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Bolted Flange Connection Leakage: a Systematic Review of Monitoring Challenges and Technologies

Ben Cloostermans, Dick Pronk, Björn Bruckenburg, Sidney Goossens, Tigran Baghdasaryan, Francis Berghmans

***Abstract*— Ensuring leak tightness and preventing emissions in bolted flange connections are critical for maintaining safety, reliability, and environmental compliance in industrial systems. This article offers a comprehensive review of techniques to improve installation processes and establish effective monitoring systems for bolted flange connections. The discussion on installation techniques focuses on achieving the appropriate gasket surface pressure to minimize leakage risks and enhance long-term reliability. The importance of proactive monitoring during installation is emphasized, as it enables the early detection and resolution of potential issues. The review also explores long-term monitoring strategies, spanning both traditional methods and advanced technologies. While direct observation is cost-effective, it lacks precision and fails to ensure safety. More advanced approaches, such as internal mass balance and real-time transient models, deliver superior detection and quantification capabilities, albeit with increased complexity and cost. External monitoring systems, such as cable-based sensors and hydrocarbon-sensing tubes, are highlighted for their effectiveness in broad-scale applications. Meanwhile, advanced techniques such as bolt load monitoring and fiber-optic sensing offer state-of-the-art solutions for identifying leaks and emissions. This work organizes these methodologies into distinct categories and provides a practical framework for applying them across various operational contexts. By emphasizing advancements in real-time monitoring and leak prevention, this study promotes safer and more sustainable industrial practices, laying the foundation for future innovations in bolted flange sealing technology.**

***Index Terms*— Condition monitoring, Flanges, Gaskets, Seals**

I. INTRODUCTION

MODERN industrial process plants exploit a multitude of bolted flange connections (BFCs). These are often considered critical components given that they ensure connections between diverse systems that process and transport substances that can possibly be harmful for the health of the personnel and the public, for the environment and/or for the climate. Such BFCs are commonly found in piping, valves, pressure vessels, boilers and heat exchangers. They typically consist of two flanges enclosing a gasket and held together by ways of multiple bolts in view of creating a tight seal, as shown in figure 1. During the last 20–30 years, great progress has been made in the understanding of how seals operate, and the sealing quality has been significantly improved. This has been accompanied by the development of new or enhanced gasket materials that serve the sealing performance [1]. Note that successfully sealing a BFC not only depends on the gasket material, but on all the components of the connection, including the bolts and the flanges [2]. The bolts are elongated by means of fastening the nuts. This elongation is accompanied with a tensile stress in the bolt material. The bolt load is applied to the flanges such that they are pressed together. The resulting load is distributed across the gasket surface, leading to the so-called ‘gasket surface pressure’. The gasket material then deforms to establish the seal, with the residual or 'operating' gasket surface pressure sustaining the seal during its use [1]. Figure 2 illustrates the mechanism for a typical configuration of a bolted flange connection for piping systems, as described in standards which are further discussed in section V. The configuration and dimensions may differ depending on the application, but the mechanisms and principles remain similar.

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Fig. 1. Picture of a typical bolted flange connection (BFC).

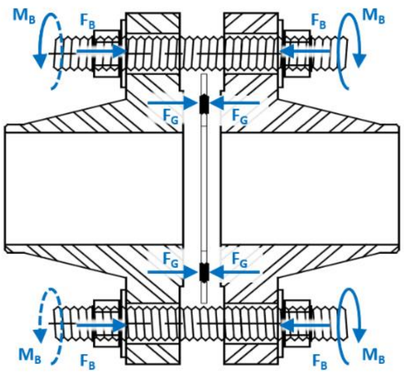

Fig. 2. A cross-sectional view of a bolted flange connection illustrating the key loads involved in establishing the seal. The applied torque MB generates a bolt load FB, which in turn creates a compressive load on the gasket. This load is redistributed across the gasket surface (FG), resulting in the gasket surface pressure. This pressure is essential for deforming the gasket and achieving a tight seal.

In parallel with the development of improved BFCs, industry also focused on digitalization in view of supporting the transition to more automated and better controlled workflows and at the same time in view of enhancing the reliability, safety and sustainability of industrial systems. Process industry took many initiatives in this sense to create digital versions or digital twins of their assets. To facilitate these efforts, sensing and monitoring of a diversity of components is vital. As simple as an individual BFC may seem, a typical process plant contains between 200.000 and 300.000 of such BFCs. Ensuring that all connections are properly sealed and remain so during the expected lifetime is an obvious challenge. This calls for developing techniques that enable the monitoring of BFCs such that plant operators can be alerted in case leakage occurs, or even better, before leakage occurs such that preventive maintenance actions can be initiated.

The purpose of this manuscript is to dive in these monitoring techniques whilst reviewing the diversity of monitoring challenges and corresponding solutions. Literature on these subjects appears fragmented, yet we attempt to summarize the best available monitoring techniques and describe the state-of-the-art in a systematic manner. While we have endeavoured to present a comprehensive review, we recognize that this work cannot cover every aspect or innovation in the evolving BFC-landscape. Due to the sheer volume of research and the constant advancements being made, some important contributions may regrettably not be included. The omissions are by no means a reflection of their significance, but rather a limitation imposed by the scope and length of this review. Section II describes the typical lifecycle of BFCs and aims to highlight challenges that can arise during the lifecycle, providing a comprehensive understanding of how these BFCs evolve and perform over time. Section III analyses the European Major Accidents Reporting System to identify common problems and challenges industry is currently facing with BFCs, as evidenced by actual reported incidents. Section IV then elaborates on the reported failure modes and effects associated with BFCs. This part addresses the definition of leakage – which is apparently subject to diverse perceptions – and its origin. Section V deals with the available standards, guidelines and calculation methods pertaining to flange connection integrity. Finally, we distinguish between monitoring challenges and techniques during the installation phase and the service phase, in section VI and section VII, respectively which contribute to safe and sustainable use of BFCs over their complete lifecycle.

II. FLANGE CONNECTION LIFECYCLE

The lifecycle of the BFC can be systematically divided into three distinct stages. First, during the installation phase, the BFC is assembled, and the bolts are tightened to establish a secure seal as described in section I. Second and once all BFCs are properly installed, the system—or a designated section of it—is subjected to a pressure test to verify the absence of leaks. Finally, in the operational phase, the system is brought into service, requiring the BFC to maintain a reliable seal until the next scheduled maintenance. As touched upon in the introduction, the gasket surface pressure is the determining factor for the seal quality [2], [3], [4], [5], [6]. The lifecycle of the seal as described above can therefore be explained based on the evolution of this parameter, as visualized in figure 3.

During the installation phase, the aim is to reach a certain surface pressure level at which the tightest possible seal is established. In general, the higher the surface pressure, the tighter the seal. The term tightness, as used in gasket terminology, deserves some explanation. It is an abbreviation for leak tightness and describes the performance of the gasket in terms of emissions. On one hand, there is a specific minimum gasket surface pressure at which the seal is sufficiently established and complies with tightness requirements. On the other hand, and given that every material has its limitations, there is also a maximum surface pressure at which the gasket simply ruptures. Somewhere in between the limits set by the gasket, there is the strength limit imposed by the properties of the flange and of the bolts. Ideally, the installation procedure should then result in a surface pressure that ensures tightness and maximizes the surface pressure such that it still complies with the strength limits imposed by the flange and the bolts. This is commonly achieved in a few steps according to a

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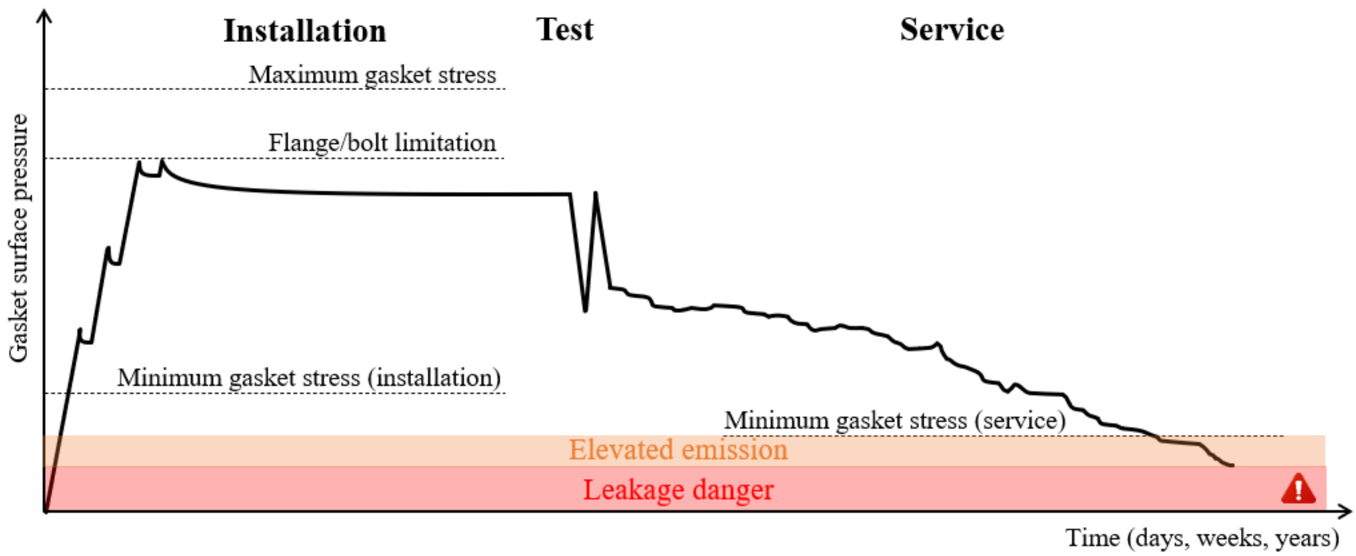

Fig. 3. Flange connection lifecycle.

specific installation protocol. After the installation, the surface pressure typically features a decrease, originating mainly from elastic interaction and relaxation of the gasket, as explained in detail in section V. Note that the test phase organized right after the installation introduces an internal pressure to assess tightness, typically using non-hazardous substances such as water or compressed air. At this stage, the hydrostatic pressure inside the system causes an internal load opposite to the initial bolt load. Consequently, the residual surface pressure decreases. After testing, the service phase commences during which the actual medium transported through the BFC causes exactly the same phenomenon as in the test phase: the residual surface pressure decreases. Note that the initial residual surface pressure in service is typically higher than in the test phase because the internal pressure during the test phase is typically above the service pressure. From this time forward, the evolution of the surface pressure is rather unpredictable. There are various causes for sudden instabilities in surface pressure, such as fluctuations of service pressure and/or service temperature. Overall, the gasket experiences long-term relaxation during use, which causes a gradual decrease of surface pressure. A crucial threshold in service is the minimum surface pressure at which the seal is no longer sufficiently tight according to industrial standards [7], [8]. Right below this threshold, leakage is qualified as elevated emission, as this is hard to observe visually. This situation is nevertheless unacceptable and should be remediated properly. Upon further decrease of surface pressure, the BFC may start to leak visibly, which is an urgency that obviously requires immediate intervention.

Research on the lifetime of gaskets [9] estimated the probability density function for failure by means of an accelerated leakage test. The resulting probability density function presents a single peak, but clearly not symmetrical such that it cannot be described by normal distribution. Therefore, the authors of [9] conclude that said lifetime may obey a Weibull or lognormal distribution. The failure rate of gasket sealing during service is time-correlated: it is low in the early stage and then increases with time. The tightness of the connection nevertheless depends largely on the material properties of the BFC, the installation procedure as well as the application parameters.

Following the above, one can understand that there are several stages that can be distinguished in the lifecycle of the BFC. First, the installation procedure establishes the initial surface pressure. Adequate control over this procedure leads to the optimum initial surface pressure, which is inherently related to the lifetime in service. Failing to establish a suitable surface pressure upfront, either by not reaching the minimum surface pressure or exceeding the maximum surface pressure, significantly impacts the test and/or service phase. Second, the service time over which a sufficiently high surface pressure should be maintained – which is often referred to as remaining useful lifetime – is often unknown. Consequently, there can be significant impact if the BFC exhibits leakage before the expected lifetime of the application. A seal providing insufficient tightness may lead to invisible leakage, which should be always avoided. In this context, the knowledge of the actual surface pressure can potentially overcome tightness issues at any stage of the lifecycle, either by optimization during the installation phase, verification during the test phase or anticipation during service phase. [4], [6], [9]

III. EUROPEAN MAJOR ACCIDENTS REPORTING SYSTEM

Literature on BFC tightness-related issues is scarce. To put things in context though, we have analysed publicly available reports that provide an indication of the impacts on today's industry. A useful source of information for that purpose is the Major Accidents Reporting System (eMARS), as established since 1982 following the Seveso Directive of the European

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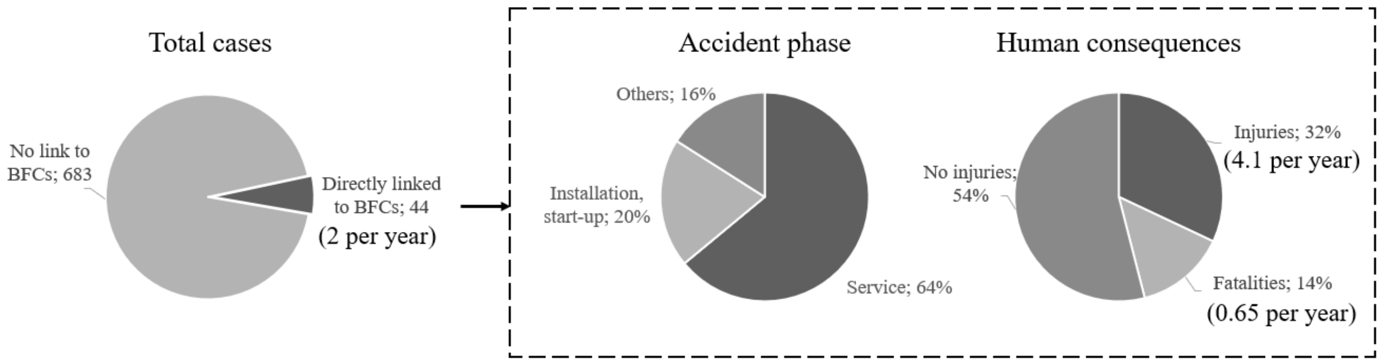

Fig. 4. Data extracted from eMARS showing the proportion of cases related to flange connections, phases in which the accidents occurred and human consequences.

Commission [10]. Its purpose is to facilitate exchange of lessons learned from accidents and near misses involving dangerous substances in order to improve chemical accident prevention and mitigation of potential consequences in industry. Starting from the year 2000, 727 major accidents have been reported of which 44 (6%) were found to be directly linked to BFCs, corresponding to 2 major accidents per year. After review of each report, 64% occurred during service, while 20% occurred during installation or start-up. The rest of the cases were not categorized as they lack details on the origin of the issue (16%). Needless to say that the impact of these major accidents cannot be underestimated. Personnel injuries were involved in 32% of the cases, with even 14% of the cases resulting in fatalities. To put things in absolute numbers, there is a reported annual rate of 4.1 injuries and 0.65 fatalities. This is in line with the general statistics of all eMARS reports [11], highlighting the contribution of BFCs in major accidents. Figure 4 visualizes these findings. The economic consequences are rarely detailed in these reports. The average reported cost was EUR 10.5 million per accident, while the highest reported cost was EUR 50 million. These costs are attributed to response, clean-up, damage and material loss as well as loss of production time. The reports nevertheless elaborate on the root causes of the accidents, but these are subject to interpretation and cannot always be validated given the level of detail of the reports. Examples of reported root causes are gasket degradation, vibrations, flange corrosion and loose bolts. We examine the root causes, the failure modes and their effects in detail in section IV.

Despite eMARS provides information on major accidents, smaller accidents and issues remain often unreported or unknown. A study of the Dutch National Institute for Public Health and the Environment [12] concludes that the failure frequency of BFCs in natural gas piping systems is 5.5e-7 per year. This essentially means that on a yearly basis, only one out of 1.75 million BFCs fails. Notwithstanding this extremely small amount of failures, it only takes into account the leaks resulting from a (partial) blow-out of the gasket (see section IV) as mentioned in [12]. To put this in perspective, the report considers small leakages and gas diffusion irrelevant. This shows that when interpreting the data on the problem scale with BFCs, the definition of failure, referred to as leakage, plays a crucial role.

In conclusion, incorrect or unmonitored use of BFCs forms a major risk in industry, with consequences that appear underestimated. On the upside, considerable efforts have been made in the past decade in view of optimizing the maintenance of industrial equipment. The most remarkable developments have led to the transition from corrective to predictive maintenance, the goal of which is to prevent the failure of equipment by early interventions triggered by adequate monitoring of the condition of the equipment. This approach often relies on regular inspections and recording of several physical quantities that are indicative for potential malfunctioning and related to the failure modes of the equipment. An extensive survey of large manufacturing and industrial organizations around the world [13] showed that 72% of large industrial organizations have made predictive maintenance a strategic objective. 20% already has established dedicated teams to lead these initiatives. Although there is a clear incentive for the development of predictive maintenance techniques for all sorts of equipment used in industrial plants, and in spite of the large numbers of BFCs used in such plants, little to no predictive maintenance techniques for these BFCs have been deployed.

IV. FLANGE CONNECTION FAILURE MODES AND EFFECTS

Abid and Nash [14] note that literature on the Failure Mode and Effects Analysis of BFCs is limited. The performance appears highly dependent on the application. Brown and Knight [15] rightfully mention that there is very little publicity of BFC failure or published industry learnings from such failures. They are often presented with limited details around the origin or experience with the particular failures referenced, which aligns with our conclusion based on the eMARS reports (see section III) One reason for that is the will to protect the anonymity of the companies involved.

Abid and Nash [14] distinguish four categories (or stages) for a BFC in which it is susceptible to failure. (1) design and fabrication, (2) storage and handling, (3) installation and (4) normal operation. They developed weight factors that define the distribution of causation for these stages. The factors are

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respectively 0.16, 0.10, 0.30, 0.44. These proportions align more or less with the ratios we found in the eMARS reports, i.e. 0.20 and 0.64 for respectively installation and service. Whilst Abid and Nash's work delivers an excellent overview of the failure causes and mechanisms, the function of the gasket is often restrictively described as creating and maintaining the seal between two surfaces, and the loss of function is often vaguely described as 'leakage'. Given that the failure modes correspond to the specific manners with which a function is lost, one can argue that it is critical to have a clear definition of leakage and of the different types of leakage for distinguishing the failure modes of flange connections.

In this context, Veiga [6] states the non-existence of 'zero leakage'. The European Sealing Association [16] also explains that there is no such thing as 100% tightness as it is technically unsustainable. Depending on the type of medium, internal pressure, type of sealing material and installation conditions there always exists an inevitable leakage rate. Furthermore, the definition of leakage essentially depends on the method with which leakage is measured or on the criterion utilized. According to Veiga [6], the following should be considered in view of establishing the criteria for maximum admissible leakage:

- substance to be sealed;
- impact on the immediate environment, upon escape into the atmosphere;
- danger of fire or explosion;
- other relevant factors in each particular situation.

In process industry, the maximum admissible leakage rate is commonly defined based on Helium leakage. In Europe, for example, the TA-Luft certification [17] for technical tightness is given for a Helium leakage rate below 10^{-2} mg/(s.m). However, in the USA, the Environmental Protection Agency (EPA) sets the limit of 500 parts per million (ppm) of Helium as maximum leak for flanges [18]. Other criteria are also being applied, such as those defined by the Johnson Space Center (NASA), which established limits for different toxicity hazard levels related to the medium. For example, the so-called class ‘critical fluids’ sets a limit of 1e-7 scc/s (standard cubic centimeter per second), given NASA-approved testing methods [19]. The use of different metrics for leakage indicates that this term is perceived differently across industries and regions. These different quantities also originate from the different methods used to measure said leakage. The most common methods are the pressure decay method using the differential pressure procedure, the mass spectrometer and the so-called sniffer (see section VII). Furthermore, the quantities are difficult to compare with each other. For example, ppm is not a measure of leakage rate, but rather provides an indication of leakage severity. The conversion between ppm and leak rate is usually accomplished by means of empirical power law correlations [1]. However, we can still categorize the failure modes qualitatively based on the severity of the leakage, as summarized below.

- **Stable emission** occurs when the acceptable leakage rate has been exceeded, however it is typically not visible.
- **Leakage** corresponds to the situation where there is typically visible leakage.
- **Blow-out** occurs when the gasket is literally blown out of the flanges. It also goes with sudden pressure release.

These three failure modes are initiated by failure causes, of which Table 1 provides a non-exhaustive list.

Failure causes	
Installation	**Service**
Flange misalignment	Fatigue
Damage to gasket or flange	Vibration
Non-uniform bolt pre-load	Thermal shock
Lack of pre-load	Wear of erosion
Excessive pre-load	Stress corrosion
	Interface corrosion
	Pre-load loss
	Creep of gasket
	Frequency of maintenance
	Load capacity

Table. 1. Failure causes of BFCs according to Abid and Nash [14].

There is growing awareness that many of these BFC related issues are caused (or at least magnified) by poor practices during installation [20]. Especially during installation, human errors such as flange misalignment or damage to the gasket or flange causes insufficient or non-uniform compression of the gasket and it can perfectly be avoided by installation trainings and inspections before use. On the other hand, non-uniform bolt pre-load, lack of pre-load and excessive pre-load also causes insufficient or non-uniform compression of the gasket and often stem from uncertainties, which in their turn make these pre-load issues more difficult to avoid. For example, there is an uncertainty on the induced bolt load by applying a certain torque, resulting from the so-called elastic bolt interaction, mainly caused by gasket relaxation. This effect is often referred to as creep-relaxation in installation [21], [22], [23] and it is a key failure cause [24]. These failure causes can often be avoided using calculation standards in combination with good installation practices, as described in section V and VI.

Long-term creep-relaxation is often responsible for emissions or leakages in service conditions as the relaxation of the material induced loss of surface pressure [25], hence loss of sealing performance. Retention of the surface pressure within the gasket is important for maintaining the level of energy stored in the BFC and hence the ability to maintain the seal. Relaxation can occur at the flange/gasket interface as well as in the gasket material itself. Materials having high elastomer content, for example, can be expected to relax significantly as the elastomer degrades over time.

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In risk assessment and reliability analysis on a more general level [26], the evaluation of critical components, including BFCs, plays a vital role in ensuring the safety and reliability of process systems. One widely used method to quantify the risk is through the calculation of the Risk Priority Number (RPN). The RPN is determined by multiplying three factors: Severity (S), Occurrence (O), and Detectability (D), each of which is assigned a score ranging from 1 to 10. A higher RPN indicates a greater level of risk.

For BFCs, the severity (S) is typically evaluated based on the potential consequences of failure within the larger system. They are often essential in maintaining the integrity of interconnected systems. Failure of the BFC, i.e. any cause of leakage, can result in not only localized issues but also disruptions to upstream and downstream processes. The critical nature of BFCs is magnified when their failure requires shutting down the process, or parts of it, to perform repairs, leading to significant operational and financial losses.

The occurrence (O) of BFC failures is typically determined based on historical data and reliability statistics. This involves analyzing how frequently failures have occurred within a certain timeframe, which can vary depending on the operational conditions. Frequent failures indicate a higher risk, and as such, improving the reliability of BFCs is critical in minimizing occurrence rates. Regular inspection and maintenance records play a key role in assessing this parameter.

Detectability (D) refers to how easily potential failures in BFCs can be identified. Detectability is largely influenced by the maintenance strategy in place. For example, if a reactive maintenance approach is used, failures may only be detected after they occur, leading to higher risks. In contrast, employing preventive or predictive maintenance strategies can greatly improve detectability. The earlier a potential failure is identified, the more time there is to address the issue before it escalates into a major issue.

To mitigate the risks associated with BFCs, it is crucial to implement effective preventive or predictive maintenance strategies. These strategies can significantly reduce the occurrence (O) of failures by addressing potential issues before they develop into major issues. Additionally, monitoring techniques and regular inspections can enhance detectability (D), allowing for early intervention. By improving both occurrence and detectability, the overall RPN can be reduced, leading to safer, more reliable systems with fewer unexpected failures. In conclusion, the implementation of proactive maintenance practices is essential for managing the risks associated with these critical bolted flange connections and ensuring the continued safety and efficiency of industrial process systems.

V. FLANGE CONNECTION INTEGRITY

A. Standards and dimensions

The working principle of bolted flange connections has a complex nature given the diverse physical interactions between the bolts, flanges and gasket. These interactions are essentially mechanical, thermal and chemical. To provide a framework and establish certain performance criteria, there are a number of industrial standards and guidelines, which provide the foundations for ensuring the integrity of BFCs by ways of adequate and precise design, supplemented with complex calculation methods. Dominant standardization bodies are the European Standards (EN) and the American Society of Mechanical Engineers (ASME).

Table 2 lists the most renowned standards on design and dimensions of flanges, gaskets and bolts. Adhering to these standard dimensions, whenever feasible, is a crucial first step in ensuring the integrity of BFCs, as they are designed to provide adequate tightness throughout the expected service life under standard installation procedures.

Standards and codes		
Flanges	**Gaskets**	**Bolts**
EN 1092 [27]	EN 1514 [28]	EN-ISO 898 [29]
EN 1759 [30]	EN 12560 [31]	ISO 3506 [32]
ASME B16.5 [33]	ASME B16.20 [34]	ISO 4014 [35]
	ASME B16.21 [36]	ASTM A563 [37]
	ASME B16.47 [38]	

Table. 2. European (EN, ISO) and American (ASME, ASTM) standards and codes for flanges, gaskets and bolts.

Most of the BFCs present in industry are standardized by design. However, when dealing with custom BFCs, or special application conditions, generating sufficient tightness often becomes a challenging concern. A tight seal is of the utmost importance for this type of applications, because these are typically referred to as critical connections for the process (see section IV). In pursuance of custom tight BFCs, there are a number of standardized calculation methods available to support engineers and designers of BFCs to comply with modern tightness requirements.

B. Calculation methods

As discussed in section II, achieving the correct gasket surface pressure is crucial for ensuring proper sealing. The installation process must reach a surface pressure at the optimal level such that it remains consistently high during both the testing and service phases of the BFC. Therefore, it is essential to calculate the surface pressure during these phases to verify that the selected flanges, bolts, and gasket are designed to maintain adequate sealing performance throughout the lifecycle. Essentially, the calculation verifies the maximum achievable gasket surface pressure, given the strength limitation of the flanges, bolts and gasket.

Commonly used calculation methods for BFC tightness are the European EN 1591 standard [39] and the Taylor Forge

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method in the ASME Section VIII standard [40]. Both methods are thoroughly elaborated and require a large number of parameters and characteristics, which are provided in respectively EN 13555 [41] and ASME Section VIII. Whilst these methods account for a good approximation of the true conditions, they rely on many assumptions. In most cases, this approximation is sufficient to meet tightness requirements, but in critical situations, these assumptions can lead to poor designs, resulting in emissions or leaks with potentially severe consequences.

The EN 1591 method takes the entire flanges-bolts-gasket assembly into account, aiming to verify tightness, based on the surface pressure generated. The calculation is based on the elastic load-deformation relationship between all BFC components, adjusted for the possible plastic behaviour of the gasket material. The load conditions considered include initial installation, hydrostatic testing and all subsequent operating conditions. The method begins by determining the required gasket surface pressure to ensure tightness, and then calculates the required minimum bolt load needed to maintain adequate residual surface pressure in any given condition. The minimum gasket surface pressure, expressed in MPa, is defined for each gasket type in EN 13555. The calculation also accounts for bending moments, also referred to as flange rotation, making it an iterative process: the gasket surface pressure depends on the effective compressed gasket width, which is influenced by the initial bolt load. Internal forces resulting from the initial bolt load are then calculated for all load conditions.

On the other hand, the Taylor Forge method in ASME Section VIII primarily considers the load conditions during installation and service. Starting from the minimum gasket surface pressure required for tightness, it calculates the resulting flange and bolt stresses. This minimum gasket surface pressure is expressed as a multiple (m) of the internal pressure, with the m-factor depending on the gasket material and construction. Unlike EN 1591, the Taylor Forge method only considers bending moments in terms of flange stress calculations and does not account for all load conditions. For instance, it does not calculate the internal forces for a given initial bolt load, making it impossible to determine the remaining bolt load and gasket reaction under subsequent load conditions. Additionally, the Taylor Forge method does not consider the leakage rate, so it cannot assess tightness.

Zerres and Guérout [42] compared the two methods and found that EN 1591 is far more detailed, allowing for the calculation of all loading conditions while also considering tightness. In contrast, the Taylor Forge method uses a simpler mechanical model that is limited in scope and cannot account for all load conditions or tightness.

In some cases, more advanced calculation methods are needed to accurately estimate the performance of BFCs, particularly when the connections are subjected to a number of complex physical loads, such as irregular geometry, non-uniform temperatures or bolt loads, and vibrations. In such cases, the Finite Element Method (FEM) is a widely used technique. FEM allows for modelling of the actual geometry and material characteristics of the BFC, enabling multi-physics simulations that can account for complex interactions between different physical domains. The typical results of interest for BFCs are stress, strain or temperature distributions of the flanges, bolts or gasket and contact stresses between them. Although FEM provides highly accurate results, it is time consuming and requires many parameters. Mackerle [43] has compiled a bibliography (1990-2002) on FEM applications for fastening and joining, including 37 references specifically related to BFCs. These studies focus on stress analysis, sealing performance, contact issues, creep relaxation, and stress determination during thermal transients. FEM remains a key research area with potential for solving many gasket-related problems in BFCs [44], [45].

VI. INSTALLATION CHALLENGES AND TECHNIQUES

The most crucial phase to prevent future leaks is the control and monitoring of the installation procedure. A good installation is indeed fundamental for ensuring tightness. The remaining useful life of the flange connection is determined by how successful the installation was carried out, given that the tightness will decrease because of usage, wear and/or other external influences. The installation procedures should specify the tightening of the bolts such that the forces are uniformly distributed over the gasket surface and lead to the generation of a sufficiently high pre-determined gasket surface pressure, and preferably as high as possible given the strength limits of the materials employed in the BFC, as explained in section II.

A. Torque control

With the methods described in section V one can calculate the required force per bolt to establish a tight seal. By approximating the friction coefficient for the given bolt-nut connection, one can derive the torque value that corresponds with the required force in the bolt. Therefore, with a torque measurement during installation one can estimate the force that is generated by the bolts, and hence assess the gasket surface pressure in the BFC. Torque is a quantity which can be applied and simultaneously measured with adequate accuracy. The most common device for such torque measurements is a torque wrench. There are many types of such torque wrenches, each coming with its respective working principle. Hamilton [46], [47] compared seventeen different torque tools, including pneumatic, hydraulic, and manual torque wrenches. The pneumatic and hydraulic wrenches can, for example, be used for significantly higher torque levels (typically starting from 300 Nm), but they require more time and experienced operators.

B. Bolt cross talk

In addition to controlling the torque level during bolt tightening, another crucial phenomenon to consider when using a torque wrench is elastic bolt interaction, also known as bolt crosstalk. The concept of bolt interaction has already been extensively investigated and is simple to describe according to Bibel and Ezell [48], [49]. When a single bolt is tightened, the flange is drawn together. The bolt is slightly elongated, and the gasket is partially compressed. As an adjacent bolt is then tightened, the gasket is being further compressed and the load is redistributed among the tightened bolts, as schematically illustrated in figure 5. This allows the initial bolt to relax a little. In a flange with a significant number of bolts, combinations of these elastic interactions become quite complicated, which in its turn leads to a wide range of final loads depending on the actual tightening sequence. Bibel and Ezell report that elastic interaction can cause some individual bolts in a flange to loosen up to 98% of their initial preload when adjacent bolts are tightened. Essentially the effect induces non-uniform gasket surface pressure which in its turn can cause leakage. Alkelani and Nassar [50], [51], [52] have analytically and experimentally investigated the effect and were able to formulate equations to predict the final load state for a given installation procedure. Based on this research, they have also investigated several bolt tightening methodologies to optimize the final load state [53], [54]. They found, for example, that some bolt tightening sequences, such as sequential or star pattern tightening, result in 98% of the target uniform bolt preload. Subsequently, numerous reports dealt with elastic bolt interaction models to optimize the tightening sequence [55], [56], [57], [58], [59], [60], [61]. These have also shown that this effect contributes more to the variation in final bolt loads than the problems associated with torque control [62].

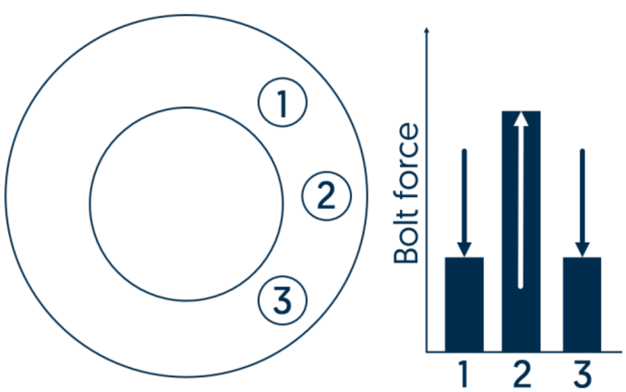

Fig. 5. Illustration of the principle of elastic bolt interaction. Tightening bolt number 2 allows the adjacent bolts number 1 and 3 to relax. Inspired by [48]

C. Bolt tensioning

As previously described, torque control and tightening procedures can assist the installation, but creating a uniform gasket surface pressure remains challenging. For critical applications, one can make use of bolt tensioning to accurately apply bolt force by eliminating the uncertainty related to friction. This system works by hydraulically tensioning the bolts, such that a precise force is induced in the bolts. Hydraulic bolt tensioners operate as follows, as illustrated in figure 6:

- the bolt is stretched by lifting a grip nut through hydraulic pressure and initial tension is produced in the bolt;
- the nut is run down onto the surface of the flange;
- the hydraulic pressure is released and the bolt tension decreases from its initial tension to clamping tension due to the deformation of the flange and the gasket.

Fukuoka [63], [64] investigated the use of bolt tensioning, given its application for tightening critical structures. He investigated the so-called effective tensile coefficient or pre-tension coefficient, which is defined as the ratio of the desired clamping force to the initial applied force. In case of BFCs, the effective tensile coefficient depends on the stiffness of the flange and the gasket. Typically, the gasket has a low stiffness, and therefore the effective tensile coefficient can be expected to be quite low, which in its turn jeopardizes the tightness. Values between 60% and 90% are reported, verified using experiments and FEM. The most prominent influences are the bolting sequence and tensioning speed [65], [66]. It is worth noting that some systems allow tensioning multiple bolts at once to mitigate the challenges related to elastic interaction. Despite these shortcomings of bolt tensioning, the residual load in the bolt can be estimated with a reasonable accuracy of ±10% [67]. However, as bolt materials become more diverse and since applying precise loads has become a requirement, bolt load verification or monitoring technique is rapidly gaining popularity.

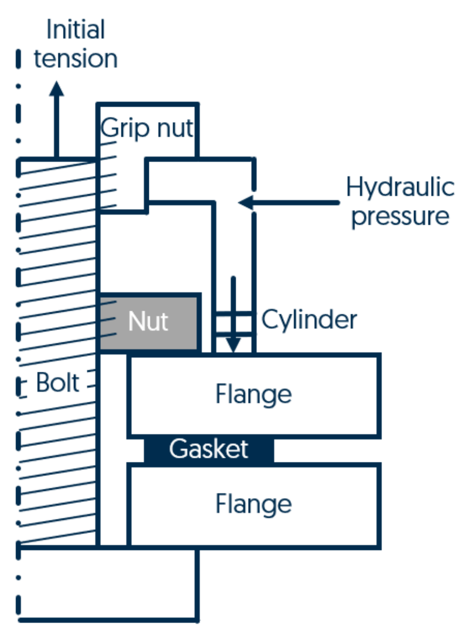

Fig. 6. Schematic representation of hydraulic bolt tensioning. Hydraulic pressure on the grip nut induces an initial tension in the bolt. Adapted from [63].

D. Bolt load monitoring

The most common method for load verification is the measurement of bolt loads. To do so, diverse techniques are available, relying on electromechanical, acoustic or optical principles. Electromechanical methods involve instrumenting the bolts with strain gauges [68], [69] and force washers [70]. The bolt load can be determined from the bolt stress, which in its turn is measured by the strain gauges. Typically, the bolts are prepared for strain gauge installation by machining the threads down to their root diameter. Then the strain gauges can be attached to the bolt by means of soldering or sticking. Solely the axial load is of interest, meaning that any bending components must be eliminated. To do so, a full bridge configuration with a longitudinal gauge and a transverse 'Poisson' gauge can be located on two surfaces oriented 180 degrees apart from each other. This configuration offers a high output as well as low nonlinearities. Another advantage of this configuration is that it provides for good temperature compensation because active gauges are present in all arms of the bridge. Despite using strain gauge-instrumented bolts, final load differences up to 8.5% are reported when using state-of-the-art assembly protocols [68]. Force washers use a similar technique using strain gauges. These washers can be clamped using the bolts, making them interchangeable and more widely applicable. Their accuracy is typically ±5%. For both strain gauges and force washers, the data can be straightforwardly recorded using commercial data acquisition systems.

The acoustic methods to monitor bolt loads [71], [72], [73], [74] involve time-of-flight (TOF), velocity ratio and mechanical resonance frequency shift. The time-of-flight methods relies on the change of time-of-flight (CTOF) as a function of bolt stress, based on the acoustoelastic effect. The TOF of acoustic waves propagating through an elastic medium is slightly altered when a mechanical stress is applied to said medium. This change stems from both the strain produced in the bolt, which changes the length of the propagation path; and from the stress-induced change in the acoustic wave velocity. It can be shown that, in the elastic region of deformation, the CTOF is a linear function of the applied stress [74], [75]. Several sensors are available to measure the CTOF such as acoustic probes and piezoelectric sensors which need to be in contact with the specimen, or electromagnetic acoustic transducers (EMAT) which do not need contact. Note that the CTOF in the bolt is only about tens of nanoseconds, and the measurement can be affected by environmental interference, especially in industrial sites. A more practical method is the velocity ratio method, which uses the difference in the acoustoelastic coefficients between longitudinal and transverse acoustic waves. The value of the axial load is calculated from the ratio of the TOF in the stressed state only and does not require the TOF in the unstressed state. As a final acoustic method, the mechanical resonance frequency shift principle relies on considering the bolt as an acoustic resonator. The resonance frequency is then proportional to the applied stress [71]. Since frequency can be measured more accurately than time delay, this method has superior resolution. Most of the aforementioned methods require high sampling rates of several hundred kHz or even MHz while the reported accuracy is between 0.73% and 10%, depending on the method. The requirement of the high sampling rate and the associated high cost of the data acquisition systems are among the major obstacles to the practical adoption and deployment of these methods for in situ bolt monitoring. In addition, the environmental noise as a main influencing factor for the precise measurement of the TOF also hinders the application of the method in the field.

The optical methods for bolt monitoring [76], [77], [78] rely mainly on optical fiber-based sensor techniques involving either so-called fiber Bragg gratings as sensor elements or optical frequency domain reflectometry (OFDR) inside an optical fiber. The main advantages of fiber-optic sensor systems are their small size, low weight, chemical inertness, immunity to electromagnetic interference and their applicability for sensing in harsh environments [79]. A fiber Bragg grating is a reflective structure in an optical fiber resulting from a periodic modulation of the effective refractive index in the core of the fiber, typically over a length of a few millimeters. This structure is wavelength selective in the sense that it reflects a narrow band of wavelengths centered around the so-called Bragg wavelength, which changes linearly with the longitudinal strain applied to the optical fiber. Measurement of the Bragg wavelength shift therefore immediately returns the strain acting on the fiber. Fiber Bragg gratings therefore essentially act as the optical equivalent of conventional strain gauges, which can be attached to the bolt. Typically, a calibration curve is then used to characterize the bolts, for example 37.48 nε/N in [77]. On the other hand, OFDR [80] relies on the measurement of Rayleigh backscattering in the optical fiber with a frequency swept laser. This technique offers a distributed measurement of strain along the optical fiber length, enabling the measurement of the strain distribution along the bolt provided the fiber can be adequately mounted. Both techniques require a dedicated and relatively expensive data acquisition system.

Each of the aforementioned bolt monitoring techniques also comes with its own specificities when considering sensor installation. Once the bolts are equipped with the sensors, the methods all enable load measurement during the complete BFC installation procedure. However, strain gauges, force washers or fiber-optic sensors are fixed to the bolts and they cannot be removed or retrieved and hence reused after the procedure. This increases the cost of the BFC as well, especially when a high number of bolts is involved. Acoustic sensors or probes can be reused and may therefore provide a more interesting alternative for a high number of bolts, despite being more susceptible to environmental influence. Finally, one should bear in mind that bolt load monitoring is still an indirect measurement technique, which does not always accurately reflect the actual gasket surface pressure during installation [2], [6]. A schematic overview of the typical locations of the discussed bolt load monitoring sensors in a

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bolt assembly is shown in figure 7.

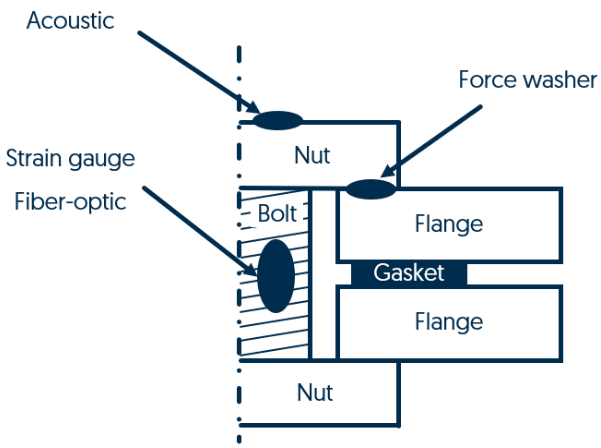

Fig. 7. Overview of bolt load monitoring locations in a bolt assembly.

VII. MONITORING CHALLENGES AND TECHNIQUES

So far, we focused on techniques to control or monitor the BFC installation procedure. These techniques aim to enhance the long-term leak tightness in the sense that a higher gasket surface pressure can be achieved such that the risk to be confronted with elevated emission and eventual leakage is mitigated (see section II). Besides, having control over the installation procedure therefore already provides a head-start for the ensuing test and service phase. The next stage would then consist in actively monitoring the BFC during these phases in view of minimizing emission and avoiding leakage. Note that failures during the service phase still account for 64% of the accidents related to BFCs according to the eMARS (see section III), which in essence justifies efforts targeting long-term in-service monitoring.

One of the most common strategies for leakage and emission prevention is the so-called leak detection and repair (LDAR) program. It consists of methods to locate and monitor leaks. In 2007, the United States Environmental Protection Agency [81] listed the elements of a model LDAR-program. For each of these elements listed below, a set of best practices has been defined.

- identifying components;
- leak definition;
- monitoring components;
- repairing components;
- recordkeeping;

We have already addressed leak definition in section IV. For the remainder of this manuscript, we will focus on the methods used for monitoring the components, specifically BFCs. Such monitoring systems have already been extensively explored in the context of pipeline leak detection [82], [83], [84], [85]. They target systems transporting water, oil and gas over very long underground distances without focusing on leakage detection in particular components of the pipeline. Literature in that field does recognize though that the most prominent causes of leakage are to be found in pipeline connections, i.e. BFCs.

A. Observation

The simplest form of BFC monitoring is direct observation. This is the number one leakage identification method because it is easy and low cost, in spite of the obvious lack of accuracy and effectiveness. Direct observation is typically conducted through inspection tours and limited by human sensory capabilities, as it relies on the inspector's ability to see, hear or smell a leak. This implies that only significant leakage can be spotted, whilst emission often remains undetected. Note that one of the most common practical inspection methods is very rudimental and consists in applying water with soap to the BFC and observe whether bubbles appear. In addition, direct observation essentially prompts curative maintenance, given that the BFC has essentially already failed. Furthermore, the safety of the observers is not guaranteed since they risk skin contact, eye contact, hearing damage and inhalation. The ASME B31.3 code [86] for process piping advises a random inspection for BFCs with no fixed rules in vigour as to an effective maintenance strategy. BFC owners define their own inspection requirements based on application know-how and experience.

B. Internal leak detection systems

Sensor-based leak detection systems tend to be more reliable as they are less dependent on qualitative judgement and rely on measurable and quantifiable data. An internal leak detection system uses operation data. It is the most extensively used and well-proven method for pipeline leak monitoring [87]. The foundations of these methods trace back to the 1970's, with work already documented by Billmann [88].

These systems typically rely on the conservation of mass. In simple terms, the amount of medium entering and leaving the BFC (or a set of BFCs) should be equal in the absence of leakage. From the perspective of a perfectly leak tight system, a leak or emission causes an apparent violation of conservation of mass in a system that is expected to be closed. Therefore, a system that checks whether conservation of mass is obeyed can act as a leak detector. Essentially the measurement of the mass imbalance of the system allows detecting and quantifying the leak. The more accurate the mass imbalance measurement, the more precise the leak detection and quantification. Given this straightforward principle, the challenge is then to measure the rate of change of mass in practice to detect and quantify leakage and emission through the BFCs. However, mass flow itself is neither measured nor calculated in piping systems. Instead, standard volumes are measured and calculated and conservation of mass is substituted with conservation of standard volume [82]. Leakage measurement on a single BFC requires one flowmeter placed before and a second placed after the BFC.

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Commercially available volumetric flow meters have a typical accuracy between 0.3% and 1%. Given the number of flow meters and accuracy required, this may introduce a high cost per BFC [89]. Using flow meters is more practical in a (sub)system topology than with individual BFCs. This approach is more cost-effective for the measurement system and generally allows for sufficiently narrowing down the location of leaks. Note also that constant temperature and pressure are required to assess the mass balance with low uncertainty and that the leak detection threshold is defined based on said uncertainty. In comparison to other leak detection methods, mass balance-based leak detection provides a very accurate quantification of the leak flow rate [90].

Simple pressure measurements can also be used as a technique for detecting transient leakage. These methods are known as real-time transient model (RTTM) based leak detection. Puust [83] and Li [91] reviewed these methods. Transient leak detection starts from the assumption that the pipeline is a dynamic system with pressure transients propagating through the pipeline system. This dynamic behaviour is modelled and compared with actual measured pressure data. Deviations between model and measurements can be indicative of leakage and also allow estimating the location, provided there are a sufficient amount of measurement points. However, this method is limited to rather large amounts of leakage, reported as 3% to 5% of the nominal pipeline flow.

C. External leak detection systems

Direct leakage detection systems

The concept of direct leakage monitoring is the detection and quantification of the actual emitted or leaked substance.

One of the most established techniques relies on cable-based leak detection [92], [93]. These use a sensing cable located near potential leakage locations. The cable is typically sensitive to hydrocarbon and water-based media, i.e. its physical properties change when exposed to the leaked substance, leading to e.g. a change of its impedance or a short circuit. These sensing cables are adequate for distributed detection and particularly useful for pinpointing the location of the leak over long distances, for example when the cable is attached along a pipeline. One can also consider running the cable around a BFC (or multiple BFCs) such that a different cable portion can be attributed to a specific BFC. Typically, leaks of 2% for liquids and 10% for gasses are needed for detection and the effective range is around 2 km in distance.

A second type of direct medium sensing relies on hydrocarbon-sensing tubes, or also known as vapor-sensing tubes (VST) [94], [95]. The tube is made of a hydrocarbon-permeable material that allows migration of the leaked substance through the tube wall whilst preventing the entrance of water and other volatile compounds. Once inside the tube, the leaked hydrocarbon is transported by means of an airflow to the output where it is finally detected. Such detection systems typically operate in a continuous or intermittent regime. In case of intermittent detection, the location of the leak along the tube can simply be derived by measuring the time upon detection at the output, given the velocity of the airflow in the tube. Continuous operation on the other hand does not allow for resolving the location of the leak, but minimizes the time delay of detection, which is especially important for long distances. The detectable leak rate with this method is between 0.001% and 0.01% of the nominal flow rate and the measurement range is reported up to 18 km. Figure 8 illustrates the working principle of a leakage sensing cable or tube.

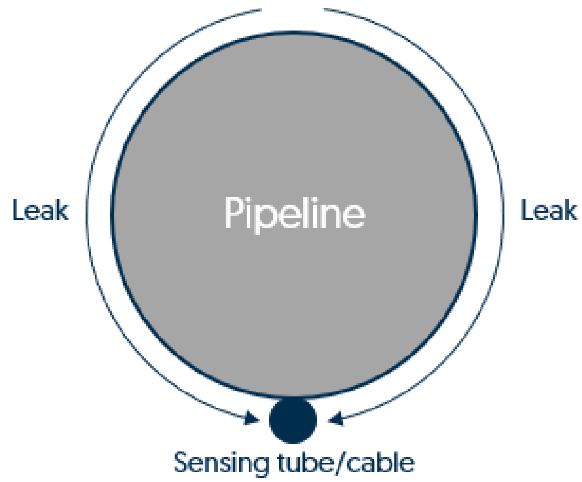

Fig. 8. *Illustration of carbon sensing tubes or cables installed for leakage detection around a pipeline or BFC. Adapted from [82]*

Another approach is a gas leak detector, also called ‘sniffer probe’ [96]. It is commonly used to detect leakage immediately after assembly and rebuild of piping systems. The principle of operation is the detection of a tracer gas (often Helium). It can rely on various sensors such as electrochemical, infrared or semiconductor sensors. Sniffers offer a good solution to detect and even pinpoint leakages during the test and service phase.

Keep in mind that most of these systems generate analog outputs, which can be sensitive to external factors, i.e. sensor noise. To ensure accurate measurements, especially in industrial or harsh environments, proper calibration is essential. Without adequate calibration, it can be difficult to differentiate between actual leakage and noise from the sensors. Therefore, most of these detection systems are categorization systems, meaning they will act as thresholding systems that rely on the ability to issue alarms when the detection threshold is exceeded. Hence these systems are less suitable for emission or leakage rate quantification. The reported threshold is as low as 10^{-6} to 10^{-3} Pa.m³/s.

Indirect leakage detection systems

Indirect measurement methods are dominated by bolt load measurement techniques, as described in section VII. They can be deployed during service as well. Static applications typically suffer from gasket relaxation which is attributed to a gradual decrease of bolt load. Dynamic applications not only experience the same issue, i.e. a gradual decrease of bolt load, but also a fluctuating gasket surface pressure under service conditions because of the internal pressure fluctuations. The leakage probability is higher in dynamic service conditions given that the internal pressure does not directly influence the bolt load, but it does directly influence the gasket surface pressure. Bolt load monitoring can nevertheless support the prediction of elevated emissions and leakages in both static and dynamic applications. In addition, it can trigger timely action such that severe leakages and their consequences can be avoided.

The most prominent practical consideration for adopting bolt monitoring techniques is the measurement frequency. Less critical static applications can benefit from low frequency measurements, e.g. one bolt load measurement taken once a month. Such applications do not start leaking overnight. Hence manual measurements with long time intervals are often sufficient to provide a periodic measurement. Note though that this approach requires qualified personnel to carry out and analyse the measurements. Critical static applications may also require higher frequency measurements, i.e. once per day or once per hour. This excludes conducting manual measurements and calls for the implementation of a continuous monitoring strategy that exploits permanently integrated sensors enabling remote monitoring.

Bolt load measurements have also proven valuable for troubleshooting [70], particularly in dynamic applications. Monitoring bolt loads provides insight into the surface pressure experienced by the gasket under varying conditions. For instance, in heat-exchangers, where temperature gradients and pressure fluctuations are common, analysing bolt loads alongside temperature and pressure measurements can help pinpointing the exact cause of leakage.

Apart from the choice for periodic, continuous monitoring or troubleshooting, there is a considerable cost associated because of measurement devices, involvement of trained personnel and sensor system integration that goes along with suitable dashboards and reporting systems. Nevertheless, such costs are easily justified when considering the safety benefits as well as potential cost savings by mitigating accidents. Of course, the application specific conditions as well as the application history supports the decision whether or not the game is worth the candle.

Indirectly sensing the leaking medium can also be achieved by using infrared and spectrographic detectors [97], [98]. They use electromagnetic radiation to detect leak signatures, for example infrared (IR) wavelengths that are absorbed by hydrocarbons. Infrared leak detection systems utilize this absorption rate to identify hydrocarbons are present within the

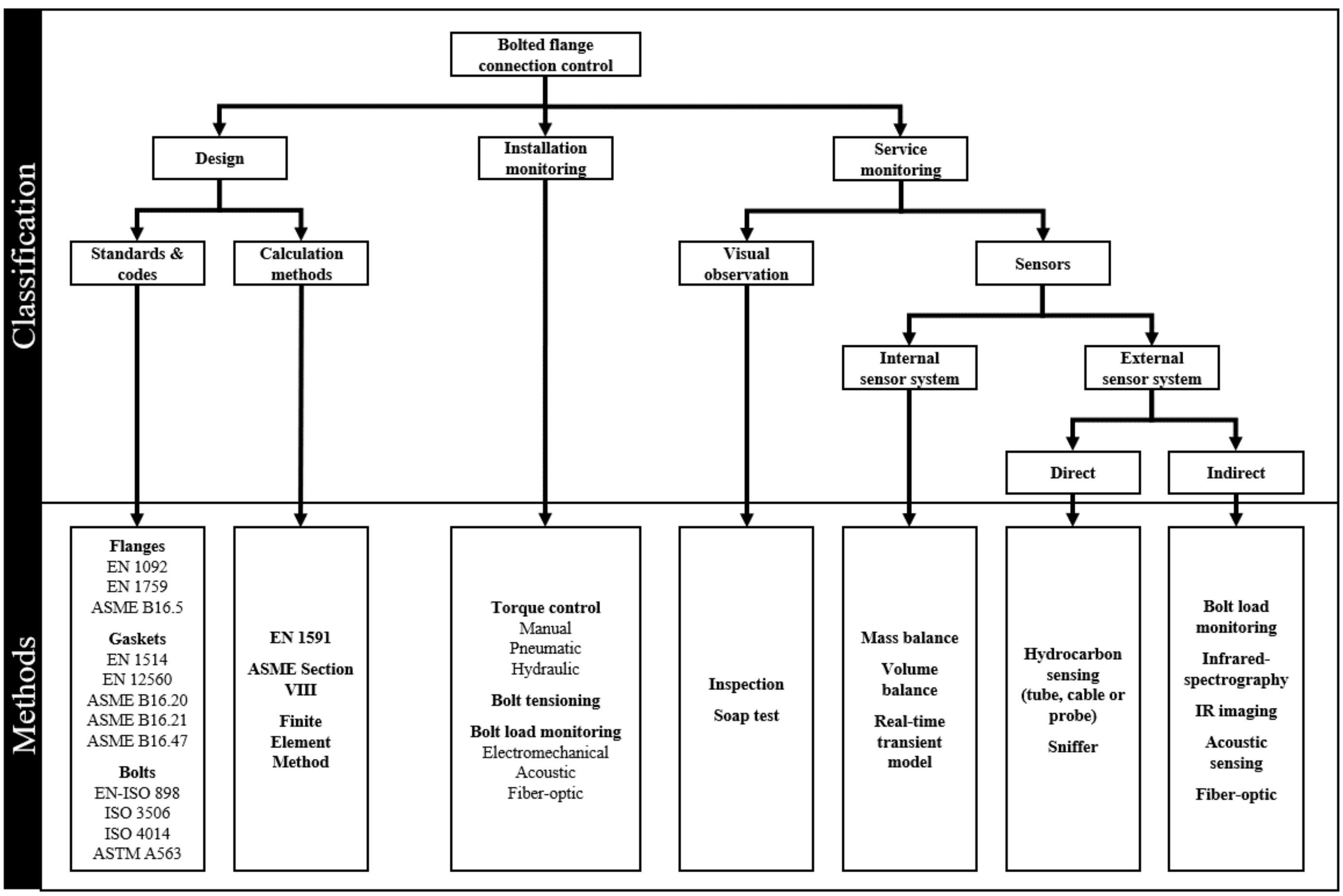

Fig. 9. Summary and classification of the discussed methods to design, installation monitoring and service monitoring for bolted flange connections.

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volume that the infrared beam passes through. There are various types available. For example, an open path detector typically works with a transmitter and receiver unit. The infrared signal is transmitted between the two units to determine whether there is a hydrocarbon present. Another type of infrared detector is known as the point IR-system. This device is fully contained in an instrument case and allows the detection of hydrocarbons at a fixed point or location. These systems require the hydrocarbon to be physically located in the working volume of the device, which can be a function of probability depending on external influences such as leak direction and wind direction. For example, a study concludes a detection limit down to 1g CH_4/h [97].

Imaging techniques also allow detecting leakages or emissions. These systems rely on the emission of thermal energy. A leak or emission can be detected based on different thermal energies that are emitted compared to the normal background thermal energy radiation. These IR-imaging devices can be handheld, or mounted on drones to cover a wide area for leak and emission detection.

Another popular technique, especially for compressed air leakages, is acoustic sensing [99], [100], [101], [102]. This technique relies on the emission of high-frequency acoustic sound that is originating from a leak. These systems are available as acoustic sensors, fixed on the sensing location. One of the studies conducted a field test, detecting leakages down to 0.9% of the nominal flow rate on a pipeline of 156km with an accuracy of ±200m. Alternatively, they can also be used in a configuration where a handheld device is equipped with a camera and several microphones to detect sources of leakage. Such a so-called ultrasound camera is able to reconstruct the sound source, generate an acoustic image and calculate the corresponding leakage rate.

Finally, and similarly to cable-based systems, fiber-optic sensing systems can also be used for indirect detection. These systems typically rely on Raman and Brillouin scattering phenomena for distributed sensing purposes, or on fiber Bragg gratings for point sensing. These sensing techniques typically exploit changes in temperature and strain attributed to the presence of a leak. There are numerous examples of distributed temperature sensing using optical fibers along pipelines for detecting leaks [103], [104], [105]. Also Paolacci [106] recently showcased fiber-optic sensing for BFCs, relying on the Joule-Thompson effect by making use of fiber Bragg grating temperature sensors.. This effect describes how the temperature of a gas will change as it is forced through a small orifice.

VIII. CONCLUSION AND OUTLOOK

Figure 9 provides as summary of the discussed monitoring approaches in this work.

This work addressed the critical challenge of ensuring leak tightness and minimizing emissions in bolted flange connections through a comprehensive review of installation control techniques and monitoring systems. We began by focusing on the optimization of gasket surface pressure during the installation phase, which plays a crucial role in reducing leakage risks and enhancing the long-term reliability of BFCs. A deeper understanding of the physical interactions during installation provides a solid foundation for implementing effective monitoring strategies that proactively detect and mitigate leakage during this phase. The most profound methods are the use of torque control equipment, bolt tensioning and bolt load monitoring systems relying on electromechanical, acoustic and fiber-optic sensing methods

Additionally, we discussed a range of long-term monitoring methods to follow-up on the leak tightness during the use phase. These range from basic direct observation to advanced sensor-based systems. Whilst direct observation remains a cost-effective initial approach, its limitations in detection accuracy and safety are evident. More advanced techniques, such as internal leak detection systems based on mass balance and real-time transient models, offer higher accuracy and improved leak quantification, but come with a higher cost and more complexity. External methods, including cable-based sensing and hydrocarbon-sensing tubes, enable distributed monitoring, while indirect techniques such as bolt load monitoring and fiber-optic sensing hold promise for detecting leaks and emissions with greater precision.

The contribution of this work extends beyond identifying and categorizing monitoring techniques and therefore provides a clear framework for their application across various operational contexts. By emphasizing the need for accurate, real-time leak detection and continuous monitoring throughout the lifecycle of BFCs, this study aims to guide future efforts to enhance safety and operational efficiency in industries relying on these critical components. Ultimately, the findings contribute to a deeper understanding of how to achieve long-term leak prevention and emission reduction, supporting safer and more sustainable industrial practices.

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