Software quality documentation for the Temperature Sensor Time Constant Code

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Version details

- Version 2.2:
    - Sent to Stephen Burt in protected and unprotected versions.
    - The protection is not password protected. It is simply there to prevent inadvertent errors.

1 USER REQUIREMENTS

The software is categorised as NPL Software Integrity Level 2.

The calculation is embedded in a spreadsheet which models the heat exchange between a temperature sensor and its environment including:

- Blackbody radiation from the environment
- Direct Radiation from a radiant source
- Heat exchange with flowing air.

The physics is described in

- *Air temperature sensors: dependence of radiative errors on sensor diameter in precision metrology and meteorology*
- Michael de Podesta, Stephanie Bell and Robin Underwood
- Published 28 February 2018
- Metrologia, Volume 55, Number 2
- https://iopscience.iop.org/article/10.1088/1681-7575/aaaa52

2 FUNCTIONAL REQUIREMENTS

The spreadsheet has a set of 15 input parameters that describe the sensor and its environment:

Using these parameters the instantaneous energy exchange (heating or cooling) of the sensor is calculated.

- A non-zero value of energy exchange will result in a change of sensor temperature.
- A new value of the sensor temperature after a time step d*t* is estimated using an estimated value of the sensor heat capacity.

The heat exchange and sensor temperature are re-estimated 208 times. The resulting temperature versus time curve (transient response) is analysed and the time constant estimated from a linear fit to the first 128 data pairs (*t*, *T*).

The entire transient response and the time constant are shown on a graph which should be examined to make sure that the time constant reasonably describes the transient behaviour.

The inputs to the spreadsheet are:

Number	Parameter
	Simulation Parameters
1	Time step d*t* (default 1 second). The total simulation lasts for 200 x this time step.
2	Delta *T* (default 15 °C). The initial difference between the sensor and the air temperature
	Sensor Parameters
3	Outer Diameter in mm (default 6 mm)
4	Length in mm (default 100 mm)
5	Emissivity of the surface of the sheath (default 0.5). This affects the response to both blackbody and direct irradiation.
6	The measurement current used in the Pt100 sensor (default 1 mA).
	Further Sensor Details
7	The thickness of sheath as a percentage of the outer diameter (default 5%).
8	Density of sheath (Default = stainless steel =7870 kg/m^3)
9	Specific Heat of Sheath (Default = stainless steel 490 J/K/kg)
10	Density of Inner Thermometer (Default = 1000 kg/m^3)
11	Specific Heat of Sheath (Default = 1000 J/K/kg)
	Irradiation
12	Wall Temperature (default 20 °C)
13	Direct Irradiation (Insolation) (default 0 W/m^2)
	Air
14	Air Temperature (default 20 °C)
15	Air Speed (default = 3 m/s)

Security is not an issue.

There are no special hardware requirements: the code will run on Excel with VB Macros enabled.

3 SOFTWARE DESIGN

The spreadsheet calculates the energy exchange 208 times across columns A to T.

			Electrical			Insolation		Irradiation		Total	
Time (s)	Sensor temperature (°C)	Log	Resistance	Power	Power	Heating	Heating	Heating on Sensor	Heating on Sensor	Total	Total
			Ohms	W	mW	W	mW	W	mW	W	mW
0.00	35.000		113.30	0.000113	0.113	0.003000	3.000	-0.112032	-112.032	-0.108919	-108.919
1.00	34.796	-0.014	113.22	0.000113	0.113	0.003000	3.000	-0.110772	-110.772	-0.107659	-107.659
2.00	34.594	-0.027	113.15	0.000113	0.113	0.003000	3.000	-0.109531	-109.531	-0.106418	-106.418
3.00	34.396	-0.041	113.07	0.000113	0.113	0.003000	3.000	-0.108310	-108.310	-0.105197	-105.197
4.00	34.200	-0.055	113.00	0.000113	0.113	0.003000	3.000	-0.107107	-107.107	-0.103994	-103.994
5.00	34.006	-0.069	112.92	0.000113	0.113	0.003000	3.000	-0.105923	-105.923	-0.102810	-102.810

Column	Descriptions
A	The elapsed time in the simulation
B	Sensor Temperature. The first value is taken from the input parameters. Subsequent values are calculated by taking the net cooling or heating power (column Q) and calculating a new temperature based on the time step and the heat capacity of the sensor (column S)
C	Quantity used to estimate the time constant
D	The estimated resistance of the PT100 sensor assuming a standard IEC response curve.
E	The power dissipated in the Pt 100 sensor in watts
F	Column E expressed in milliwatts for ease of reading
G	The estimated heating of the sensor from direct irradiation
H	Column G expressed in milliwatts for ease of reading
I	The estimated heating of the sensor from blackbody irradiation
J	Column I expressed in milliwatts for ease of reading
K	The Sum of electrical, direct and blackbody heating (Columns E,G and I)
L	Column K expressed in milliwatts for ease of reading

Air							
Reynolds Number	Prandtl Number	Nusselt Number	Heat Transfer Coefficient	Cooling Power	Net Power	Delta T	Fraction of radiant heating
			W/(m^2 K)	W	W	K	
1175.29	0.708	17.361	74.89	2.1173499	-2.23	-0.204	5%
1175.29	0.708	17.361	74.89	2.0885284	-2.20	-0.201	5%
1175.29	0.708	17.361	74.89	2.0600964	-2.17	-0.199	5%
1175.29	0.708	17.361	74.89	2.0320486	-2.14	-0.196	5%
1175.29	0.708	17.361	74.89	2.0043796	-2.11	-0.193	5%
1175.29	0.708	17.361	74.89	1.9770845	-2.08	-0.191	5%

Column	Descriptions
M	Reynolds number for the air flowing at the specified speed past the sensor
N	Prandtl number for the air in the specified conditions
O	Nusselt Number calculated from columns M and N using a VB macro.
P	Heat transfer coefficient for the sensor calculated from the Nusselt number in column O.
Q	The cooling power due to the air flow calculated from P
R	The net power calculated from columns Q and K
S	The expected change in temperature of the sensor calculated from Column R, the time step and the sensor heat capacity.
T	This shows the percentage of the instantaneous heat exchange deriving from radiative effects.

3.1 INFERENCE OF TIME CONSTANT

- The time constant is estimated from analysis of the temperature versus time curve.
- The assumed equation is

$$T = T_0 + \Delta T\left(1 - e^{-\frac{t}{\tau}}\right)$$

$$\frac{(T - T_0)}{\Delta T} = 1 - e^{-\frac{t}{\tau}}$$

$$\ln\frac{(T - T_0)}{\Delta T} = \ln(1) + \frac{t}{\tau}$$

- So if the equation is appropriate, then we expect the slope of a fit of $\ln\frac{(T-T_0)}{\Delta T}$ versus *t* will have a slope of $1/\tau$
- On the spreadsheet, this fit is carried out using the *Excel*™ SLOPE least squares fitting function on log data in column C and *t* data in column A.
- The result of the SLOPE fitting is displayed in cell A13 and its inverse – the time constant – is displayed in cell A14

4 OUTPUT

The outputs of the spreadsheet are (a) a graph of the temperature versus time of the sensor and (b) an estimate of the time constant of the sensor. The time constant is approximately the time required for the temperature to change by a fraction (1-1/e) i.e. ~63% of the eventual temperature change.

It is possible to choose some simulation parameters which give outputs that appear unphysical. The user is advised to check the output graph and to ensure that the time constant reasonably characterises the data.

If this examination shows that the total simulation time is much less than the estimated time constant, then the user is advised to lengthen the time step so that the eventual simulation time is approximately 2 to 5 time constants. Similarly, if the total simulation time is much greater than the estimated time constant, then the user is advised to shorten the time step so that the eventual simulation time is approximately 2 to 5 time constants.

The user is reminded that because of radiative interactions the final cooling curves will not be exactly exponential.

4.1 TESTING

- There is no definitive test in which the correct answer is already known: that is why this paper is relevant.
- Also, because the test accounts for radiative losses and other non-linear effects, the 'true' curve would only be approximately exponential.
- To account for this, the calculated time constant is displayed by two straight lines drawn on the graph:
    - A horizontal line from t = 0 to $t = \tau$ at the value $y = T_0 + \Delta T/e$
    - A vertical line from y = 0 to $y = T_0 + \Delta T/e$ at the value $x = \tau$
    - See below for an example.
- Additionally the instructions say in red
- ***To avoid misleading results, always check that the Transient Response graph matches the indicated time constant.***