# NTC Thermistors

## General technical information

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EPCOS AG is a TDK Group Company.

## 1 Definition

As defined by IEC 60539, NTC (Negative Temperature Coefficient) thermistors are thermally sensitive semiconductor resistors which show a decrease in resistance as temperature increases. With −2%/K to −6%/K, the negative temperature coefficients of resistance are about ten times greater than those of metals and about five times greater than those of silicon temperature sensors.

Changes in the resistance of the NTC thermistor can be brought about either externally by a change in ambient temperature or internally by self-heating resulting from a current flowing through the device. All practical applications are based on this behavior.

NTC thermistors are made of polycrystalline mixed oxide ceramics. The conduction mechanisms in this material are quite complex, i.e. either extrinsic or intrinsic conduction may occur. In many cases NTC thermistors have a spinel structure and then show valence conduction effects.

## 2 Manufacture

EPCOS thermistors are produced from carefully selected and tested raw materials. The starting materials are different oxides of metals such as manganese, iron, cobalt, nickel, copper and zinc, to which chemically stabilizing oxides may be added to achieve better reproducibility and stability of the thermistor characteristics.

The oxides are milled to a powdery mass, mixed with a plastic binder and then compressed into the desired shape. Standard shapes of NTC thermistors are:

| | |
|---|---|
| Disks: | The thermistor material is compressed under very high pressure on pelleting machines to produce round, flat pieces. |
| Chips: | The ceramic material is compression-molded or drawn and then cut to the required shape. |
| SMD NTC thermistors: | Produced in ceramic multilayer technology with and without inner electrodes. |

The blanks are then sintered at high temperatures (between 1000 °C and 1400 °C) to produce the polycrystalline thermistor body. Disks are contacted by baking a silver paste onto the flat surfaces. Depending on the application, the thermistors are fitted with leads, coated or additionally incorporated in different kinds of housing. Finally the thermistors are subjected to a special aging process to ensure high stability of the electrical values. Otherwise the NTC resistance would possibly change even at room temperature due to solid-state reactions in the polycrystalline material.

Flow charts in the quality section of this book (see chapter "Quality and Environment") show the individual processing steps in detail. The charts also illustrate the extensive quality assurance measures taken during manufacture to guarantee the constantly high quality level of our thermistors.

## 3 Characteristics

A current flowing through a thermistor may cause sufficient heating to raise the thermistor's temperature above the ambient. As the effects of self-heating are not always negligible (or may even be intended), a distinction has to be made between the characteristics of an electrically loaded thermistor and those of an unloaded thermistor. The properties of an unloaded thermistor are also termed "zero-power characteristics".

## 3.1 Unloaded NTC thermistors

### 3.1.1 Temperature dependence of resistance

The dependence of the resistance on temperature can be approximated by the following equation:

$$R_T = R_R \cdot e^{B \cdot \left(\frac{1}{T} - \frac{1}{T_R}\right)} \qquad \text{(formula 1)}$$

| | |
|---|---|
| $R_T$ | NTC resistance in Ω at temperature T in K |
| $R_R$ | NTC resistance in Ω at rated temperature $T_R$ in K |
| T | Temperature in K |
| $T_R$ | Rated temperature in K |
| B | B value in K, material-specific constant of NTC thermistor |
| e | Euler number (e = 2.71828) |

The actual characteristic of an NTC thermistor can be roughly described by the exponential relation. This approach, however, is only suitable for describing a restricted range around the rated temperature or resistance with sufficient accuracy.

For practical applications a more precise description of the real R/T curve is required. Either more complicated approaches (e.g. the Steinhart-Hart equation) are used or the resistance/temperature relation is given in tabulated form. Following the application notes section you will find tables for real R/T curves (see chapter "Standardized R/T characteristics"). These standardized curves have been experimentally determined with utmost accuracy over the whole specified temperature range at a sufficient number of measuring points. They are also available for temperature increments of 1 degree.

### 3.1.2 B value

The B value is determined by the ceramic material and represents the slope of the R/T curve. It can be expressed from formula (1):

$$B = \frac{T \cdot T_R}{T - T_R} \cdot \ln \frac{R_R}{R_T} \qquad \text{(formula 2)}$$

Fomula 2 indicates that the rated B value is defined by two temperatures and can be generalized as:

$$B = \frac{T_1 \cdot T_2}{T_2 - T_1} \cdot \ln \frac{R_1}{R_2} \qquad \text{(formula 3)}$$

with two arbitrary temperatures $T_1$ and $T_2$.

The specifications in this databook refer in most cases to resistance values at temperatures of 25 °C ($T_1$) and 100 °C ($T_2$); i.e. $B_{25/100}$ is stated. For SMD NTCs $B_{25/50}$ and $B_{25/85}$ values are additionally given for information. Glass-encapsulated NTCs refer also to $B_{0/100}$, $B_{25/200}$, $B_{100/200}$ and $B_{200/300}$. Inserting these temperature combinations into (formula 3) leads to:

$$B_{25/100} = 1483.4 \cdot \ln \frac{R_{25}}{R_{100}} \qquad \text{(formula 4a)}$$

$$B_{25/50} = 3853.9 \cdot \ln \frac{R_{25}}{R_{50}} \qquad \text{(formula 4b)}$$

$$B_{25/85} = 1779.7 \cdot \ln \frac{R_{25}}{R_{85}} \qquad \text{(formula 4c)}$$

$$B_{0/100} = 1019.3 \cdot \ln \frac{R_{0}}{R_{100}} \qquad \text{(formula 4d)}$$

$$B_{25/200} = 806.1 \cdot \ln \frac{R_{25}}{R_{200}} \qquad \text{(formula 4e)}$$

$$B_{100/200} = 1765.6 \cdot \ln \frac{R_{100}}{R_{200}} \qquad \text{(formula 4f)}$$

$$B_{200/300} = 2711.9 \cdot \ln \frac{R_{200}}{R_{300}} \qquad \text{(formula 4g)}$$

The B value for a particular NTC thermistor can be determined by measuring the resistance at $T_1$ and $T_2$ and inserting these resistance values into the appropriate equation (formula 4).

B values for common NTC materials range from 2000 through 5000 K. Figure 1 illustrates the dependence of the R/T characteristic on the B value.

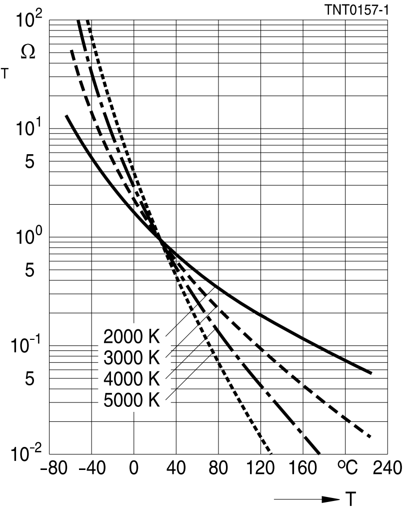

Figure 1
Resistance/temperature characteristics (parameter: B value)

### 3.1.3 Temperature coefficient

The temperature coefficient of the resistance is defined as the relative change in resistance referred to the change in temperature. The temperature coefficient is proportional to the derivative of the R/T curve and is an indication of the sensitivity at the given temperature.

$$\alpha = \frac{1}{R} \cdot \frac{dR}{dT} \qquad \text{(formula 5)}$$

### 3.1.4 Tolerance

The rated resistance $R_R$ and the B value are subject to manufacturing tolerances. Due to this tolerance of the B value, an increase in resistance spread must be expected for temperatures that lie above or below the rated temperature $T_R$. For practical examples concerning this topic see chapter "Standardized R/T characteristics".

**Resistance tolerance**

The resistance tolerance for an NTC thermistor is specified for one temperature point, which is usually 25 °C. Upon customer request other temperatures than those specified in the data sheets are possible.

Generally, the resistance tolerance can be expressed by the following relation:

$$\Delta R_T = \left|\frac{\partial R(T)}{\partial R_R}\right| \cdot \Delta R_R + \left|\frac{\partial R(T)}{\partial B}\right| \cdot \Delta B + \left|\frac{\partial R(T)}{\partial T}\right| \cdot \Delta T \quad \text{(formula 6)}$$

If the third temperature-dependent term in (formula 6) is neglected, the equation can be simplified as follows:

$$\left|\frac{\Delta R_T}{R_T}\right| = \left|\frac{\Delta R_R}{R_R}\right| + \left|\frac{\Delta R_B}{R_T}\right| \quad \text{(formula 7)}$$

In this formula $\Delta R_B$ denotes the resistance tolerance resulting from the spread of the B value.

For practical usage of (formula 6) the partial derivatives can be calculated from the exponential model given in (formula 1), which leads to

$$\left|\frac{\Delta R_T}{R_T}\right| = \left|\frac{\Delta R_R}{R_R}\right| + \left|\frac{\Delta B}{B}\right| \cdot B \cdot \left|\left(\frac{1}{T_R} - \frac{1}{T}\right)\right| \quad \text{(formula 8)}$$

As can be seen from this equation, the resistance tolerance at a certain temperature is influenced by two variables: the manufacturing tolerance of the rated resistance and the variation of the B value.

**Temperature tolerance**

By means of (formula 5) the temperature tolerance can be calculated for small temperature intervals.

$$\Delta T = \frac{1}{\alpha} \cdot \frac{\Delta R}{R} \quad \text{(formula 9)}$$

For practical application we recommend that the standardized R/T curves (see chapter "Standardized R/T characteristics") be used; the temperature steps tabulated there are small enough to permit calculation by the approximation formula given above.

### 3.1.5 Zero-power measurement

Zero-power resistance is the resistance value measured at a given temperature T with the electrical load kept so small that there is no noticeable change in the resistance value if the load is further decreased. At too high measuring loads the test results will be distorted by the self-heating effect (see chapter 3.2, "Electrically loaded NTC thermistors").

## 3.2 Electrically loaded NTC thermistors

When a current flows through the thermistor, the device will heat up more or less by power dissipation. This self-heating effect depends not only on the load applied, but also on the thermal dissipation factor $\delta_{th}$ and the geometry of the thermistor itself.

The general rule is:

The smaller the device, the smaller is the permissible maximum load and the measuring load (zero power).

The following general rule applies to self-heating of an NTC thermistor by an electrical load:

$$P_{el} = V \cdot I = \frac{dH}{dt} = \delta_{th} \cdot \left(T - T_A\right) + C_{th} \cdot \frac{dT}{dt} \qquad \text{(formula 10)}$$

| | |
|---|---|
| $P_{el}$ | Electrical power applied |
| V | Instantaneous value of NTC voltage |
| I | Instantaneous value of NTC current |
| dH/dt | Change of stored thermal energy with time |
| $\delta_{th}$ | Dissipation factor of NTC thermistor |
| T | Instantaneous temperature of NTC thermistor |
| $T_A$ | Ambient temperature |
| $C_{th}$ | Heat capacity of NTC thermistor |
| dT/dt | Change of temperature with time |

### 3.2.1 Voltage/current characteristic

If a constant electrical power is applied to the thermistor, its temperature will first increase considerably, but this change declines with time. After some time a steady state will be reached where the power is dissipated by thermal conduction or convection.

In case of thermal equilibrium dT/dt equals 0 and thus one obtains

$$V \cdot I = \delta_{th} \cdot (T - T_A) \qquad \text{(formula 11)}$$

With Ohm's law $V = R \cdot I$ (formula 11) can be written as

$$I = \sqrt{\frac{\delta_{th} \cdot (T - T_A)}{R(T)}} \qquad \text{(formula 12a)}$$

or

$$V = \sqrt{\delta_{th} \cdot (T - T_A) \cdot R(T)} \qquad \text{(formula 12b)}$$

This is a parametric description of the voltage/current curve with R (T) being the temperature-dependent NTC resistance. With the aid of the above equations these curves can be calculated for different ambient temperatures.

By plotting the voltage values obtained at constant temperature as a function of current one obtains the voltage/current characteristic of the NTC thermistor.

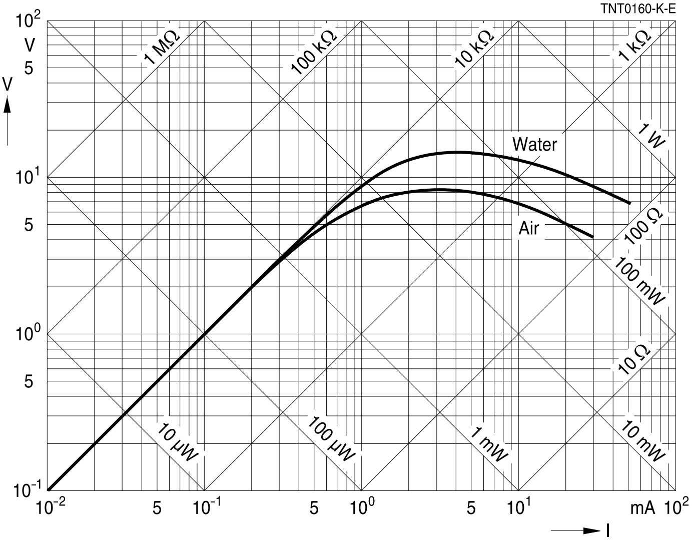

Figure 2
Current/voltage characteristic

On a log-log scale the curves for constant power and constant resistance take the shape of a straight line.

The voltage/current characteristic of an NTC thermistor has four different sections:

1. The straight rise section where the dissipation power only produces negligible self-heating. Voltage and current are proportional to each other. The resistance value is exclusively determined by the ambient temperature. Use of this curve section is made when NTC thermistors are employed as temperature sensors.→ (dV/dI = R = constant)
2. The section of non-linear rise up to maximum voltage where resistance already begins to drop. → (R > dV/dI > 0)
3. At maximum voltage the incremental resistance is zero.→ (dV/dI = 0)

4. The falling-edge section where the decrease in resistance is greater than the relative increase in current. This curve section in the operating area of NTC thermistors when a self-heating effect is desired (e.g. inrush current limiters, liquid level sensors).→ (dV/dI < 0)

### 3.2.2 Self-heating of NTC temperature sensors

All considerations in this section refer to the NTC B57861S0103F045 as an example, whose rated resistance is $R_R$ = 10 kΩ ±1.0% and whose B value is B = 3988 K ±0.3%. The self-heating effect as a function of applied current is plotted logarithmically in figure 3 for different ambient temperatures.

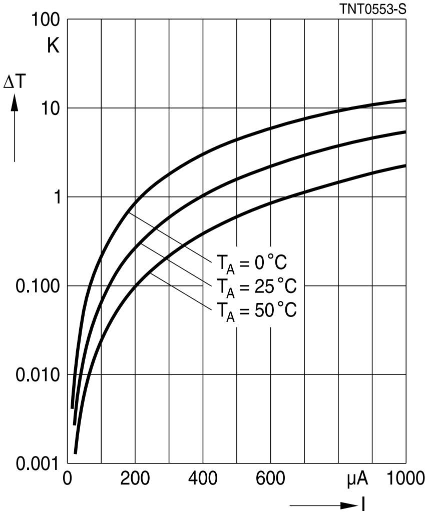

Figure 3
Self-heating of NTC B57861S0103F045 for different ambient temperatures

There is a major difference in self-heating depending on whether the feed-in of the NTC is a constant current supply or a constant voltage supply combined with a series resistor (figure 4).

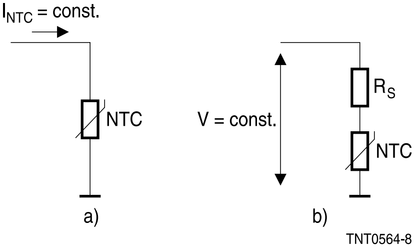

Figure 4
Circuit with constant current supply (a) and circuit with constant voltage supply combined with a series resistor (b)

The self-heating effect of both cases is compared in figure 5. The constant current is 200 µA and the constant voltage is 5 V. In the case of constant voltage the self-heating effect is shown for three different series resistors ($R_S$ = 5 kΩ, $R_S$ = 10 kΩ and $R_S$ = 20 kΩ).

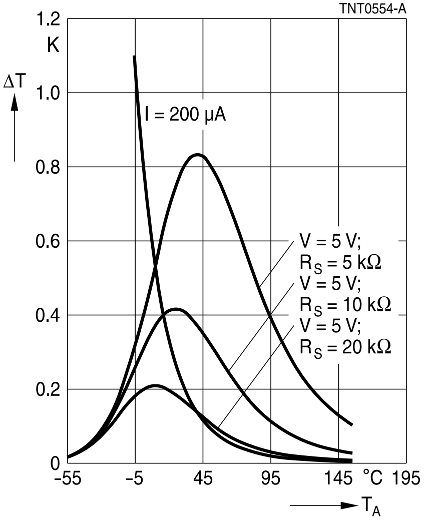

Figure 5
Comparison of the self-heating effect for constant current supply and constant voltage supply
(self-heating ΔT is plotted for various ambient temperatures $T_A$)

In the case of constant current the self-heating strongly depends on the ambient temperature (there is a steep gradient at $T_A$ = 25 °C and below), whereas in the case of constant voltage the self-heating is better distributed over the whole temperature range.

A straightforward fact is that the higher the series resistor, the smaller will be the voltage that declines at the NTC thermistor ($V_{NTC}$). So there is always a compromise between performance and measurability. The intersections of the constant current curve with the constant voltage curves denote points with a current of 200 µA. Thus the voltage declining at the NTC can be calculated at these points:

V = 5 V; I = 200 µA

a) $R_S = 5\ k\Omega$ $\quad R_{NTC} = \frac{V}{I} - R_S = 20\ k\Omega$ $\quad V_{NTC} = I \cdot R_{NTC} = 4\ V$

b) $R_S = 10\ k\Omega$ $\quad R_{NTC} = 15\ k\Omega$ $\quad V_{NTC} = I \cdot R_{NTC} = 3\ V$

c) $R_S = 20\ k\Omega$ $\quad R_{NTC} = 5\ k\Omega$ $\quad V_{NTC} = I \cdot R_{NTC} = 1\ V$

At the maximum of the constant voltage curves the series resistor $R_S$ equals the resistance of the NTC thermistor $R_{NTC}$. To the left of the maximum $R_{NTC}$ is larger than $R_S$ and to the right of the maximum $R_{NTC}$ is smaller than $R_S$.

The considerations above show that it has to be taken into account at which temperature the highest accuracy should be obtained when designing a circuit that includes an NTC thermistor.

### 3.2.3 Dissipation factor $\delta_{th}$

Dissipation factor $\delta_{th}$ is defined as the ratio of the change in power dissipation and the resultant change in the thermistor's body temperature. It is expressed in mW/K and serves as a measure of the load that causes a thermistor in steady state to raise its body temperature by 1 K. The higher the dissipation factor, the more heat is dissipated by the thermistor to its surroundings.

$$\delta_{th} = \frac{dP}{dT} \qquad \text{(formula 13)}$$

For measuring $\delta_{th}$ the thermistor is loaded such that the V/I ratio corresponds to the resistance value measured at $T_2 = 85$ °C.

$$\delta_{th} = \frac{V \cdot I}{T - T_A} = \frac{P}{T - T_A} \qquad \text{(formula 14)}$$

| | |
|---|---|
| $T$ | Body temperature of NTC thermistor (85 °C) |
| $T_A$ | Ambient temperature |

Designing an NTC thermistor into a circuit will always produce some kind of increase in its body temperature that leads to falsification of the measured result in a temperature sensor application. To keep this small, make sure the applied power is as low as possible. No general details can be given for optimal wiring in a specific application because our products have a wide bandwidth of both resistance and thermal conductivity. Please note that all figures for the thermal characteristics of our NTC thermistors refer to still air. As soon as other ambient conditions apply (e.g. agitated air) or once a component obtained from EPCOS is subsequently prepared, the thermal characteristics illustrated in our library are no longer valid.

### 3.2.4 Behavior in different media

As shown by the equations (formula 12a) and (formula 12b) the voltage/current curve is influenced not only by the NTC resistance R (T) but also by the dissipation factor $\delta_{th}$. The dissipation factor, in turn, depends on size, shape and leads of the device as well as on the medium surrounding the thermistor.

The voltage/current curves specified in the data sheets apply to still air. In agitated air or in a liquid the dissipation factor increases and the V/I curve shifts towards higher values of voltage and current. The opposite applies when the thermistor is suspended in a vacuum.

The voltage/current curve thus indicates by which medium the thermistor is surrounded. This means that NTC thermistors can be used for sensing the flow rate of gases or liquids, for vacuum measurement or for gas analysis.

### 3.2.5 Maximum power $P_{25}$

$P_{25}$ is the maximum power an NTC thermistor is capable of handling at 25 °C ambient temperature. When the maximum power $P_{25}$ is applied to the NTC thermistor, it operates in the self-heating regime (see chapter 3.2.1).

### 3.2.6 Thermal time constant $\tau_a$

Thermal time constant $\tau_a$ can be a crucial parameter when selecting a temperature sensor to match an application. The thermal time constant (thermal response time) of a temperature sensor is mainly influenced by:

- its design (e.g. sensor element, material used to assemble the sensor element in the sensor case, connection technology, housing),
- its mounting configuration (e.g. immersed, surface-mounted),
- the environment it will be exposed to (e.g. air flow, inactive air, fluid).

When a temperature sensor with temperature $T_1$ is immersed in a medium (air, water) with temperature $T_2$, the change in temperature of the sensor as a function of time follows to a first approximation an exponential law:

$$T(t) = T_2 + (T_1 - T_2) \cdot e^{-\frac{t}{\tau_a}} \qquad \text{(formula 15)}$$

After the thermal time constant $\tau_a$ the temperature change of the sensor is $1 - 1/e = 63.2\%$ of the temperature difference $T_1 - T_2$, this means $T(\tau_a) = T_1 + (T_2 - T_1) \cdot (1 - 1/e)$ (see figure 6).

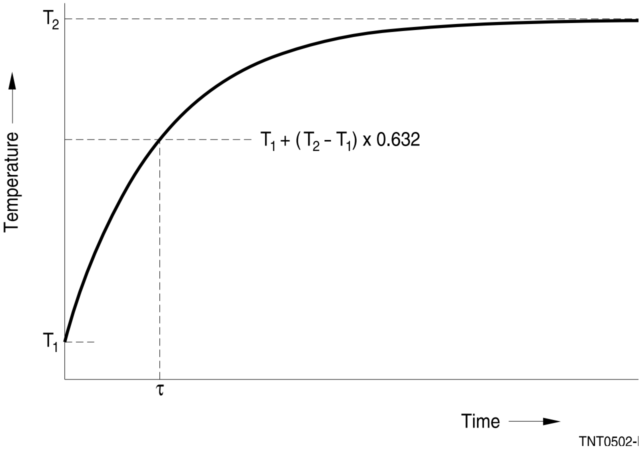

Figure 6

Temperature increase from $T_1$ to $T_2$ of a sensor modeled with an exponential law

EPCOS possesses extensive and sophisticated inhouse facilities to test the performance and reliability of temperature sensors. Test stations exist to carry out thermal response time measurement in air/water[1)] or air/air.

### Measurement of thermal time constant in water

The thermal response time is determined by a modified two bath method according to EN 60539, outlined in figure 7. The temperature sensor is held in an air channel having the temperature $T_1$. Below the air channel is a vessel filled with water having a temperature $T_2$. The thermal covering between air channel and vessel takes the form of a slider that can be moved horizontally.

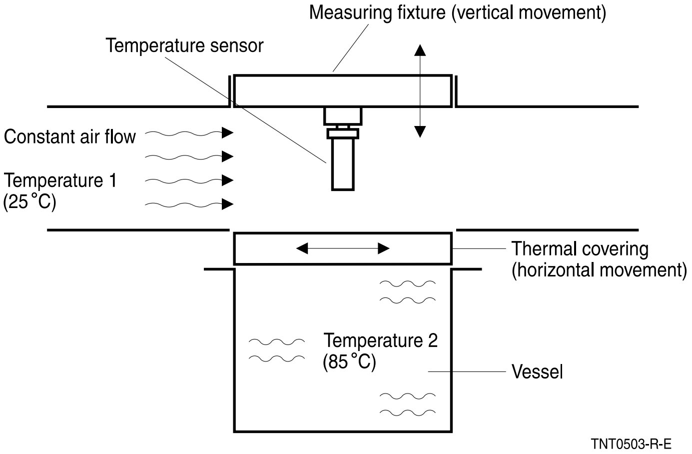

Figure 7
Measurement of thermal time constant in water

Before measurement, the zero-power resistance of the NTC thermistor at $T_1$, $T_2$ and a temperature between $T_1$ and $T_2$ are determined in a temperature controlled bath. Then the temperature sensor is exposed to an air flow constantly controlled to temperature $T_1$ until it has reached the surrounding temperature. Afterwards the slider is moved horizontally and simultaneously the fixture is quickly moved vertically to immerse the temperature sensor in the vessel. The software analyzes the data and calculates the thermal time constant $\tau_\alpha$.

By default $T_1$ is set to 25 °C $T_2$ is set to 85 °C.

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1) Note that only NTCs with special protection (e.g. K504, K276) can be exposed to liquid.

**Measurement of thermal time constant in air**

The thermal response time is determined by a double air channel method whose temperatures can be set separately. Furthermore, the air speed in each channel can be adjusted and measured with a calibrated anemometer.

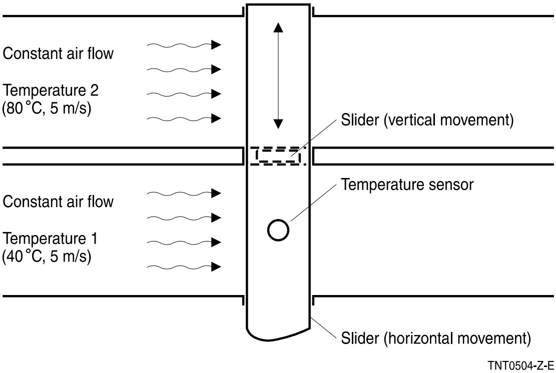

Figure 8

Measurement of thermal time constant in air

Figure 8 shows the two air channels from the top side. The temperature sensor can be moved horizontally from one air channel to the other. A slider between the two air channels can be moved vertically and opens a gap between the two air channels during movement of the sensor.

The resistance values of the NTC thermistor are determined at three different temperatures in a temperature controlled bath. When the test run starts, the temperature sensor is placed in one air channel with defined air speed and stabilized at temperature $T_1$ until it reaches the temperature of the ambient air. The sensor is then quickly moved to the other air channel with the same air speed at upper temperature $T_2$. When the experiment is finished the software calculates the thermal time constant $\tau_a$.

By default $T_1$ is set to 40 °C, $T_2$ is set to 80 °C, and air speed is adjusted to 5 m/s.

### 3.2.7 Thermal cooling time constant $\tau_c$

The thermal cooling time constant refers to the time necessary for a thermistor to vary its temperature by $1 - 1/e = 63.2\%$ of the difference between its mean temperature and the ambient temperature.

$\tau_c$ depends to a large extent on component design. The values of $\tau_c$ specified in this data book were determined in still air at an ambient temperature of 25 °C.

The NTC thermistor is internally heated to 85 °C to measure subsequently the time it requires to cool down to 47.1 °C at an ambient temperature of 25 °C. This adjustment to the ambient is asymptotic and occurs all the faster, the smaller the device is.

### 3.2.8 Heat capacity $C_{th}$

The heat capacity $C_{th}$ is a measure of the amount of heat required to raise the NTC's mean temperature by 1 K. $C_{th}$ is stated in mJ/K.

$$C_{th} = \frac{\Delta H}{\Delta T} \qquad \text{(formula 16)}$$

The relationship between heat capacity, dissipation factor and thermal cooling time constant is expressed by:

$$C_{th} = \delta_{th} \cdot \tau_c \qquad \text{(formula 17)}$$

### 3.2.9 Aging and stability

At room temperature the polycrystalline material shows solid-state reactions which lead to an irreversible change in the characteristics (usually resistance increase, change of B value etc).

Physical reasons for this may be thermal stress causing a change in concentration of lattice imperfections, oxygen exchange with the environment (with unprotected, non-glass-encapsulated thermistors) or diffusion in the contact areas of metallized surface contacts. At low temperatures these reactions slow down, but at high temperatures they accelerate and finally decline with time. To enhance long-term stability, our NTC thermistors can be subjected to an aging process directly after manufacture.