Journal of Physics: Conference Series

Air temperature measurement challenges in precision metrology

To cite this article: M de Podesta *et al* 2018 *J. Phys.: Conf. Ser.* **1065** 122027

Air temperature measurement challenges in precision metrology

M de Podesta, R Underwood, L Bevilacqua and S Bell

National Physical Laboratory, Teddington, TW11 8QL, UK
E-mail: michael.depodesta@npl.co.uk

Abstract. The measurement of air temperature is important in many types of metrology. Despite being generally an auxiliary measurement, in some fields poor knowledge of air temperature represents a limiting uncertainty. Applications where this is the case include interferometric dimensional measurements, in which the air refractive index correction is required, and the determination of relative humidity. Yet despite its ubiquity, relatively little attention has been paid to determining air temperature with low uncertainty. In this paper we discuss an under-appreciated systematic error in air temperature measurements: the diameter-dependence of the radiation correction for cylindrical and spherical sensors. After a discussion of the typical magnitude of the effect we consider ways to mitigate the effect by the careful design of air temperature sensors, and through use of non-contact air temperature measurement techniques.

1 Air temperature

1.1 Importance for precision metrology

Air temperature is a critical parameter in many areas of precision metrology. In some cases, the temperature of the air itself is critical. In other cases, air temperature is used to control and to infer the temperature of metrological artefacts, for example dimensional standards, and weights. However, even after equilibration in good laboratory conditions, thermometers themselves commonly differ in temperature from room air by 0.1 °C or more, and larger objects can differ by several tenths of a degree. Errors at this level are highly significant for precision metrology.

2 Radiative effects

2.1 The diameter-dependence of radiation error

It is well known that temperature sensors can be affected by optical and infrared radiation and that the effect can difficult to detect [1]. However, it is typically considered that the magnitude of the errors induced by a specific radiative load depends on ‘obvious’ factors such as the emissivity of the sensor surface [2, 3]: sensor size has rarely been considered in the metrological literature [3]. The reason is that in the steady state, when the thermometer has reached a stable temperature, the radiative heating or cooling is balanced by air flow around the sensor. At first glance both these effects appear to be directly proportional to the surface area of the sensor [4].

However, analysis of the air flow around a sensor reveals that heat exchange between the air and the sensor only occurs within a thin boundary layer [5, 6]. This layer rapidly equilibrates with the sensor surface close to the stagnation point (Figure 1). The temperature difference between the boundary layer and the sensor surface becomes increasingly small as the boundary-layer air flows over the surface, and it thus becomes increasingly ineffective at changing the temperature of the sensor.

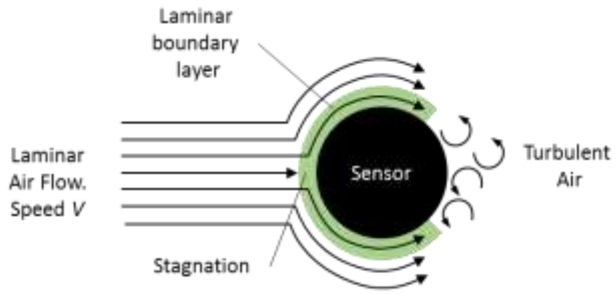

Figure 1. Cross-sectional illustration of the way in which laminar air flows around a cylindrical sensor. Heat exchange only takes place in the thin boundary layer and becomes increasingly ineffective as the sensor diameter D increases. Eventually the boundary layer leaves the surface of the sensor and turbulent mixing improves thermal contact on the rear of the sensor.

We refer the reader to de Podesta *et al* [7] for a more detailed analysis and references. Here we note that over the range of sensor diameter (D) and air speeds (V) generally encountered in metrological settings, the radiative temperature error ΔT is expected to vary as:

$$\Delta T \propto \varepsilon \sqrt{\frac{D}{V}} \tag{1}$$

where ε is the emissivity of sensor surface. This form applies for spherical sensors and for perpendicular air flow across cylindrical sensors. The effect is better known in meteorology [8, 9] but even there, the effect is frequently neglected [7].

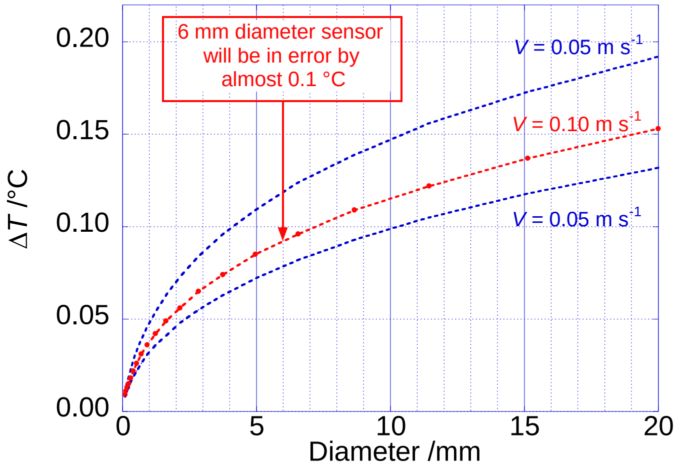

Figure 2. Calculation of the temperature error ΔT as a function of sensor diameter for a cylindrical sensor with a surface emissivity of 0.5, subject to 10 W m^{-2} of visible light – a level typical of many laboratory situations. The calculations show a characteristic square-root dependence on sensor diameter and an inverse square-root dependence on air speed.

2.2 *Typical Magnitude*

A wide range of scenarios are modelled in [7], but here we confine our calculations to a single situation typical of a metrological laboratory in which the walls are at the same temperature as the air (20 °C), but in which there is an illuminance of 1200 lumens per square metre, a typical laboratory lighting level. The irradiance is difficult to calculate unless the spectrum of the light source is known, but for typical spectra, this corresponds to roughly 10 W m^{-2} – approximately 1% of full sunlight. The calculated temperature error for a sensor with a surface emissivity of $\varepsilon = 0.5$ is shown in Figure 2 for three air speeds: 0.05, 0.10 and 0.15 m s^{-1}. The first point that we notice from Figure 2 is that a calibrated sensor with a diameter of 6 mm will be in error by almost 0.1 °C for an air flow of 0.1 m s^{-1}. The sensitivity to air speed means that fluctuations in air speed will manifest themselves as apparent fluctuations in air temperature. However, averaging these fluctuations will still result in a systematic over-estimate of the air temperature.

2.3 Consequences

In many laboratories, the temperature of an object is assumed to be equal to the air temperature after the object has been left to equilibrate. However, because of the size dependence of the radiant heating error, neither the object nor the thermometer will be at the temperature of the air (Figure 3). For irregular objects with dimensions on the order of 10 cm errors of 0.3 °C has been observed in our laboratories. For materials with a low thermal diffusivity, temperature gradients can be expected within artefacts. Errors of this kind can also be expected within environmental chambers where heating or cooling elements are in radiative contact with objects in the chamber.

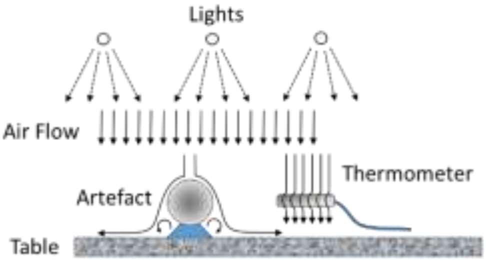

Figure 3. In a dimensional laboratory, with a uniform temperature air flow, the temperature of all the objects in the laboratory: thermometers, measurement artefacts and laboratory furniture, will differ from each other and from the true temperature of the air, typically by several tenths of a degree.

A second consequence arises when a working thermometer is ‘calibrated’ against a larger diameter reference thermometer. In general the larger sensor will show a larger error than the smaller sensor. If the origin of the discrepancy between the sensors is not understood, then the larger error of the reference thermometer can be ‘inherited’ by the working thermometer.

The magnitude of the error in any particular circumstance is difficult to estimate. For example, the emissivity of the stainless steel in which many sensors are enclosed can vary from 0.2 to 0.8 depending on the condition of the surface. Thus it is desirable to use techniques which either minimise the radiant heating or which are unaffected by thermal and optical radiation.

3 Mitigation

3.1 Working in the dark

For dimensional measurements, one option would be to work in the dark or in extremely low ambient light levels. However where human access is regularly required this may be impractical.

3.2 Sensor Design

The implication of Equation 1 is that using sensors with a low emissivity surface (i.e. a polished metal surface) and smaller diameters will yield estimates of air temperature closer to the true value. The choice of sensor and sensor size will depend on details of the application but possible choices include platinum resistance thermometers (PRTs), thermistors, thermocouples and fibre-optic thermometers.

PRTs would generally be the sensor of choice for most metrological applications. After determination of the sensor self-heating, uncertainties below 0.01 °C are possible for calibrated devices. However when reducing the diameter of PRTs, the self-heating generally becomes more significant and it may be necessary to reduce the measurement current to obtain acceptably small self-heating. Thermistors can be as small as a millimetre in diameter and offer excellent sensitivity over a small temperature range. However self-heating is even more significant for thermistors than for small-diameter PRTs.

The requirement to reduce the measurement current in PRTs and thermistors can make the use of thermocouples competitive with resistance sensors. Thermocouples are available with diameters as small as 0.025 mm and have no intrinsic self-heating. Nicolaus and colleagues [10, 11] at PTB have developed a hybrid technique involving thermocouples in which the temperature of the reference junction is stabilised in a metal block measured with low uncertainty using a capsule SPRT.

Fibre optic sensors are rarely used because of their expense and their generally low resolution. However there may be applications where either point sensors or distributed sensors interrogated using Optical Frequency Domain Reflectometry [12, 13] may be competitive.

Acoustic methods of air temperature measurement show no radiative heating effect and have been demonstrated to work at speeds of more than 30 measurements per second [14, 15] and over distances of up to 182 metres [16]. In the longer term, acoustic techniques could potentially yield air temperature measurements with substantially lower uncertainties than techniques using contact sensors.

4 Acknowledgements

This work was partly funded by the UK Department for Business, Energy and Industrial Strategy, and also by the European Metrology Research Program (EMRP) through the METEOMET and METEOMET2 projects. The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union.

5 References

[1] Traceable Temperatures, 2nd Edition, J.V. Nicholas and D. R. White., Published by Wiley 1991, Chichester. ISBN 0-471-49291-4

[2] Heinonen, M., Anagnostou, M., Bartolo, J. et al. Int J Thermophys (2014) 35: 1251. https://doi.org/10.1007/s10765-014-1654-9

[3] S. Friederici, E. Tegeler, in Proceedings of TEMPMEKO 2004, 9th International Symposium on Temperature and Thermal Measurements in Industry and Science, ed. by D. Zvizdi´c, L.G. Bermanec, T. Veliki, T. Staši´c (FSB/LPM, Zagreb, 2004), pp. 795–800

[4] Temperature Measurement, 1st Edition, L. Michalski, K. Eckersdorf, J. McGhee, Published by Wiley 1991, Chichester. ISBN 0 471 92229 3

[5] Frank P. Incropera and David P. De Witt, Fundamentals of Heat and Mass Transfer, Wiley (2011) ISBN-10: 0470501979

[6] Heat and Mass Transfer: Fundamentals and Application (5th Edition).

Yunus A Çengal and Afshin J. Ghajar: Published by McGraw-Hill Education, New York. ISBN 978-0-07-339818-1

[7] M de Podesta, S Bell and R Underwood, Air temperature sensors: dependence of radiative errors on sensor diameter in precision metrology and meteorology 2018 *Metrologia* **55** 229 https://doi.org/10.1088/1681-7575/aaaa52

[8] Erell, Leal and Maldonaldo: Measurement of air temperature in the presence of a large radiant flux: an assessment of passively ventilated thermometer screens. Boundary Layer Meteorology (2005)114: 205-231.

[9] R.G. Harrison, Meteorological Measurements and Instrumentation (2015) Published by Wiley, Chichester, ISBN 9781118745809

[10] A Nicolaus, G Bartl, A Peter, E Kuhn and T Mai, Volume determination of two spheres of the new 28Si crystal of PTB Metrologia 54 (2017) 512–515 https://doi.org/10.1088/1681-7575/aa7153

[11] R. Arnold Nicolaus and Ralf D. Geckeler, Improving the Measurements of the Diameter of Si Spheres IEEE Transactations on Instrumentation and Measurement 56 (2007) pp517-522

[12] Sensuron: http://www.sensuron.com/summit/

[13] Luna Technology http://lunainc.com/fiber-optic-solutions/fiber-sensing-solutions/

[14] Underwood, R., Gardiner, T., Finlayson, A., Few, J., Wilkinson, J., Bell, S., Merrison, J., Iverson, J. J. and de Podesta, M. A combined non-contact acoustic thermometer and infrared hygrometer for atmospheric measurements. (2015), Met. Apps, 22: 830–835. doi: 10.1002/met.1513

[15] R Underwood, T Gardiner, A Finlayson, S Bell and M de Podesta (2017), An improved non-contact thermometer and hygrometer with rapid response. Metrologia 54 S9

[16] Marco Pisani, Milena Astrua and Massimo Zucco An acoustic thermometer for air refractive index estimation in long distance interferometric measurements 2018 Metrologia 55 67 https://doi.org/10.1088/1681-7575/aa9a7a