JOHNSON MATTHEY
TECHNOLOGY REVIEW

technology.matthey.com

Guest Editorial

Facility Process Safety and Control

NON-PEER REVIEWED FEATURE

Received 30th September 2022; Online 21st December 2022

Temperature and Practical Thermometry

Temperature is a fundamental quantity relevant to almost all spheres of human endeavour. It is measured and controlled in a very wide range of applications, for example in combustion (engines, heating), heat treatment of high value components, healthcare (fever screening), meteorology and climate monitoring. Measurement and control of industrial process temperature in particular is key to maximising product quality, optimising energy efficiency, reducing waste and minimising carbon dioxide and other harmful emissions. It is also essential for ensuring safety; an accurate measure of temperature minimises the risk of operating outside the required process envelope (for example in nuclear power generation). There are several settings in which recent innovations have brought about significant improvements in thermometry, and these are described in this themed issue. Also discussed in this issue is the assessment and optimisation of safety in lithium-ion batteries, which is also a very important topic given the ubiquity of those devices, and testing for corrosion in chemical process plants, again a widespread issue of great relevance to many practitioners.

In May 2019 the kelvin, which is the SI unit of temperature, was no longer defined by a physical artefact (the triple point of water), but instead *via* a fixed value of the Boltzmann constant. One of the consequences of the redefinition of the kelvin is new approaches to temperature measurement with primary thermometry where in principle the thermometer measures temperature directly without the need for calibration. These implications are discussed by Machin (1).

Further detail on an advanced practical primary thermometer is given by Pearce *et al.* (2). For conventional thermometers, drift of the sensor calibration due to harsh environmental factors causes a progressively worsening temperature measurement error. This paper discusses self-validation techniques, which make use of the melting of a miniature fixed-point (an ingot of metal or a metal-carbon alloy) with a known melting temperature. These self-validating thermometers can self-calibrate in process, mitigating the effect of sensor drift. The resulting improved measurement assurance yields improved efficiency (in terms of energy use and also reduced product rejection rates) and correspondingly reduced greenhouse gas emissions, as well as enabling larger safety margins. Another key aspect of traceability is management of calibration data, and the paper outlines progress in practical digital calibration certificates. This development is important to demonstrably assure measurement traceability compliance with regulations; in particular, the corresponding audits are often too complicated to manage with paper-based certification.

Thermocouples are by far the most widely used temperature sensor in industry, but management of their calibration drift in harsh environments can be time-consuming and expensive. Some key aspects of their practical use are given by Edler (3), as well as more detail on recent thermocouple development with an emphasis on improved stability for optimising process monitoring and control. These new developments are already having an impact in terms of enhanced energy efficiency (and hence reduced greenhouse gas emissions), reduced product rejection and improved safety margins.

Accurate non-contact surface temperature measurements are important for controlling product quality, energy consumption and safety. Thermal imaging is now widely used following dramatic technical improvements and price reductions. However, reliable temperature measurement with thermal imaging is very difficult, with confounding factors such as the influence of surface emissivity, background radiation and reflections all contributing to often large uncertainties. Simpson *et al.* (4) review the topic from a metrological perspective, and describe the steps needed to ensure measurement confidence in applications such as condition monitoring of infrastructure and healthcare diagnostics.

Future Energy and Chemicals

Despite the increased focus on combustion-free energy production, combustion will remain the main energy and heat production mechanism worldwide for the foreseeable future. Optimisation of combustion is aimed at reducing undesirable byproducts such as nitric oxide, nitrogen dioxide and CO_2, minimising fuel consumption and maximising heat production. The key parameter in any combustion process is reliable flame and post combustion gas temperature measurement and control, which is very challenging. Fateev (5) describes how various combustion environments such as waste incineration, internal combustion engines or pyrotechnic explosions cause the appearance of various optical emission features in different spectral ranges not accessible to the human eye which can enable reliable thermometry. Fast spectral optical techniques permit detailed snapshots of what is happening in the combustion process, and some applications in specific combustion environments are outlined.

Battery powered devices are now ubiquitous. Introducing a specific aspect of safety which is applicable to almost everybody, failure assessment of lithium-ion batteries is described by Patel *et al.* (6). Failure caused by mechanical and thermal abuse are investigated using non-invasive X-ray computed tomography, which builds insights into critical architectural weak points, electrode behaviours and particle cracks. Such measurements are essential to inform improved design and safety of lithium-ion batteries.

The result can be at best inconvenient, and at worst catastrophic, so corrosion must be rigorously tested for to ensure the effective and safe operation of the plant. Doing this after a process plant has been constructed can be difficult and expensive, so testing programmes must be developed in advance and incorporated into the scheme. Several methodologies to assess corrosion in highly aggressive conditions are described and their application in two case studies are presented by Holt and Atkins (7).

JONATHAN PEARCE
Science Area Leader, Temperature & Humidity Group, National Physical Laboratory, Hampton Road, Teddington, TW11 0LW, UK
Email: jonathan.pearce@npl.co.uk

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