Validation of sensitivity of the UST-Method with a test leak

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Abstract
The test sensitivity of classic sniffer test methods is limited by the helium concentration in the air with 5.2 ppm, but by reducing the atmospheric helium concentration of the sniffer method B3 from the DIN EN 1779 the test sensitivity can be significantly improved by the sensitivity factor 500,000. In contrast to conventional vacuum leak test methods, the UST-Method reduces the helium partial pressure in a chamber with a helium free gas. This brings the helium partial pressure down to 1x10^{-08} mbar (10 ppt), so the gas tightness of components can be easily and reliably determined with a sensitivity of 10^{-11} mbar*l/sec. During the construction of the fusion experiment Wendelstein 7-X (W7-X), it was firstly shown that leaks at normal pressure (1013 mbar and 20°C) up to 10^{-09} mbar*l/sec are easily detectable. This means that, with the UST-Method, leaks with a theoretical loss of gas of 5 cm^3 in 30 years are well within the detectable range.

Keywords: atmospheric leak detection method, sniffing method, partial vacuum effect, UST-Method

1. Introduction

The fusion experiment W7-X of the Planck Institute for Plasma Physics in Greifswald is the largest stellarator experiment of this kind in the world [1]. The aim of the experiment is the inclusion of a stationary plasma with 3 Tesla in a super-conducting magnetic cage. To run the fusion experiment W7-X, the magnetic cage with its 70 superconducting coils in the cryostat, cooled by liquid helium, must be absolutely free of helium leaks. Before the start of the physical experiment in August 2015, the absolute helium leak security of the cryostat had to be assured. This meant that the absolute helium leakage of all the components of the magnetic cage had to be tested with 1x10^{-09} mbar*l/sec. Due to the complex structure of the superconducting coils, it was not possible to localize leaks with classic test methods of the DIN EN 1779 [2]: the vacuum test gas, the overpressure test gas methods. Therfore, the team decided to improve the sensitivity of the overpressure test gas method DIN EN 1779 B3 by leveraging the partial vacuum effect. The overpressure test gas method in combination with the partial vacuum effect, led to an improved sensitivity from 1 ppm to 1 ppt and led to the development of the Ultra-Sniffer-Testgas-Method (UST-Method). Because the extreme increase of sensitivity of the UST-Method by factor 500,000, the method required a special test leak as well as a validation from an independent testing laboratory.
2. The UST-Method

The UST-Method is an overpressure gas test method according to DIN EN 1779. The inherent difference between the classic overpressure test gas method B3 of the DIN EN 1779 and the UST-Method is the partial vacuum effect. This effect allows it, in contrast to the vacuum test gas methods of the DIN 1779, to reduce the helium concentration, not by evacuating the chamber, but rather by flushing the chamber with a helium free gas. This makes it possible to reduce the partial helium pressure inside in the test chamber with the helium free gas from 5.2 ppm to 10 ppt. To ensure that the test chamber, which is filled with the helium free gas, reserves its helium purity, the test chamber is pressurized with a slight overpressure to ambient pressure [3].

Extensive testing with the UST-Method at the Max Planck Institute for Plasma Physics showed that with the UST-Method samples could be tested for the first time at atmospheric pressures with a system sensitivity of \(1 \times 10^{-11}\) mbar*L/sec. This means that the UST-Method has a 500,000 times higher measurement sensitivity than the classical sniffing method B3 of DIN EN 1779. Because of the extremely high sensitivity of the UST-Method, the detection of ten helium atoms in one trillion atoms, it is possible to prove the gas loss of a sample with 5 cm\(^3\) in 3,000 years. This corresponds to a leakage rate of \(5 \times 10^{-11}\) mbar*L/sec. It is also possible to locate leaks of the size of \(1 \times 10^{-09}\) mbar*L/sec precisely. This corresponds with a gas loss of 1 cm\(^3\) in 30 years.

As part of the construction of the fusion experiment W7-X, the UST-Method located several leaks [4], also a leak in a superconducting coil of the W7-X experiment [5][6]. To locate the leak, components of the coil were wrapped in to plastic bag and the superconductor of the coil were pressured with 33 bar helium, so that the leakage could be located in the area of an aluminum weld of a interlayer joint. In addition, measurements with the overpressure test gas method B4 and the vacuum test gas method A2.1 showed that the leakage could not be located be using these leak detection methods.

3. Mathematical Description of the helium concentration rise

To validate the sensitivity of the UST-Method, in the first step of the validation the theoretical rise of the helium concentration in a test chamber was determined. The increase of the helium concentration inside of the chamber follows the function:
Measurements showed that the increase of the helium concentration in a metallic chamber could be described very well by the function (1).

4. UST-Method / vacuum test gas method: Comparative Measurement

To validate the relationship between the UST-Method and the vacuum test gas method comparative measurements were done with plastic slices. For these comparative measurements between the UST-Method and the vacuum test gas method several plastic slices were clamped into a CF flange and the plastic slices was pressured with 10 bar helium. For the determination of the leakage rate, the CF flange with the plastic slices was inserted into a metallic chamber. In the first step of comparative measurements, the helium gas stream was measured by the UST-Method. By raising a certain helium gas concentration, for example 9.25x10^{-07} mbar*l/sec, the measurement was terminated with the UST-Method and it was continued with the vacuum test gas method. To illustrate the relationship between the UST-Method and the vacuum test gas method in the range of 4x10^{-09} to 4x10^{-06} mbar*l/sec, the results were plotted in a graph. It was found out that the measured helium gas stream of the UST-Method and the vacuum test gas method are linear related. It has been shown over the measurement range, that the leakage rate of the vacuum test gas method is 1.2 times higher than the UST-Method. The explanation is that the UST-Method runs with a difference pressure of 10 bar and the vacuum test gas method with a difference pressure of 11 bar. In the assumption that the helium gas flow of a molecular leakage increases linearly with the pressure difference, the relation between the UST-Method and the vacuum test gas method could describe by the function [7]:

\[ Q_t = (Q_{\text{leak}} - Q_{\text{UST-Gas}}) - \left( (Q_{\text{leak}} - Q_{\text{UST-Gas}}) - Q_0 \times \exp \left( \frac{\Delta t \times S_{\text{eff}}}{V_{\text{chamber}}} \right) \right) \]  

(1)

Where:
- \( Q_t \) = leakage rate (mbar * l/s)
- \( Q_{\text{leak}} \) = leakage rate of the leak (mbar * l/s)
- \( Q_{\text{UST-Gas}} \) = Leakage rate of the UST-Gas (mbar * l/s)
- \( Q_0 \) = leakage rate in the chamber (t = 0)(mbar * l/s)
- \( \Delta t \) = testing time (s)
- \( S_{\text{eff}} \) = flow rate sniffer probe (l/s)
- \( V_{\text{chamber}} \) = volume of the chamber (l)
Based on the measured results with the plastic slices and a pressure difference of 10 bar and 11 bar, it can be assumed, that the leakage rate of the UST-Method and of the vacuum test gas method are linear related by the function (2). This will be accurate also for laminar leakage with a quadratic pressure relationship [7].

\[
Q_{\text{Vacuum}} = \frac{Q_{\text{UST}} \times \Delta P_{\text{Vacuum}}}{\Delta P_{\text{UST}}} = \frac{Q_{\text{UST}} \times 11 \text{bar}}{10 \text{bar}} = 1.1 \times Q_{\text{UST}} \tag{2}
\]

\(Q_{\text{Vacuum}}\) = leakage rate vacuum test gas method (mbar * l/s)
\(Q_{\text{UST}}\) = leakage rate UST method (mbar * l/s)
\(\Delta P_{\text{Vacuum}}\) = pressure difference vacuum test gas method (bar)
\(\Delta P_{\text{UST}}\) = pressure difference UST method (bar)

5. Development of a test leak for the UST-Method

Test results of the UST-Method could be reproduced for very small leaks, but could not be validated. Therefore, there was a need to develop an own test leak for the UST-Method to validate test results. This test leak allows to inject a steady stream of helium into a chamber. In the first step of the validation of the test leak, the leakage rate of the test leak was determined by a test setup with a metallic chamber. This validation of the leakage rate of the test leak allowed to determine the sensitivity even of a test set up with a flexible plastic bag. To determine of the sensitivity of the set up with a flexible bag, the bag was pressurized with a helium free gas. After reaching a stable leakage rate of less than

\(1 \times 10^{-09}\) mbar*L/sec, helium was injected into the flexible bag with the test leak. With a test leak of \(1.2 \times 10^{-07}\) mbar*L/sec, the leakage rate rise in a few minutes from \(7 \times 10^{-10}\) to \(9.7 \times 10^{-08}\) mbar*L/sec. So, the UST test leak allowed to determine the sensitivity of the UST-Method. For the qualification of these results a further validation of the leakage rate was done by a certificated testing laboratory [8]. The validation through the testing laboratory showed that the leakage rates, which were measured from the testing laboratory, were equal the leakage rate from the earlier measurements.
6. Conclusions

The different steps of the validation of the UST-Method showed that the leakage rate of the vacuum test gas method and the leakage rate of the UST-Method rate correspond. In addition, the leakage rate of the UST-Method has got a proven linear relationship with the leakage rate of the vacuum test gas method from $4 \times 10^{-09}$ to $4 \times 10^{-06}$ mbar·lit/sec. Furthermore, it was shown that with the test leak for the UST-Method, even with a test setup with a flexible plastic bag, the sensitivity of the UST-Method can be reliably measured. This means that just like the vacuum test gas method, the integral gas tightness of a sample can be determined with a sensitivity of 1 ppt. In addition, tests during the construction of the W7-X have also shown that the leakage rate of the UST-Method is comparable with the leakage rate from the vacuum test gas method. It was also shown that the expenses for the leak location by using the UST-Method, because of the sensitivity increase of 500,000 of the overpressure test gas method B3, could be significantly reduced.

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