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A P_{QR}-based approach to creep-dependent design of thermoplastic flange joints

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Thermoplastic flange joints are increasingly used in corrosive service but exhibit pronounced viscoelastic creep, leading to a time-dependent loss of bolt preload and gasket surface pressure. Existing analytical standards such as EN 1591-1 neglect creep of thermoplastic collars and are therefore insufficient for reliable tightness assessment. This work extends the P_{QR} concept by determining individual and combined creep relaxation factors for gaskets and thermoplastic collars through component- and system level experiments. The results show strong dependencies on material, temperature, load, geometry and time and demonstrate that simple multiplicative approaches are inadequate. The proposed method enables an EN 1591-1 oriented calculation with improved prediction of surface pressure loss and defined applicability limits.

1 Introduction and limitations of existing design methods for thermoplastic flange systems

Thermoplastic materials exhibit significantly more pronounced creep behavior compared to metallic materials such as steel. Under constant load, this time-dependent deformation leads to a continuous reduction of bolt force in flange connections. As a consequence, the gasket surface pressure decreases over time and may fall below the minimum required level for tightness. In such cases, leakage can occur.

The current state of the art analytical design method for bolted flange connections is defined in DIN EN 1591-1 [1]. This approach does not account for the time-dependent material behavior of flange components, particularly the creep of thermoplastic collars. The method is primarily based on elastic assumptions for metallic flanges. Time-dependent effects are only considered for the gasket material by means of the creep relaxation factor (P_{QR}), which is determined experimentally according to DIN EN 13555 [2]. While this approach is suitable for describing the relaxation behavior of gaskets, it does not capture the additional creep-induced deformation of thermoplastic flange components.

As a result, no established analytical method currently exists for the reliable tightness assessment of thermoplastic flange systems. In practice, the verification of tightness is therefore typically performed by means of component testing, see [3]. However, such experimental validation is time-consuming and cost-intensive compared to analytical design approaches.

2 Experimental determination of PQR for gaskets and thermoplastic collars

Since creep relaxation effects are already partially integrated into existing analytical design approaches through the gasket creep relaxation factor (P_{QR}), it is reasonable to extend this concept to thermoplastic flange systems. The loss of bolt force in such systems is primarily caused by a reduction in the effective clamping length due to time-dependent, viscoelastic deformation of the involved materials.

This deformation behavior depends on several influencing parameters, including material properties, temperature, applied surface pressure, geometry (e.g., thickness) and time. These dependencies must be considered when assessing the long term performance of thermoplastic flange connections.

Within the current normative framework, the creep relaxation behavior of gasket materials is described by the P_{QR} factor, defined according to DIN EN 13555 as:

$$P_{QR} = \frac{Q_{rest}}{Q_{initial}} \epsilon \, [0,1] \tag{1}$$

The P_{QR} value ranges between 0 and 1, where a value of 1 indicates no loss of gasket surface pressure, while a value approaching 0 represents a complete loss of residual surface pressure.

While this parameter adequately describes the relaxation behavior of gasket materials, it does not account for the additional contribution of thermoplastic flange components. Therefore, experimental investigations are carried out not only for the gasket material but also for thermoplastic collars. The objective is to quantify the creep relaxation behavior of each component separately, providing a basis for a subsequent combined assessment at the system level.

Table 1 summarizes the experimental results obtained for DN 40 thermoplastic collars made of polyethylene (PE-100) and polypropylene (PP-H) at room temperature (21 °C) and elevated temperature (60 °C) under different surface pressures. The testing procedure is based on DIN EN 13555 and described also in [4].

Table 1: P_{QR} values for thermoplastic materials under loading and temperature conditions

Surface Pressure [MPa]	PP-H (21 °C)	PP-H (60 °C)	PE-100 (21 °C)	PE-100 (60 °C)
5	0.78	0.73	0.75	0.56
10	0.84	0.69	0.73	0.53
15	0.86	0.48	0.75	0.39

The results clearly indicate that polyethylene exhibits a more pronounced creep behavior compared to polypropylene, see also figure 1. This can be attributed to its lower stiffness, which facilitates time-dependent deformation under load. Furthermore, the influence of temperature is significant for both materials. At elevated temperatures, the available thermal energy increases, leading to enhanced mobility of polymer chains. This results in increased chain slippage and a higher creep tendency. This behavior is characteristic of the viscoelastic nature of thermoplastic materials. For further detail see [5] and [6].

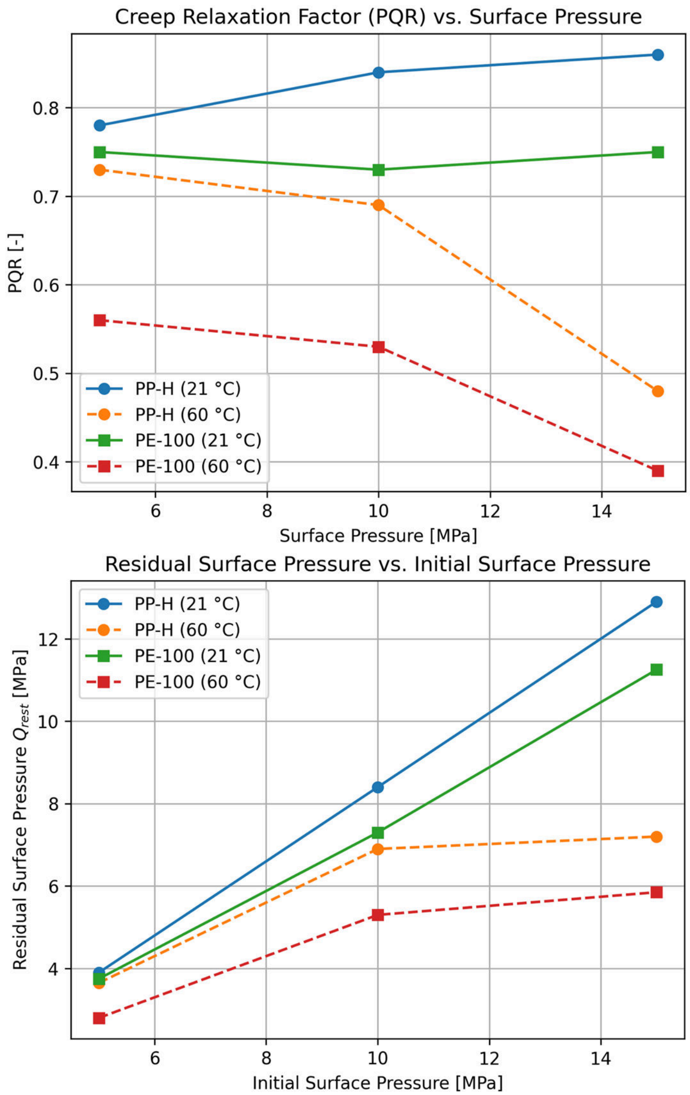


Figure 1: Effect of creep relaxation on residual surface stress as a function of material, temperature and initial surface stress

At room temperature, the P_{QR} values show only minor variation with increasing surface pressure. This effect can be explained by the testing methodology: the applied load is not maintained constant but decreases as creep deformation occurs. This simulates creep relaxation effects, which in real flange systems manifest as a reduction in bolt preload.

At elevated temperature, however, the creep effects become significantly more pronounced. As a result, the relative residual surface pressure decreases with increasing initial load, leading to lower P_{QR} values at higher surface pressures. Despite this relative reduction, the absolute residual surface pressure can still be higher due to the increased initial loading level. This absolute residual value is of primary relevance for the assessment of tightness.

3 Experimental Analysis of Flange System Behavior Under Service Conditions

As mentioned, existing calculation methods in particular those based on EN 1591-1 do not adequately capture the creep and relaxation behavior of thermoplastic flanges. Since qualified creep-relaxation data (P_{QR}) are currently available only for gaskets, a holistic assessment of the overall system requires a combination of individual component tests and full system investigations. Against this background, a dedicated measurement cell was developed as the central experimental tool for analyzing the complete bolted flange assembly at the *Materials Engineering Laboratory* of *FH Münster*. A compact measurement cell is developed consisting of two metallic flanges in accordance with DIN EN 1092 [7], between which the thermoplastic collars are clamped. The components are bolted together using specially designed bolts equipped with digital dial gauges, enabling precise measurement of deformations and load changes. In addition, two inductive displacement sensors are mounted on the upper flange, capable of capturing axial displacements and flange plate rotations, see figure 2.

The measurement cell thus constitutes a highly instrumented system, designed to investigate both individual component parameters and the behavior of the overall assembly under realistic loading conditions.

The measurement cell allows for a detailed analysis of the various influencing parameters acting on the flange system. The primary focus is on the applied bolt force and its evolution over time. In addition, the viscoelastic behavior of the thermoplastic materials and the interaction between flange, gasket and loading are analyzed with respect to sealing performance. The applied bolt forces are converted into equivalent surface pressure in order to determine the resulting load distribution within the flange system. Particular attention is given to the interplay between the material properties of the collars, the gasket characteristics and the applied contact pressure, as these factors critically govern the leakage rate.

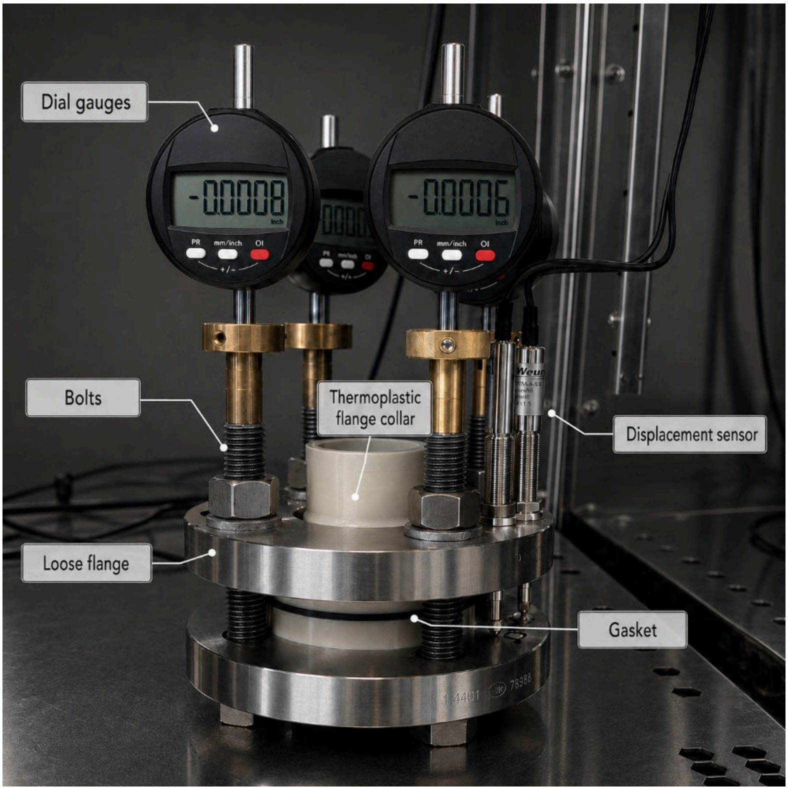


Figure 2: Design of the measurement cell used

To capture dynamic bolt force variations, the bolts are specially instrumented, allowing relaxation and creep effects to be monitored with high precision. The integrated sensors continuously measure displacement changes following bolt tightening, thereby providing valuable information on settling processes and deformations within the system. Furthermore, the sensors enable the detection of flange plate rotations, allowing tilt behavior and its influence on the load distribution across the sealing interface to be systematically assessed.

By combining mechanical instrumentation with high-precision sensing, the measurement cell provides a comprehensive platform for experimental investigation and analytical description of the complex interactions within thermoplastic flange systems. It forms the basis for well-founded conclusions regarding material and gasket behavior, supports the design and optimization of flanged joints and contributes to the development of robust and durable piping systems.

Considering the measured quantities recorded by the measurement cell, various influencing factors are systematically investigated. These include the collar materials, the gasket materials and the ambient conditions prevailing during the experiments.

The thermoplastic materials PE-100 and PP-H are used for investigations. NBR and PTFE gaskets serve as the sealing materials under examination. In addition, temperature is considered as a key influencing parameter. The experiments are conducted both at room temperature and at an elevated temperature of 60 °C within a climate chamber. Beyond material and temperature parameters, the temporal evolution of the system is also examined in order to capture relaxation and creep effects.

Beyond material and temperature effects, the time dimension plays an equally important role. Monitoring the system over extended periods allows the gradual onset of relaxation and creep to be captured phenomena that are inherent to thermoplastic materials and that can significantly affect long-term sealing performance. The effect of bolt retightening is also examined, providing further insight into how maintenance interventions may help compensate for bolt preload losses over time.

By varying these parameters, a comprehensive dataset is generated, enabling the evaluation of individual influencing factors as well as their interactions within the flange system. Table 2 shows a selection of the collected measurement data and illustrates the interaction between the thermoplastic and the seal. In all cases, the creep relaxation is greater than the individual values, but less than the simple product of those values.

Table 2: Combined P_{QR} values for thermoplastic materials and rubber gasket (NBR) under loading and temperature conditions

Surface Pressure [MPa]	**PP-H + Gasket (21 °C)**	**PP-H + Gasket (60 °C)**	**PE-100 + Gasket (21 °C)**	**PE-100 + Gasket (60 °C)**
5	0.72	0.45	0.75	0.45
10	0.74	0.42	0.70	0.42
15	0.69	0.42	0.65	0.39

In the case of polypropylene, increased stress leads to greater divergence and a tendency to creep. In the case of polyethylene, the creep of the collar is so significant under increased stress that the gasket becomes virtually irrelevant.

Figure 3 presents the temporal evolution of the contact pressure for PP-H with the rubber gasket at 60 °C. Immediately after bolt tightening, an initial increase in contact pressure is observed, which is attributed to the thermal expansion of the entire measurement cell upon heating. As the test progresses, however, the contact pressure decreases, a behavior that is ascribed to the creep of the thermoplastic collars. The rotation of the flange plates is calculated from the readings of the two displacement sensors.

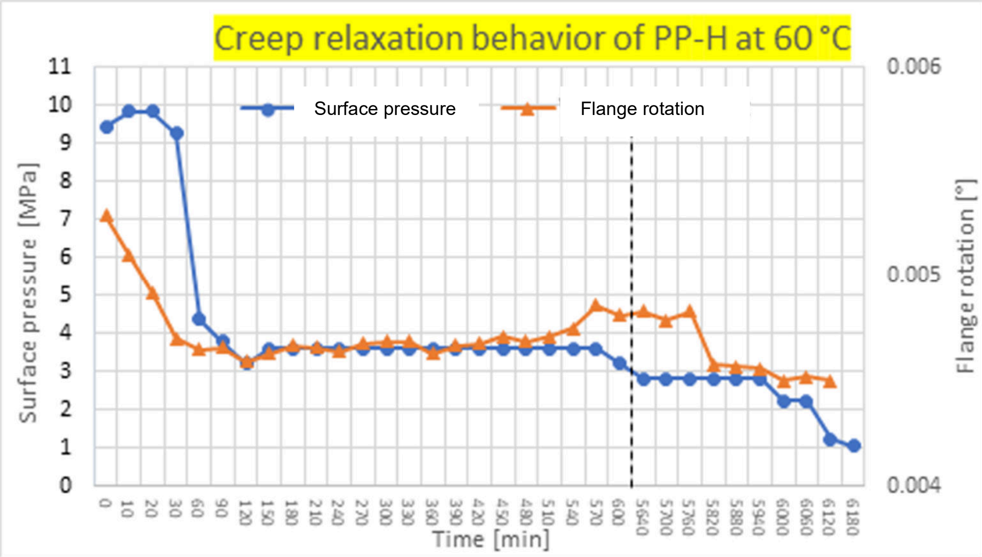


Figure 3: Effect of creep relaxation on surface pressure and flange rotation over time

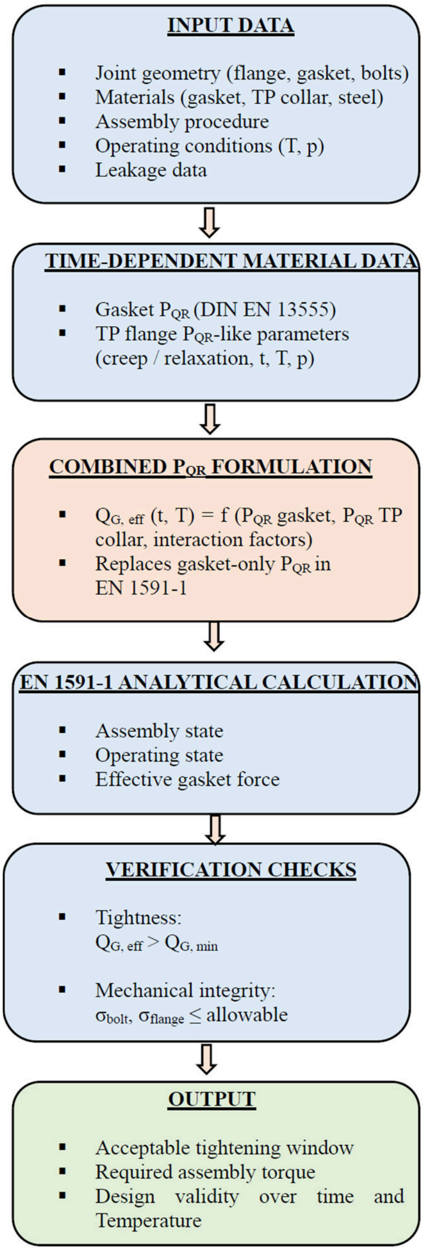
The greatest loss in contact pressure is recorded within the first 3 - 4 hours, which is consistent with the P_{QR} determination after 4 hours in accordance with DIN EN 13555. The vertical dashed line indicates a time jump beyond this point. The diagram represents a 100-hour test run. At the beginning of the experiment, the flange plate rotation changes significantly, attributable to the onset of creep relaxation. Simultaneously, the bolt forces decrease. After approximately 4 hours, only minimal changes in the measured values are observed (see scale). The remaining fluctuations are attributed to measurement uncertainties inherent to the instrumentation employed. The pressure drop at the end is caused by the cooling back to room temperature.

4 Extension of EN 1591-1 for Thermoplastic Flange Systems

A straightforward approach to describe the creep relaxation behavior of thermoplastic flange systems would be to combine the experimentally determined P_{QR} values of the individual components. In such an idealized case, the overall system behavior could be approximated by a multiplicative superposition of the respective P_{QR} factors.

$$P_{QR,ideal} = P_{QR,gasket} \cdot P_{QR,collar} \quad (2)$$

However, the experimental results obtained from the system-level investigations (measurement cell) clearly indicate that this assumption is not valid for thermoplastic flange systems. The deviation arises from the fact that creep relaxation processes in the individual components occur simultaneously and are mechanically coupled.



As a result, the deformation of one component directly influences the load distribution and deformation behavior of the others.

In particular, the reduction of bolt force due to creep in thermoplastic collars leads to a decrease in gasket surface pressure, which in turn affects the creep response of the gasket material itself. This interaction results in a nonlinear system behavior that cannot be captured by a simple decoupled consideration of individual P_{QR} values.

The magnitude of the deviation between the experimentally observed system behavior and the idealized multiplicative approach depends on several influencing parameters. These include e.g. material properties, temperature, applied surface pressure and geometric characteristics (e.g. effective clamping length and stiffness). Each of these factors affects both the rate and extent of viscoelastic deformation, as well as the interaction between the components.

$$P_{QR,eff.} = P_{QR,gasket} \cdot P_{QR,collar} \cdot K_{material} \cdot K_{temperature} \cdot K_{loading} \quad (3)$$

Based on these findings, an extended modeling approach is required. This approach must account for the coupled creep relaxation behavior of all relevant components within the load-bearing system. The required adaptation factors for the respective thermoplastic materials are determined based on a combination of component-level and system-level experimental investigations. By evaluating both the individual creep relaxation behavior and the coupled system response, it becomes possible to quantify the interaction effects between gasket and thermoplastic collar.

Figure 4: Schematic illustration of the modified calculation procedure, including the effects of creep relaxation

On this basis, an effective, combined creep relaxation factor can be derived for each specific thermoplastic - gasket combination. This effective P_{QR} value implicitly accounts for the coupled viscoelastic behavior of the system, provided that the gasket characteristic values under the relevant operating conditions are known.

The resulting analytical calculation procedure follows, in principle, the established workflow defined in DIN EN 1591-1. The extended approach supplements the existing method by incorporating the additional influence of thermoplastic creep through adapted or combined P_{QR} values. A schematic representation of the extended calculation procedure is shown in figure 4.

5 Conclusions and Outlook

Thermoplastic flange joints exhibit a pronounced time-dependent behavior due to the viscoelastic nature of the involved materials. The present study demonstrates that creep deformation and stress relaxation significantly affect the long-term tightness of such systems by reducing bolt preload and gasket surface pressure over time.

The experimental investigations on individual components have shown that both gasket materials and thermoplastic collars contribute to creep relaxation, with the thermoplastic collar representing the mechanically weakest component in the load path. Polyethylene (PE-100) exhibits a higher creep tendency compared to polypropylene (PP-H) and temperature has been identified as a dominant influencing factor.

The system-level investigations using the measurement cell reveal that the creep relaxation of the complete flange system, comprising bolts, flange components and gasket, is influenced by the interaction between the gasket and the thermoplastic flange components. This clearly indicates that the interaction between components must be taken into account. In particular, the combined behavior cannot be described by a simple multiplication of individual P_{QR} values, as the creep processes occur simultaneously and are mechanically coupled.

For a consistent and realistic design approach, it is therefore essential to consider the creep relaxation of all relevant components within the system. In the investigated configuration, this includes the gasket and the thermoplastic collars on both sides of the joint. The experimental results show that the combined creep relaxation of the system is significantly higher than the contribution of the individual components alone, which necessitates the use of an extended analytical approach.

Based on the conducted investigations, an EN 1591-1 oriented calculation method has been developed, in which the creep behavior of thermoplastic components is adapted. This method combines P_{QR} values with empirically derived influence factors. This approach enables a more realistic prediction of the time-dependent loss of surface pressure and provides a solid basis for the definition of assembly torques, including the consideration of retightening strategies and clearly defined applicability limits.

The applicability of the proposed method is currently limited to the investigated parameter range, including material types, temperature levels, surface pressures and geometrical configurations. Future work will focus on extending the database to additional thermoplastic materials and gasket types to improve generalization and robustness.

Furthermore, the influence of retightening cycles represents a critical aspect for practical application and requires systematic investigation. In addition, the present study deliberately considers a metallic loose flange to isolate the creep effects of the thermoplastic components. In industrial applications, however, thermoplastic loose flanges are also commonly used. In such cases, an additional component with its own creep relaxation contribution must be considered. This will further modify the load distribution within the system, including changes in lever arms and flange rotation behavior and must therefore be incorporated into future modeling approaches.

6 Nomenclature

Variable	*Description*	*Unit*
$K_{material}$	Influencing factor material	[-]
$K_{loading}$	Influencing factor surface pressure	[-]
$K_{temperature}$	Influencing factor temperature	[-]
P_{QR}	Creep relaxation factor	[-]
$P_{QR,collar}$	Creep relaxation factor from the collar	[-]
$P_{QR,eff.}$	Creep relaxation factor with all relevant influences	[-]
$P_{QR,gasket}$	Creep relaxation factor from the gasket	[-]
$P_{QR,ideal}$	Multiplied creep relaxation factor	[-]
$Q_{G,eff.}$	Effective surface pressure on the gasket	[MPa]
Q_{inital}	Initial surface pressure	[MPa]
$Q_{G,min}$	Minimum surface pressure on the gasket	[MPa]
Q_{rest}	Remaining surface pressure	[MPa]
σ_{bolt}	Boltstress	[MPa]
σ_{flange}	Flangestress	[MPa]

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