A European Roadmap for Thermophysical Properties Metrology

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Abstract

A roadmap for thermophysical properties metrology was developed in spring 2011 by the Thermophysical Properties Working Group in the EURAMET Technical Committee in charge of Thermometry, Humidity and Moisture and Thermophysical Properties metrology. This roadmapping exercise is part of the EURAMET activity towards increasing impact from national investment in European metrology R&D. The roadmap represents a shared vision of how thermophysical properties measurements and standards should develop over the next 15 years to meet future social and economic needs.

Since thermophysical properties metrology is a very broad and diverse field, in this roadmap the authors have limited themselves to the following families of properties:

- Thermal transport properties (conductivity, diffusivity…)
- Radiative properties (emissivity, absorbance, reflectance, transmittance)
- Caloric quantities (specific heat, enthalpy…)
- Thermodynamic properties (PVT and phase equilibria properties)
- Temperature-dependent quantities (thermal expansion, compressibility…)

This roadmap identifies the main societal and economic triggers that drive developments in thermophysical properties measurements and standards. Energy, environment, advanced manufacturing and processing, citizen safety, security and health were considered as key topics. Key targets that require improved thermophysical properties measurements are also identified in order to address these triggers. Behind these triggers and selected targets, ways are proposed for defining the necessary skills and the main useful means to be implemented. These proposals will have to be revised as needs and technologies evolve in the future

Keywords: Thermophysical properties, Radiative properties, Thermal Transport properties, Caloric quantities, Thermodynamic properties, Roadmap, Euramet TC-T

Foreword

This roadmap is a 'live' document, which can and should be updated as developments progress to incorporate short-term developments and their long-term implications. Comments on the present version of the roadmap and proposals for input to future revisions are welcome at any time. The updated version of the thermophysical properties metrology roadmap is available at http://www.euramet.org.

1. Introduction

A roadmap for thermophysical properties metrology was drafted during a workshop by the authors on behalf of the Thermophysical Properties Working Group in the EURAMET Technical Committee - Thermometry, Humidity and Moisture, and Thermophysical Properties. This roadmapping exercise is part of the EURAMET activity towards increasing impact from national investment in European metrology R&D.

The objectives of the roadmapping process were to identify future developments in thermophysical properties fields and to initiate planning and collaborations in the wider community of thermophysical properties metrology experts within Europe and also cooperation with the international community. This exercise follows a previous one performed during the period 2006-2007 and published in 2009 [1].

During the workshop, experts considered the following sequence:

1) The societal and economic needs (Triggers)
2) The resulting objectives for addressing the societal challenges (Targets)
3) The corresponding experimental realisations to meet the targets
4) The metrological application of basic science and technologies
5) Enabling science and technologies for achieving the global objectives

Since thermophysical properties metrology is a very broad and diverse topic, in this roadmap the Thermophysical Properties Working Group has limited themself to the following properties - thermal conductivity and diffusivity, viscosity, thermal expansion and compressibility, specific heat and enthalpy, radiative (optical) properties, thermodynamic properties (PVT and Phase Equilibria properties),.

The roadmap for thermophysical properties metrology is shown in Appendix 1 (see Roadmap of Euramet TCT_Thermophysical Properties_v11.pdf). The horizontal axis shows an approximate time scale and the vertical axis shows the sequence that has been considered. All the element blocks that are adjacent to each other are treated as a cluster, which means that the elements within a cluster have some degree of connections with other elements. The heavy weight arrows reflect the development chains from one cluster to another. The normal weight arrows represent the parallel routes of progress on a couple of other topics in thermophysical properties field. The following sections provide the accompanying text to this thermophysical properties roadmap.

This roadmap is in full compliance with the objectives of “Horizon 2020 - The Framework Programme for Research and Innovation” of the European Commission [2,3] by “refocusing R&D and innovation policy on major societal challenges, and strengthening the links from frontier research right through to commercialisation” [4].

2. Societal Challenges (Triggers)

In line with the challenges that are outlined in Horizon 2020 [2], the working group has identified that the main social and economic triggers driving the development of thermophysical measurements are Energy, Environment, Advanced Manufacturing & Processing, Safety/Security and Health. Thereby metrology for thermophysical properties will contribute substantially to the six priority “Societal Challenges” which are in the focus of Horizon 2020 [5].

Energy - Secure, clean and efficient (Trigger 1.1)

The EU has decided to increase the renewable energy consumption up to 20% by 2020 [2]. The development of the new alternative energy sources to the fossils energy or nuclear energy has to be strengthened and speeded up. Experts of the field propose to implement new developments in the area of Thermophysical Properties Metrology (TPM). New measuring techniques, an extended range of measurements and a wider data base should be considered for improving the efficiency of production, conversion, storage, transportation, and use of energy and also for supporting ways for saving energy (e.g. energy harvesting).

Environment – Climate action: efficient use of resources for protection of our planet (Trigger 1.2)

This topic is strongly connected to Energy and Industry areas. Reducing emissions of greenhouse gases are at the heart of public policies. The goal is mainly to contribute to limit global warming through the reduction of energy consumption. Improving industrial processes and the building energy efficiency also answers the main key requirements. Furthermore, sustainable technologies within the field of renewable, nuclear and fossils energies are more and more increasingly applied and used. Therefore one of the objectives is to optimize the use of the resources and to select and use eco-efficient materials for reducing the environmental impact. In this last case, it is highly recommended to contribute on reducing energy consumption through improving the thermal performance of building envelopes. Heating and cooling buildings equates to 40-50% of total energy consumption in many European countries and “constitute” the widest potential energy saving. This way of investigation should strengthen the development and the impact of new renewable energy sources. In the field of TPM, the increase of the basic knowledge in physics and chemistry of materials and expertise on their intrinsic properties are development priorities.

Advanced manufacturing and processing - Competitive industries: building industrial leadership in Europe (Trigger 1.3)

Growth in global production needs to challenge the efficiency of current processes. Materials with temperature dependent properties are used everywhere in the industry. Needs for Thermal performance measurements in developing new and innovative high-technology, high-value products are required [6]. Furthermore appropriate methodologies with the objective to assess and qualify performances or safety of new materials, new systems, new use of materials (e.g. in the field of electronics, building, automotive,…) have to be available. With regard to these challenges and considering the materials aspects, each metrological methodology should be studied, developed, applied and furthermore regularly adapted, optimized, improved or upgraded to ensure that it always meets the needs of the end-users and the industry practice. Research and transfer in the field of TPM have to seek to be in agreement with the final goals. Innovating Thermophysical Properties (TP) measuring solutions should be developed for ensuring the traceability and to improve the efficiency of every manufacturing process.

Safety/Security - Safe and secure society (Trigger 1.4)

The enhancing of the homeland security and also the safety and security of buildings are both listed as a strong priority. Scientific and technical supports of TPM to vulnerability and risk analysis should be considered. For instance;

Homeland security:

Response to prevent the society from any disasters (natural or human-caused) consists in studying or modelling structural effects and impacts on any infrastructures. Defence applications are also another field of regular investigations for TPM.

Fire protection technologies:

Various materials as well as complex systems can be employed. Implementing the technologies implies studying, modelling and simulating the reaction or the resistance to fire of the materials used.

Health - Longer and healthier lives and safe and secure food supply (Trigger 1.5)

Supporting innovation in health research should be the last but not the least trigger to consider.

Implants:

Some grand challenges for improving the testing methods and the metrological characterization of biomaterials or new materials should appear during the current decade. Future engineered materials used as replacements or complements for instance of tissues, dental materials or bones should require the development of new characterization techniques. It is easy to understand that it should be necessary better managing the interface between tissues and biomaterials. Multiphysics approaches, modelling and development of experimental determinations of thermophysical properties of living complex systems should be investigated. This topic is clearly a case where simultaneous gathering of knowledge and expertise from different scientific areas could improve research significantly.

Food and Chemical industry:

As stated in Horizon 2020 [2] “90 million tons of food waste in the EU each year”, the TPM need to support the investment for a safe and secure food supply. During processing, manufacturing, storage or transportation, food products can be heated or cooled. Therefore, the capacities of one product to be heated or cooled rapidly need to be studied. Managing the thermophysical properties of the “system” and understanding the process of heat and mass transfer inside the product are challenges and one of the aspects of the engineering properties of foods. Thus, modelling of the process requires the knowledge of both heat and mass transfer properties on changes in volume. This approach is similar for chemical products.

3. Addressing the societal challenges (Targets)

To address these triggers, targets of thermal properties metrology were discussed and the short list was limited to **five groups of targets**.

The targets and triggers are connected hereafter. For highlighting the connections, a non-exhaustive list of examples was identified as follows:

Energy: (Block 2.1)
New energy sources and improved efficiency of production, conversion transportation, use and storage:

Thermal management of buildings: Better thermo-physics knowledge should lead to less energy losses and to waste heat upgrading using new working fluids for low temperature power cycles. It will also lead to optimisation of design, control and process for achieving better efficiencies.

Conventional power plants (either fossil or nuclear fuel): Increasing steam temperature increases efficiency of generators: high performance steel and high temperature super alloys, welding, soldering, and thermal shielding (including thermal barrier coating) materials for turbines, water walls and fire walls.

Nuclear fusion: Containment of the plasma, transfer of the heat generated in the walls to the turbine, knowledge of thermophysical properties under extreme conditions.

Solar: Heat generated from solar radiation, thermal efficiency of absorber materials, storage media for seasonal changes and night periods, insulation and shell of buildings associated to the radiative aspects and passive solar gain.

Energy storage: Storage of thermal energy in latent heat storage systems based on the use of phase change materials (e.g. paraffin waxes, hydrated salts…). Storage of electricity; Thermal management of batteries in confined environment, especially lithium based in cars, conversion into hydrogen, methane, synthetic gas [7].

Environment: (Blocks 2.2.1, 2.2.2)
Improved understanding of climate change and Waste and CO_2 management

To underline the ways to investigate, several topics have been discussed. The main following topics are presented as example:

Reduction of carbon dioxide emissions:

The reduction of carbon dioxide emissions needs to go through the design and testing of new innovative generation of fuels or energy production, a better control of industrial waste but also by improving the energy efficiency of processes and buildings. This is an immediate need, which implies an excellence in TPM for developing reference skills, diagnosis tools applied to new advanced technological materials.

Low carbon vehicles and Infrastructures:

The “TPM” community should be able to help the automotive industry for breaking potential barriers and also for accelerating the dissemination of these emerging low carbon vehicle technologies:

- Improving conversion of chemical energy into mechanical work
- Reducing fuel consumption in cars by using thermally optimised engines
- Investigate higher combustion temperature, less heat losses, recovering waste heat using thermal-electric devices…

As a result of this support, the air quality will be improved and the dependency towards fossil fuels will be reduced.

Nuclear:

Next generation of reactors, especially future high-temperature designs, could become an important low-carbon alternative to fossil fuels as a source of process heat. Furthermore, the waste management issues in this industrial sector will be around for a long period, and will continue to require R&D and technical expertises. Reliable thermophysical properties data and management of the thermal aspects are therefore crucial for nuclear waste storage and disposal.

Manufacturing/Processing: (Blocks 2.3.1, 2.3.2)
Improved control and efficiency of process and production and New materials and technologies:

Developments are to provide industries with reliable thermal properties design data and knowledge of heat transfer in various materials. The objective is to enable them to optimise their design, control and process, therefore to achieve improved control and efficiency of process and production, to have improved efficiency of energy production, use and storage, and to confidently choose the newly developed materials and technologies.

For instance, the implementation of advanced, high-performance refractories and insulation products for high temperatures are essential for European process industries to reduce losses of high-quality energy and to develop thermal management systems in heat-intensive engineering, such as thermal shields in nuclear and space applications. It is particularly important for novel insulations to drive energy efficiency improvements in the industrial installation and building sectors to meet energy directive challenges.

Other examples of awaited developments:

Added value, High performance manufacturing:

- Compatibility between mechanical and thermal properties of base materials and hard layers, e.g. for milling
- Prediction of heat treatment: diffusion, building of crystallites, anisotropy
- Nano technologies, interfaces, surface morphologies, thin films.

Safety/Security: (Block 2.4)
Improved public screening, fire protection and safety monitoring:

Public screening systems:

New screening technologies for screening passengers at airport checkpoints are regularly tested and upgraded. Advanced Imaging Technologies (AIT) systems are now current and more and more widely deployed. This technique is considered as a full-body scanner or a body imaging system.
Nevertheless, this method does not detect easily explosives. As a consequence a new request arising is how to implement technologies and procedures for screening passengers for explosives. It has been envisaged that it should be possible to perform testing and technical assessments on screening technologies or to make modelling based on thermophysics knowledge.

Fire protection:

With regard to the trigger described 1.4., to implement fire protection needs, it is required to better manage the data on thermo-physical properties of materials and implement or improve reference measurements, reference methods as well as standards applied.

Safety monitoring:

Controlling supervision of nuclear power plant sites can be considered as a part of this field. For instance, the construction of the future fusion reactors or even the different generation (I to IV) of fission reactors requires the development or the improvement of new structural materials. These materials and systems should be able to bring under control any damage at elevated temperatures resulting from the possible fusion reaction.

Nuclear decommissioning, Waste management:

In this case, the objective is to support Hazard reduction. The planned transport and storage of nuclear waste during current and future decommissioning, will require a very much higher level of traceability and international infrastructure. Thermophysical property measurements providing the input data for thermal modelling (e.g. radiative properties and thermal transport properties of materials for containers) have to be improved or strengthened.

Health: (Blocks 2.5.1, 2.5.2)
Improved medical treatment and diagnosis + Improved production and quality control for food;

It has been identified that the contribution to a better healthcare could consist in supporting technical realisations or modelling validations of integrated medical systems or (bio)-systems dedicated to medicine, food or chemical industry.

Medical Area:

- Contributing to strengthen the quality and performance of implants. Successful industrial competition in this sector requires a high degree of quality and high technical performances. Control of products and processes through manufacturing are on the critical path of this need. Knowledge of the thermophysical parameters (thermal expansion, thermal behaviour of the materials used…) is therefore critical.
- Studying physico-chemical properties (temperature dependency) of living tissues

Better production processes in food or chemical industry:

- Thermophysical data for modelling of chemical synthesis, including thermodynamic data, especially enthalpy of formation
- Metrological analysis of ab-initio methods for calculating thermodynamic data and reactivities - Same approach for semi-empirical techniques or purely empirical techniques (group contribution theories)

4. Experimental Realization (Blocks 3.1.1 to 3.4)

Priorities for the experimental realizations to be made are distributed in four families and listed as follows:

Blocks 3.1.1 and 3.1.2: Reference materials completed by reference facilities and reference procedures / Extension of capabilities: range and spatial resolution

Blocks 3.2.1 to 3.2.3: Facilities related to PVT properties / Implemented and validated computational tools (including databases) / Portable sensors for In-situ measurements

Block 3.3: New measurement facilities for studying heat and mass transfer in interfacial systems (at micro and nano meter scale)

Block 3.4: Realization for implementing R&D in the field of virtual human

The development of new steady-state and transient methods at higher temperatures and also at micro and nano meter scales, the thorough uncertainty analysis for transient techniques and the validated heat transfer models in complex advanced materials will lead to the extended thermophysical properties measurement capability at higher temperatures and also at extended scales (from macro to nano meter). These developments will also lead to the development of certified reference materials and new European measurement standards and best practice procedures. Certified reference materials will be needed to provide traceability for industries and be used to calibrate and check the instruments and measurement techniques used in industries and academic laboratories. Reference materials are also required to aid in the investigation of anomalies between reference laboratories and different measurement techniques. They are essential tools to improve European equivalence.

To achieve these goals, it should be necessary to develop, implement or investigate [8]:

- Reference materials normally be able to cover all or most of the main quantities (thermal diffusivity, thermal conductivity, emissivity, thermal expansion, specific heat, heat of fusion/transition/reaction, wetting behaviour, surface tension, viscosity) under all main critical conditions (temperature, pressure, atmosphere, size (multi-scales))
- Methods to qualify new measuring techniques (not yet identified) and to establish their traceability
- Methods for modelling thermophysical quantities

5. Metrological Application of Basic Science and Technology (Blocks 4.1.1 to 4.4)

Priorities for the metrological application of basic science and technology are distributed in four families and listed as follows:

Blocks 4.1.1 and 4.1.2: Steady-state and Transient methods, Uncertainties / Modelling and experimental validations

Blocks 4.2.1 and 4.2.2: Multiple properties at small scales / 3D mapping thermophysical properties of materials

Block 4.3: Caloric properties of materials

Block 4.4: New techniques for measuring interfacial thermal transport properties including contact resistance and effusivity

At high temperatures there is a need to develop new measurement techniques for thermal transport properties, using both steady-state and transient methods. For instance, there is currently large scattering in high temperature thermal conductivity measurement data, especially for highly heterogeneous materials [9,10].

Steady-state methods use a simple principle but require extensive engineering to make accurate thermal conductivity measurements. Their advantage is that measurement uncertainty analysis is straight forward. Therefore, steady-state methods are often used in developing thermal conductivity reference materials to provide traceability for industries. However, at higher temperatures steady-state thermal conductivity measurements face challenges in material and sensor degradation, and will require advances in new materials, temperature sensors and also new techniques.

In contrast, the **transient** methods use relatively simple measurement technique but rely on complicated mathematic models. This has meant that the measurement uncertainty analysis according to the *Guide for the expression of uncertainty in measurement* (GUM) [12] needs further investigations.

The modelling of heat transfer in various complex materials in steady-state and transient conditions also needs to be validated experimentally. This would require the improvement of both measurement techniques and the fundamental understanding of heat transfer in complex materials.

The underpinning metrologies for thermal transport properties at micro to nano metre scales are needed to support the R&D and manufacturing of new high-tech innovative materials and devices. This includes areas such as thermoelectric thin films, photoelectric thin films and thermal and environmental barrier coatings. These technologies are used in waste heat recovery in automotive and space industry, solar power generation and organic light emitting diodes, and turbines in next generation power plants and clean aviation.

6. Enabling Science and Technology (Blocks 5.1.1 to 5.2.3)

It should be necessary to strengthen basic knowledge in different fields of science.

Priorities for enabling Science and Technology are distributed in two main families and listed as follows:

Blocks 5.1.1 to 5.1.3: Thermophysical Properties Metrology including: Transport properties, Radiative properties, Calorimetry, Thermal analysis and Thermodynamics / Material states: solid, liquid, gas; Multiphase: equilibrium & transition; type: bulk, advanced, multifunctional/smart and interfacial/multilayer systems.

Blocks 5.2.1 to 5.2.3: Advanced metrology for thermophysical properties / Newly developed advanced materials / Fundamental understanding of heat and mass transfer at multiple scales. Advances in technology are increasingly dependent on micro and nanoscale engineering from simple thin-film coatings to highly complex, nano-structured systems. For many such applications thermal performance is an essential component. However, thermal transport on these length scales is poorly understood due to the substantial challenge of measuring heat transfer with sufficient resolution.
Furthermore, it is noticed that the advance of thermal measurements at higher temperatures requires newly developed advanced ceramics, composites, alloys and specific temperature sensors or instrumentation. The fundamental understanding of heat transfer in highly complex or porous material (bulk material) and at their boundaries (interfaces) is vital when comparing thermophysical properties data measured using different measurement techniques.

7. Conclusions

The outcomes of the roadmapping exercise were to identify the current state of art and the future developments in thermophysical properties metrology field. To achieve all the identified objectives would require the collaboration and also cooperation in the wider international community. It is anticipated that this roadmap will become a useful tool for demonstrating need and rationale for further research in the field of thermophysical properties metrology development and metrology infrastructure, wherever justifications are needed at national and international levels. These proposals on the direction of future thermophysical properties metrology will, if implemented, address the issues.

Acknowledgements

The authors thank NPL for facilitating the organization of the thermophysical roadmapping exercise. They also are grateful to the comments provided by Stefan Sarge from PTB, and Bruno Hay from LNE, and to the discussions issued from the German Thermophysics Working Group (AK Thermophysics) in 2011, especially with Hans-Peter Ebert from ZAE.

References

1. J. Bojkovski, J. Fischer, G. Machin, F. Pavese, A. Peruzzi, E. Renaot, E. Tegeler, "A roadmap for thermal metrology", Int. J. Thermophys., 30, 1-8, 2009

2. Horizon 2020 website:
   http://ec.europa.eu/research/horizon2020/index_en.cfm?pg=h2020

3. Horizon 2020 – The Framework Programme for Research and Innovation, COM(2011) 808 final, Brussels 30.11.2011
   http://ec.europa.eu/research/horizon2020/pdf/proposals/com(2011)_808_final.pdf

4. European Commission, Commission Staff Working Paper – Executive Summary of the Impact Assessment, Horizon 2020 – The Framework Programme for Research and Innovation, SEC(2011) 1428 final, p. 2, , Brussels 30.11.2011
   http://ec.europa.eu/research/horizon2020/pdf/proposals/horizon_2020_impact_assessment_report_executive_summary.pdf

5. European Commission, Commission Staff Working Paper – Impact Assessment, Horizon 2020 – The Framework Programme for Research and Innovation, SEC(2011) 1427 final, pp. 35, Brussels 30.11.2011
   http://ec.europa.eu/research/horizon2020/pdf/proposals/horizon_2020_impact_assessment_report.pdf

6. European Metrology Research Programme-Outline 2008, report available @ http://www.euramet.org/index.php?, 2008

7. J.-R. Filtz, B. Hay, J. Hameury, "Thermophysical Properties of Materials: New metrology challenges at LNE to reduce the uncertainties", Int. J. Thermophys., Volume 32, Numbers 11-12, 2741-2751, 2011

8. S. Sarge, private communications, PTB, Braunschweig, 2011 & 2012

9. German working group for thermophysical properties, (AKT: Arbeitskreis Thermophysik), "Roadmap for the determination of thermophysical properties", not published, PTB workshop, Berlin, 2011

10. D. Salmon, R. Tye, N. Lockmuller, "A critical analysis of European standards for thermal measurements at high temperatures: I. History and technical background" Meas. Sci. Technol. 20, 015101, 2009

11. D. Salmon, R. Tye, N. Lockmuller, “A critical analysis of European standards for thermal measurements at high temperatures: II. Recommendations for inclusion in a new standard” Meas. Sci. Technol. 20, 015102, 2009

12. Évaluation des données de mesure - Guide pour l’expression de l’incertitude de mesure. Evaluation of measurement data — Guide to the expression of uncertainty in measurement. Joint Committee for Guides in Metrology, JCGM 100, 2008

Appendix 1

(see Roadmap of Euramet TCT_Thermophysical Properties_v11.pdf)