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by

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Preface
This technical report is written based on investigations of Dantec measurement equipment used in a master thesis project by the authors in the period September 2014 to June 2015 (Kristensen & Jensen, 2015).

This report uses English/US notation for decimal and thousands separators, e.g. a large number is written as 476,456.76.

Department of Civil Engineering, Aalborg University, April 2015

Martin Heine Kristensen

Jakob Søland Jensen

Rasmus Lund Jensen

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1 Introduction

1.1 Scope

This technical report presents methods for practical use and calibration of Dantec Dynamics hot-sphere draught probes type 54R10 for measurements of air temperature simultaneously with measurements of air speed. As the probes are not intended as a stand-alone air temperature sensor investigations of temperature accuracy and possibilities of calibrating the temperature sensor are important to improve accuracy in indoor measurements. As such, it is the scope of this report to examine whether or not the probes contain an untapped potential in relation to thermal comfort measurements. Such a potential would be beneficial in many practical applications and situations, where more stationary setups with e.g. thermocouples are not suitable.

1.2 Report structure

The report is structured around an initial description of equipment characteristics and functionality, which is given prior to guidelines for proper measurement setup and calibration that enables the user to perform accurate measurements of air temperature. Moreover, the accuracy of which temperature measurement may be performed using the Dantec equipment is estimated based on individual probe calibration.

Information presented in this report originates from a combination of manufacturer manuals and white papers describing equipment specifications (please refer to the references in the end of this report) and the authors own experimental investigations performed at Aalborg University, Department of Civil Engineering.

The report contains no information about air speed calibration, as this is described in detail in other publications and standards, and performed by Dantec Dynamics on request.

2 Description of equipment

Equipment treated in this report is all part of the Thermal Comfort range manufactured by Dantec Dynamics A/S. A description of this product series is available on their website: http://www.dantecdynamics.com

2.1 Draught probes

Investigated sensor probes (transducers) include two variations of the Dantec 54R10-series thermal comfort probe; the old 54R102 and the newer upgraded version 54R103.

The draught probe is a so-called hot-sphere anemometer capable of measuring low and varying air speeds in the range of 0.05-5 m/s, air temperature and turbulence intensity. From these three measured parameters the calculation of draught rating (DR) is possible. The probe requires DC voltage input and provides an analogue output consisting of two non-linear voltage signals: one for velocity and one for temperature.

Both the old 54R102 and the upgraded 54R103 probes are equipped with the same output plug, which is seen on Figure 1 also showing the 3 main parts, that the probe consist of;

1. 54R10-series draught probe with adjustable shield
2. Spherical wire-cage for protection of fragile sensors
3. Bottom plate for securing a stable position when placed on horizontal surfaces

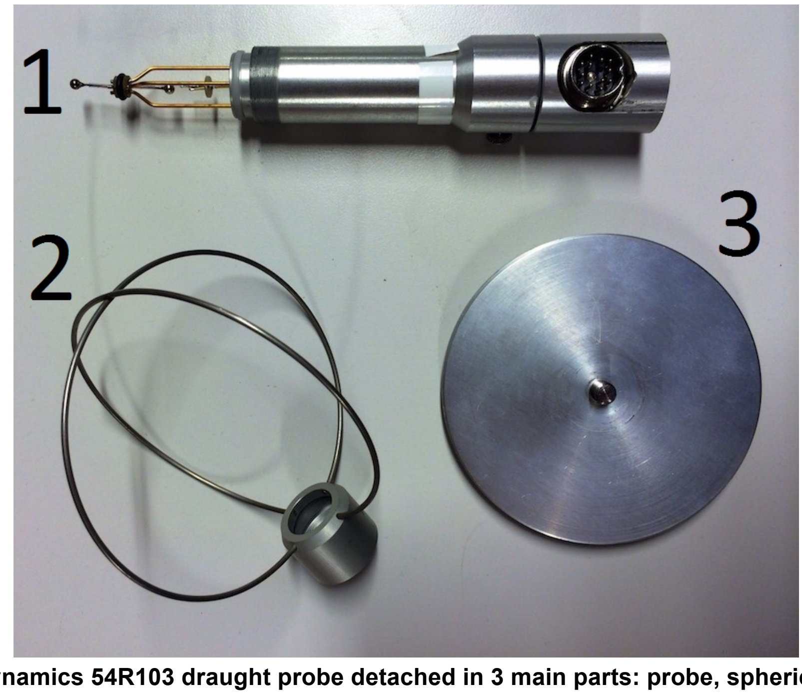

Figure 1 – Dantec Dynamics 54R103 draught probe detached in 3 main parts: probe, spherical wire-cage and bottom plate.

Figure 2 shows the assembled probes standing on a level surface.

Figure 2 – Dantec Dynamics 54R10-series draught probes assembled and ready for use. Source: Dantec Dynamics A/S (2013a).

2.1.1 Air speed sensor (anemometer)

Air speed is measured using a thin-film omnidirectional sensor consisting of two 3 mm quartz spheres coated in a thin film of nickel and covered by a layer of quartz. The fragile spheres are protected by a thin spherical wire-cage. The sensor may be seen on Figure 3 below.

Figure 3 – Close-up picture of air speed sensor consisting of two spheres aligned.

The topmost of the spheres in Figure 3 is kept at a constant over-temperature relative to the other hereby requiring a supply of energy dependent on the air speed, which the spheres are exposed to. A transfer function (calibration formula) converts the measured heat loss in terms of voltage output into air speed. In Figure 4 a thermographic picture of the hot spheres are seen where it is clear that the topmost sphere is the hottest.

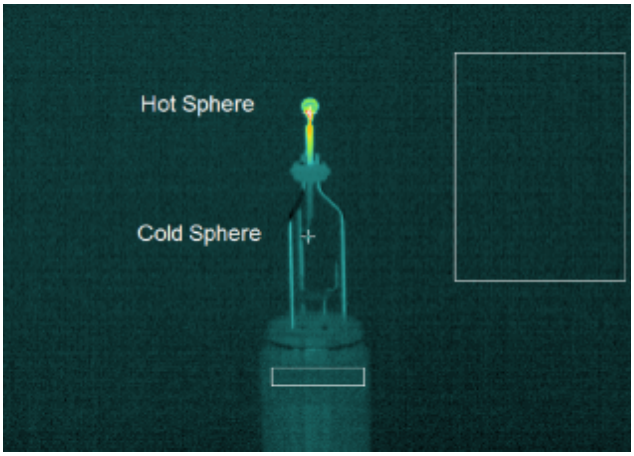

Figure 4 – Thermografic picture of hot spheres.

Anemometer specifications of the 54R103 probe are listed below in Table 1.

Table 1 - Technical specifications of 54R10-series draught probes. Source: Dantec Dynamics A/S (2013a).

Parameter	Anemometer
Range	0.05-5 m/s
Accuracy, 0-1 m/s	+/- 2 % of reading +/- 0.02 m/s
Accuracy, 1-5 m/s	+/- 5 % of reading
Time constant	2-3 s depending on air speed

2.1.2 Air temperature sensor

Air temperature is measured using a build-in thermistor located just below the two spheres. The thermistor is a type of resistor whose resistance varies significantly with temperature, more so than standard resistors. Thermistors differ from resistance temperature detectors (RTDs) in that the material used in a thermistor is generally a ceramic or polymer, while RTDs use pure metals. The temperature response is also different; RTDs are useful over larger temperature ranges, while thermistors typically achieve a higher precision within a limited temperature range, typically −90 °C to +130 °C.

Both the old 54R102 and the upgraded 54R103 probes measures air temperature using a thermistor. The thermistor in the 54R10-series probes are intended for usage in the interval 0 °C to +45 °C, however the reading range extends up to -20 °C to +80 °C for the upgraded 54R103 probe according to Dantec. The two different thermistors are seen from Figure 5 below. It should be noticed how the physical appearance of the two thermistors varies significantly with the old 54R102 thermistor being much smaller compared to the upgraded 54R103 thermistor.

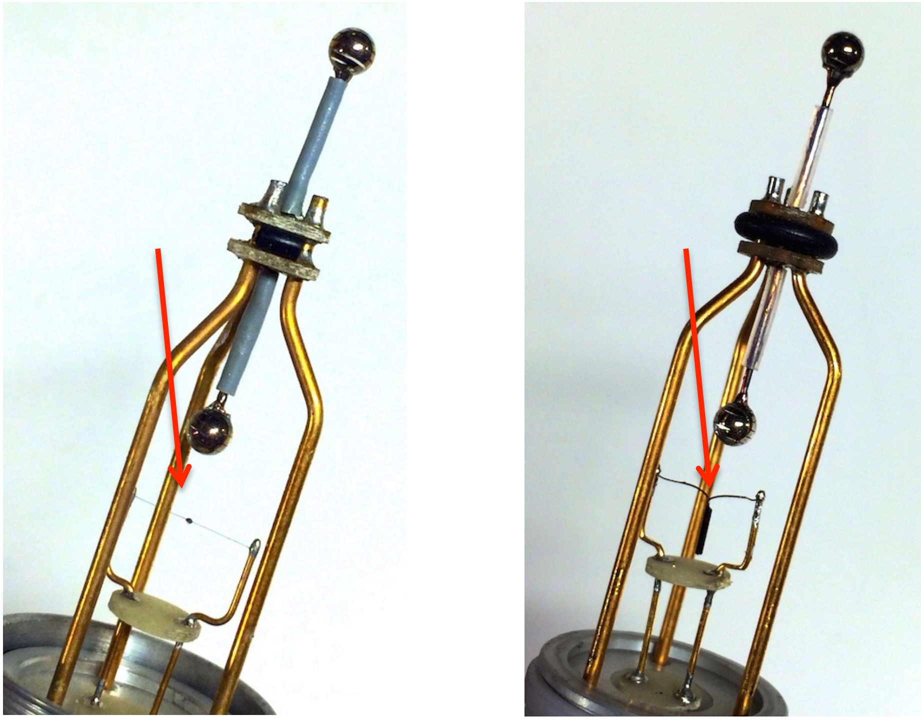

Figure 5 – Close-up pictures of old (54R102) draught probe sensors on the left and new (54R103) draught probe sensors on the right.

In Figure 5 the 54R102 probe is missing the black rubber O-ring placed midway between the two spheres, and the colour of the plastic shielding the rod holding the spheres are different. These differences are coincidental and propose no technical significance.

As seen from Figure 5, the thermistor has been upgraded in the new 54R103 probe to match the specifications of the newer Dantec 54T33 draught probes (not shown here). The internal electronics are also updated to match specifications of the 54T33. However, drift and directional characteristics of the air speed sensor is not upgraded, as the physical geometry of the sensors is not upgraded.

Thermistor specifications of the 54R103 probe is listed below in Table 2. Retrieving thermistor specifications of the 54R102 probes is not possible and therefore not tabulated below.

Table 2 – Technical specifications of 54R103-draught probes. Source: Dantec Dynamics A/S (2013a).

Parameter	Thermistor
Range	-20 °C to 80 °C
Accuracy	+/- 0.45 °C
Time constant	4-5 s depending on air speed

2.2 Data loggers

At time of writing several different data loggers are available at AAU, which all may be used for thermal comfort measurements together with the draught probes to some extend:

- Dantec 54N10 MultiChannel Flow Analyzer
- Dantec 54N60 FlowMaster
- Dantec Indoor Flow System with National Instruments USB-6341 data logger.
- Dantec 54N90 ComfortSense

The different data loggers represent a technological development across more than 30 years and as such, one should be aware that the oldest version (54N10) are not capable of meeting current measurement standards when it comes to e.g. turbulence intensity, which requires a sampling rate of at least 2 Hz. Pictures of the loggers are shown below.

2.2.1 Dantec 54N10 MultiChannel Flow Analyzer

The oldest logger available at AAU is the Dantec 54N10 MultiChannel Flow Analyzer featuring up to 24 analogue input channels of the old plug type (see section below about cables). With a sampling frequency lower than 2 Hz it is not suitable for accurately measuring thermal comfort parameters such as draught rating and turbulence intensity according to ISO 7726 and ISO 7730 (actual data sampling frequency is unknown).

Figure 6 – Dantec 54N10 MultiChannel Flow Analyzer. Logger has 24 input channels.

The 54N10 is equipped with 2 analogue output channels for air speed and temperature plotting with a X-T recorder; these outputs are suitable for testing and troubleshooting. One digital IEEE-488 output socket is fitted for communication with a computer, which by using a GPIB adapter may be used with modern computers applying an USB-cable. Measuring period for the data logger is 1 second to 12 hours with 1 second resolution.

2.2.2 Dantec 54N60 FlowMaster

The more mobile 54N50 FlowMaster features 1 analogue input channel of old plug type (see section below about cables). With its display on the front panel it is ideal for spot measurements of air speed and temperature. The integration time may be set as either 1 second, 10 seconds, 60 seconds or 180 seconds, in which interval it is possible to see maximum, minimum or average measured values. However, its analogue output channel on the back panel also enables data logging using third party equipment. Air speed analogue output is given in the interval 0-3 VDC, while temperature is given in between 0.7-2.7 VDC. Data sampling frequency of the logger is 1 Hz.

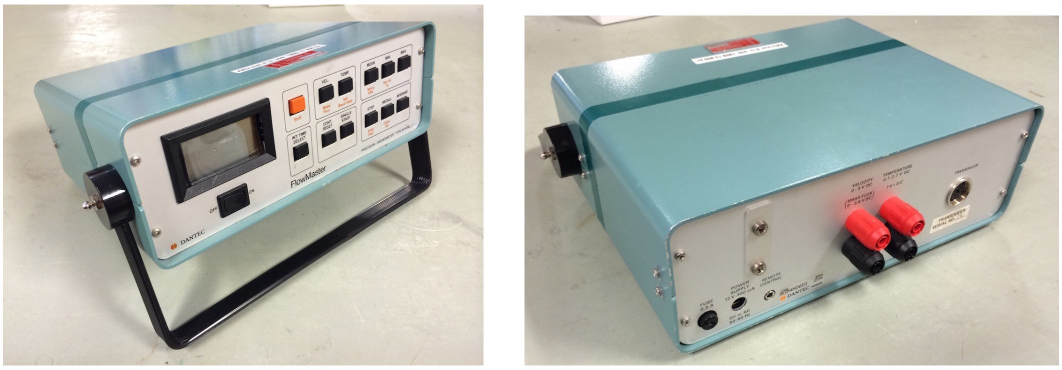

Figure 7 – Dantec 54N60 FlowMaster. Logger has 1 input channel.

2.2.3 Dantec Indoor Flow System with National Instruments USB-6341 data logger.

A 16-channel Dantec “Indoor Flow System” with National Instruments (NI) DAQ700 data logger has been upgraded at AAU in 2014 to feature a build-in NI USB-6341 logger. A 16-bit ADC converts the 16 analogue input channels with USB 2.0 interface making data communication with a computer easy and accurate. With a maximum multichannel sampling rate of 500 kS/s the logger is capable of scanning data with a sampling rate of more than 500,000 Hz per channel, which is 5 times faster than the previously used NI DAQ700. As such, it is the fastest data logger available at AAU at time of writing for measuring air speed and temperature. To obtain high stability and measurement accuracy it is advised by the manufacturer to average samples for at least every 10,000 Hz or 100,000 Hz, however this sampling rate is unnecessarily high, when taking into account the time constant of the probes. Measurements of indoor environmental parameters, such as air speed and temperature, do not require sampling rates higher than 2-5 Hz.

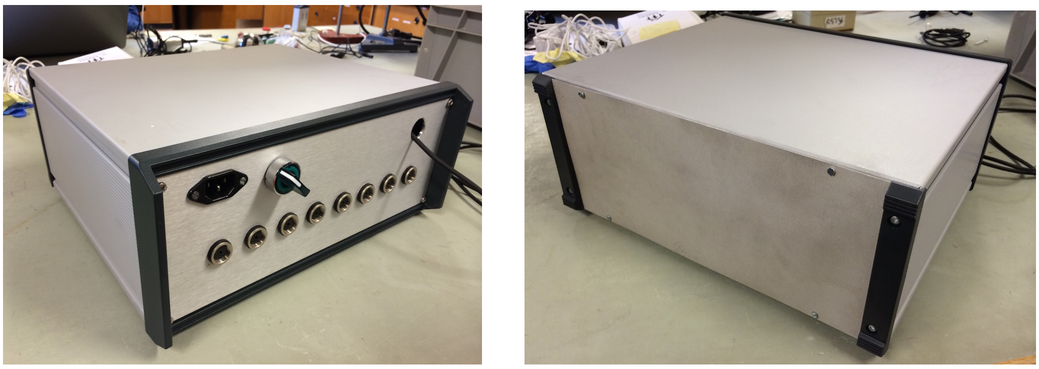

Figure 8 – Upgraded Dantec 16-channel Indoor Flow System with National Instruments USB-6341 data logger build into a single frame at AAU. Logger has 16 input channels and USB-connectivity.

2.2.5 Dantec 54N90 ComfortSense

The Dantec 54N90 ComfortSense data logger consists of a main frame with a build-in National Instruments NI USB-6218 logger with analogue input channels for up to 32 channels. It has a build-in 16-bit ADC with USB 2.0 interface making data communication with a computer easy and accurate. With a maximum multichannel sampling rate of 250 kS/s the logger is capable of scanning data with a sampling rate of more than 250,000 Hz per channel. Also, if wanted 4 analogue non-linearized output channel are also available for monitoring input channel 1, 2, 3 and 4 (plug 1 and 2). These 4 channels are found on the front of the frame and may be useful for testing and troubleshooting by connecting to a digital voltmeter (air speed sensor give outputs between 0.5 and 1.1 VDC at zero flow).

Figure 9 – Dantec 54N90 ComfortSense. Logger has 32 input channels.

2.3 Cables

Signal cables used between probes and loggers are of the type Dantec 9054B, which transfers two analogue voltage DC signals; one from the air speed sensor and one from the air temperature sensor. Moreover, the cable provides voltage to heat the spheres (see Figure 12).

2.3.1 Plug types

Two different cable plug standards are utilized in the sensor cables because the old plug type is not used in newly fabricated equipment anymore as e.g. in the 54N90 ComfortSense data logger.

The old plug standard is the one that the 54R10-series probes are equipped with and features a screw cap compared to the new, which is a direct-plug socket. The following loggers share the old type of plug:

- Dantec 54N10 MultiChannel Flow Analyzer
- Dantec 54N60 FlowMaster
- IFS 2000 logger modified with National Instruments USB-6341 data logger

When using the 54R10-series probes with one of the above mentioned data loggers a signal cable with the old plug type in both ends should be used. The old plug standard is shown in Figure 10.

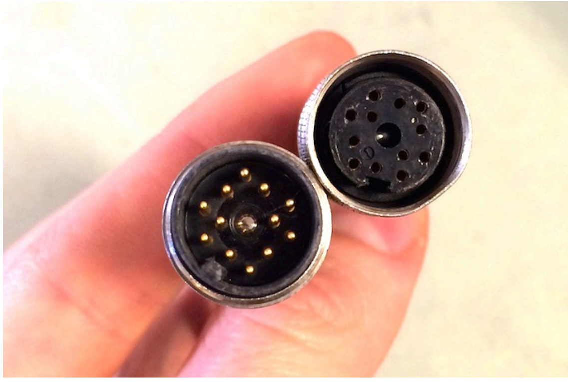

Figure 10 – Sensor cable 9054B with old plug standard in both ends (9113M0021 DIN-FATN. 12 PO)

When using the probes together with the new Dantec 54N90 ComfortSense data logger another cable has to be used. Because the 54N90 logger uses the new plug standard for signal input, the data cable needs to have a female socket of the old plug standard and a male socket with the new standard. Such a cable is shown in Figure 11 and schematically in Figure 12 where it is shown how the different signal wires are connected.

Figure 11 – Sensor cable 9054B with old plug standard in the female end (9113M0021 DIN-FATN. 12 PO) and the new standard in the male end (9113L0055 ODU Mini Snap Plug Straight).

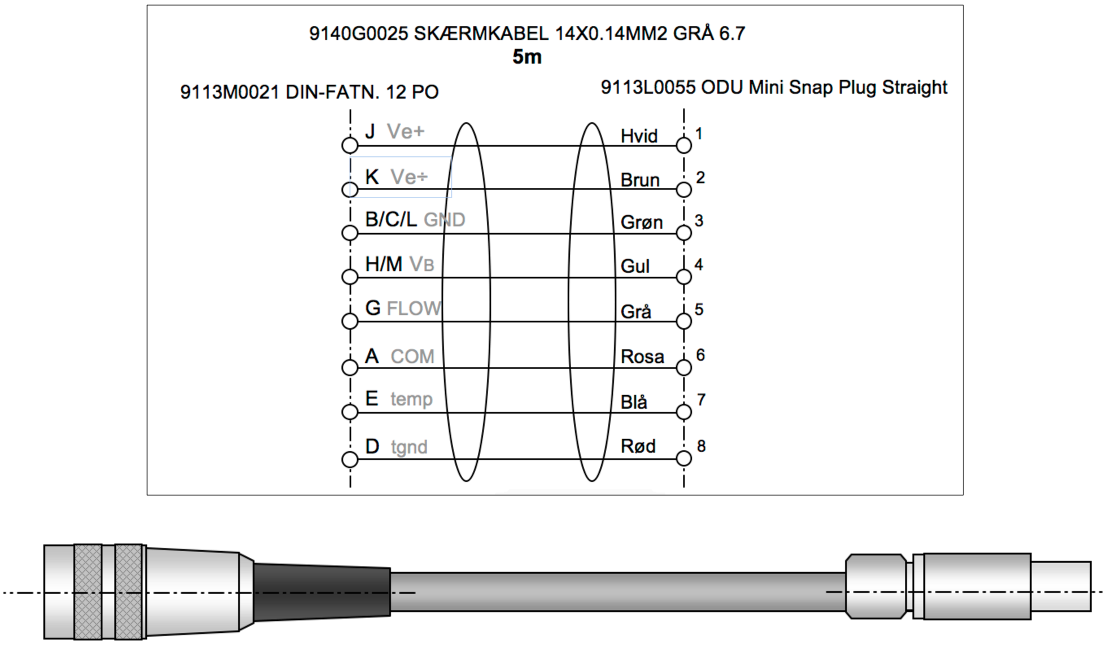

Figure 12 – Connection diagram for Dantec 9054B signal cable for use with ComfortSense logger. Diagram is in Danish. Reproduced from Dantec Dynamics A/S (2013b).

2.3.2 Cable for temperature calibration

When calibrating the temperature sensor of the 54R10-series probes it is necessary to be able to turn OFF the air speed sensor as the hot spheres generate heat, which influences the temperature readings. Therefore, a special “thermistor-only” cable has been made, which only allows power input for the thermistor to pass through to the probe. The connection diagram for this special cable is shown on Figure 13. Tests show that conductor 1, 2 and 3 are necessary for the temperature signal to pass through.

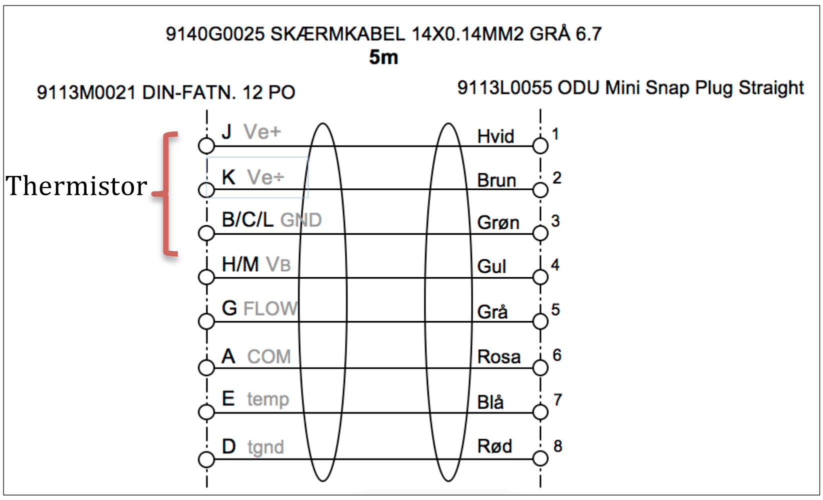

Figure 13 - Connection diagram for 'Thermistor Only'-cable, where air speed sensor is disconnected.

Even though some of the conductors disabled in the ‘thermistor only’ cable might indicate a relationship with temperature measurements, e.g. conductor number 7 (‘temp’ / blue) in Figure 13, experiments show that this is not the case.

3 Measurement setup

Performing measurements of air speed and temperature is rather straightforward. The process is described below when using the Dantec 54N90 ComfortSense logger.

3.1 Setup

Up to 16 Dantec 54R10-series probes may be connected to each Dantec 54N90 ComfortSense logger. The analogue wired connection between probe and logger is plug-and-play and does not require any tools.

From the logger two options are available for data output:

1. Analogue output of channel 1 and 2 only
2. Digital output for all 32 channels using USB 2.0

Option 1 using the analogue outputs on the front panel is suitable for testing and troubleshooting of probe functionality using e.g. a digital voltmeter. It may also be beneficial for spot measurements during e.g. a field study where the setup of an additional computer and data acquisition software is troublesome. This will however require manual data calibration afterwards.

Option 2 using digital output via USB is often the best solution suitable for monitoring and logging all 32 channels in either the included Dantec application software or in manually configured LabView data acquisition software. A digital output solution also brings down the overall uncertainty. Accuracy depends, among many other factors, on the build-in ADC of the logger.

3.2 Grounding and noise reduction

Proper grounding of the measurement setup – both Dantec equipment and computer hardware – is crucial in order to minimize noise, which could cause both random and systematic errors.

All devices should be grounded but only at one point as it would otherwise create ground loops, which should be avoided. If radiation from external noise sources penetrates the setup, currents are generated in such loops disturbing the measurement signals. As the shield of different devices often touch each other through data cable etc., which is the case with the Dantec probes and the logger, only the data logger needs to be grounded as it would otherwise create a ground loop.

Data cables, thermocouples, power cables etc. should never be laid in a stack but instead carefully separated as currents might be generated and cause noise in the setup. Especially high voltage power cables and frequency transformers are high-risk sources of noise and should never touch signal cables. Moreover, frequency transformers should be connected to another power supply than the measurement equipment as it could influence the stability of the mains supplying the measurements.

3.3 Accuracy of measurements

Measurements are exposed to random errors in terms of measurement uncertainty. The accuracy of air speed and air temperature measurements are affected by many parameters, whereas the most important ones are taken into account in the following derivation of the measurement uncertainty. The estimations are based on National Instruments technical specifications (National Instruments, 2014).

3.3.1 Accuracy of sensor readings

The obtainable accuracy in sensor readings is a result of sensor calibration. Accuracies given below are based on the default calibration by Dantec. A manual calibration of the thermistor is outlined in the following Chapter 4.

The accuracy of sensor readings is given by Dantec Dynamics A/S (2013a). For the upgraded 54R103 probe the accuracy of air speed readings are:

$$Absolute\ Accuracy\ \left(0-1\frac{m}{s}\right) = Reading\ \pm 2\% \cdot Reading\ \pm 0.02\frac{m}{s}$$

$$Absolute\ Accuracy\ \left(1-5\frac{m}{s}\right) = Reading\ \pm 5\% \cdot Reading$$

For air temperature readings it is:

$$Absolute\ Accuracy\ (0-45\ ℃) = Reading\ \pm 0.5\ ℃$$

3.3.2 Accuracy of data logging

Noise uncertainty in the analogue input signals of the Dantec 54N90 ComfortSense logger may be estimated based on the following formula (National Instruments, 2014):

$$Noise\ Uncertainty = \frac{Random\ Noise \cdot Coverage\ Factor}{\sqrt{Sample\ Size}}$$

Random noise is an equipment quality parameter of the data logger. For the 54N90 it is 229 µV when the nominal range utilized is 10 V (National Instruments, 2014). Coverage factor is a parameter expressing the confidence of the result. A Coverage factor of 3 (3 times the standard deviation, σ) gives a confident result covering 99.73% of the random noise. Sample size is the number of samples to integrate or average in a measurement. As the sampling size is increased the noise-generated uncertainty is decreased. A typical example is given below with logging of 100 samples.

$$Noise\ Uncertainty = \frac{229\ \mu V \cdot 3}{\sqrt{100}} = 68.7\ \mu V$$

As the data logger can sample up to 500,000 Hz, it is possible to make the sample size sufficiently big to make to noise uncertainty insignificant. As such, 500,000 Hz will provide a sample size of 100,000 samples to be averaged 5 times each second if the data logging requirement is 5 Hz. That would result in a noise uncertainty of only 0.97 µV.

The combined absolute accuracy of the data logging may be estimated based on the following formula.

$$Absolute\ Accuracy = Reading \cdot Gain\ Error + Range \cdot Offset\ Error + Noise\ Uncertainty$$

The gain and offset errors are factors expressing the imbedded uncertainty of the logger. The gain error expresses the random uncertainty of each reading and its sensibility towards temperature variations inside the logger and last calibration. The offset error expresses the error of the chosen range and its sensibility towards temperature variations inside the logger and last calibration. They are calculated as follows for the 10 VDC input range (National Instruments, 2014).

$$Gain\ \ Error\ (10V) = 75\ ppmOR + \left(7.3\frac{ppm}{°\mathrm{C}} \cdot 1°\mathrm{C}\right) + \left(5\frac{ppm}{°\mathrm{C}} \cdot 10°\mathrm{C}\right) = 132\ ppmOR$$

$$Offset\ \ Error\ (10V) = 20\ ppmOR + \left(34\frac{ppm}{°\mathrm{C}} \cdot 1°\mathrm{C}\right) + 76\ ppmOR = 130\ ppmOR$$

Where ‘ppmOR’ is: parts per million of reading.

The accuracy of any logged reading can then be obtained as follows when the range is 0-10 V.

$$Absolute\ \ Accuracy = Reading\ \ \cdot 132\ ppmOR + 10\ V \cdot 130\ ppmOR + \ 68.7\ \mu V$$

An example would be a reading of 0.7891 V from the air speed sensor and 0.4352 V from the air temperature sensor. The absolute accuracy would maximum constitute:

$$Absolute\ \ Accuracy\ (speed) = 0.7891\ V \cdot 132\ ppmOR + 1{,}369\ \mu V\ \ = 1{,}473\ \mu V$$

$$Absolute\ \ Accuracy\ (temperature) = 0.4352\ V \cdot 132\ ppmOR + 1{,}369\ \mu V = 1,426\ \mu V$$

As seen, accuracies are in the range of microvolts. As mentioned above about the noise uncertainty, an increment of sample size from 100 to 100,000 decreased the noise uncertainty from merely 68.7 μV to 0.97 μV equivalent to 67.7 μV. In the overall picture, that reduction is neglectable. The exemplified readings would be accurate within the following limits:

$$U_{speed} = 0.7891\ V\ \ \pm 0.0014\ V$$

$$U_{temperature} = 0.4352\ V\ \ \pm 0.0014\ V$$

Assessing the absolute accuracy with a 10 V input range is a very conservative approach securing an overestimation of the uncertainty. Often the anemometer input range is well below 2.5 V for normal air speeds and the thermistor range only above 1.2 V for negative temperature readings, which it is rarely used for.

From Figure 14 the absolute accuracy is plotted as function of read voltage input for a nominal voltage range of 10 V and 5 V.

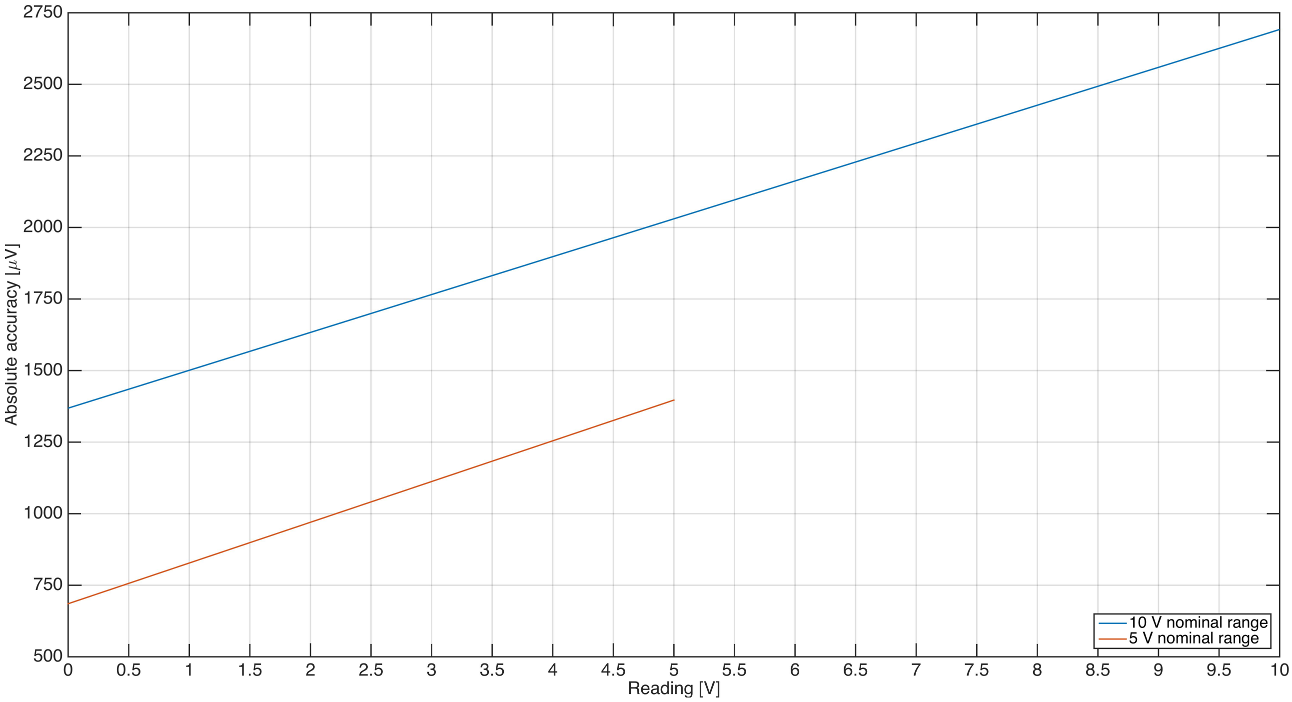

Figure 14 – Absolute accuracy of sensor reading as function of reading.

4 Thermistor calibration

Dantec Dynamics recommends their draught probe to be calibrated at least once a year. However, Dantec only calibrates the air speed sensor (anemometer) individually, and not the thermistor measuring air temperature. For temperature calibration they apply a standard calibration curve identical for all probes of the same type.

4.1 Dantec calibration for 54R102

For the old 54R102 probe the temperature calibration is a 5th order polynomial:

$$T(U) = aU + bU^2 + cU^3 + dU^4 + eU^5 + f$$

Where

T	*Temperature [°C]*
U	*Voltage DC [V]*
a	*Equation coefficient: -54.77305*
b	*Equation coefficient: +42.82077*
c	*Equation coefficient: -27.40397*
d	*Equation coefficient: +10.26861*
e	*Equation coefficient: -1.619883*
f	*Equation coefficient: +44.92619*

4.2 Dantec calibration for 54R103

For the upgraded 54R103 probe Dantec applies a variant of the Steinhart-Hart equation with two sets of coefficients; above 15 °C (X1) and below 15 °C (X2). The coefficients may be used from -20 °C to +70 °C:

$$T(U) = \frac{1}{A + B \cdot \ln(U) + C \cdot \ln^2(U) + D \cdot \ln^3(U)} - 273.15$$

Where

A	*A1: 3.591E-03 ,*	*A2: 3.588E-03*
B	*B1: 3.231E-04 ,*	*B2: 3.113E-04*
C	*C1: 4.501E-05 ,*	*C2: 2.139E-05*
D	*D1: 4.135E-05 ,*	*D2: 2.617E-06*

The two Dantec calibration curves are plotted in Figure 15.

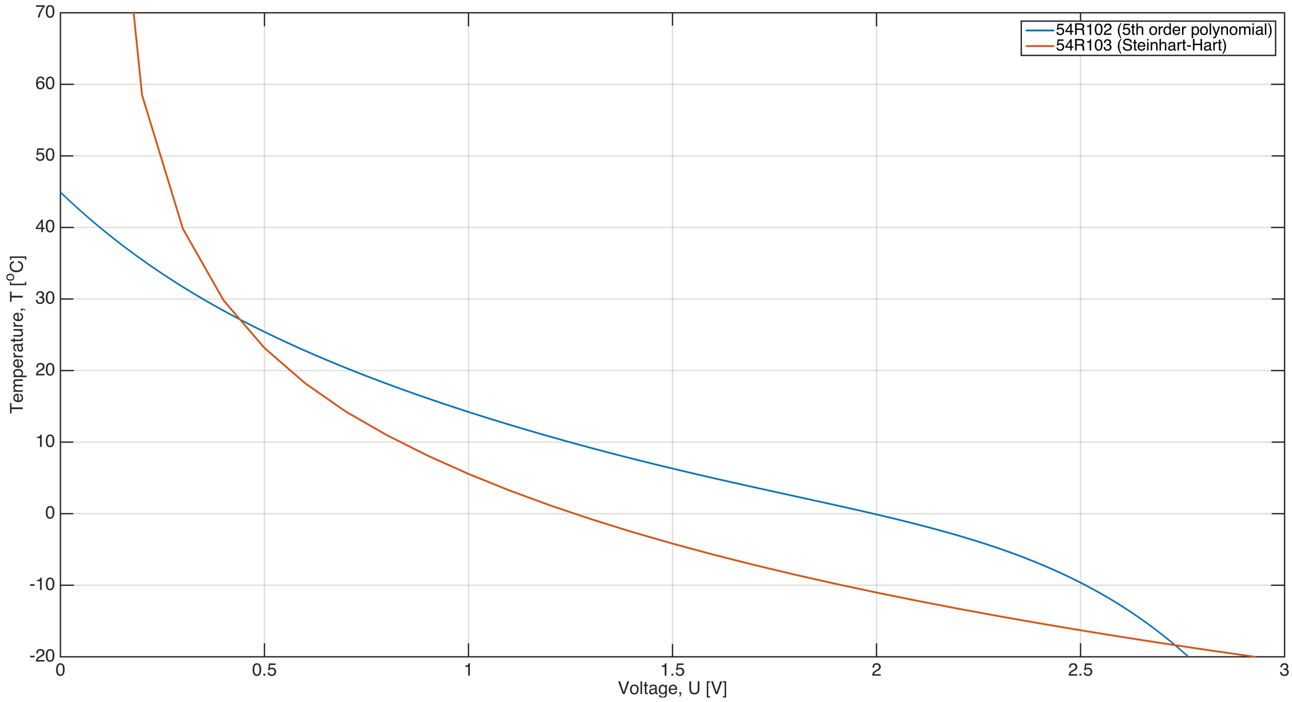

Figure 15 – Calibration curves for temperature conversion formulas supplied by Dantec.

In the following it is described how the thermistor of the upgraded 54R103 probe may be calibrated individually without using Dantec batch calibration. Individual calibration of the thermistor has not previously been performed at AAU at time of writing, and hence no comparable data for the upgraded 54R103 probes is available.

4.3 Calibration methodology

Because one of the spheres and the thermistor are placed very close to each other (approximately 1 cm apart), it is expected that the hot spheres of the anemometer interfere with the temperature measurement of the thermistor, giving it a bias. To investigate the influence of the hot spheres, the calibration is divided into two parts:

1. Temperature calibration
2. Correction calibration for active hot spheres and airflow direction

4.3.1 Temperature calibration

The calibration is performed as a *comparison calibration*, meaning that a correlation between sensor output voltage, U, and corresponding temperature in a reference instrument, T_{ref}, based on a number of calibration points, is used for the creation of a curve fitted calibration expression using the method of least squares.

$$T_{thermistor,V_0} = T_{ref}\left(U\right)$$

Where

$T_{thermistor,V0}$	*Calibrated temperature output at zero air velocity (hot spheres turned off)*
T_{ref}	*Reference temperature used for calibration*
U	*Sensor output voltage DC*

Calibration points are created using a steady temperature well (Isotech 948 Hyperion Basic, see Figure 16), which is able to keep a constant uniformly stable temperature in its well with an accuracy of ±0.025 °C (Isotech 2015a). Using a special “homemade” aluminium insert (see Figure 16), it is possible to fit up to 4 Dantec 54R103/54R102 probes in the well at the same time. The well must be dry and empty when calibrations are performed so only air surrounds the probes.

Figure 16 – Isotech Hyperion temperature bath with aluminium insert for temperature calibration of four Dantec 54R103 probes. ALS F200 Precision Thermometer is used for temperature reference.

In the middle of the insert, space is made for a temperature probe to be used with a reference instrument. For this, the ALS F200 Precision Thermometer is suitable. It measures temperature in a PT100 resistance thermometer probe with a resolution of 0.001 °C and an accuracy of ± 0.01 °C (Isotech 2015b).

6 calibration points are created in the +0 to +45 °C range, which is suitable for indoor environmental studies. However, using more calibration points, e.g. 10 point, would increase the accuracy of the calibration. The temperature in the Hyperion is manually adjusted for the different calibration points. For each temperature setpoint the reference temperature is logged with a F200 Precision Thermometer.

When calibrating the thermistor the hot spheres needs to be turned off in order to not interfere the temperature measurements. This is done by the use of a special calibration cable where only voltage wires for the thermistor are present (see section 2.3.2).

Thermistor output voltage is logged using the Dantec 54N90 ComfortSense and LabView software. Reference temperature of the F200 Precision Thermometer is also logged in LabView software.

4.3.2 Correction calibration for active hot spheres and airflow direction

As mentioned above, temperature calibration is performed with the hot spheres turned off, as it would interfere the thermistor measurements in the aluminium well of the Isotech Hyperion. However, as one often wants to measure air speed and temperature at the same time, the presence of the hot spheres needs to be taken into account. This is done in another calibration using a jet wind tunnel where the interference of the hot spheres is investigated under varying air speeds and angles of incidence between probe and dominating wind direction to account for maximum accuracy of the temperature measurements.

Calibration is yet again performed as a *comparison calibration*, however this time the spheres are turned on and the temperature output of the already calibrated thermistor at zero air speed, $T_{thermistor,V0}$, is compared to the F200 Precision Thermometer, T_{ref}, at varying air speeds, V_x. By measuring the reference temperature, a temperature correction expression of the thermistor is obtained.

$$T_{thermistor,V_x} = T_{thermistor,V_0} - \Delta T_{correction,V_x}$$

Where

$T_{thermistor,Vx}$	*Calibrated temperature output at given air velocity V_x (hot spheres turned on)*
$T_{thermistor,V0}$	*Calibrated temperature output at zero air velocity (hot spheres turned off)*
$\Delta T_{correction,Vx}$	*Excess temperature measured at given air velocity V_x due to hot spheres*

The temperature correction calibration is performed in the jet wind tunnel. Calibration is obtained for an incident angle of 0 degrees (perpendicular to the probe length axis) in accordance with Figure 17. To account for the variation in the hot sphere interference, incident angles of -90 degrees (airflow from bottom) and +90 degrees (airflow from top) is also spot tested at three different air speeds as shown on Figure 17.

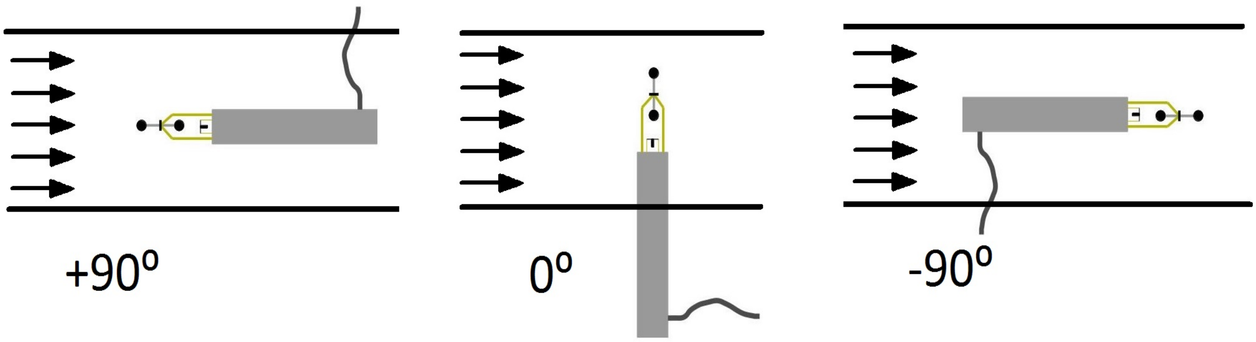

Figure 17 - Placement of Dantec probe in jet wind tunnel for the three investigated angles of incident.

From Figure 18 below the jet wind tunnel setup is depictured with the reference thermometer in background measuring the upstream air temperature before it hits the Dantec probe. This is done in order to minimize the thermal influence of the hot spheres on the reference temperature. However, some thermal radiation is expected to bias the results.

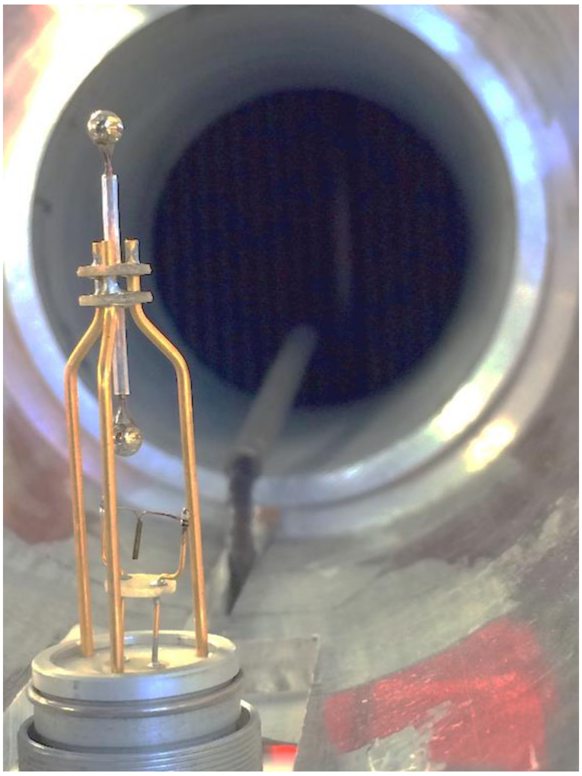

Figure 18 – Picture of calibration setup in jet wind tunnel. Reference thermometer probe is located upstream of the Dantec probe. Both probes are located in same height.

In a test-calibration a large temperature gradient was discovered in the tube of the jet wind tunnel (approximately 1 °C from top to bottom). As such, it is very important that the probe of the reference thermometer and the calibrated Dantec thermistor sensor is located at the same vertical height. On Figure 19 the placement of the Dantec probe in the middle of the exhaust tube of the jet wind tunnel can be seen. It is important the reference thermometer is placed upstream from the probe.

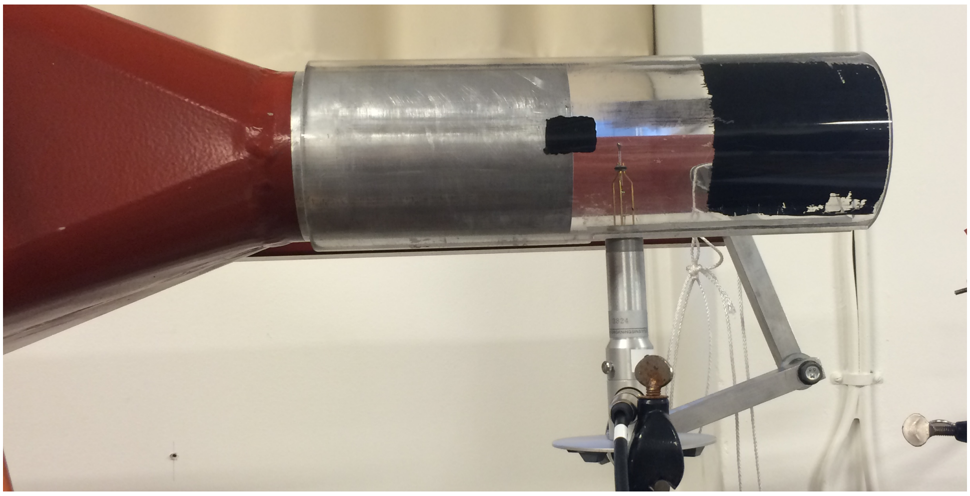

Figure 19 - Picture of calibration setup in jet wind tunnel. Dantec probe is placed in the middle of the exhaust tube of the tunnel, and reference thermometer must be at same height.

4.4 Calibration results and analysis

4.4.1 Temperature calibration

Temperature calibration of 32 Dantec 54R103 probes has been done in accordance with the methodology described above. To reach and stabilise each calibration point in the temperature well approximately 45 minutes is required to establish reliable results.

From Figure 20 below a two-term power series model is curve fitted to the calibration points of one of the Dantec 54R103 thermistors (Serial Number SN240) using the method of non-linear least squares in Matlab software. A general expression of the calibration model is given below.

$$T(U) = a \cdot U^b + c$$

Where a, b and c are coefficients of the calibration formula.

Fitting the calibration points to e.g. a 2nd order polynomial is also possible but yields less useful results (fit is of worse quality resulting in decreased calibration accuracy).

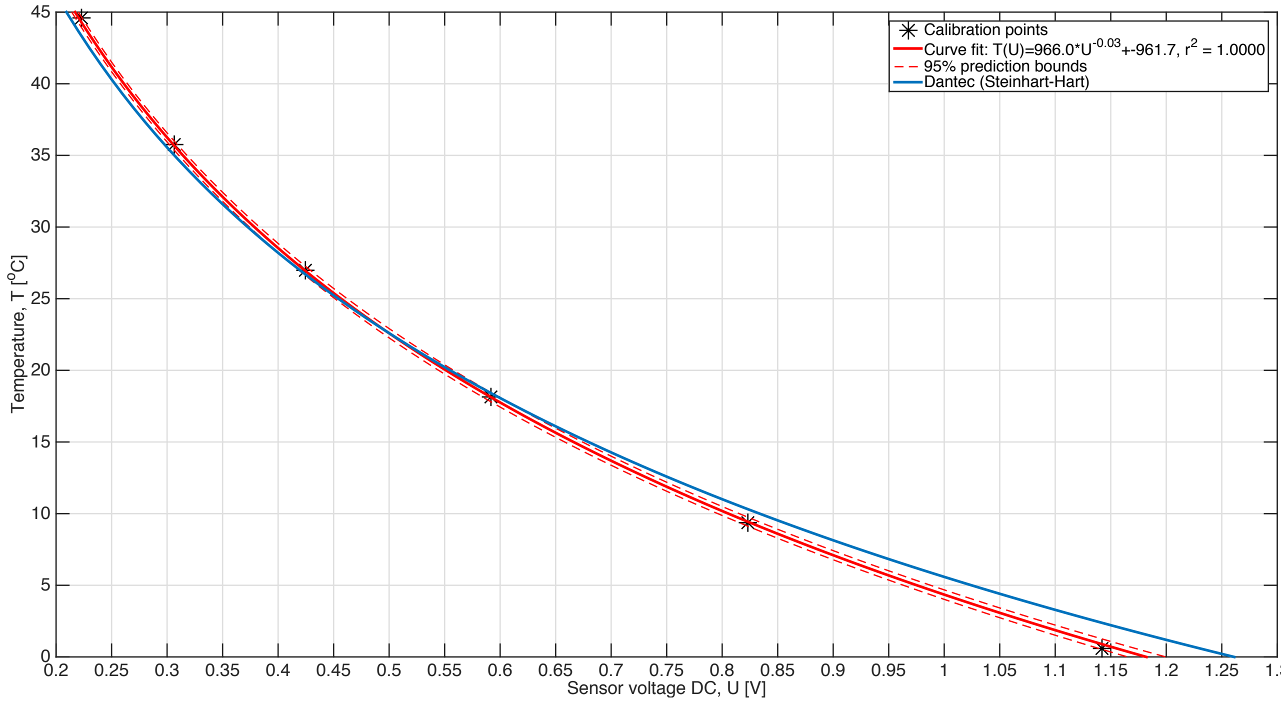

Figure 20 – Curve fitted temperature calibration of 54R103 thermistor, SN240, as well as Dantec calibration for the same sensor type.

The dotted prediction bounds illustrate the band wherein additional calibration points would lay, predicted with 95% confidence. Goodness-of-fit statistics of the calibration is given in the table below.

Table 3 – Goodness-of-fit statistics of temperature calibration using Matlab least square methodology.

	SN240	Average of all 32 probe calibrations	Note
R-square	1.000	1.000	Fit quality form 0-1. Value closer to 1 indicates better fit.
Adjusted R-square	1.000	1.000	Fit quality from 0-1 considering the degree of fitted coefficients. Value closer to 1 indicates better fit.
Root Mean Squared Error, RMSE	0.096°C	0.093 °C	Fit standard error. Considers the fit usefulness for prediction. Value closer to 0 indicates better fit with smaller random error.

Calibration coefficients (a, b and c) for the two-term power series model for all 32 thermistors are found in the appendices enclosed this report.

From Figure 20 the standard Dantec Steinhart-Hart calibration (blue curve) is plotted as well to illustrate the difference. The deviation between the two calibration expressions is given in Figure 21 as function of the true temperature.

$$\Delta T(T_{ref}) = T_{manual}(T_{ref}) - T_{Dantec}(T_{ref})$$

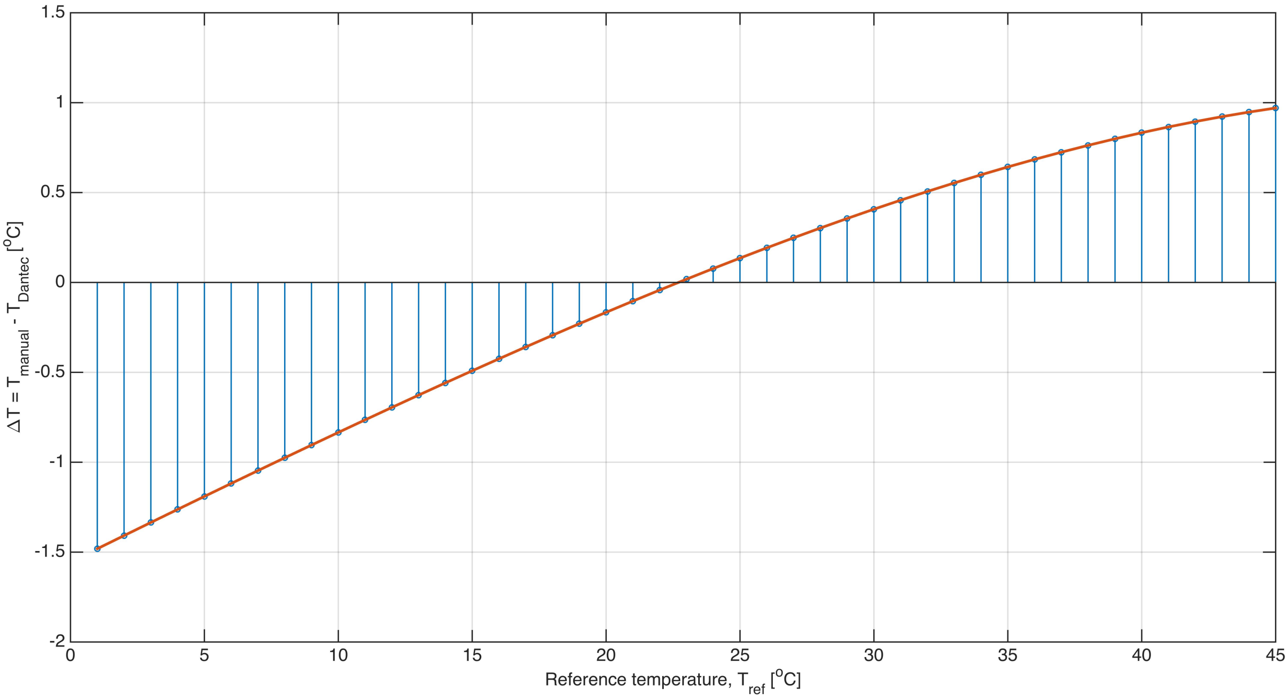

Figure 21 – Deviation between the author's manual calibration and Dantec standard calibration, as function of reference temperature in the given calibration range.

From Figure 21 it is obvious how important a device-specific calibration is. In the investigated range from +0 to +45 °C, applying the standard Dantec calibration will result in maximum -1.5 °C error at +0 °C. In the standard measurement range for indoor environmental applications, roughly +15 to +30 °C, the error is approximately ± 0.5 °C.

4.4.3 Correction calibration for active hot spheres and airflow direction

An additional correction calibration (assessment of the measurement accuracy when also measuring air speed) has been performed for one Dantec 54R103 probe (SN240). Results of the calibration are shown in Figure 22 below. A one-term exponential function is fitted to 18 calibration points. The exponential regression is chosen based on its easy physical interpretation, however, other fit types, such as the Gaussian function has better goodness-of-fit statistics.

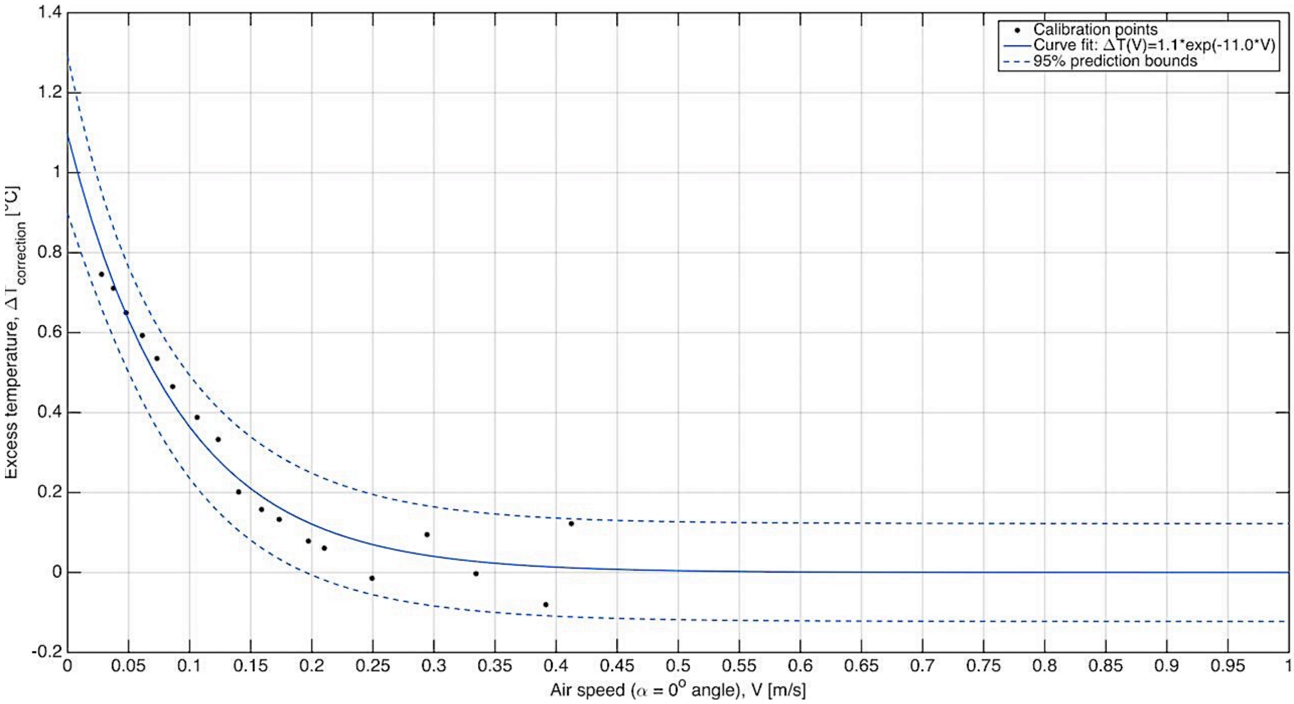

Figure 22 – Exponentially curve fitted temperature correction calibration for varying air speeds at an incident angle of 0 degrees (perpendicular to probe length axis).

Goodness-of-fit statistics for the chosen exponential fit and a Gaussian fit are given below in Table 4.

Table 4 – Goodness-of-fit statistics of correction calibration for presence of hot spheres.

	Exponential function	Gaussian function	Note
R-square	0.987	0.989	Fit quality form 0-1. Value closer to 1 indicates better fit.
Adjusted R-square	0.984	0.987	Fit quality from 0-1 considering the degree of fitted coefficients. Value closer to 1 indicates better fit.
Root Mean Squared Error, RMSE	0.034°C	0.030 °C	Fit standard error. Considers the fit usefulness for prediction. Value closer to 0 indicates better fit with smaller random error.

The analysis show how the hot spheres increase the temperature reading with maximum around 1.1 °C at stagnant air, which decreases to around 0.1 °C at 0.2 m/s air speed. However, this conclusion is only valid for airflows at incident angles of 0 degrees (perpendicular to probe length axis). From Figure 23 the excess temperature is shown at 3 different air speeds for the two extreme airflow directions; -90 degrees and +90 degrees, respectively (see Figure 17).

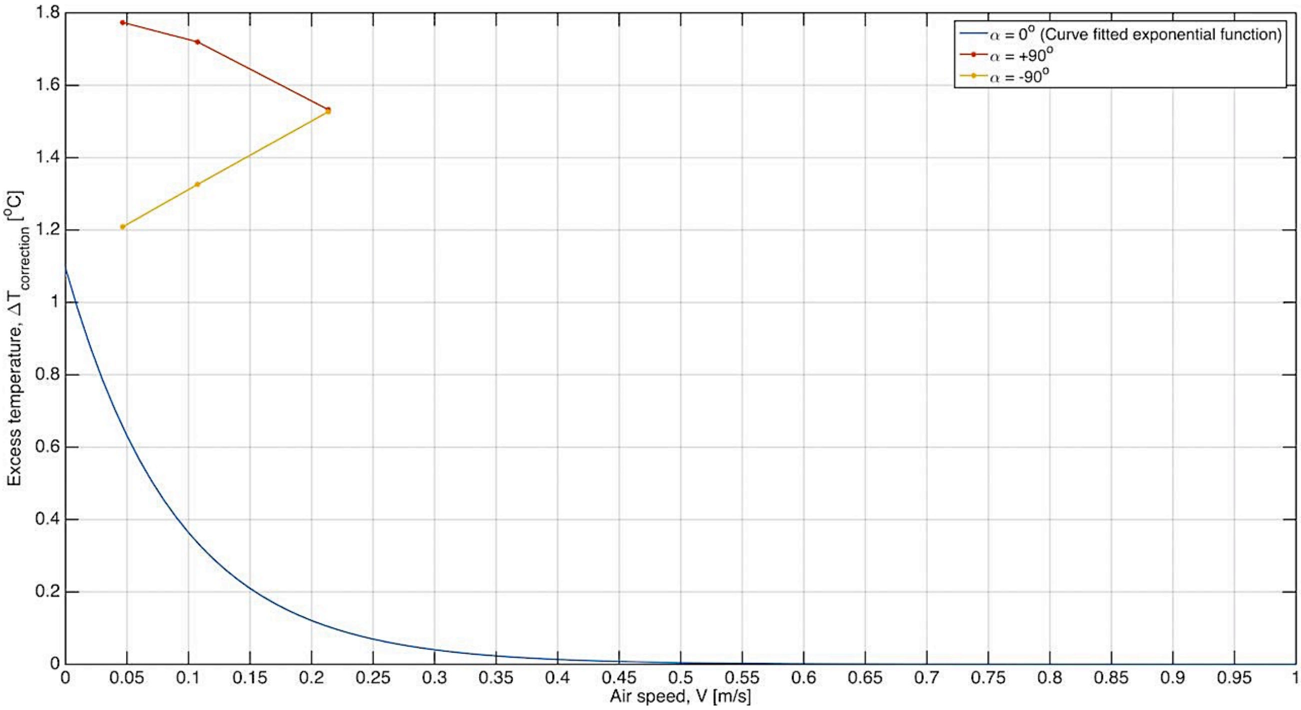

Figure 23 – Excess temperature reading in thermistor as function of air speed for different angles of incidence of airflow.

The speed-temperature (V,ΔT) correlation for angles of +90 degrees and -90 degrees seems ambiguous – at least for the -90 degree direction (yellow and red lines in Figure 23)

The higher ΔT-values in the +90 degree correlation compared to the 0 degree correlation is expected as the hot sphere heat release is forced through the thermistor resulting in maximum hot sphere temperature interference. At 0.05 m/s air speed, which is the anemometer minimum range, maximum excess temperature is around 1.8 °C. The decreasing tendency at increasing air speeds may be explained by increasing turbulence and thus entrainment of cooler surrounding air. Conversely, at -90 degree incident angle it would be expected that the hot sphere heat release would be forced away from the thermistor, lowering the interference to a minimum below what is observed in the 0 degree case. However, the results show otherwise; an increasing tendency is observed at increasing air speeds. Even though the increasing tendency of the -90 degree case seems incorrect a possible explanation could be the presence of increased turbulence and vortex shedding at the probe edges near the sensors because the airflow is separated when arriving along the probe axis hereby creating a undisturbed flow region in the wake of the sensor casing where heat can easily transfer upstream from the sphere to the thermistor. The principle of this phenomenon is sketched on Figure 24.

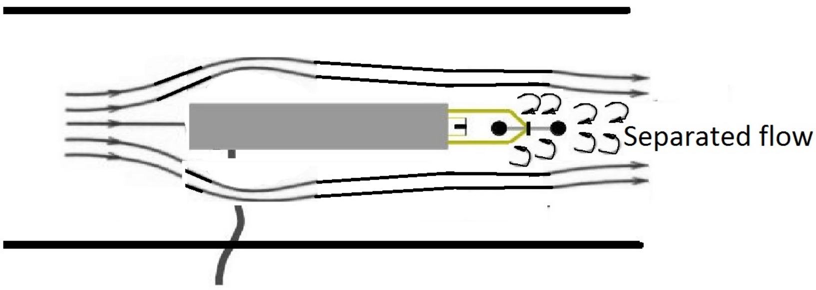

Figure 24 - Sketch of wake region behind the probe casing for incident angle -90 degrees.

5 Conclusion

Dantec draught probes of type 54R103 have been studied and their applicability in terms of air temperature measurements investigated. The following conclusions are highlighted:

The thermistor (temperature sensor in 54R103 probes) may be calibrated using existing equipment at AAU at time of writing. A two-term power series model has shown suitable in the range of 0°C to +45°C resulting in a calibration accuracy in terms of probe-average RMSE (root mean square error) of ±0.09°C. The device-specific calibration proved to deviate -1.5°C from the standard Dantec calibration at +0°C and +1°C at +45°C. At +22.5°C the two calibrations give the same result.

Paired with the 54N90 ComfortSense data logger, high frequent stand-alone air temperature measurements may be performed accurately; however, responsiveness in transient environments is limited to a time constant of around 4-5 seconds depending on air velocity.

The accuracy of air temperature measurements is strongly dependent on the angle of incident between probe and dominating airflow direction when using the associated omnidirectional anemometer, which in practise always is the case. Due to heat release from the hot spheres of the air speed sensor, temperature readings are biased by an excess reading of approximately +0.1°C to +1.8°C depending on both air speed, turbulence intensity and direction. As the air direction by default is unknown, it is difficult to take this phenomenon into account. However, if the governing airflow direction is perpendicular to the probe length axis, which is often wanted, the excess temperature reading may be approximated by an exponential function with maximum interference of around 1.1°C at 0 m/s, decreasing to less than 0.1 °C at 0.2 m/s and being negligible for air speeds above 0.5 m/s.

6 References

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7 Appendix

7.1 Air speed vs. air velocity

It is important to notice that the air speed sensor (anemometer) measures omnidirectional air speed, $V_{omnidirectional}$, and NOT air velocity, V_{vector}, even though Dantec writes so in their manuals (as done in e.g. Dantec Dynamics A/S (2013a)). Koskela et al. (2001) writes the following about air speed and velocity:

"*Air velocity is a vector quantity described by its magnitude (speed), and direction. In most fluid dynamics applications, attention is focused to either instantaneous or averaged velocity vector field. For thermal comfort assessment, however, the air speed is the relevant parameter, because it is related to the cooling effect of the air flow on the skin. Therefore, the air speed is used for the determination of the PMV index, which concerns the whole body thermal comfort in ISO 7730 standard. In a turbulent flow, the fluctuation of air speed also has an effect on thermal comfort. The effect of fluctuations has so far been incorporated into the prediction of draught, which is defined as unwanted local body cooling because of air motion.*"

It is not possible to measure air velocity, V_{vector}, nor any directional air speed (magnitude of any selected velocity component) with a single hot-sphere omnidirectional sensor. That would require directional sensors that are capable of measuring one, two or all three velocity components individually. This also means that any turbulence intensity calculated based on measured air speed with the Dantec 54R10-series probes is in fact omnidirectional turbulence intensity.

Omnidirectional air speed measured by the 54R10-series probes is defined as follows:

$$V_{omnidirectional} = \left|V_{vector}\right| = \sqrt{u^2 + v^2 + w^2}$$

Where

$V_{omnidirectional}$	Omnidirectional air speed (as measured by Dantec 54R10 probes) [m/s]
V_{vector}	Air velocity [m/s]
u	x-component of air velocity [m/s]
v	y-component of air velocity [m/s]
w	z-component of air velocity [m/s]

These definitions often lead to misunderstandings of what is actually measured. In practise it is only a problem when comparing experimentally measured air speeds with simulated air speeds in e.g. CFD-software, as such programs often calculate the directional or "true" air speed based on the calculated air velocity (vectors). The following formulas derived by Koskela et al. (2001) may be used for transforming simulated mean air speed, $\left|\overline{V}_{vector}\right|$, and turbulence intensity, I_{turb}, into omnidirectional mean air speed, $\overline{V}_{omnidirectional}$.

$$\frac{\overline{V}_{omnidirectional}}{\left|\overline{V}_{vector}\right|} = 1 + I_{turb}^2 , \qquad I_{turb} \leq 0.45$$

$$\frac{\overline{V}_{omnidirectional}}{\left|\overline{V}_{vector}\right|} = \frac{1.596 \cdot I_{turb}^2 + 0.266 \cdot I_{turb} + 0.308}{0.173 + I_{turb}} , \qquad I_{turb} > 0.45$$

The relationship is plotted in Figure 25.

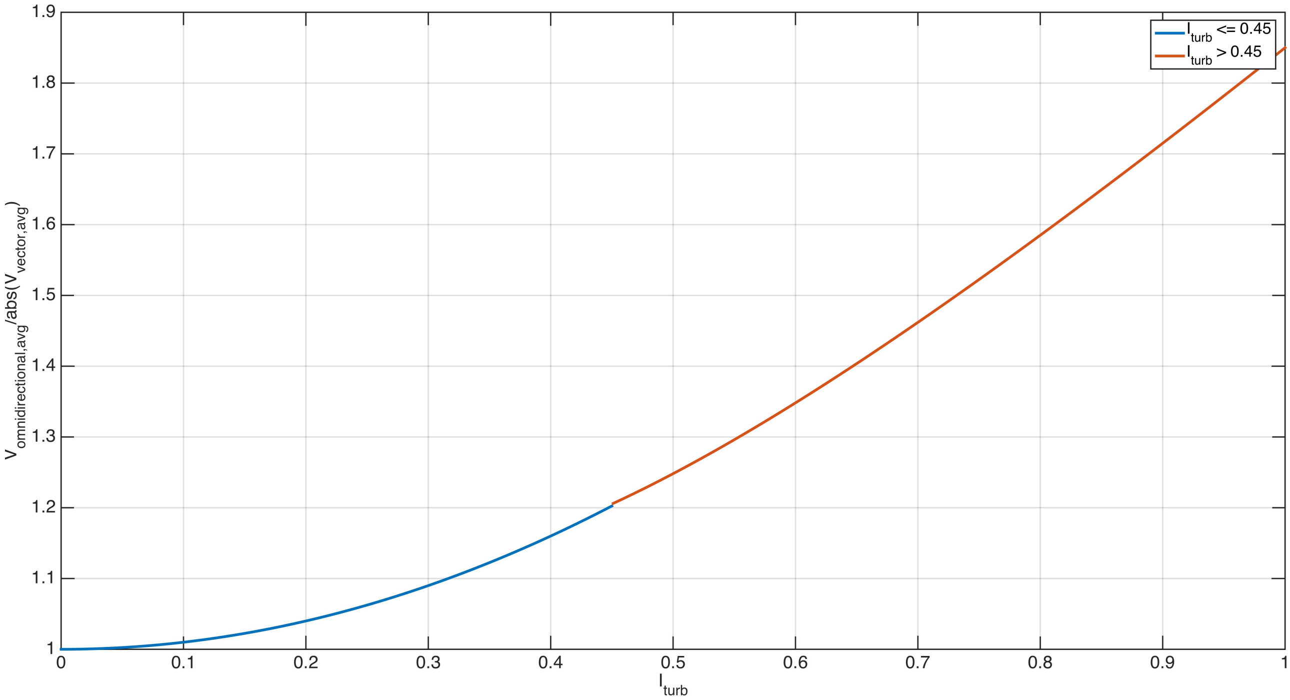

Figure 25 – Transformation factor between omnidirectional mean air speed and mean air velocity as function of air turbulence intensity.

7.2 Coefficients for thermistor calibration

Calibration coefficients (a, b and c) to for the conversion of thermistor voltage signal (U) into temperature (T) using a two-term power series model are given for 32 Dantec 54R103 probes in the table.

$$T(U) = a \cdot U^b + c$$

Coefficients are determined using non-linear least squares methodology in Matlab 2015a Curve Fitting Tool.

Table 5 – Calibration coefficients for thermistor calibration (calibration date: 16-01-2015).

Serial Number (SN)	a [-]	b [-]	c [-]	Adjusted R-square [-]	RMSE [°C]
240	966.002	-0.027	-961.653	0.99997	0.086
323	1107.709	-0.024	-1103.464	0.99997	0.095
356	1123.646	-0.023	-1119.394	0.99997	0.084
361	899.536	-0.029	-895.369	0.99997	0.094
362	951.253	-0.028	-947.070	0.99997	0.095
367	767.066	-0.034	-762.667	0.99997	0.094
375	937.281	-0.028	-933.116	0.99996	0.103
384	903.468	-0.029	-899.314	0.99997	0.085
524	919.106	-0.029	-914.963	0.99997	0.089
721	858.748	-0.031	-854.554	0.99996	0.101
809	956.780	-0.027	-952.492	0.99997	0.091
829	1540.980	-0.017	-1537.003	0.99999	0.059
1026	771.871	-0.034	-767.859	0.99997	0.096
1055	944.752	-0.028	-940.520	0.99997	0.087
1070	858.193	-0.030	-853.974	0.99995	0.118
1074	873.616	-0.030	-869.260	0.99997	0.093
1124	874.794	-0.030	-870.594	0.99996	0.107
1273	796.476	-0.033	-792.160	0.99998	0.076
1275	1201.167	-0.022	-1197.024	0.99997	0.084
1277	956.108	-0.028	-951.979	0.99997	0.092
1278	766.689	-0.034	-762.273	0.99995	0.113
1279	902.472	-0.029	-898.181	0.99996	0.102
1281	920.607	-0.028	-916.313	0.99997	0.091
1283	892.998	-0.029	-888.863	0.99997	0.091
1288	975.757	-0.027	-971.692	0.99997	0.097
1290	872.268	-0.030	-868.034	0.99996	0.099
1293	855.622	-0.030	-851.293	0.99997	0.089
1294	964.003	-0.027	-959.790	0.99997	0.092
1296	842.531	-0.031	-838.396	0.99998	0.064
1299	927.937	-0.028	-923.647	0.99996	0.100
1678	814.598	-0.033	-810.742	0.99996	0.110
1681	1043.333	-0.025	-1039.290	0.99997	0.086