CCM-PV 2023

2023 CCM & IMEKO INTERNATIONAL CONFERENCE ON PRESSURE AND VACUUM METROLOGY

WASHINGTON DC • MAY 15-19, 2023

Welcome Pressure and Vacuum Metrologists to the

2023 CCM & IMEKO Conference

On behalf of the Consultative Committee for Mass and Related Quantities (CCM) and IMEKO (International Measurement Confederation) we want to welcome you to the Hilton Washington DC/Rockville Hotel & Executive Meeting Center. We are looking forward to a great conference along with some important meetings related to improving the realization, dissemination, and metrology of pressure and vacuum measurements.

The CCM operates under the exclusive supervision of the International Committee for Weights and Measures (CIPM) which itself comes under the authority of the General Conference on Weights and Measures (CGPM). The CGPM is the intergovernmental organization established in 1875 under the terms of the Metre Convention through which member states act together on matters related to measurement science and measurement standards. The CCM working group on Pressure and Vacuum meets in person every 6 years to discuss up coming changes in the realization, dissemination, and metrology of pressure/vacuum and related measurements.

IMEKO often partners with the CCM working group on Pressure and Vacuum to further the goals of improving dissemination of metrology. IMEKO TC16 focus on pressure measurement including the more practical sensors used in industrial sectors like process and semiconductor industry, photovoltaic, coating, metallurgy, packaging, pharmaceutical, research applications and more.

We are glad you made it to the USA and hope that you enjoy your time here. I hope that the conference and discussions at the breaks, vendor show, and reception improve our international relations and improve pressure metrology worldwide.

Thank you,
Regards,

Jacob Ricker, Local program Chair

CONFERENCE LAYOUT

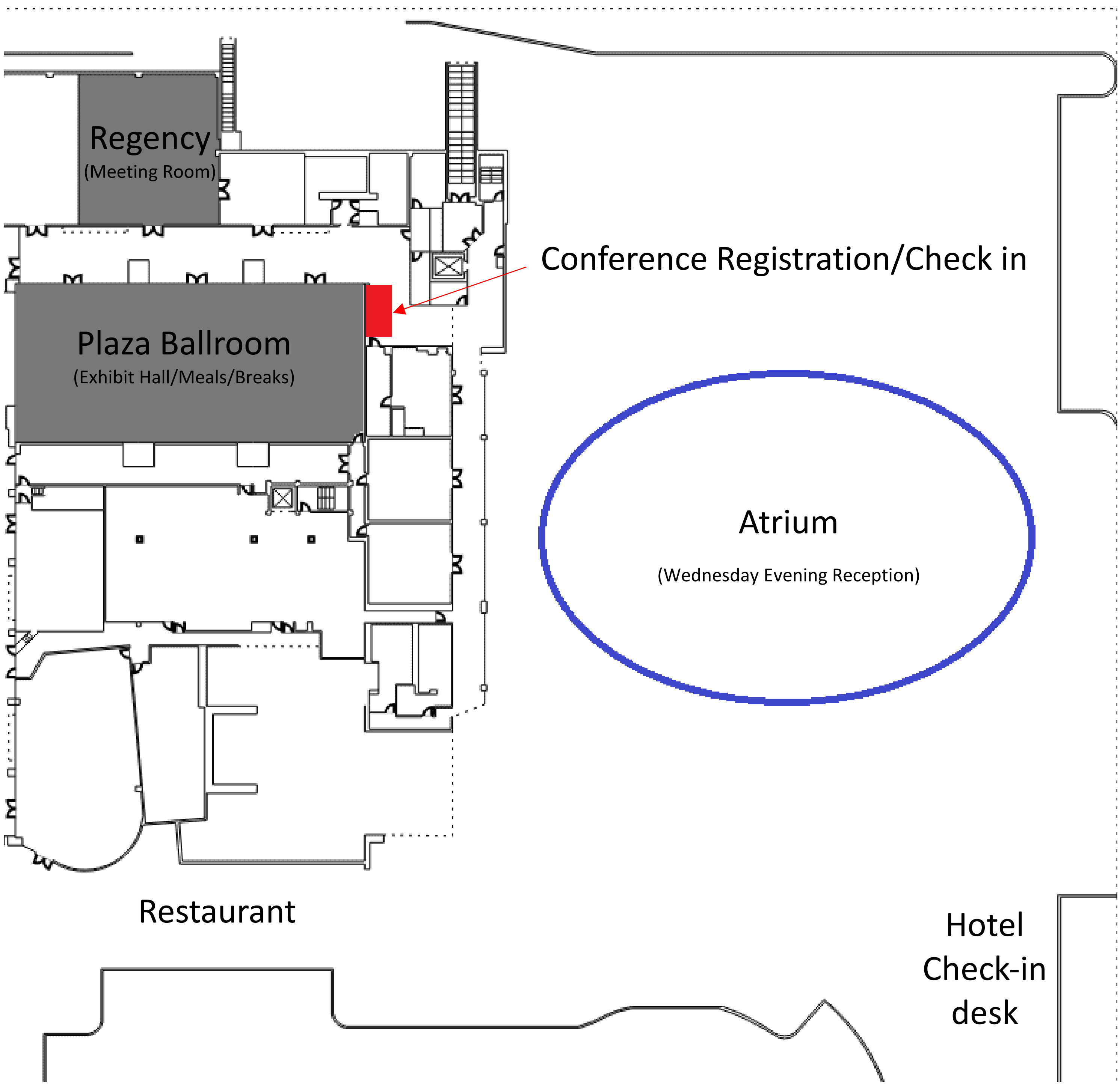
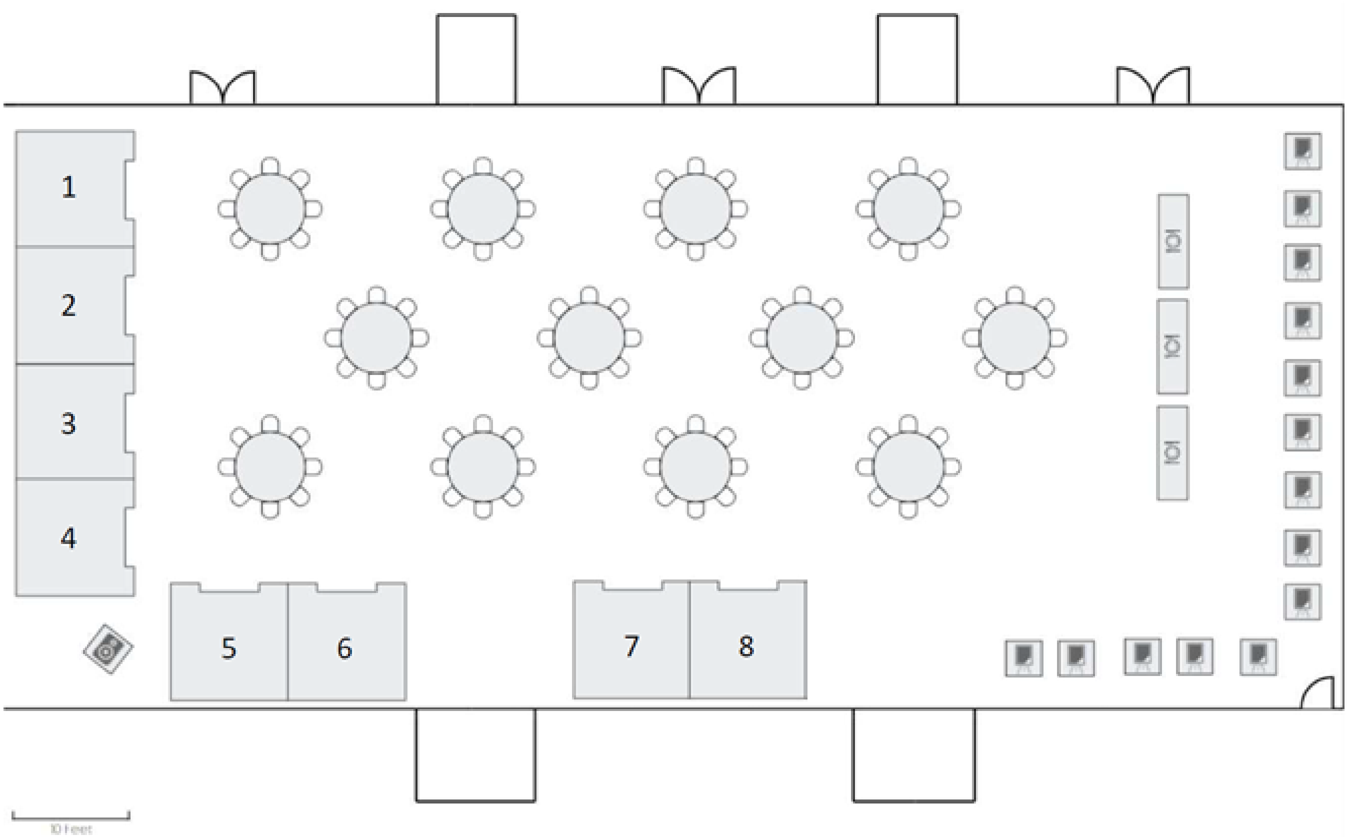


EXHIBIT HALL INFORMATION



Vendor Booths

1:	Yokogawa Test&Measurement	https://tmi.yokogawa.com/us/
2:	Inficon	https://www.inficon.com/en
3:	Fluke	https://www.fluke.com/
4:		
5:	Druck	https://www.bakerhughes.com/druck
6:	NIST	https://www.nist.gov/
7:	Additel Corporation	https://www.additel.com
8:	MKS Instruments	https://www.mks.com/

Food and drinks will be available in the Exhibit Hall during all breaks and meals. The Wednesday evening reception will be located in the Hotel Atrium.

If you have special food allergies or requirements, please speak to a hotel staff.

CONFERENCE SCHEDULE

Monday May 15th, 2023

☐ 8:30 am – 5 pm: Instructional Courses at NIST *(NIST Lecture Room C & D)*

Tuesday May 16th, 2023

☐ 9:00 am – 5:00 pm: Registration open *(Plaza Ballroom Foyer)*
☐ ~~9:00 am – 11:00 am: (SIM) Pressure and Vacuum Meeting~~ *(Regency)* canceled.
☐ 10:00 am – 11:00 am: Breakfast *(Plaza Ballroom)*
☐ 11:00 am – 12:00 pm: Panel discussion on drafting and review of CMCs *(Regency)*
☐ 12:00 pm – 1:00 pm: Lunch (all vendors and attendees welcome) *(Plaza Ballroom)*
☐ 1:00 pm – 5:00 pm: Vendor check-in/Exhibit hall setup *(Plaza Ballroom)*
☐ 1:00 pm – 5:00 pm: Consultative Committee for Mass and Related Quantities (CCM) Working Group on Pressure and Vacuum (CCM-WGPV) Meeting *(Regency)*
NOTE: This meeting is designated for CCM-WGPV members, others may attend as observers by invitation only.

Wednesday May 17th, 2023

☐ 7:30 am – 5:00 pm: Registration open *(Plaza Ballroom Foyer)*
☐ 7:30 am – 4:20 pm: Exhibition hall open *(Plaza Ballroom)*
☐ 7:30 am – 8:00 am: Breakfast *(Plaza Ballroom)*
☐ 8:00 am – 10:00 am: Oral Session 1 *(Regency)*
☐ 10:00 am – 10:40 am: Break, Vendor Exhibit *(Plaza Ballroom)*
☐ 10:40 am – 12:40 pm: Oral Session 2 *(Regency)*
☐ 12:40 pm – 1:40 pm: Lunch, Vendor Exhibit *(Plaza Ballroom)*
☐ 1:40 pm – 3:00 pm: Oral Session 3 *(Regency)*
☐ 3:00 pm – 4:00 pm: Poster session, Vendor Exhibit *(Plaza Ballroom)*
☐ 4:00 pm – 6:00 pm: Oral Session 4 *(Regency)*
☐ 6:30 pm – 7:30 pm: Evening Reception *(Atrium)*
☐ 7:30 pm – 9:00 pm: Dinner *(Atrium)*

Thursday May 18th, 2023

☐ 7:30 am – 10:00 am: Registration open *(Plaza Ballroom Foyer)*
☐ 7:30 am – 4:00 pm: Exhibition hall open *(Plaza Ballroom)*
☐ 7:30 am – 8:00 am: Breakfast *(Plaza Ballroom)*
☐ 8:00 am – 10:00 am: Oral Session 5 *(Regency)*
☐ 10:00 am – 10:40 am: Break, Vendor Exhibit *(Plaza Ballroom)*
☐ 10:40 am – 12:20 pm: Oral Session 6 *(Regency)*
☐ 12:20 pm – 1:20 pm: Lunch, Vendor Exhibit *(Plaza Ballroom)*
☐ 1:20 pm – 3:20 pm: Oral Session 7 *(Regency)*
☐ 3:00 pm – 4:00 pm: Break, Vendor Exhibit *(Plaza Ballroom)*
☐ 4:00 pm – 6:20 pm: Oral Session 8 *(Regency)*

Friday May 19th, 2023

☐ 7:50 am – 6:30 pm: Optional Tour ($100 – Registration closes May 15th) *(Hotel Lobby)*
Arrive in the hotel lobby by 7:50 am. Bus departs at 8:00 am. The bus returns to the hotel at 6:30 pm. Have an evening flight from Dulles Airport (IAD)? We can drop you off at Dulles Airport at 5:35 pm.

Wednesday May 17th, 2023

8:00 (Invited Speaker) Karl Jousten - PTB

Accurate high vacuum measurement by means of a novel standardized ion gauge

A novel ionisation vacuum gauge has been developed with the aim of providing a measuring instrument of high metrological quality for high vacuum. The new gauge is intended to serve as a reference standard for the calibration of other vacuum gauges and quadrupole mass spectrometers, and as a transfer standard for comparison between fundamental vacuum standards in the range 10^{-6} Pa to 10^{-2} Pa. The gauge has been developed after careful analysis of existing ionisation vacuum gauges and an extensive literature review.

In the new design, the electrons take a straight path from the emitting cathode through the ionisation space into a Faraday cup [1]. This has the advantage over existing ionisation vacuum gauges that the electron path length is well defined. It is independent of the point and angle of emission and is not affected by the space charge around the collector. In addition, the electrons do not hit the anode where they can be reflected, generate secondary electrons or cause desorption of neutrals or ions. The design is mechanically rigid (no grids or thin wires are used) to ensure transport stability.

The sensitivity for nitrogen of the novel gauge is predictable within a range of 2.5 %. Repeatability, reproducibility, and transport stability are within 1 %. Even the cathode can be exchanged without any significant change of sensitivity. For a calibrated gauge, a standard measurement uncertainty of 1 % can be expected [2]. The success of the development makes the gauge suitable for standardization at ISO level, but also attractive for industrial applications, because gauge replacement does not require calibration or readjustment of a vacuum process. The presentation will outline the new design and report on the main metrological features.

8:40 Martin Wüest - INFICON Ltd

Applications of a new reference ionization vacuum gauge

A novel ionization gauge was developed in the framework of the EURAMET EMPIR 16NRM05 project. The goal was to develop a stable gauge for the pressure range 10^{-6} to 10^{-2} Pa suitable as a reference standard in the high vacuum range. A robust design eliminates many of the weak points of present day Bayard-Alpert gauges. Results of performed measurements at national measurements institutes show sensitivity spread within an interval ± 1.5 % at 95 % confidence level. Due to the excellent performance of the gauge, the gauge design is now being proposed as a standard ionization gauge in the framework of an ISO Technical Specification 6737.

Due to its simple geometry, sensitivity values can in principle be computed for any gas with a known ionization cross section. Known and stable relative sensitivity factors are important properties for the calibration of mass spectrometers. Therefore, this gauge is also well suited for the calibration of mass spectrometers. INFICON is the first company that has integrated such a gauge according to the proposed standard in its product line. We will present some aspects of our gauge design and performance in conjunction with an associated controller.

9:00 Janez Setina - Institute of Metals and Technology

Precise characterization of nonlinearity of gas conductance of sintered stainless steel leak element

Pressure dependence of gas conductance through a leak element in a shape of small orifice or capillary depends on the gas flow regime. In vacuum metrology the most favorable is molecular flow regime, where pressure dependence of conductance diminishes, so the gas flow is proportional to pressure difference across the leak element. Gas flow is in the molecular regime when the average mean free path of gas molecules is at least several times greater than the characteristic physical length scale of the leak element. For practical realization of gas leak this means a very small orifice or capillary, or very low gas pressure on the high-pressure side. In both cases the gas flow through leak element may become too small for a practical work. This can be avoided by connecting a large number of molecular leaks in parallel, which was realized in a sintered stainless steel filter developed by NMIJ and became commercially available under the name "standard conductance element (SCE)".

We investigated the pressure dependence of the SCE with a nominal conductance of 2.2×10^{-8} L/s very carefully. To determine the relative change in conductance, we applied two methods using a spinning rotor gauge (SRG): (i) a pressure difference across a fixed conductance, and (ii) a method of increasing pressure in a closed volume. The SRG is distinguished by high linearity, and by changing the operating parameters of SRG and combining two methods we were able to measure gas flow with a precision of 0.2% in the pressure range between 10 Pa and 100 kPa. The conductance of investigated SCE for nitrogen showed very little pressure dependence (variations less than +/- 0.2%) in the range between 10 Pa and 3 kPa. At a pressure of 10 kPa conductance increases by 1% and at a pressure of 100 kPa by approximately 15%. Results of measurements for gasses He, Ne, Ar and Kr will be presented also.

9:20 Martin Vičar - Czech Metrology Institute

New Method of a Constant-Pressure Flowmeter Traceability

Czech Metrology Institute (CMI) covers the range of high vacuum by a primary standard based on the orifice-flow (also continuous or dynamic expansion) principle. A continuous and precisely determined gas throughput is admitted into a calibration chamber, which is pumped through a precise orifice by a known pumping speed (in our case cca 11 l/s). The calibration pressure in the chamber can be calculated as their ratio. The gas throughput must be generated by means of a suitable primary gas flowmeter. In our case, the utilization of two constant pressure flowmeters (CPF) was necessary to cover the entire demanded range of the generated pressures 10^{-5} - 0.1 Pa; CPF-A for the range 2×10^{-5} - 8×10^{-2} Pa×m³/s and CPF-B for 1×10^{-7} - 5×10^{-4} Pa×m³/s. Volume displacers of both flowmeters are based on directly compressed welded bellows (consisting of the welded metal foil annuli), each compressed by a screw driven by a step motor. The degree of compression is measured optically. Time of a complete compression can vary in the range 200 - 2000 s. Pressure of a working gas is set between 10^3 and 10^5 Pa (but always lower than atmospheric). Outgassing occurs in the flowmeters and it is determined before each measurement. The speed of translation of the free end of the bellows must be lower than 0.1 mm/s. The minimal change of volume during one measurement must be kept higher than 50 % of the total variable volume. The temperature of the bellow must be kept within ±0.15 K and its change rate below $5\cdot10^{-4}$ K/s.

The volume variations by the compression (and moreover by the difference between the ambient pressure and the pressure of the gas inside the welded bellows) are a crucial parameter and must have a very precise calibration. However, it is not possible to calculate the displaced volume from the geometric dimensions of such a complicated structure. Hence, we use a precisely dimensionally calibrated piston sliding in a hollow cylinder (with an elastomer sealing), which is connected to a CPF. A step change of piston position is in parallel followed by a corresponding volume-change of a bellow to be calibrated. This procedure proved well but it was painstakingly long with challenging and difficult evaluation of displaced volumes.

After a fatal leakage had occurred in our CPF-B, the leaky welded below has been replaced with an identical one. Of course, its pressure-compression dependence of displaced volume had to be calibrated. On this occasion, the quicker calibration method has been developed. The new method utilizes a very slow but constant displacement of the piston with a tied-up but discontinuous volume-change of the bellow. Thus, a several times shorter calibration time can be achieved with the same or slightly lower uncertainty of the volume-change. This method is described in detail.

9:40 Matthias Bernien - PTB

Reduction of the uncertainty of PTB's pressure scale in the range from 10 mPa to 130 Pa by fully automated Aluminum static expansion system

Static expansion primary standards are one of the most accurate realizations of the pressure scale in the high and medium vacuum range. At PTB, the new static expansion system SE3 has been set up and validated in the pressure range from 1×10^{-2} Pa to 130 Pa. The reduction of uncertainty and a high degree of automation have been the main focus of its design.

The principle of static expansion relies on the transfer of a fixed amount of gas from a small volume into a larger volume. If the initial pressure and the ratio of the two volumes are precisely known, a well-known lower pressure is generated. In SE3, initial pressures are converted to lower pressures by factors of 10000, 1000 and 100 by means of 3 different starting volumes and a vacuum vessel of 200 l. The filling pressure is measured by means of a so-called group standard consisting of 15 capacitance diaphragm gauges and a quartz Bourdon spiral. When approaching smaller uncertainties many influences on the generated pressure must be investigated in detail and accounted for by corrections or uncertainty contributions, e. g. real gas effects, influence of height differences, and volume changes by fatigue of valves. In particular, the pressure differences that arise due to the movement of valves during closing were investigated both experimentally and by simulations [1]. A central aspect is the uncertainty in gas temperature. SE3 is built from vacuum components made of aluminum whose thermal conductivity is higher by more than one order of magnitude compared to stainless steel. In addition, SE3 is thermally isolated and thermostated. The temperature is measured by 90 Pt100 sensors in total. A maximum temperature difference of only 30 mK is obtained. As a result, relative standard measurement uncertainties between 0.8 ‰ and 0.12 ‰ were achieved in the pressure range from 1×10^{-2} Pa to 130 Pa.

The operation of SE3 is fully automated. Before a calibration, automated self-tests are performed to verify the correct operation of the primary standard as well as to determine outgassing rate and the additional volume introduced by the devices under test. The calibration measurements are integrated in an automated workflow from the generation of an offer for calibration to the digital calibration certificate.

10:40 (Invited Speaker) Marcy Stutzman – Jefferson Lab

Extreme high vacuum for polarized electron sources

Nuclear physics experiments often require highly polarized electron beams to do precise measurements of the structure and size of nucleons and the nucleus, as well as for searches for physics beyond the standard model. Jefferson Lab's electron source, with polarization near 90%, has been providing polarized electron beams for CEBAF for over two decades. Development is underway for polarized electron sources at MESA at Mainz and the Electron Ion Collider at Brookhaven National Lab, and there is potential for polarized electron beam in the future at facilities including the International Linear Collider, an electron upgrade at CERN, and the SuperKEKB collider in Japan. At Jefferson Lab there are even plans to make use of polarized electrons to make a polarized positron source for experimental nuclear physics.

High polarization electron beams are generated using photoemission from strained superlattice GaAsbased photocathodes, and photocathode lifetime is limited by the ionization of residual gas in the system, which is then accelerated into the photocathode. Extreme high vacuum (near $1\text{x}10^{-10}$ Pa) is required to operate the Jefferson Lab polarized electron source with an acceptable lifetime, and the upcoming projects will need various combinations of higher current, higher bunch charge and longer photocathode lifetimes.

To meet the vacuum requirements for polarized electron sources, every component for a polarized electron source must be optimized, including chamber materials, pumps, bakeout procedure and the high voltage electrode geometry and processing. Each change in these components must be evaluated offline before being used in the accelerator, and effects on pressure are difficult to evaluate even using XHV-optimized hot filament ionization gauges. In fact, we do not get a final evaluation of system modifications until an electron source is built, installed and lifetime measurements are made over the course of months or years of operation.

I will be discussing the evolution of vacuum in the Jefferson Lab polarized source system toward XHV pressures and discuss the characterization and limitations measured for commercially available XHV vacuum gauges. Finally, I'll present the effect of system pressure on photocathode lifetime and highlight how XHV pressure standards can benefit the ongoing efforts to improve vacuum for the next generation of polarized electron sources.

11:20 (Invited Speaker) Stephen Eckel - NIST

Quantum-based measurement of ultra-high vacuum using cold atoms

We describe the cold-atom vacuum standards (CAVS) effort at the National Institute of Standards and Technology. The CAVS relates the measured loss rate of laser cooled atoms from a magnetic trap to pressure in the ultra-high vacuum regime through first-principles quantum scattering calculations. The resulting measurement of pressure is traceable to the second and the kelvin, making it a primary realization of the pascal. We have developed two versions of the CAVS: a laboratory standard (l-CAVS) used to achieve the lowest possible uncertainties and pressures and a portable version (p-CAVS) that is a potential replacement for the Bayard-Alpert ionization gauge. Recently, we have used the l-CAVS and p-CAVS to measure the collisional loss rate coefficients of ultra-cold ^{7}Li and ^{87}Rb colliding with room-temperature He, Ne, N_2, Ar, Kr, and Xe and compare with the first-principles quantum scattering calculations. In these experiments, a vacuum metrology standard--a combined flowmeter and dynamic expansion system--is used to set a known number density for the room-temperature gas in the vicinity of magnetically trapped ultracold ^{7}Li or ^{87}Rb clouds. The change in the atom loss rate with background gas density is used to determine the loss rate coefficients with fractional standard uncertainties that are better than 1.6 % for ^{7}Li and 2.7 % for ^{87}Rb. We find consistency between the measurements and recent quantum-scattering calculations of the loss rate coefficients [J. Klos and E. Tiesinga, *J. Chem. Phys*. **158** 014308 (2023)] except for the loss rate coefficient for ^{87}Rb colliding with Ar.

12:00 Annas Ali - PTB

Reference leaks for traceable outgassing rate measurements of hydrocarbons and water

We describe the cold-atom vacuum standards (CAVS) effort at the National Institute of Standards and Technology. The CAVS relates the measured loss rate of laser cooled atoms from a magnetic trap to pressure in the ultra-high vacuum regime through first-principles quantum scattering calculations. The resulting measurement of pressure is traceable to the second and the kelvin, making it a primary realization of the pascal. We have developed two versions of the CAVS: a laboratory standard (l-CAVS) used to achieve the lowest possible uncertainties and pressures and a portable version (p-CAVS) that is a potential replacement for the Bayard-Alpert ionization gauge. Recently, we have used the l-CAVS and p-CAVS to measure the collisional loss rate coefficients of ultra-cold 7Li and 87Rb colliding with room-temperature He, Ne, N2, Ar, Kr, and Xe and compare with the first-principles quantum scattering calculations. In these experiments, a vacuum metrology standard--a combined flowmeter and dynamic expansion system--is used to set a known number density for the room-temperature gas in the vicinity of magnetically trapped ultracold 7Li or 87Rb clouds. The change in the atom loss rate with background gas density is used to determine the loss rate coefficients with fractional standard uncertainties that are better than 1.6 % for 7Li and 2.7 % for 87Rb. We find consistency between the measurements and recent quantum-scattering calculations of the loss rate coefficients [J. Klos and E. Tiesinga, J. Chem. Phys. 158 014308 (2023)] except for the loss rate coefficient for 87Rb colliding with Ar.

12:20 Robert Smith - RAL Space

Investigation into the Temperature Dependence of Cold Cathode Ionization Gauges

As we wish to operate cold cathode ionization gauges (CCIGs) at temperatures below those specified in the manufacturer's documentation, we have performed an investigation into the in-vacuum operation of CCIGs at sub-ambient temperatures in order to verify the operation of the gauges under these conditions, integrate the equipment into our existing systems, and determine whether the engineering of a solution for heating the gauges during operation would need be required. Two Pfeiffer IKR060 gauges were mounted on separate thermal plates inside a vacuum chamber, one plate temperature controlled by a LAUDA thermal plant, and the other remaining at ambient temperature to serve as a reference. Control cables were fed from a Pfeiffer TPG500 controller outside the chamber through a feedthrough to the gauges inside. Both gauges were mounted in a configuration such that they had equivalent vacuum conductance paths to the pumping system and thermal conductance paths to their thermal plates and were tested and inspected before and after the investigation to identify any changes in function. The temperature of the test gauge (Ttest) was held at various temperatures between -39°C and +45°C, these temperature fluctuations caused pressure fluctuations in the chamber between $4.5\text{x}10^{-6}$mbar and $1\text{x}10^{-5}$mbar (as read by the reference gauge) due to the effect of sorption and outgassing phenomena on the thermal plate. To quantify the temperature effect on the gauge, the ratio of the test gauge pressure reading (Ptest) and reference gauge pressure reading (Pref) is used as a relative representation of pressure in order to minimize the effect of the pressure fluctuations. This investigation suggests a temperature dependence of cold cathode gauges and results will be presented.

13:40 (Invited Speaker) Tom Rubin - PTB

Progress and goals towards the quantum-based realization of the Pascal

In 2019 -the year of the redefinition of the SI -twelve European institutions combined their capabilities within the Quantum Pascal project to drive forward traceable pressure measurements utilizing quantum-based methods that evaluate the number density instead of force per area. To target the wide pressure range between 1 Pa and 3 MPa by assessing the density of helium or argon several challenges needed to be mastered. Among other things, this included precise knowledge of the required gas parameters, temperature control and determination of the gas temperature, or minimization of the influence of pressure-induced deformation of relevant components. Following the successful completion of the Quantum Pascal project, the follow-up project MQB-Pascal, in which 19 institutions are participating, will now start in 2023. This time, the focus is on the use of nitrogen as a measuring gas as well as feasibility studies for practical applications such as measurements in gauge mode or of dynamically changing pressures.

14:20 Kevin Douglass - NIST

Optical Pressure Measurements approaching Ultra-High Vacuum

With the goals of achieving quantum traceability over a broad pressure scale NIST is developing a Vacuum Fixed Length Optical Cavity (VFLOC) that will have a base pressure in the ultra-high vacuum range. The current FLOC operates in the 1 kPa to 150 kPa pressure range and the Cold Atom Vacuum Standard (CAVS) has an upper limit near 10^{-5} Pa. The VFLOC will fill the traceability gap in, which is also an important region for many industrial applications where standards and high accuracy sensors are not available nor cover as broad a pressure range. The main limitation for pressure resolution and ultimate base pressure is the fractional frequency stability or frequency noise of dual cavity heterodyne signal. For operation at 1542 nm, hertz level frequency noise is required for achieving pressure noise floor on the order of 10^{-6} Pa (10^{-8} Torr). We will discuss current system status, design and recent results.

14:40 Amazigh Rezki - LNE-Cnam

Status and performance of the Fabry-Perot refractometer developed at LNE-Cnam for pressure measurement

We present the status of the single-cavity Fabry-Perot interferometer developed at the LNE-Cnam laboratory for measuring thermodynamic low-pressure. After measuring the intrinsic parameters of this refractometer, it is used as an optical method to measure the refractivity of nitrogen gas and, consequently, its pressure in the range of 30 kPa to 100 kPa. This device operates as a high-resolution pressure sensor with an objective of complementing and eventually replacing traditional primary pressure measurement techniques such as piston gauge balance and force-balanced piston gauge.

The change in refractivity inside the interferometric cavity is measured by comparing the frequency of a laser locked to a longitudinal TEM_{00} mode of a Fabry-Perot cavity against another similar 532 nm laser (reference laser) whose frequency is locked on a hyperfine component of a molecular transition of iodine and is known to be highly accurate.

By measuring the refractive index of a gas, its density can be deduced using the Lorentz-Lorenz equation and the molar polarizability of the gas, at a specific wavelength. Moreover, accurate temperature measurement of the gas inside the cavity enables the calculation of gas pressure using an equation of state.

The pressure uncertainty measurement relies on the knowledge of the molar polarizability and the higher order virial coefficients of the gas at 532 nm, as well as the cavity length deformation. The effective coefficient of thermal expansion, the pressure-induced distortion coefficient, the free spectral range, the cavity aging rate and the penetration depth of the light in the mirrors were measured with their associated uncertainties. Among these parameters, the pressure-induced distortion coefficient is the most significant, mainly due to the uncertainty of the nitrogen gas molar polarizability at 532 nm, which is necessary to measure this coefficient.

Finally, a direct pressure comparison between the optical sensor and a reference PG7607 rotary piston pressure balance was carried out, indicating no deviation greater than 8 parts per million for $p \geq 30$ kPa. This corresponds to a reproducibility of $2\times10^{-6} \cdot p$, within this range.

16:00 (Invited Speaker) Giovanni Garberoglio - Fondazione Bruno Kessler - ECT*

Ab-initio calculations for the highly accurate calculation of the virial expansion of pressure and dielectric constant

We present the status of the single-cavity Fabry-Perot interferometer developed at the LNE-Cnam laboratory for measuring thermodynamic low-pressure. After measuring the intrinsic parameters of this refractometer, it is used as an optical method to measure the refractivity of nitrogen gas and, consequently, its pressure in the range of 30 kPa to 100 kPa. This device operates as a high-resolution pressure sensor with an objective of complementing and eventually replacing traditional primary pressure measurement techniques such as piston gauge balance and force-balanced piston gauge.

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16:40 Domenico Mari - INRIM

Experimental determination of molar polarizability of nitrogen by a multi-reflection interferometric technique

In the new SI, the uncertainty of the Boltzmann constant kB was eliminated, making advantageous to realise the pascal through number density measurements via optical methods, resulting in significant progress achieved in recent years at various metrological institutes and universities all around the world. The performance of these novel generation of photon-based pressure standards, in long term, would be mainly limited by the accuracies of determination of relevant gas parameters and the temperature assessment. In this contest, a novel optical pressure standard, alternative to Fabry-Perot cavity-based realizations, has recently developed. It is based on the measurement of the refractive index of a gas through an unbalanced homodyne interferometer with fixed arms. The interferometer was designed to have the measurement arm formed by a multi reflection double mirror assembly to establish an unbalance length L between the two arms larger than 6 m in a compact set-up. This talk will discuss the device design and recent results.

17:00 Martin Zelan - RISE Research Institutes of Sweden

Fabry-Perot based refractometry utilizing gas modulation: Accuracy, precision, and transportability

Fabry-Perot based refractometry is a powerful technique for pressure assessments that, due to the recent redefinition of the SI system, also offers a new route to realizing the SI unit of pressure, the Pascal. Although the technique has demonstrated impressive results, it normally requires extraordinary experimental preparation to avoid unwanted contribution from a range of external factors, such as thermal drifts, material aging, outgassing and leaks, to mention a few. As a mean to remedy this, we have over the recent years developed a gas modulation methodology(GAMOR) that allows high-performance Fabry-Perot based refractometers to be operated with significantly less constrains on the experimental system. In this talk we will provide a basic overview over the methodology and explain how the use of GAMOR allows the construct of systems that are virtually immune to linear drifts and fluctuations and has allowed for non-conventional cavity material, e.g., Invar, which have some significant advantages over glass-based material. Utilizing the advantages from Invar-based cavities and GAMOR, we have constructed two similar, but different system, one higher performance stationary system, equipped with a fix-point gallium cell for high-accuracy temperature assessment, and one 19-inch rack-based transportable system, that can be shipped by standard low-cost shipping services. We will present the experimental realization of these system in some detail as well as the discuss the performance, capabilities, and short comings in terms of accuracy and precision.

17:20 Jacob Ricker - NIST

Use of a Fixed Length Optical Cavity (FLOC) for Differential Pressure Measurements for Air Data Calibrations

NIST has constructed several Fixed Length Optical Cavity (FLOC) pressure standards based on gas refractivity and shown that they are effective at measuring absolute pressure. The US Air Force has expressed interest in using these standards for the calibration of their Air Data Calibration Systems. These Air Data Systems provide calibration for altimeters and air speed indicators and traceability of these sensors is required on all operational military and commercial aircraft. The calibration of these systems requires a standard that operates from 1 Pa to 360 kPa in absolute and differential pressure (relative to pressure around 100 kPa).
As opposed to other standards such as piston gauges and manometers that can measure differences in pressures, the gas refractivity measurement method utilized by the FLOC determines an absolute number of molecules in a system and therefore it cannot be used for differential measurements. However, a second measurement tool can be used to determine the reference pressure and provide a calculated differential pressure measurement. As operating two FLOCs would be prohibitively expensive, NIST evaluated the feasibility of using a sensor that can be calibrated at the time of use to determine the reference pressure. The test was completed using the MKS Instruments FLOC prototype (designed under a cooperative research and development project with NIST). The uncertainty of this system was estimated to determine if it would be capable of meeting the needs of the air data calibration systems. Data taken in both absolute and differential vs piston gauges and other calibrated standards will be shown.

17:40 Ashok Kumar - NPL India

Progress in Optical Pressure Standards at CSIR-NPL

The CSIR-National Physical Laboratory (NPL), New Delhi, India, has been working to establish the Optical Pressure Standard (OPS) using the fixed length dual Fabry-Perot Cavity and 1542 nm central wavelength external cavity diode lasers (ECDL). The average length of the cavity will be nearly 150 mm, made of ultra-extreme low expansion glass with thermal coefficients less than 35 ppb/0C. The cavity will be made of a spacer with optically contacted plane-plane and plane-concave mirrors on both sides of the cavity, respectively. The central portion of the cavity will be contacted with a metal flange to connect with the vacuum system. The FP cavity will be kept inside the specially designed copper and aluminum chamber to control the pressure and temperature inside the FP cavity. To understand Helium gas's refractivity, we have theoretically calculated the refractivity of the Helium gas at 300 K for wavelengths of laser light at 1542 nm (nanometer) in the pressure range 1 Pascal to 1000 Kilopascals. The two fundamental equations, i.e., the real gas equation and the Lorentz-Lorenz equation, are used in theoretical calculations to define the relationship between pressure and refractivity. It was found that refractivity values rise uniformly with increased pressure, which matched the earlier report. We have also theoretically calculated the effective fractional frequency of helium, which further required experimental validation and verification. In brief, I will discuss the design and development of the FP cavity, Laser locking systems, Vacuum chamber of FP Cavity, and theoretical estimation of refractivity and effective fraction frequency calculation for helium gas for 1542 central wavelength laser.

Thursday May 18th, 2023

8:00 (Invited Speaker) Sarah White – MKS Instruments

Fixed-Length Optical Cavity as a Pressure Metrology Tool

The fixed-length optical cavity (FLOC) is a new pressure standard that uses gas refractometry to measure pressure. In partnership with the National Institute for Standards and Technology (NIST), MKS Instruments has developed a table-top FLOC pressure standard designed to replace existing commercial pressure standards currently used at MKS.

As a leading manufacturer of high-performance pressure transducers, MKS must maintain pressure metrology capabilities for calibrating MKS pressure products. Existing commercial pressure standards do not meet future needs for the MKS pressure metrology lab due to limited operational range and insufficient accuracy. A table-top FLOC calibration system was designed to replace existing commercial pressure standards and improve calibration accuracy, throughput, and metrology sustainability.

The FLOC outperforms existing commercial pressure standards used at MKS with lower measurement uncertainty, most significantly in the low-pressure measurement range (< 100 millitorr), as demonstrated by the FLOC expanded measurement uncertainty and comparisons against national primary standards at NIST and existing MKS commercial standards. The FLOC improves calibration accuracy as compared with existing commercial pressure standards and expands the low-pressure calibration range by more than a decade resulting in better unit calibration repeatability at lower pressure ranges for MKS pressure products.

The MKS FLOC utilizes technologies and collaboration across MKS vacuum solutions and photonic solutions divisions. The MKS FLOC could replace commercial pressure standards and has the possibility of becoming a new commercial pressure standard for pressure globally used across many industries.

8:40 Christoph Reinhardt - DESY

Nanomechanical trampoline sensors for pressure and vacuum metrology

In recent years, there has been a rapid advancement in the development of nanomechanical resonators that possess ultra-high mechanical quality factors Q. As a result, these devices have become increasingly sensitive to even the slightest changes in environmental parameters, such as the surrounding gas pressure. In this study, we showcase the practical use of mm-scale nanomechanical trampoline resonators with an intrinsically-limited Q~107, for the purpose of gas pressure sensing.

To study the dependency of the trampoline's Q and resonance frequency f on the surrounding gas pressure P, we place it inside an ultra-high vacuum chamber with up-and downstream pressure control. This enables tuning the pressure inside the chamber from 10^{-8} mbar to 10^{3} mbar. The oscillatory motion of the trampoline is measured by aligning its central pad at the end of a Michelson interferometer's arm. In our presentation we will provide additional details on the results. Here, a particular focus will lie on the model function, combining the common analytical expression for FMF [5] and a two-parameter fit function for VF. Also, we will discuss insights on precision and accuracy of our sensor and present current developments on increasing the sensitivity range towards both lower and higher pressure.

9:00 SamYong Woo - KRISS

Characteristics of a Commercial MEMS Quartz Tuning Fork as a Tiny Vacuum Sensor

Quartz tuning forks (QTFs) are widely used in a variety of fields including instrumentation, physics, and engineering. It is used as an accurate frequency reference due to its high stability and accuracy. The QTF is a piezoelectric device that vibrates at a resonant frequency when an AC voltage is applied to its electrodes. We investigated the possibility of using it as a small economic vacuum sensor. Vacuum pressure measurements using the QTF are based on the resonant frequency shift that occurs when a slight force is applied to a tuning fork. The frequency change characteristics according to the pressure change were investigated using an inexpensive QTF that is commonly available on the market. The QTF has been shown to linearly increase in resonant frequency as the ambient pressure decreases. Interestingly, however, it has been observed that this property does not apply below a certain low pressure. This property has not been observed so far, and we are confident that it can be greatly used to improve the accuracy of commercial quartz watches.

9:20 Neculai Moisoi - Druck Ltd - Baker Hughes

Negative gauge pressure calibration methods using a PACE CM3 pressure controller

The development of pressure controllers has seen a great focus and development over the last few decades, specifically in terms of their metrological capabilities. This advancement now makes them a suitable candidate to measure negative gauge pressure, either directly or in conjunction with other devices such as pressure balances. The PACE in conjunction with CM3 (control module) has demonstrated performant characteristics in line with those required to complete during negative gauge pressure calibrations. There were three different calibration methods were developed within the Druck Ltd laboratory, from which two of them used a 200 kPa absolute pressure CM3, containing TERPS© (Trench Etched Resonant Pressure Sensor). The unit under test was a PACE1000 indicator built with a piezoresistive sensors with a pressure range from -100 to 100 kPa. The expanded uncertainty was evaluated for each method, as well as identifying the advantages and shortcomings of each method. As the calibrations were performed for gauge mode (not differential), the calibration range was -950 to -50 hPa. The first method (Method A) was a direct method and the CM3 was used to apply the pressure to the PACE1000 indicator, while using a barometer to record the atmospheric pressure variation. In order to reduce the impact of the atmospheric pressure changes, an A-B-A method was used to collect the data, where A is the barometer reading and B is unit under test, while maintaining the applied pressure constant (within the repeatability of the CM3 controller). The second method (Method B) used the CM3 controller to apply a negative pressure to the bell jar of a pressure balance, while the positive port is open to the atmospheric pressure. The applied pressure from the pressure balance was computed at each measurement point, while minimizing the influencing factors effects. The unit under test was connected opposite the controller, through the bell jar, which helped to reduce the pressure variation observed during the measurements. The third method (Method C) used an inverted piston-cylinder assembly of a pressure balance with the unit under test directly connected to its port. This method is a well-established method in the Druck UKAS laboratory and it was used as a comparison with the first two methods. The results were analysed to understand the current expanded uncertainty capability given by these methods as well as the potential to develop these methods further to give the users the possibility to perform easier calibrations with high accuracy and relative low cost.

9:40 Hiroaki Kajikawa - NMIJ

Development of pressure calibrator applying 0-A-0 pressurization to reference pressure transducers

The National Metrology Institute of Japan (NMIJ, AIST) has been developing efficient pressure calibration methods using precise pressure transducers as the reference. To use them appropriately and to estimate the relevant uncertainties, several important characteristics need to be quantitatively evaluated, such as the effects of surrounding conditions and tilt, short-term and long-term stabilities, and the effect of pressurization procedure (hysteresis).

Calibrations of pressure gauges are conducted typically with a stepwise pressurization. However, difference in the pressurization procedures can affect the outputs of the reference gauge, and then, ultimately affects the calibration results of the test gauge. In our previous works, we found that applying the 0-A-0 pressurization to the reference pressure gauge highly eliminates the effect of pressurization procedure, and then, enables us to precisely calibrate test pressure gauges with various pressurization procedures.
In this study, we have developed a pressure calibrator that implements the 0-A-0 type pressurization and enables precise automatic calibration of pressure gauges. The developed pressure calibrator is mainly equipped with a pressure controller, two constant-volume valves, two reference pressure transducers (Paroscientific, Inc., 9000-15K-101), tilt sensors in two directions, and an environment monitoring device. The maximum calibration pressure is 100 MPa.
The primary feature of this calibrator is that the reference transducer is pressurized with the 0-A-0 procedure, while the test gauge can be pressurized with various procedures, with the operation of the pressure controller and two constant-volume valves located on either side of the controller. Also, to reduce the installation-angle dependence, we evaluated the effects of the angle on the output of each reference transducer, and then adjusted the installation angles of the two horizontally placed transducers so that the effects of the tilt of each transducer would be canceled out.
The calibration results of pressure gauges with this calibrator were found to be consistent with those with a pressure balance. In the presentation, we will show how pressure is applied to reference and test gauges, and also show calibration results of the test pressure gauges under stepwise and constant pressure applications.

10:40 (Invited Speaker) Frank Härtig - PTB

Digital Transformation in Metrology

At its 114th meeting in March 2023, the International Metre Convention with its 64 Member States and 36 Associate States and Economies decided to lay the foundations for a Digital System of Units, the so called Digital-SI. Almost 150 years after the introduction of the international system of units, the foundations for a harmonised digital quality infrastructure will be established and provided. This is indeed necessary, as worldwide activities in metrological applications have already begun several years ago. Standardisation organisations are in the process of making their documents machine-interpretable. Machine-readable and machine-interpretable digital calibration certificates (DCCs) have meanwhile found their way starting from the metrology institute via calibration service providers down to the industry. The lecture gives an overview of the structure of digital certificates, pre-normative documents and public available support, which the Physikalisch-Technische Bundesanstalt develops together with national and international partners. DCCs from the fields of flow measurement and pressure measurement will be shown. In general, DCCs are used in the electronic transfer of data as well as inside digital product passports. Using the example of mass, a study of a digital metrological twin will be presented where an autonomously acting module carries out a key comparison today. Moreover it will explained what role AI modules could play in the future.

11:20 Jay Hendricks - NIST

The Changing Role of the NMI with SI Redefinition and NIST on a Chip

This oral presentation covers a bit of metrology history of how we got to where we are today and gives a forward-looking vision for the future of measurement science. The role of NIST as a National Metrology institute (NMI) is briefly described considering the world-wide redefinition of units that occurred on May 20th, 2019. The re-definition of units is now aligned with physical constants of nature and fundamental physics which opens new realization routes with quantum-based sensors and standards. The NIST on a Chip program (NOAC) is briefly introduced in this context. The re-definition of the SI units enables new ways to realize the units for the pascal and the kelvin. These quantum-based systems; however exciting, do raise new challenges and several important questions: Can these new realizations enable the size and scale of the realization to be miniaturized to the point where it can be imbedded into everyday products? What will be the role of metrology institutes in the is new ecosystem of metrology and measurement? What will be the NMI role for quality systems and measurement assurance for these new quantum-based systems? This talk will begin to explore these important philosophical questions.

11:40 Karl Jousten - PTB

Written standards for vacuum metrology - an overview

The Technical Committee (TC) 112 of the International Standardization Organisation (ISO) is responsible for the standardization in the field of vacuum technology. 26 written standards have been published under the responsibility of ISO TC 112, and three are under development (January 2023). Three working groups (WG) cover vacuum pumps (WG 1), vacuum instrumentation (WG 2) and vacuum hardware (WG 3).
The ISO 3529 series defines the terms for vacuum metrology and technology. In 2019, the vacuum ranges have been redefined. High vacuum now ranges from 10-6 Pa to 0.1 Pa, ultra-high vacuum from 10-9 Pa to 10-6 Pa and extreme-high vacuum is newly defined and covers the range below 10-9 Pa. For vacuum metrology, specific definitions and specifications for ionisation vacuum gauges and quadrupole mass spectrometers are given in ISO 27894 and ISO 14291.
Written standards related to vacuum metrology are developed in the WG 2, but vacuum metrology is also relevant to the measurement of vacuum pump performance.
The basics of a calibration apparatus for the calibration of vacuum gauges have been laid down in the standard ISO 3567, the treatment of the uncertainties for the calibration of vacuum gauges in ISO 27893. These two standards form the basis for other gauge specific standards: ISO 19685 for the calibration of Pirani gauges, ISO 20146 for capacitance diaphragm gauges, ISO 24477 for spinning rotor gauges.
Technical Specifications (TS) are developed as preliminary guidelines for field testing. ISO TS 20175 describes procedures for characterising quadrupole mass spectrometers for partial pressure measurement, and ISO TS 20177 specifies procedures for measuring outgassing rates in a traceable and comparable manner. Currently under development is ISO TS 6737, which specifies the design of a high-precision ionisation vacuum gauge.
The presentation will highlight the standardisation work and future plans within ISO TC 112.

12:00 Sindy Higuera - Instituto Nacional de Metrología de Colombia INM

Exploring Fit Approaches for Pressure Calibration: An Interactive Web Application for Comparative Analysis

Pressure balances are widely used to calibrate pressure sensing devices and to realise the SI unit of pressure, the Pascal (Pa). The calibration procedure of a piston gauge is known as “crossfloat” and means the determination of its effective area as a function of the pressure. The piston gauge effective area at zero pressure is obtained from the fit of the calibration results to a function of the pressure. For example, when we have a linear function of pressure, y=ap+b, the effective area at zero pressure will be A_0=b and the distortion coefficient λ=a/b, then the effective area in function of the pressure will be $A_{pi}=A_0(1+\lambda p_i)$. There exist several regression techniques to fit data, with Ordinary Least Squares (OLS) being the most straightforward and commonly used. Additional methods include Weighted Least Squares (WLS) and Generalized Least Squares (GLS). These techniques differ in their assumptions and properties, and numerous studies have compared and analyzed their performance indifferent scenarios [Vishal Ramnath (2020)].

The Ordinary Least Squares method assumes that the residuals are homoscedastic, or that they are distributed with equal variance at each level of the predictor variable. However, when using this method to estimate the effective area A_{pi} and pressure distortion coefficient λ, certain fit assumptions may affect the statistical uncertainty and increase the residual standard error, particularly at lower pressure points. This can be attributed to the fact that these points have higher uncertainties, which can impair the determination of the fitting. Therefore, it is important to carefully assess the validity of the homoscedasticity assumption when applying the Ordinary Least Squares method for estimating A_{pi} and λ, and consider alternative regression techniques if needed [Pierre Otal (2020)].
This work focuses on the application of the Weighted Least Squares (WLS) method, as it is relatively simple to implement and can improve the accuracy of parameter estimates. We have developed a user-friendly web application that simplifies many of the necessary calculations and definitions. The application incorporates various features of the powerful R programming language, which is specifically designed for statistical calculations and high-quality graphical representations. With this tool, users can easily take advantage of the advanced capabilities of R without requiring extensive programming knowledge.

13:20 (Invited Speaker) Wladimir Sabuga - PTB

Recent research results on piston gauges

The need for highly accurate pressure measurements required in the experiments, carried at PTB, on redetermination of the Boltzmann constant (kB) by the Dielectric Constant Gas Thermometry (DCGT) stimulated development of new state-of-the-art pressure balances (PBs), further referred to as kB PBs, for absolute pressure measurements in gases up to 7 MPa in the end of 2000s. Their target relative standard uncertainty of 1×10-6 was achieved thanks their special design, special weights and, foremostly, by improvement in the determination of the zero-pressure effective area (A0) and the pressure distortion coefficient (l) of their piston-cylinder assemblies (PCAs), which included 3 PCAs of 20 cm2 and 3 PCAs of 2 cm2 nominal A0. The results of the theoretical studies were supported by the first measurement campaign, finished in 2010, in which the PCAs were compared with each other and other primary pressure standards of PTB in absolute pressure mode with nitrogen as pressure medium. Later, in the second measurement campaign, performed with helium gas, further improvements were achieved as for consistency of PCAs' l and agreement between the theoretical A0 and experimental A0-ratios, as well as due to reduction of the experimental standard deviation of the cross-float measurements. In the second measurement campaign, stability of the PCAs was demonstrated, the theoretical results obtained for nitrogen and helium media confirmed, and final parameters of the PCAs used in the DCGT measurements of kB stated. Ten years after the 1st measurement campaign, in 2020 – 2021, dimensional measurements on selected PCAs and cross-float measurements in absolute mode with nitrogen were repeated, and PCAs stability was analysed. In the last decade, the kB PBs were used to improve accuracy of the pressure scale realisation, including that of gauge pressure, and the new approaches used within the kB project were applied to different types of PBs at PTB and other National Metrology Institutes (NMIs) will be described.
The progress in the PB-based technologies achieved in the past decades was triggered by emerging needs for reduction of measurement uncertainties or extension of the measurement pressure range. With future new drivers, further developments of the PB-based technologies can become necessary. Possible ways for improvement of the PB manometry and its principal limits are discussed.

14:00 Kajikawa Hiroaki - NMIJ

Progress towards dimensional measurements for piston-cylinder of pressure balance

Pressure gauges and vacuum gauges are calibrated with higher accuracy pressure gauges and vacuum gauges to measure pressure with high accuracy. The high-accuracy pressure gauges and vacuum gauges are calibrated with pressure standards based on physical phenomena. Pressure balance that is one of the pressure standards generates pressure from the effective cross-sectional area of its piston-cylinder, the mass of its dead-weight, and the gravitational acceleration in the field. The effective cross-sectional area of the piston-cylinder has been determined from mercury manometers. On the other hand, it can also be determined from the radius of each position of the piston and cylinder based on Dadson's theory. PTB (Physikalisch-Technische Bundesanstalt) in Germany was the first in the world to put this method to practical use. NMIJ (National Metrology Institute of Japan) and other metrology institutes are also researching and developing this technology. As the measurement policy at NMIJ, the diameter of a reference sphere (~12.7 mm) is first measured using an ultra-precision CMM (μ-CMM) in comparison with a block gauge. Then, the diameter of the piston and cylinder (~35.4 mm) are measured in comparison to the reference sphere using a roundness measuring machine. The goal is to measure the 35.4 mm diameter of the piston and cylinder with a standard uncertainty of 180 nm first and 40 nm in the future. So far, the motion error of the rotary table of the roundness measuring machine has been evaluated by a multi-step method. The motion error of the Z-axis stage was also evaluated by an inversion method. A laser was introduced to measure the movement of the R-axis. The diameter of the reference sphere and the piston (and cylinder) were repeatedly compared. Furthermore, the uncertainty of the diameter measurement for the piston (and cylinder) was estimated. In the future, we will improve the measurement conditions and the measurement environment to achieve our goal.

14:20 Dominik Pražák - Czech Metrology Institute

New Geometrical Characterizations of the Pressure Balances of the Czech Metrology Institute

The improvements of the geometrical characterisations of the pressure balances of the Czech Metrology Institute will be presented. The effective area (Aeff) of a pressure-undistorted piston-cylinder assembly (PCA) of a pressure balance can be calculated in a primary way by applying the Dadson's numerical procedure to the known gap profile. This requires a very precise measurement of the PCA geometry. Luckily, since 2018, we have been able to utilize a novel and very precise Karl Zeiss Xenos 3D-machine. We used it to redetermine the geometries of both the classical and the digital pressure balances working in gas medium.
Our most important standard for the medium pressures is a classical pressure balance Fluke-DHI PG7601. Its base is two nominally 10 cm2 PCAs which cover the gauge and absolute pressures in the range from cca 10 kPa to 360 kPa. They had older primary evaluations from 2001 and 2009. We remeasured their geometries by Xenos in 2018 and 2021. On this occasion, we also improved our programme for computation of the limit values of Aeff for gauge and absolute modes. It is based on that of Dadson which was published in Algol 60, but we had to transpose it into C++. To test the correctness of our implementation, we solved the analytical formulae of Dadson for seven simple PCA geometries with a constant gap width. Then we compared the analytic values with the outputs of our programme with a perfect agreement. After that we determined the values of Aeff for the new geometry data. We got the better uncertainties, a satisfying agreement with the older evaluations and proved the long-term stability of these parameters.
Using the support of the project “pres2vac”, we were also able to get improved the evaluations of our digital pressure balances. The first is Furness Controls FRS4 HR. The nominal area of its PCA is 100 cm2, the covered range spans from 1 Pa to 3.2 kPa of gauge and differential pressures. The first, coarse attempt to evaluate its Aeff from the simple geometrical measurements at both ends and the middle of the gap of the PCA was performed in 2002. The resultant value proved well during the comparisons. However, during the mentioned above project, the new geometrical measurements were performed in 2017 and the data were given to the University of Thessaly which was able to evaluate the effective area in a rigorous way. The resultant value led to a better uncertainty and a satisfying agreement with the old value. The second is Fluke-DHI FPG8601. It is based on a nominally 10 cm2 PCA and it covers gauge and absolute pressures in the range from 1 Pa to 15 kPa. We made the first, coarse attempt to evaluate its Aeff from the simple geometrical measurements at both ends of the PCA in 2004. Also, this value proved well during the comparisons. Again, during the project, the new geometrical measurements were performed in 2017 and by Xenos in 2018. The latest values for gauge mode and absolute mode from the University of Thessaly have the lower uncertainties and are within a satisfying agreement with the older determinations.

14:40 Matthew Brown - NRC Canada

Hydraulic Pressure Measurement at NRC Canada

The pressure laboratory at the National Research Council of Canada (NRC) is responsible for maintaining Canada's primary and secondary standards, and for the realization of the Pascal through a 200 kPa mercury manometer with uncertainty (k=2) of the order of 5 ppm. Piston-cylinder assemblies are used to increase the traceable pressure scale up to 7000 kPa in pneumatic media for which NRC has three CMC's that cover a range of 5 kPa to 350 kPa, 25 kPa to 1750 kPa and 100 kPa to 7000 kPa. A cross over to hydraulic pressure at 3000 kPa is achieved using an oil-lubricated gas piston-cylinder assembly.
NRC participated in CCM.P-K7 (hydraulic gauge pressure, 10 MPa to 100 MPa, November 2002–June 2004) with success but has never applied for a CMC in hydraulic pressure. Recent client requirements necessitate that NRC obtain a CMC in hydraulic pressure for a pressure range up to 100 MPa. This talk will highlight topical laboratory investments in hydraulic pressure equipment, and describe NRC's pressure scale, uncertainties and capabilities in hydraulic pressure. While NRC has been unsuccessful in finding another SIM-region NMI for a supplemental comparison to validate our recent results, we demonstrate excellent normalized errors with the manufacturer of the piston-cylinder assemblies. Future efforts will be discussed.

15:00 Peter McDowall - Measurement Standards Laboratory of New Zealand

Temperature inhomogeneity in the MSL primary pressure standard during operation

We report on our initial investigations to empirically assess temperature gradients within MSL's primary pressure balance. The design of our primary pressure balance requires manually loading masses onto a modified Fluke PG7601 base with all active electronic components placed away from the piston cylinder mounting post so as to reduce their possible heating impacts on the piston cylinder unit. Temperature measurements for the piston and cylinder are currently inferred from a platinum resistance thermometer (PRT) installed in the mounting post. In the absence of any reliable data for our system we conservatively estimate a 1.8 ppm contribution to the pressure standard uncertainty due to temperature inhomogeneity across the mounting post and piston cylinder unit. This current work aims to empirically measure the temperature gradient across the piston cylinder unit while in use with the goal of reducing its uncertainty contribution to generated pressure.
The temperature gradient across the piston cylinder unit was assessed by observing variations between temperature measurements taken in the mounting post and the top of the piston. A small hole was drilled through the bolt connecting the cap to the top of the piston allowing a PRT to be placed in contact with the top of the piston. Using a battery operated temperature logger mounted to the piston cap, we were able to take temperature readings at the top of the piston while the piston was rotating and compare them to readings taken by the PRT in the mounting post. We assume a linear gradient across the vertical separation between the two PRT's. Using this method, we investigated the temperature difference across the piston cylinder unit under different conditions.
The influences of mechanically spinning the piston, manually adding masses, adjusting piston height, ambient temperature as well as shielding the piston cylinder unit while in gauge mode are investigated. Furthermore, temperature measurements of key areas in the laboratory such as the mass and piston cylinder unit storage areas allowed us to assess appropriate wait times to achieve thermal equilibrium after events such as cleaning/changing piston. Initial results suggest our current estimate of 1.8 ppm contribution to the standard uncertainty in generated pressure due to the temperature gradient is indeed conservative for this system. When left for an extended time to thermally equilibrate (e.g. overnight) and while not pressurising the pressure balance we observe stable, close agreement in temperature between the two PRT's suggesting minimal temperature inhomogeneity across the piston cylinder unit when not in use. However, manual operation of the pressure balance may introduce possible errors by increasing the temperature gradient across the piston cylinder unit which are still being investigated.

16:00 Zdeněk Krajíček - Czech Metrology Institute

Bilateral Comparison of CMI and SMU up to 900 MPa

The demands for the metrology of the very high gauge pressures in oil medium have recently grown in Europe. It was also reflected by an unusual European interlaboratory comparison in 1 GPa range (EURAMET.M.P-S14). However, when we look into the Key Comparison DataBase (KCDB) of the BIPM, we can find only two other completed similar comparisons (EURAMET.M.P-K6, APMP.M.P-S8) while another has not been finished yet (COOMET.M.P-S3). The Czech Metrology Institute (CMI) has had to rely on a very outdated and unsatisfactory pressure multiplier system from 0.5 GPa to 1 GPa. It was also the reason for its participation in the comparison EURAMET.M.P-S14 had to be limited only up to 0.5 GPa.
Hence, in summer 2021 a novel instrument on the market, type BH5-10000B by company Aréméca, was purchased by the CMI. It has a 0.5 mm2 tungsten-carbide piston-cylinder of a simple free deformation design. A nominal working range of the instrument is from 0.02 GPa to 1 GPa. The accuracy class stated by the manufacturer for the nominal range equals 25 kPa + 0.05 % of measured value. It was calibrated by the CMI up to 0.5 GPa in autumn 2021. However, due to the low range of this calibration, a question remained whether to use a linear or a quadratic approximation of effective area dependence on pressure.
Meanwhile, the Slovak Metrology Institute (SMU) utilized a novel stand of its own design as a base for a commercial 2 mm2 tungsten-carbide piston-cylinder by company Desgranges et Huot. The SMU calibrated it up to 0.2 GPa and tested up to 1 GPa.
A bilateral comparison of both these new high-pressure standards took place in the laboratories of the CMI in November 2022. The original intended scope of the comparison was from 0.1 GPa up to 1 GPa but due to the leakage, piston fall-rate and sensitivity problems at the uppermost pressure point and the limited time for the measurements it was reduced to 0.9 GPa. The results of comparison were evaluated twofold – with a linear approximation for the Czech piston-cylinder and a quadratic one (a linear one for the SMU piston-cylinder in both cases). The results of both evaluations were satisfying but the quadratic approximation led to the values of the evaluation numbers to be lower by cca 20 % in average.
The first results and experience with both new standards are very promising. However, an interlaboratory comparison with a long-established high-pressure standard is necessary to find the most suitable way of evaluation of the effective area pressure-dependence and to confirm a correctness of our determination of the uncertainty budget.

16:20 Christian Wuethrich - METAS

Circular comparison of piston-cylinders using a differential sensor.

Traditionally the effective area of primary piston-cylinders used in pressure balances is based on dimensional measurement of the piston and of the cylinder. The models used for the determination of the effective area include the deformation of the solid parts and the flow of the gas in the interface between the piston and the cylinder. The models, based on a cylindrical symmetry hypothesis, are not completely in agreement with the real complexity, unexpected uncertainty may be present.
In this work we propose an innovative technique that allow an unlimited number of piston-cylinders to be compared with a single reference piston-cylinder. The comparison of a large number of piston-cylinders allows to validate the hypothesis used in the calculation of the effective area and to determine a weighted mean value for the pressure defined by the set of piston-cylinders.
A pressure balance, PG 7607, equipped with a piston-cylinder of 20 cm2, is connected to a differential pressure sensor, which is equipped with a bypass, which can be closed by a valve. A set of several pressure balances are connected through a manyfold and isolations valves to the differential sensor. The differential sensor is

used a bit like the electrical force compensation in a mass comparator and all the piston-cylinders can be compared to the reference pressure balance very quickly. In less than five minutes the effective area of three pressure balances is measured and the operation is repeated three time.
The results obtained confirm the definition of the effective area by dimensional metrology. Three pistons are in agreement within 1 ppm while the fourth has discrepancy of 6 ppm that could be due to a thermal gradient of 0.5 °C between the thermometer and the piston. The characterisation has been performed in gage and in absolute pressure.

16:40 (Invited Speaker) Richard Högström - VTT MIKES

Recent advances in dynamic pressure metrology

Dynamic pressure measurements are a key requirement for process control in many demanding applications, such as automotive, marine and turbine engines, manufacturing processes, and ammunition and explosion safety. However, the current practice of calibrating pressure sensors under static conditions significantly limits the achievable measurement accuracy — errors of up to 10 % can occur when sensors are used at dynamically changing conditions. Improvements in accuracy and reliability of dynamic measurements will enable development of next generation technologies and products with improved quality, energy and material efficiency, and safety. For instance, better knowledge about the pressure inside an internal combustion engine is needed for improving engine performance, i.e. engine power and fuel consumption. Within the European metrology research project DynPT1 (Development of measurement and calibration techniques for dynamic pressures and temperatures; 2018 - 2021) improved measurement and calibration techniques for dynamic pressures up to 400 MPa were developed. This paper summarizes the main outcomes of the project: (a) Development of new measurement standards and validated calibration procedures; (b) Results of studies on the effect of different influencing factors on the dynamic sensor response with the aim of defining the most appropriate calibration procedures and measurement uncertainties in industrial applications; (c) Development and validation of new sensors for measuring dynamic pressure in demanding industrial applications, such as inside an internal combustion engine. Measurement standards for dynamic pressures (shock tubes and drop-weight devices) were developed to provide SI traceable calibrations in a wide pressure and frequency range 0.1 – 400 MPa and 1 – 30 kHz, respectively. The target uncertainty of 1 % for dynamic pressure was achieved in the pressure and frequency range up to 5 MPa and 100 Hz. At higher pressures and frequencies, the uncertainties were in the order of 2 % and 5 %, respectively. Studies on the influence of process conditions show that the response of dynamic pressure sensors is strongly frequency dependant even at frequencies well below the nominal resonance frequency of the sensor. Also, temperature was found to influence the response. Moreover, a novel sensor for dynamic pressure measurements at harsh conditions was developed and validated in real engine environments. As an outcome of the project, a solid metrological basis for dynamic pressure measurements was established for the first time. Calibration services, guidelines and new measurement technologies have been made available to industry to facilitate a shift from static to dynamic methods.

17:20 Fredrik Arrhén - RISE Research Institutes of Sweden

The development of dynamic pressure standards in gas at RISE - past, present and future

The need for dynamic calibration of measurement systems depends on a difference between the time constants of the properties to be measured and the time constants of the measuring system. If the time constant of the measuring system is in the same regime or longer than the observed system, the observed signal will not reflect the physical output. Another case occurs when the observation is performed in a very short time, even if the property measured is quite constant, for example Weighing in Motion (WIM).
RISE (former SP) started the practical work on dynamic pressure around 2006 after some years of studies of the industrial needs as well as studies of the previous work done in the area. The first European project started in 2010, EMRP IND09 and continued with EMPIR DynPT in 2018. During these projects together with several national projects the Shock tuba at RISE was developed and improved to its current status.
This presentation will discus the shock tube progress and future work along with plans to hopefully see CMCs in this area in the next five years.

17:40 In-Mook Choi - KRISS

Development status of KRISS dynamic pressure standards

Dynamic pressure measurements play a crucial role in various industries, such as aircraft, turbines, and rockets. To ensure the accuracy and consistency of these measurements, it is essential to develop dynamic pressure standards that are traceable to SI units. This presentation provides an overview of the development of dynamic pressure standards at the Korea Research Institute of Standards and Science (KRISS). KRISS has developed two methods for realizing high dynamic pressure standards with traceability to SI units. The first method involves using a step-pressure generator with a quick-opening valve, while the second method utilizes an impulse pressure generator with either a drop-weight method or a shock acceleration exciter.
KRISS has established oil and gas step-pressure generators as primary standards, ensuring SI traceability based on the transmitting medium density change. These generators have a measurement range of up to 830 MPa for oil pressure and 70 MPa for gas pressure, respectively. They utilize quick-opening valves to produce fast step pressure with a rise time of less than 1 ms. Although a small ripple exists in the measurement signal, the mean values are highly reliable. In addition, KRISS has developed impulse pressure generators with traceability ensured based on the measurement of a piston displacement and the corresponding medium density change. The impulse pressure generator uses a drop weight or a shock acceleration ex citer to produce a half-sine impulse pressure with a short duration time of a few milliseconds It has been characterized according to various parameters such as drop height, drop mass, Piston/cylinder effective area, and transmitting medium. However, the impulse pressure standard generates a very noisy signal due to the system vibration and the standing wave, and the peak pressure cannot be estimated accurately despite the use of low pass filters. Therefore, it is suggested that a step-pressure generator be used as the primary dynamic pressure standard, and an impulse pressure generator be used as a secondary dynamic pressure standard with a reference sensor calibrated by the primary one.

Poster Session - May 17th, 2023 - 3:00 to 3:40 PM

Sven Ehlers – PTB

A Height Difference Measurement System for the Liquid Column Manometer of PTB

At PTB, a primary liquid column manometer (LCM) is under development for the low-pressure measurement up to 2kPa in gauge and absolute pressure. Those instruments make use of the quantities density, gravitational acceleration, and length, all traceable to the International System of Units (SI), to calculate pressure, that makes such an instrument a primary pressure standard. The LCM is well suited to identify small force induced errors, especially of force compensated pressure balances with non-rotating piston in their lower measurement range, and disseminate there with the Pascal, the unit of Pressure. This abstract focuses on the measurement of the height difference measurement inside the instrument, where homodyne interferometry is applied, using the liquids free surface as the laser beam reflecting mirror.

Hideaki Iizumi – NMIJ

Characterizations of three types of pressure gauges for high-pressure gas

In recent years, the demand for the use of high-pressure gas and its pressure measurement has been increasing. For example, hydrogen stations for fuel cell vehicles use gases with pressures higher than 80 MPa. National Metrology Institute of Japan (NMIJ/AIST) started calibration service for gas pressure up to 100 MPa for digital pressure gauges in 2017. The standard device of gas pressure up to 100 MPa is liquid-lubricated pressure balance, and the relative expanded(k= 2)uncertainty is 4.0×10-5at 100 MPa. The traceability is ensured from liquid pressure standard in NMIJ/AIST. In this presentation, we evaluate these three types of pressure gauges and compare their basic performance such as short-term stability and repeatability.

Alper Elkatmaş - TUBITAK UME National Metrology Institute

Comparison of two procedures based on the cascade expansion method enabling the improvement of the measurement range of the static expansion system at TÜBİTAK UME

The measurement range of the multi-stage static expansion system at TÜBİTAK UME Vacuum Laboratory is between 0.9 mPa and1 kPa. This study focuses on the improvement of the measurement range of the system by applying the cascade method. The cascade method is based on pressure reduction by pumping the expansion volume after the first step with the adjacent transfer volume isolated and then once again expanding the gas from the transfer volume to the expansion volume. In this study, two procedures with different approaches were compared at 0.3 mPa and 0.9 mPa for N2. The method was applied after the last expansion in the first procedure, whereas after the first expansion in the second procedure. Two spinning rotor gauges (SRGs) were utilized to compare the pressure readings with the standard pressures obtained through the static system. Deviations from the standard pressures were found lower in the second procedure as compared to the first procedure. As a result, the lowest pressure point of the system was reduced to 0.3 mPa by applying the cascade expansion method. Before the procedure comparison measurements, calibration of the SRGs based on determining the calibration factor known as the accommodation coefficient was carried out on the static system in the nominal pressure range between 0.1 Pa and 1 Pa using N2.The lowest pressure point, which was not generated in the previous interlaboratory comparison, was achieved successfully using the second procedure in the latest participated interlaboratory comparison.

Mary Ness Salazar – KRISS

Development of new standard leak element based on Polymicro capillary tubings

Leak artefacts made of different materials with well-defined geometry are in constant development to improve the knowledge of gas dynamics in narrow channels. Highly sophisticated processes are involved in fabricating these leak elements causing these artefacts to be expensive and hardly reproducible. In this study, a unique, cost-effective material of micro-scale capillary tubing was used to develop a standard leak element (SLE) that will be practical and easily duplicated for industrial use. Two designs of the SLE were fabricated using commercial fittings and adaptors as base structure. Both designs were developed with variable lengths and throughputs were measured through the pressure-rise method. An established model involving the viscous flow in long pipes was used to verify the results of the actual measurements as well as a comparison by a Monte Carlo simulation through the Molflow software. This study utilized the ideal gases such as Helium and Nitrogen. Behaviour of the results of actual measurements of throughputs of the first design contradicts the theoretical predictions of the conventional theory, while that of the second design is in agreement with the classical theory. In this paper, the focus will solely be on the second SLE design with promising actual measurement throughput results proving that the structure may be an excellent choice for a standard leak artefact whose flow rate can be predicted by controlling the geometry of the leak element, in this case, the length of the capillary tube at the viscous flow mode from vacuum to above atmospheric pressure. An estimate of the flow rate measurement expanded uncertainty (k = 2) using the values obtained in the capillary length of 10 mm at 200 kPa upstream pressure in Nitrogen gas as the pressure medium was 6.9 %. Future study will focus on using different gases and extending the flow mode to the molecular or transitional flow regime.

Han Wook Song – KRISS

Development of optical vacuum standard system in KRISS

Recently, 'a new realization of the Pascal' by using photon technology showed comparable results in terms of performance compared to the existing primary standard based on a mercury manometer. With photon technology, the resolution is improved by 20 times, the response time of the detection is 100 times faster, the measurable pressure range is extended by 100 times or more, and the technology is improved in terms of both reproducibility and hysteresis. In this study, we describe KRISS photonic pressure standard system uses a 633 nm He-Ne laser, specially made by KRISS, as a light source, and a 15-cm-long Fabry-Perot (FP) cavity made from ZERODUR with a 5 cm-by-5 cm cross-section. We independently fabricated a single-mode He-Ne laser instead of a commercially available laser to modulate a frequency freely and to make a single polarization regardless of the quantum number. Hardware construction for KRISS optical pressure standard system has been completed. Currently, as the first step, it is aimed at calculating the pressure according to the frequency in the pressure range of 1 Pa to 10 kPa. We are also studying theoretically the second and third virial constants for He gas by ab initio molecular dynamics (MD) computation. Using the measured beating frequency, we determined the internal pressure in the cavity considering the refractive index virial coefficients (AR, BR and CR) and density virial coefficients (Ap, Bp and Cp), the Boltzmann constant kB, and the thermodynamic temperature. The uncertainty is currently in evaluation taking into account the uncertainty factor.

Poster Session - May 17th, 2023 - 3:00 to 3:40 PM

Jaspar Halbey – University of Bremen, Center of Applied Space Technology and Microgravity (ZARM)
Dual Species Cold Atom Based Pressure Standard

The fundamental advantage of cold atom based pressure sensors is that atoms constitute immutable sensor elements that never age, degrade or change with use. This is why atoms are the basis for modern-day time and frequency standards. Using atomic sensors to detect gas molecules in vacuum and thus measure the absolute pressure or particle flux offers the perfect solution to the problem of sensor degradation and drift between calibrations that limits all other technologies capable of measurements in the UHV and XHV ranges. By observing the loss rate of magnetically trapped atoms caused by collisions with the background gas one can conclude on the pressure of the background gas. The Quantum Degenerate Gas Laboratory at the University of British Columbia(UBC) and Scherschligt et al. at the National Institute of Standardsand Technology (NIST) developed such sensors using cold rubidium and lithium atoms, respectively. In cooperation with the Physikalisch-Technische Bundesanstalt (PTB) and the UBC, ZARM plans to develop a quantum pressure standard based on cold atoms. This setup will be the first of its kind with the ability to operate using rubidium and potassium atoms consecutively. With this approach, a direct comparison of measurements with different species can be conducted while minimizing errors among others caused by pressure gradients within the chamber. Pressure measurements based on cold potassium atoms have not been realized up to now and will add a valuable data point for theoretical evaluations. Ultimately, this comparison shall validate the quantum diffractive universality developed by Madison et al. at the UBC enabling cold rubidium and potassium atoms to serve as a primary quantum pressure standard.

Fernando AndrésMonge - LACOMET
Evaluation of linear fit models for the effective area determination of a pneumatic piston-cylinder assembly in the range of 175 kPa to 2000 kPa

Piston gauges are known for their high accuracy on pressure determination however, thorough characterization is required for them to be considered as primary standards. One of its main characteristics to be determined is the effective area of the piston-cylinder assembly which can be determined by cross float method and data fit analysis to model its deformation. In this paper, 3 linear fit models are evaluated for a pneumatic piston-cylinder assembly calibrated on the range between 175 kPa and 400 kPa using another piston gauge as a standard. The evaluated models are constant area (no deformation), linear regression (experimental linear deformation coefficient) and least squares method (linear deformation coefficient reported by its manufacturer). The resulting equations are used to extrapolate the effective area up to 2000 kPa. The results are validated by calibrating the piston-cylinder assembly with another piston gauge on the range of 700 to 2000 kPa. The value of effective area at 2000 kPa is compared from the linear fit models to the calibration results through a normalized error. Also, a residual analysis is performed to assess the good fit of the calibration data to the estimated models.

Ivan Matas - Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb
Simultaneous characterization of piston fall rate and verticality of a piston-cylinder assembly

A contactless laboratory method for the determination of the pressure balance piston fall rate and a vertical alignment of piston-cylinder assembly is described. Being the crucial part of a pressure balance, precise information of the piston-cylinder unit's operational characteristics is indispensable for achieving best performance with a high accuracy piston gauge. The determination of the piston fall rate has proven to be an important measure for quality assurance since it can indicate deformation or changes in piston-cylinder effective area. Also, fall rate is regularly determined during the calibration of pressure balances using cross-floating method. The absence of standardized procedure for determination of pressure balance piston fall rate and the constant need for maintenance of confidence in the performance of pressure standards through intermediate checks, stimulated the development of simple, efficient, traceable and repeatable method with sufficient precision. Laboratory method presented in this paper uses custom laser triangulation setup, where the collimated He-Ne laser beam is being reflected from the piston's top surface and tracked with a position sensing photodiode (PSD) during rotation at full load. The developed method has been tested on four piston-cylinder units using both gas and oil as pressure medium. Obtained results and associated measurement uncertainties have been compared to results from recent calibration certificates of the tested units.

Tom Rubin – PTB
Working equation for a Fabry-Perot cavity based optical pressure standard

A Fabry-Perot (FP) cavity based optical pressure standard (OPS) is very promising to be the next generation primary standard covering the range from 1 Pa to 1 MPa, due to its high accuracy and universality. To operate an OPS at the highest level of accuracy, a consensus should be achieved on its working equation, which converts the measurand of frequency and temperature to the pressure. From basics of FP resonator and roundtrip phase, a complete working equation is derived and presented which includes corrections of reflection phase-shift and diffraction. In addition, the working equation accounts for pressure-induced distortion, which is the major correction.

Akobuije Chijioke - NIST
Optical-Cavity-Based Primary Sound Standard

We describe an optical sound standard in which the sound pressure is directly measured by using a high-finesse optical cavity to observe the induced change in the refractive index of the medium (acousto-optic effect). The optical refractive index of a substance varies with density, and for a compressible substance it will therefore depend on the varying pressure in an acoustic field. To accurately measure the small refractive index changes due to acoustic pressure variations, we enhance the optical phase shifts induced by the index change using a high-finesse optical cavity. By tracking the shift in the optical cavity resonance frequency we sensitively track the shift of the refractive index of the cavity medium. This in turn provides us with the acoustic pressure in the cavity. In order that this be useful for calibrating acoustic devices, we arrange that this pressure be the same as (or at least have a known relationship to) the sound pressure at the location of the device to be calibrated.