealing designs can be compared. It can be used to calculate leak rate for gaskets or seal rings as well as any surfaces in contact. In that way, it is also a useful tool for new product development and design optimization and comparison.

GENERAL CONCEPT

As computing power gets more accessible, the DBA methodology is becoming more common. The design methodology is often based on the ultimate capacity assessment by FEA. The functionality check, where required, needs to be assessed in accordance with the standard. Requirements for the functionality check (in front of real testing) is the responsibility of the designer/engineer and are often arbitrary and depends on the interpretation of the standard (see ASME VIII, Div. 2, part. 5 [13] or ISO 13628-7 [19] for example). One of the most common and important checks for flange connection functionality is leakage assessment. A simple rule based on the sealing contact pressure to be twice the inside pressure requirement was proposed for CF flange connections [20]. That simple rule of thumb is robust and easy to use, but will not predict/estimate a possible leak rate. A formula, which will allow engineers to calculate the leak rate for any seal, can be a useful tool for new product development and existing design optimization. This tool can also be utilized to improve connection reliability and therefore, reduce the impact on the environment. This is an important aspect, especially for the increasing need for HPHT components. Any tool needs to be simple to use and must capture as much of the complex problem characteristics as possible. Therefore, the proposed method is based only on 3 fundamental steps.

Step 1 Collating data

At this initial step, the contact pattern/profile is taken from FEA results as an input for the further calculations. The connection behavior (components interactions) should be taken into account in the FEA. Therefore, data should be collected for all load cases being evaluated. For nonstandard components, this can be easily done as the interaction between components should be already modelled by FEA for DBA assessment.

Step 2 RSE analysis

The other important factor, which needs to be taken into account is the contact surface condition. The characterization of the contact surface, base material properties as well as coating layer (if applicable) should be addressed. To break down such complicated problem to a simple case, the Representative Surface Element concept is used. The RSE is a sub-modeling type concept, where a small repeatable section (RSE) of the contact surface pattern can be used for the general behavior description. As the RSE concept is general, each RSE can be different (for example in geometry), but all needs to be representative and as simple as possible. Based on those assumptions, each RSE is linked with certain surface conditions (roughness value, surface pattern), seal/gasket/seal ring and coating materials which are also specified by the design requirements. By analyzing the RSE behavior under the contact pressure load, the RSE characteristic parameter curves are produced. Those parameters are expressed as functions of contact pressure. They are used to describe the passage (capillary) geometry change. To obtain/define those functions, hand calculations or FEA can be utilized.

Step 3 Leak rate calculations

In this step, the Hagen-Poiseuille flow theory equations are used. The capillary shape at each load case is described based on the RSE analysis and contact pressure profile along the sealing path. The leak rate is calculated based on the sealing conductance, which is integrated over the leak path by using an analogy to the electrical conductance of a series circuits (see equation (6)). The calibration factor α can also be used if any real test results are available.

The concept presented above is general and can be adopted to many different sealing solutions (in shape and materials). An engineering example follows in order to show the calculation details.

ENGINEERING EXAMPLE

Connection Description

An 18in SPO CF 15K HXL-385 flange connection is the considered example. The connection is subjected to a 22.5 ksi (155.1 MPa) test pressure at room temperature. The connection was assessed by the DBA method and the 2D axisymmetric FE model is based on ASME VIII, Div. 2 rules [13]. APDL scripting and the ANSYS R17.0 program was used. The FE model contains a SPO CF flange, seal ring and bolt representation (see FIGURE 1).

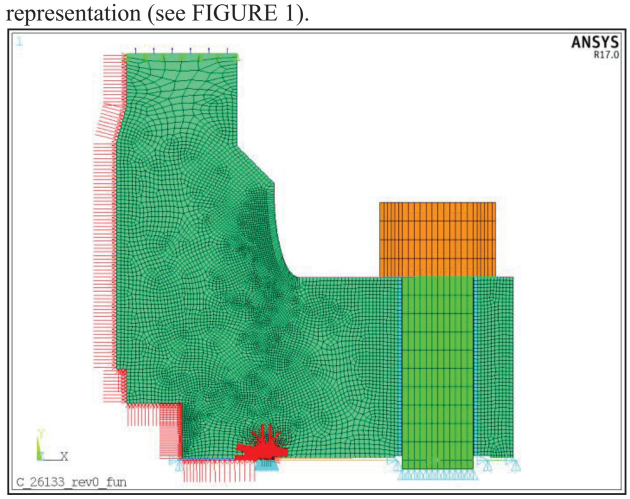

FIGURE 1: Example - FE model used for DBA assessment.

Symmetric boundary conditions were applied and reflects the project specification. Elastic plastic material formulation (based on ASME II, Part D [24]) was used. The leak rate was assessed for the seal ring seal under the test pressure load case.

Assumptions

Nominal flange and seal ring dimensions are used. The metal-to-metal seal type is evaluated. No coating layer is assumed as well as no scratches or other surface defects. The sealing surfaces (seal ring and flange groove) are assumed to be machined by turning and with maximum specified roughness value of 0.8 µm. The example for machined contact surface condition is presented in FIGURE 2.

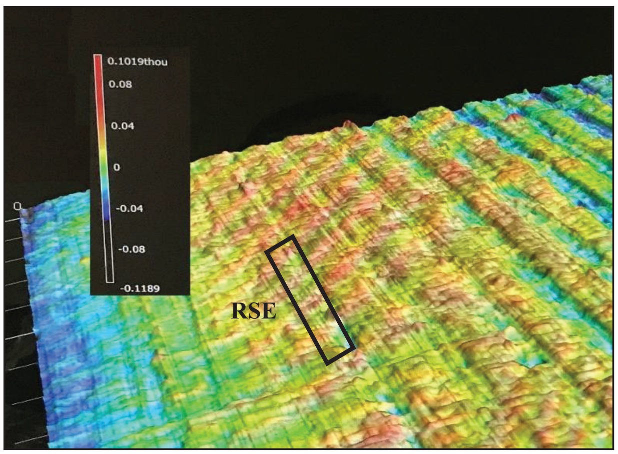

FIGURE 2: Example - The contact surface roughness 3D measurement.

During the makeup process, the sealing surfaces slide over each other until the seal ring is fully engaged. For seal rings, it is believed that the contact surface waves can overlap each other and can move/fit to the most optimal position (flange groove wave tips are in the seal ring waves walleyes). However, to be on the conservative side, the flange seat is assumed to be flat and infinitely rigid for RSE model (see FIGURE 3).

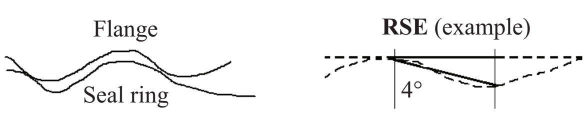

FIGURE 3: Example – Contact configurations.

Based on measurements and experience [2], the sealing surface can be defined sinusoidally or simply by a serrated profile in radial direction as in this example. A slope angle of 4° is used. In the circumferential direction, each roughness wave height differs by approximately 1/6 of the roughness value. For simplicity, the triangular profile for the circumferential direction is also used for the example calculation. The circumferential wave length is defined to be around 125 times greater than the radial wave.

The medium contained inside is water. Only laminar flow is assumed for the leak path. Water viscosity at 20°C is used ($1.002 \cdot 10^{-3}$ Pa·s) in the calculations. The capillaries are assumed straight and in radial direction only. The capillary cross-sections are triangular or trapezoidal and uniformly distributed on the sealing circumference. The RSE model reflects those assumptions. SB-564 N06625 material properties are used for the seal ring. The material model used is elastic plastic (see FIGURE 4) and is based on true stress and strain curve according to the material values and curve shape defined by ASME II, Part D [24].

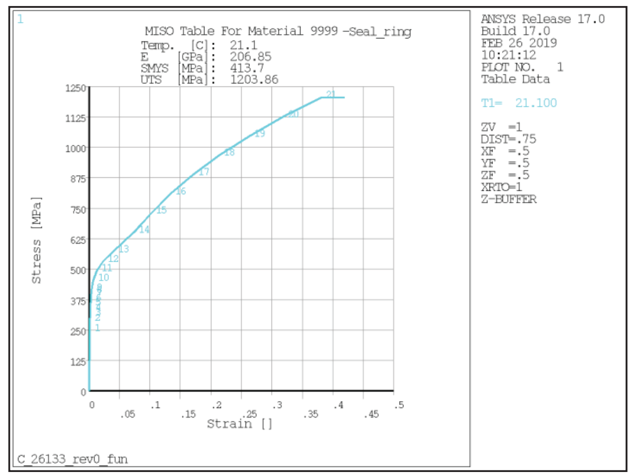

FIGURE 4: Example - Seal ring material model.

Step 1 Collating data

The FEA results related with the DBA flange assessment are used. The seal ring to flange seat contact pressure profile is subtracted from the FEA results. Conservatively, the pressure is applied up to the sealing diameter. The contact pressure profile for the outer seal ring lip is used. The contact pressure profile is described by the function P(s) and depends on the path parameter s (see FIGURE 5). Parameter s describes the position on the leak path and starts (=0) at the first contact point from the seal ring groove side. The total contact path length L is 6.7 mm; therefore, s ∈ (0 mm, L). External pressure P_{out} equal to 1 atm and an internal test pressure P_{in} of 22.5 ksi (155.1 MPa) are used. The maximum contact pressure is 81.7 ksi (563 MPa). This is higher than two times the inside pressure (2 x 22.5 ksi or 2 x 155.1 MPa) and therefore, meets the previous CF tightness criterion [20].

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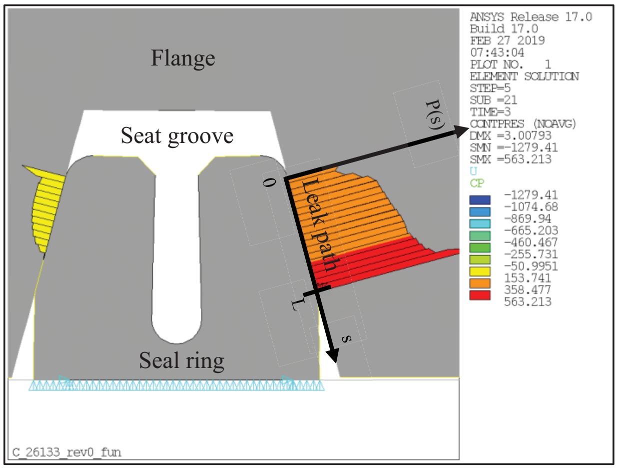

FIGURE 5: Example - Contact pressure profile.

Step 2 RSE analysis

The RSE model needs to be simple but also representative. For our example, the RSE geometry represents the radial waviness of the machined surface as well as the circumferential differences in the wave peak height (circumferential waves). The RSE height used was 100 times of the roughness R_a value. The width is equal to half of the radial wave length (0.5 L_a). The RSE length is equal to half of the circumferential wave length (0.5 L_{aL}). The RSE geometry follows the assumptions presented above and the simple triangular wave shape is used. There is also no coating specified; therefore, the same material properties are used as for the base material. The RSE volume is defined by half of the radial and circumferential wave as shown in FIGURE 6.

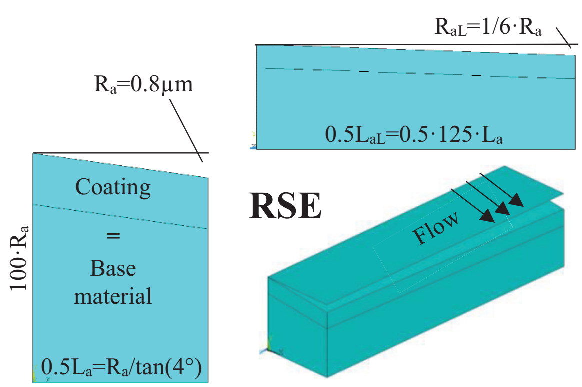

FIGURE 6: Example – The RSE model.

FEA is used for the RSE analysis. A 3D FE model was created and consists of the seal ring material, base volume section (solid elements) and rigid contact surface. The RSE FE model has symmetric boundary conditions in each direction except the bottom of the base volume. On the bottom base, all nodes are coupled in the direction normal to the rigid contact surface and uniform pressure load is applied. The applied pressure load in the RSE analysis is equivalent to the contact pressure between seal ring and flange in the global DBA assessment FE model (see FIGURE 5). For our example, the pressure load goes up to 362.6 ksi (2500 MPa) in value during the analysis. From the RSE analysis results, two representative curves are constructed to describe the RSE under contact pressure load (see FIGURE 7). One of them describes the R_a change as a function of contact pressure ($RSER_a(P)$ reduction factor). The other one describes the circumferential height R_{aL} change ($RSER_{aL}(P)$ reduction factor). For simplicity, both reduction factors are conservatively described by linear functions and bounded by 0.9999 in value (also to protect against dividing by 0 for future leak rate calculations).

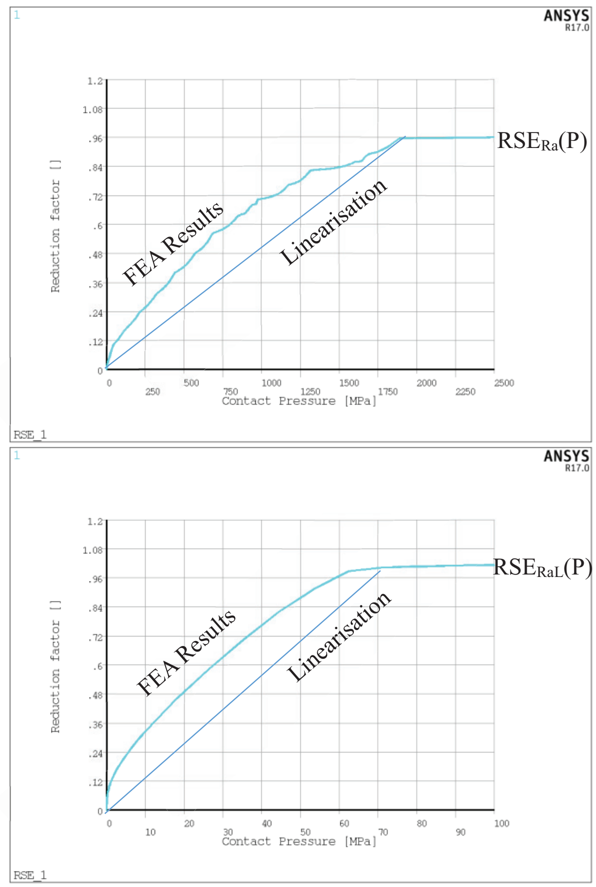

FIGURE 7: Example – RSE results (reduction factor functions).

Step 3 Leak rate calculations

Analytical calculations are done by using the PTC Mathcad Prime 3.1 program. In that way, calculations are not sensitive on units used, and different units can be mixed in calculations (for example; 1in+1mm+0.4ft=0.148m). Thus, equations presented in this paper are without unit conversion factors.

The leak rate calculations are based on the Hagen-Poiseuille law. The original theory describes the laminar fluid flow (viscosity η) through the long, circular in section, capillary (length L, radius r) for the pressure difference (Pin-Pout) and average pressure, Pave. Conductance C and flow throughput θ are described by equations (1), (2) and (3).

$$\theta = \frac{\pi \cdot r^4}{8 \cdot \eta \cdot L} P_{ave} \cdot (P_{in} - P_{out}) \quad (1)$$

$$C = \frac{\pi \cdot r^4}{8 \cdot \eta \cdot L} P_{ave} \quad (2)$$

$$\frac{\pi \cdot r^4}{8 \cdot \eta \cdot L} = \frac{1}{2 \cdot \eta \cdot L} \cdot \frac{(\pi \cdot r^2)^3}{(2 \cdot \pi \cdot r)^2} \quad (3)$$

By using section area A and capillary perimeter p, the Poiseuille law can be presented in another form (see equation (4) and (5)). In addition, the capillary shape function A_s is introduced to describe the relation between section area and capillary perimeter (see equation (6)). By doing so, the formula is more general and can be used for other capillary shapes. Parameter γ is a calibration factor/function, which can make a link between calculations results and real test measurements. For this example, γ=1.0 is used.

$$\theta = \frac{1}{2 \cdot \eta \cdot L} \cdot \gamma \cdot A_s \cdot P_{ave} \cdot (P_{in} - P_{out}) \quad (4)$$

$$C = \frac{1}{2 \cdot \eta \cdot L} \cdot \gamma \cdot A_s \cdot P_{ave} \quad (5)$$

$$A_s = \frac{A^3}{p^2}\ ;\ \gamma = 1 \quad (6)$$

For our example, the capillary has a triangular cross section at the peak of the radial wave and doubled trapezoidal for the valley of the radial wave (see FIGURE 8). Therefore, our shape parameter A_s is a function of the location on the contact path ($A_s(s)$, where the s direction is defined in FIGURE 5). The capillary geometry is also described by the roughness geometry parameters (R_a, R_{aL}, L_a, L_{aL}). Two of them can be described as dependent on the contact pressure ($R_a(P)$, R_{aL} (P)) by using reduction functions $RSE_{Ra}(P)$ and $RSE_{RaL}(P)$ from RSE analysis. Conservatively, other capillary dimensions are assumed to be constant in value (L_a, L_{aL}). By doing so, now we can describe the shape function A_s as a function of local contact pressure and location ($A_s = A_s(s, P)$,) The section parameters p and A are described by equations (7) to (9) for the valley of the radial wave location.

$$h_a = R_a \cdot RSE_{Ra};\ h_{aL} = R_{aL} \cdot RSE_{RaL} \quad (7)$$

$$p_{valley} = L_{al} + 2 \cdot h_a + 2\sqrt{{h_{aL}}^2 + L_{aL}^2} \quad (8)$$

$$A_{valley} = \frac{h_{aL} + 2 \cdot h_a}{2} \cdot L_{aL} \quad (9)$$

As we already know the contact pressure profile, and we have defined it as a function of the location P(s), we can link all to the position s on the leak path.

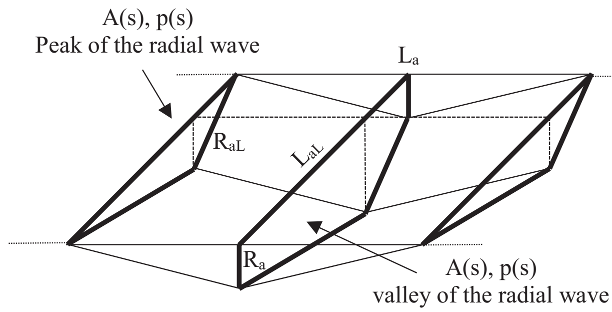

FIGURE 8: Example – The capillary shape (L_a section).

As the capillary geometry is changing along the sealing path, we need to have a method to integrate calculations along the path. The electrical conductance of a series circuits analogy (see equation (10)) was used for the conductance calculations. By dividing the leak path to the n number of sections (conductors) with conductance C_i, the total conductance C can be expressed by equation (11). Each conductance C_i is a function of position s on the leak path (see equation (12)).

$$\frac{1}{C} = \sum_{i=1}^{n} \frac{1}{C_n} \quad (10)$$

$$C = \frac{\prod_{i=1}^{n} C_i}{\sum_{i=1}^{n} \prod_{j=1}^{n} {C_j}^{1-\delta(i,j)}} \quad (11)$$

$$C_i = C_i\big(s, P(s)\big) = C_i(s) \quad (12)$$

For our example we assume 1000 divisions per radial wave length L_a. Because of the calculation program limitations, the total conductance C calculation had to be done in a loop. Calculations starts from one division conductance, adding the next one and saving it as an initial value for next step and repeat, until all divisions are evaluated (see FIGURE 9).

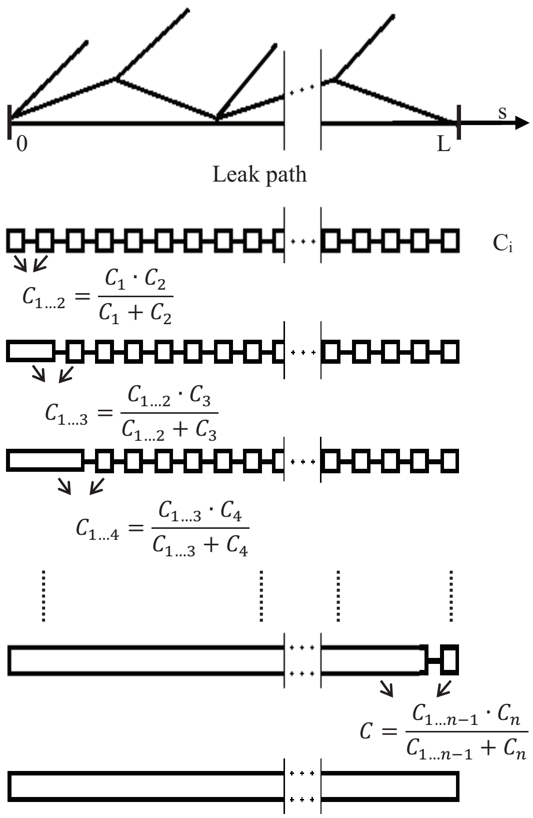

FIGURE 9: Example – Conductance integration.

The total conductance C is used for leak rate calculations. The flow throughput θ for the single capillary is described by equation (13). Unit leak rate ϕ_{1m} calculations are made by assuming unit sealing circumference (see equation (14)) and uniform distribution of the radial capillaries.

$$\theta = C \cdot (P_{in} - P_{out}) \tag{13}$$

$$\phi_{1m} = \theta \cdot \frac{1}{L_{aL}} \tag{14}$$

For the example presented in this paper, the unit leak rate of 7.816×10^{-10} mbar l s^{-1} m^{-1} is calculated, which corresponds to a water drop over a few years and follows ASME Tight leak rate class requirements. By changing medium viscosity properties to helium, 3.935×10^{-8} mbar l s^{-1} m^{-1} leak rate is calculated, which is lower than AH ISO class reequipment for fugitive emissions.

DISCUSSION

The calculated leak rate is extremely low, even when considering the simplifications and conservative assumptions applied during the calculations. Operational experience shows that the SPO CF system is as reliable as welded pipe connection [26] [27]. Recently, fugitive emission tests were performed in accordance with BS N ISO 15848-1 [12] standard [28][29]. Based on these results, the AH tightness class was confirmed.

This paper focused on the methodology and presentation of the RSE concept. It can be adopted to many different applications based on the definition of RSE. For the RSE model, other wave shapes can be used, such as sinusoidal profiles. The coating material can be utilized in with the RSE model (with proper coating thickness and properties different than the base material). The R_a and R_{aL} values, as well as L_a and L_{aL}, can be based on the manufacturing specification, or be supported by some surface measurement recorded history. Material curves can also be based on the manufacturing specification and/or be supported by material testing. The coating material does not need to be metallic, and therefore, proper material modeling is important to get reasonable results from the RSE analysis for coated surfaces. In addition, the RSE reduction factors can be described more precisely (by quadratic or step functions) to get more accurate results. The concept of the RSE can also be adapted for FFS assessments. FFS assesments can be used for radially scratched sealing surfaces, based on single scratch geometry, and the contact pressure profile.

The presented equations are based on laminar flow only (Poiseuille law), as HPHT is in focus, and those effects are dominant. It is possible to use the same methodology (RSE analysis) and extend leak rate equations for the molecular flow, which is relevant for the UHV applications [2][21].

To increase accuracy of the method, other than equal to unity, calibration factor/function γ can be used in calculations. Calibration factor γ can be obtained by result comparison to the test measurements, and can take into account statistical data (repeatability and production quality).

CONCLUSIONS

In this paper, the focus was on a leak rate calculation methodology. General calculation steps were defined. The RSE methodology has a high potential for adoption to different conditions (e.g. surface finish, materials, coating). In this paper, the methodology presentation was supported by an engineering example. Finally, example results were linked to operational experience in relation to SPO CF design (comparison to fugitive emission tests [28][29] and reliability evaluation studies [26] [27]).

The presented method is constructed to be a simple tool and effective for leakage rate prediction. By using it, designers and engineers will be able to compare different concepts, and judge new designs before production and testing.

It is believed that the RSE concept methodology can be adopted by any other company, and/or become a new standard method for design.

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Contact Us

Freudenberg Oil and Gas Technologies

Headquarters
10035 Brookriver Drive, Suite 400
Houston Texas 77040
Phone: +1 281 233 1400

www.fogt.com
sales@fogt.com

Corporate Sales

+1 514 428 5900 Phone
+1 514 426 9222 Fax
+1 866 643 5999 Toll-Free

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