

Summary report of recent activities in thermometry, thermophysical quantities and humidity at LNE (December 2020)

Contact thermometry (LNE-Cnam)

- Measurement of the Boltzmann constant [CT1 – CT5]
- Measurement of the thermodynamic temperature with acoustic gas thermometry [CT5]
- Measurement of thermodynamic temperature with the single-pressure refractive-index gas thermometry [CT6 – CT17]

Radiation Thermometry and Thermocouples (LNE-Cnam)

- Measurement of the thermodynamic temperature with radiometric traceability in the radiance mode from 400 °C to 2900 °C [RT1 – RT4]
- Construction, characterization and thermodynamic temperature assignment to high-temperature fixed points (Cu, Co-C, Pt-C, Re-C) and medium temperature fixed points (Zn, Al, Ag) [RT5 – RT7]
- Development of a new thermodynamic temperature measurement technique: the synthetic double-wavelength technique [RT8]
- Realization of the ITS-90 with competitive uncertainty levels using a monochromator-based radiance comparator [report CCT-K10, RT9]
- Development of new HTFPs for the mise-en-pratique of the definition of the kelvin at high temperature (WC-C, Ru-C) in the frame of the EMPIR project Real-K (in progress) – Lead of high-temperature workpackage
- Thermocouples at high temperature and self-calibration methods [RT10 – RT15]

Thermophysical quantities (LNE-Cnam)

- Development of protocols for thermal conductivity measurements at nanoscale and calibration of Scanning Thermal Microscopes (SThM) [TQ1 – TQ3]
- Development of an absolute method for the enthalpy of fusion measurements up to 1000 °C using a Calvet calorimeter [TQ4, TQ5]
- Construction of calorimeter prototypes for the thermal power measurement of nuclear waste packages [TQ6, TQ7]
- Improvement of a guarded hot plate for the thermal conductivity measurement of low and medium conductive materials up to 800 °C [TQ8, TQ9]
- Development of facilities and methods for the characterization of the metrological capabilities of Raman and Brillouin distributed temperature sensors (DTS) [TQ10, TQ11]
- Lead of the supplementary comparison CCT-S2 on thermal conductivity measurements of insulating materials by guarded hot plate [TQ12, TQ13]

Humidity (LNE-CETIAT)

- Measurement in meteorological applications : enhancement factor, hysteresis of hygrometers [H1]
- Moisture measurements based on dielectric permittivity [H2 – H4]

- Humidity measurements at high temperatures and transient conditions [H5, H6]

Bibliography (2015-2020)

- [CT1] Pitre L., Sparasci F., Risegari L., Guianvarc'h C., Martin C., Himbert M. E., Plimmer M. D., Allard A., Marty B., Giuliano Albo P. A., Gao B., Moldover M. R. and Mehl J. B. "New measurement of the Boltzmann constant k by acoustic thermometry of helium-4 gas" *Metrologia* **54** (2017) 856–873. DOI: /10.1088/1681-7575/aa7bf5
- [CT2] I Yang, L Pitre, MR Moldover, J Zhang, X Feng, JS Kim "Improving acoustic determinations of the Boltzmann constant with mass spectrometer measurements of the molar mass of argon" *Metrologia* **52** (5), S394 doi:10.1088/0026-1394/52/5/S394
- [CT3] Pitre L., Sparasci F., Risgari L., Plimmer M.D, Himbert M.E., Giuliano Albo P.A. "Determination of the Boltzmann constant k from the speed of sound in helium gas at the triple point of water" *Metrologia* **52**, (2015) S263-S273. doi:10.1088/0026-1394/52/5/S263
- [CT4] J Fischer, B Fellmuth, C Gaiser, T Zandt, Laurent Pitre, Fernando Sparasci, MD Plimmer, M De Podesta, R Underwood, G Sutton, G Machin, RM Gavioso, D Madonna Ripa, PPM Steur, J Qu, XJ Feng, J Zhang, MR Moldover, SP Benz, DR White, L Gianfrani, A Castrillo, L Moretti, B Darquié, E Moufarej, C Daussy, S Briaudeau, O Kozlova, L Risegari, JJ Segovia, MC Martín, D Del Campo The Boltzmann Project *Metrologia* **55** (2018) R1–R20 <https://doi.org/10.1088/1681-7575/aaa790>
- [CT5] L Pitre, MD Plimmer, F Sparasci, ME Himbert "Determinations of the Boltzmann constant" *Comptes Rendus Physique* **20** (1-2), 129-139 <https://doi.org/10.1016/j.crhy.2018.11.00>
- [CT6] Roberto M Gavioso, Daniele Madonna Ripa, Peter PM Steur, Christof Gaiser, Thorsten Zandt, Bernd Fellmuth, Michael de Podesta, Robin Underwood, Gavin Sutton, Laurent Pitre, Fernando Sparasci, Lara Risegari, Livio Gianfrani, Antonio Castrillo, Graham Machin "Progress towards the determination of thermodynamic temperature with ultra-low uncertainty" *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* Volume 374 Numéro 2064 <https://doi.org/10.1098/rsta.2015.0046>
- [CT7] Gao B, Zhang H, Han D, Pan C, Chen H, Song Y, Liu W, Hu J, Kong X, Sparasci F, Plimmer M, Luo E and Pitre L 2020 "Measurement of thermodynamic temperature between 5 K and 24.5 K with single-pressure refractive-index gas thermometry" *Metrologia* **57** 065006 <https://doi.org/10.1088/1681-7575/ab84ca>
- [CT8] Patrick MC Rourke, Christof Gaiser, Bo Gao, Daniele Madonna Ripa, Michael R Moldover, Laurent Pitre, Robin J Underwood 2019 "Refractive-index gas thermometry" *Metrologia* **56** (3), 032001 <https://doi.org/10.1088/1681-7575/ab0dbe>
- [CT9] Gao B, Pitre L, Luo E C, Plimmer M D, Lin P, Zhang J T, Feng X J, Chen Y Y and Sparasci F 2017 "Feasibility of primary thermometry using refractive index measurements at a single pressure" *Measurement* **103** 258–62 <https://doi.org/10.1016/J.MEASUREMENT.2017.02.039>
- [CT10] Pan C Z, Chen H, Han D X, Zhang H Y, Plimmer M D, Imbraguglio D, Luo E C, Gao B and Pitre L 2020 "Numerical and experimental study of the hydrostatic pressure correction in gas thermometry: A case in the SPRIGT" *Int. J. Thermophys* **41** 108 <https://doi.org/10.1007/s10765-020-02686-9>
- [CT11] Pan C Z, Gao B, Song Y N, Zhang H Y, Han D X, Hu J F, Liu W, Chen H, Plimmer M, Sparasci F, Luo E C and Pitre L "Active suppression of temperature oscillation from a pulse-tube cryocooler in a cryogen-

freecryostat: part 1. Simulation modeling from thermal response characteristics" *Cryogenics* 109 103096
 DOI: 10.1016/j.cryogenics.2020.103097

- [CT12] Pan C Z, Gao B, Song Y N, Zhang H Y, Han D X, Hu J F, Liu W, Chen H, Plimmer M, Sparasci F, Luo E C and Pitre L "Active suppression of temperature oscillation from a pulse-tube cryocooler in a cryogen-freecryostat: part 2. Experimental realization" *Cryogenics* 109 103097
<https://doi.org/10.1016/j.cryogenics.2020.103096>
- [CT13] Zhang H Y, Gao B, Liu W J, Pan C Z, Han D X, Luo E C and Pitre L 2020 "Resonance frequency measurement with accuracy and stability at the 10–12 level in a copper microwave cavity below 26 K by experimental optimization". *Meas. Sci. Technol.* 31 075011 DOI: 10.1088/1361-6501/ab796e
- [CT14] Bo Gao, Hui Chen, Dongxu Han, Pascal Gambette, Haiyang Zhang, Changzhao Pan, Yingwen Liu, Bo Yu, Ercang Luo, Mark Plimmer, Laurent Pitre "Realization of ppm level pressure stability for primary thermometry using a primary piston gauge" *Measurement* 160 107807 DOI: 10.1016/j.measurement.2020.107807
- [CT15] Bo Gao, Changzhao Pan, Laurent Pitre, Yanyan Chen, Haiyang Zhang, Yaonan Song, Hui Chen, Wenjing Liu, Dongxu Han, Ercang Luo, 2018 "Chinese SPRIGT realizes high temperature stability in the range of 5–25 K" *Sci. Bull.* 63(12) 733-734 DOI: 10.1016/J.SCIB.2018.05.023
- [CT16] Chen YanYan, Zhang Haiyang, Song Yaonan, Changzhao Pan, Gao Bo, Liu Wenjing, Chen Hui, Han Dongxu, Luo Ercang, Plimmer Mark, Sparasci Fernando, Pitre Laurent, 2019 "Thermal response characteristics of a SPRIGT primary thermometry system" *Cryogenics* 97 1–6 DOI: 10.1016/J.CRYOGENICS.2018.10.015
- [CT17] Gao B, Pan C Z, Chen Y Y, Song Y N, Zhang H Y, Han D X, Liu W J, Chen H, Luo E C and Pitre L 2018 "Realization of an ultra-high precision temperature control in a cryogen-free cryostat" *Rev. Sci. Instrum.* 89 104901 DOI : 10.1063/1.5043206.
- [RT1] S G R Salim, S Briauudeau, F Bourson, B Rougié, D Truong, O Kozlova, J-M Coutin and M Sadli 2016 "A reference radiance-meter system for thermodynamic temperature measurements" *Metrologia* 53 945
<https://doi.org/10.1088/0026-1394/53/3/945>
- [RT2] Helen McEvoy et al 2020 "Methodologies and uncertainty estimates for T – T90 measurements over the temperature range from 430 K to 1358 K under the auspices of the EMPIR InK2 project" 2021 *Meas. Sci. Technol.* 32 035001 <https://doi.org/10.1088/1361-6501/abc50f>
- [RT3] Woolliams E et al 2016 "Thermodynamic temperature assignment to the point of inflection of the melting curve of high temperature fixed points" *Phil. Trans. R. Soc. A* 374 20150044
- [RT4] D H Lowe et al 2017 "The equilibrium liquidus temperatures of rhenium–carbon, platinum–carbon and cobalt–carbon eutectic alloys" *Metrologia* 54 390 <https://doi.org/10.1088/1681-7575/aa6eeb>
- [RT5] M Sadli et al 2016 "Dissemination of thermodynamic temperature above the freezing point of silver" *Phil. Trans. R. Soc. A* 374 20150043
- [RT6] G. Machin, J. Engert, R.M. Gavioso, M. Sadli, E. Woolliams "Summary of achievements of the European Metrology Research Programme Project "Implementing the new Kelvin" (InK 1)" *Measurement*, Volume 94, 2016, Pages 149-156, ISSN 0263-2241 <https://doi.org/10.1016/j.measurement.2016.07.069>.
- [RT7] M Sadli, C. Garcia-Izquierdo, F. Bourson, S. Briauudeau "Aluminium fixed-point cells for thermodynamic temperature assignment" 2018 *J. Phys.: Conf. Ser.* **1065** 122020 <https://doi.org/10.1088/1742-6596/1065/12/122020>

- [RT8] S Briaudeau, F Bourson, O Kozlova, M Sadli, A Razet 2020 "The synthetic double wavelength technique: a simple robust method for thermodynamic temperature determination" *Metrologia* 57 025014
<https://doi.org/10.1088/1681-7575/ab7173>
- [RT9] Helen McEvoy et al 2018 "Report on the measurement results for the EURAMET 658 extension: project to examine underlying parameters in radiance scale realisation" *Metrologia* 55 03001
<https://doi.org/10.1088/0026-1394/55/1A/03001>
- [RT10] Bourson, F., Sadli, M., Rougié, B. et al. Influence of the Opening of a Blackbody Cavity Measured at the Ag and Cu ITS-90 Fixed Points. *Int J Thermophys* 35, 516–525. <https://doi.org/10.1007/s10765-014-1610-8>
- [RT11] D del Campo et al 2020 "Calibration of thermocouples from 419,527 °C (freezing point of Zn) up to 1492 °C (melting point of the Pd-C eutectic), by the temperature fixed point and comparison methods" *Metrologia* 57 03006 <https://doi.org/10.1088/0026-1394/57/1A/03006>
- [RT12] Pavlasek et al. "Procedure for an Investigation of Drift Behavior of Noble Metal Thermocouples at High Temperature" *Int J Thermophys* 40, 47 (2019). <https://doi.org/10.1007/s10765-019-2511-7>
- [RT13] G. Machin, K. Anhalt, M. Battuello, F. Bourson, P. Dekker, A. Diril, F. Edler, C.J. Elliott, F. Girard, A. Greenen, L. Křazovická, D. Lowe, P. Pavlásek, J.V. Pearce, M. Sadli, R. Strnad, M. Seifert, E.M. Vuelban "The European project on high temperature measurement solutions in industry (HiTeMS) – A summary of achievements" *Measurement*, Volume 78, 2016, Pages 168-179, ISSN 0263-2241,
<https://doi.org/10.1016/j.measurement.2015.09.033>.
- [RT14] Mokdad, S., Failleau, G., Deuzé, T. et al. A Self-Validation Method for High-Temperature Thermocouples Under Oxidizing Atmospheres. *Int J Thermophys* 36, 1895–1908 (2015). <https://doi.org/10.1007/s10765-015-1891-6>
- [RT15] Diril, A., Bourson, F., Parga, C. et al. Construction and Characterization of Mini-ruthenium–Carbon Eutectic Cells for Industrial Use. *Int J Thermophys* 36, 3355–3365 (2015). <https://doi.org/10.1007/s10765-015-1971-7>
- [TQ1] L. Ramiandrisoa, A. Allard, Y. Joumani, B. Hay, S. Gomes, "A dark mode in scanning thermal microscopy" *Rev. Sci. Instrum* **88** 125115 (2017) <https://doi.org/10.1063/1.5002096>
- [TQ2] L. Ramiandrisoa, A. Allard, B. Hay, S. Gomes, "Uncertainty assessment for measurements performed in the determination of thermal conductivity by scanning thermal microscopy" *Meas Sci Technol* **28** 115010 (2017) <https://doi.org/10.1088/1361-6501/aa8892>
- [TQ3] E. Guen, P. Klapetek, R. Puttock, B. Hay, A. Allard, T. Maxwell, P.-O. Chapuis, D. Renahy, G. Davee, M. Valtr, J. Martinek, O. Kazakova, S. Gomes "SThM-based local thermomechanical analysis: Measurement intercomparison and uncertainty analysis" *Int. J. Therm. Sci.* **156** 106502 (2020) <https://doi.org/10.1016/j.ijthermalsci.2020.106502>
- [TQ4] R. Razouk, O. Beaumont, B. Hay, "A new accurate calorimetric method for the enthalpy of fusion measurements up to 1000 °C" *J. Therm. Anal.* **136** 1163 (2019) <https://doi.org/10.1007/s10973-018-7772-z>
- [TQ5] R. Razouk, B. Hay, M. Himbert, "Uncertainty assessment of enthalpy of fusion measurements performed by using an improved Calvet calorimeter" *Metrologia* **52** 717 (2015) <https://doi.org/10.1088/0026-1394/52/5/717>
- [TQ6] R. Razouk, G. Failleau, O. Beaumont, S. Plumeri, B. Hay, "A heat-flux calorimeter prototype for measuring the thermal power released by radioactive waste packages" *IEEE Trans Nucl Sci* **65** 2518 (2018) <https://doi.org/10.1063/1.5003214>

- [TQ7] R. Razouk, O. Beaumont, G. Failleau, S. Plumeri, B. Hay, "Development of an air flow calorimeter prototype for the measurement of thermal power released by large radioactive waste packages" *Rev. Sci. Instrum* **89** 034902 (2018) <https://doi.org/10.1063/1.5003214>
- [TQ8] J. Hameury, A. Koenen, B. Hay, U. Hammerschmidt, E. Turzó-András, J. Wu, E. K. Rafeld, R. Strnad, A. Blahut, "Identification and Characterization of New Materials for Construction of Heating Plates for High-Temperature Guarded Hot Plates" *Int. J. Thermophys.* **39** 16 (2018) <https://doi.org/10.1007/s10765-017-2326-3>
- [TQ9] V. Scoarnec, J. Hameury, B. Hay, "A New Guarded Hot Plate Designed for Thermal Conductivity Measurements at High Temperature" *Int. J. Thermophys.* **36** 540 (2015) <https://doi.org/10.1007/s10765-014-1794-y>
- [TQ10] G. Failleau, O. Beaumont, S. Lesoille, S. Plumeri, R. Razouk, Y.-L. Beck, J.M. Hénault, J. Bertrand, B. Hay, "Development of facilities and methods for the metrological characterization of distributed temperature sensing systems based on optical fibres" *Meas Sci Technol* **28** 015009 (2017) <https://doi.org/10.1088/1361-6501/28/1/015009>
- [TQ11] G. Failleau, O. Beaumont, R. Razouk, S. Lesoille, M. Landolt, B. Courthial, J.M. Hénault, F. Martinot, J. Bertrand, B. Hay, "A metrological comparison of raman-distributed temperature sensors", *Measurement* **116** 18 (2018) <https://doi.org/10.1016/j.measurement.2017.10.041>
- [TQ12] B. Hay, R. Zarr, C. Stacey, N. Sokolov, L. Lira Cortés, J. Zhang, U. Hammerschmidt, J.-R. Filtz, A. Allard, "Report on the CCT Supplementary comparison S2 on thermal conductivity measurements of insulating materials by guarded hot plate" *Metrologia* **57** 03003 (2020) <https://doi.org/10.1088/0026-1394/57/1A/03003>
- [TQ13] R. Zarr, W. Guthrie, B. Hay, A. Koenen, "Collaborative guarded-hot-plate tests between the Laboratoire national de métrologie et d'essais and the National Institute of Standards and Technology" *Metrologia* **54** 113 (2017) <https://doi.org/10.1088/1681-7575/aa4e55>
- [H1] A. Merlone et al, "The MeteoMet2 project—highlights and results", *Measurement Science and Technology*, Volume 29, Number 2, 2018; DOI: 10.1088/1361-6501/aa99fc
- [H2] M. W. Ben Ayoub et al., "Combination of Two Measurement Techniques to Expand the Measurements Frequency Range of the Dielectric Permittivity," *Progress In Electromagnetics Research Letters*, Vol. 71, 77-82, 2017, DOI:10.2528/PIERL17090602
- [H3] M. W. Ben Ayoub et al., "Quantification of free and bound water in selected materials using dielectric and thermo-coulometric measurement methods", *Journal of Physics Communications*, Volume 2, Number 3, 2018, DOI: 10.1088/1361-6501/aa9908
- [H4] R. Aro et al., "Moisture in Solids: Comparison Between Evolved Water Vapor and Vaporization Coulometric Karl Fischer Methods", *International Journal of Thermophysics* volume 41, Article number: 113, 2020, DOI:10.1007/s10765-020-02697-6
- [H5] E. Georgin et al.; "New calibration facility developed at LNE-CETIAT", 19th International Congress of Metrology, 18004 (2019), DOI:10.1051/metrology/201918004
- [H6] E. Georgin " Response time measurement of hygrometers at LNE-CETIAT", 19th International Congress of Metrology, 18004 (2019), DOI:10.1051/metrology/201924001