Sensor Heater Operation Modes

AN003e-0 (03/2026)

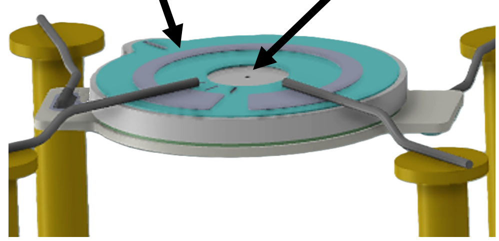
Scope

Outlines the fundamental heater characteristics and covers basic and advanced modes to control the heater of the sensor chip.

1 Heater location and function

The sensor heater is a platinum heater track located on the O2-sensitive sensor chip inside the sensor housing. It is heating the sensor chip to 550-600°C to enable the oxygen ion conductivity of the sensor cell. The heater temperature also defines the temperature at the diffusion hole. Stable temperatures at the diffusion hole ensure a stable sensor characteristic.

The heater can be treated as a resistive heater element and at the same time it acts as a temperature-dependent resistor like a Pt element. So, by accurately measuring the applied heater voltage and current via a 4-wire-setup, it is possible to measure the heater temperature.



2 Basic heater characteristics

- Heater cold resistance at 25°C: 3.25 ± 0.25 Ω
  - ± 0.25 Ω is the manufacturing tolerance, so for accurate heater temperature calculations, it is important to measure the individual heater cold resistance of each sensor
- Typical electrical operating parameters
  - Heater voltage 3.6 – 4.1 Vdc
  - Heater current ~400mA
  - Heater power 1.4-1.8 W

2.1 Temperature coefficient of the heater

$$\boldsymbol{T_H = \frac{\frac{R_H}{R_{25C}} - 1}{\alpha_{Pt550C}} + 25°C}$$

T_H ... *actual / measured heater temperature in °C*
R_{25C} ... *heater resistance at 25°C in Ω*
R_H ... *actual / measured heater resistance in Ω*
α_{Pt550C} ... *temperature coefficient for the Pt heater*

Assuming a cold resistance measurement at 25°C and a heater temperature set point range of 550~600°C the linear approximation of the temperature coefficient is: $\boldsymbol{\alpha_{Pt550C} = 3245ppm/K = 0.003245/K}$

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3 Heater operation modes

3.1 Constant heater voltage control

Operation with constant heater voltage is the basic mode. The sensor data sheets specify a constant heater voltage based on the sensor housing, which will ensure an acceptable heater temperature at standard conditions (O2/N2-mixture, 25°C, 1bar, low airflow/ventilation). The constant heater voltage operation mode will not compensate for external influences like:

- Variation of the ambient temperatures
    - For constant heater voltage the ambient temperature should stay within +/-10°C
- Variation of airflow, ventilation
    - In case of flow-through housing: Variation of the gas flow through the housing
- Variations of the gas pressure
    - Constant heater voltage under vacuum conditions might overheat the sensor, as vacuum provides better thermal insulation of the sensor chip
- Changes in gas composition
    - Gases with lower thermal conductivity (e.g. argon) might cause overheating
    - Gases with high thermal conductivity (e.g. helium) might cause underheating.
- Combustion processes on the heated sensor chip
    - The sensor must not be used in an explosive atmosphere
    - Combustible atmospheres might influence the sensor chip temperature, but the main concern is oxygen consumption, which will influence the sensor reading

In case of external influences, the heater temperature of the sensor might change, and this will affect the sensor accuracy. The loss of accuracy will be most prominent at full scale reading, while readings at the lower detection limit will barely be affected. So, for inertisation monitoring at low O2-levels the constant heater voltage mode could be an option despite its limitations.

In case of massive deviation from the standard conditions the sensor heater might be overstressed, which could reduce the sensor lifetime.

3.2 Constant heater resistance control

This control mode stabilizes the chip temperature by applying a control loop to keep the resistance of the heater constant. This includes the following elements:

- Define a heater set point resistance R_{HSP} for the control loop
    - This means measuring the sensors R_{25C} (cold resistance at 25°C) and apply section 3.2.1
    - Standard example R_{25C}=3.25 Ω => R_{HSP} =2.8 · 3.25Ω = 9.1 Ω
- Perform a soft start of the heater to reduce thermal stress during heat-up, see section 4.1
- Start the actual heater resistance control loop
    - Measure the actual heater resistance R_H, see section 3.2.2
    - Compare with heater set point resistance R_{HSP} and adjust the heater voltage accordingly
    - Apply plausibility checks to detect heater fault conditions

3.2.1 Heater set point temperature, respectively heater set point resistance value / ratio

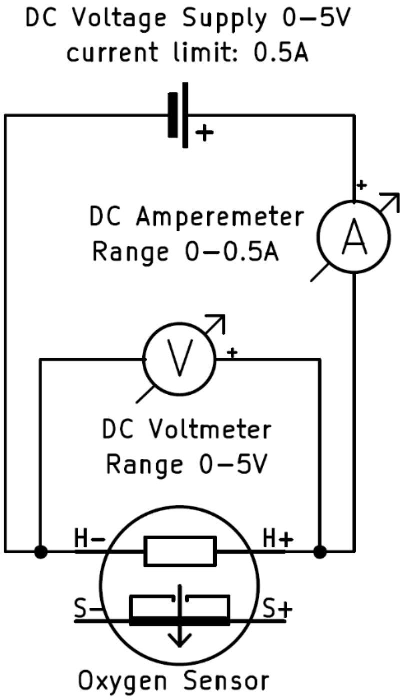
The equation of 3.2.1 could be used to convert a heater set point temperature T_{HSP} into a heater set point resistance R_{HSP} based on the cold resistance R_{25C} value of each individual sensor. For a general description it is useful to define the ratio $\frac{R_{HSP}}{R_{25C}}$. The standard recommendation is to use $\frac{R_{HSP}}{R_{25C}} = 2.8$.

Recommended heater set point temperature T_{HSP} and bias voltage are optimized to ensure optimal performance and lifetime stability up to the full-scale reading. By lowering the set point temperature and/or the bias voltage it might be possible to achieve better sensor performance at lower scale reading, but this will risk lifetime stability at full-scale. The table below shows possible deviation from the standard recommendation.

R_{HSP}/ R_{25C}	T_{HSP} [°C]	
<2.5	<487	unstable operation in upper range => not recommended
2.5	487	high risk of unstable operation in upper range=> not recommended
2.6	518	risk of unstable operation in upper range=> not recommended
2.7	549	lower limit
2.8	580	recommended
2.9	611	upper limit
3	641	high heater stress => reduced lifetime => not recommended
>3	>641	risk of immediate heater failure => not recommended

3.2.2 Measuring the heater resistance with 4-wire circuit

For an accurate heater resistance measurement, it is mandatory to apply a 4-wire circuit like in the picture on the right.



Cold resistance (R_{25C}) measurement:

- To avoid measurement errors due to self-heating only a small measurement voltage or current must be applied: <10mA or < 35mV. The measurement is temperature sensitive, deviations should be compensated by a calculation similar to section 2.1, at 25°C the linear approximation of the temperature coefficient is $\boldsymbol{\alpha_{Pt25C} = 3600ppm/K = 0.0036/K}$.
  It is also important that the sensor has not been previously operated, it might take up to 15min for the internal sensor chip to cool down to ambient temperature.

Measurement of actual heater resistance R_H during operation:

- The measurement is the same as for the cold resistance just at much higher heater voltage and current. The DC voltage supply can be used to adjust the heater resistance. The actual heater temperature can be calculated by applying section 2.1

3.2.3 Accuracy Considerations

The relative accuracy of the heater temperature control/measurement is more important than the absolute accuracy. Recommended relative accuracy is around +/-1°C at stable conditions and +/-5°C over a wider range of conditions. For absolute accuracy +/-20°C would be fully sufficient but this must include the measurement errors of the heater cold resistance, which is usually the dominating error.

The potential issues caused by cold resistance measurement / variations are illustrated by the following table. It calculates the resulting heater temperature T_H, if the control loop would use a fixed R_{HSP}=9.1 Ω, which does not include the correction based on the individual R_{25C}.

R_{H25C} [Ω]	ΔR_{H25C} [Ω]	R_{HSP} [Ω]	R_{HSP}/R_{H25C} [1]	T_H [°C]	Comment
3.25	0.00	9.1	2.800	580	best case
3.30	0.05	9.1	2.758	567	optimal range
3.20	-0.05	9.1	2.844	593	
3.35	0.10	9.1	2.716	554	acceptable range
3.15	-0.10	9.1	2.889	607	
3.50	0.25	9.1	2.600	518	higher risk of signal drift at full scale reading
3.40	0.15	9.1	2.676	542	
3.10	-0.15	9.1	2.935	621	not recommended (high heater stress)
3.00	-0.25	9.1	3.033	652	

These results also underline the importance of an accurate cold heater resistance measurement.

4 Heater protection and plausibility checks

4.1 Heater protection during heat-up

Inrush currents could occur when the heater voltage is turned on and the heater is still cold, e.g. a heater voltage of 3.6V and a cold resistance of 3.25Ω, would cause a short current peak of ~1.1A. Such event would stress the heater and could therefore reduce the sensor lifetime and should therefore be avoided. Therefore, the sensor datasheet specifies a heater current limit of 0.5A, which is usually ensured by one of the following approaches

Apply a heat-up ramp (constant heater resistance control):

- If the sensor is operated with a heater resistance control loop the straightforward approach is to slowly ramp up the heater control. Starting voltage of such a ramp should be ≤1.5V, this would reduce the inrush current to <0.5A. Typical duration of such a ramp should be 30s, assuming further 30s for thermal settling of the sensors. The overall heat-up time might be about 1minute.

Limitation of heater current (constant heater voltage control):

- For constant heater voltage control the current implementation should be part of the heater voltage control circuit, e.g. by using a DC-DC-converter with adjustable current limit.

4.2 Heater plausibility check during steady-state operation

Heater plausibility checks can be easily implemented for systems with constant heater resistance control. Heater voltage and current are already measured, while heater power can be calculated. Actual plausibility limits for these three heater values will be influenced by sensor housing and the thermal environment. Deviations from the expected range might indicate error conditions of the heater or the heater wiring.

Heater current:

- Typical heater current will be between 360mA and 480mA
- Heater current monitoring is the preferred way to detect heater or wiring issues. Open circuit would lead to 0mA while a short circuit would lead to an overcurrent condition

Heater voltage:

- Typical heater voltages will be between 3.3Vdc and 4.3Vdc.

Heater power:

- Typical heater powers will be between 1.3W and 1.9W and will be roughly defined be the sensor housing. Standard TO-8 housings will be on the lower end, while D0 and D1 housings are on the upper end of the power range.
- In case of a constant heater resistance control, the heater power will change indirect proportional to the ambient temperature around the sensor, i.e. if the sensor is used in hot environments, it will need less heater power.
- Heater power can also be influenced by thermal sinking and high ventilation/gas flow.

4.3 Heater plausibility check on the cold sensor

For a successful application of the constant heater resistance control the long-term stability of the heater resistance characteristics is important. Stability of the heater characteristic has been demonstrated during sensor life tests, nevertheless it might be negatively affected by specific environmental conditions of the application; e.g. chemical aggressive conditions or excessive operating temperatures could cause a drift of the heater characteristics.

A straightforward plausibility test would be a periodic check of the heater cold resistance at 25°C (R_{25C}).

5 Not recommended operation modes

5.1 Not recommended: heater operation with pulse wide modulation (PWM)

The recommended power source for sensor heater is a DC voltage supply like shown in 3.2.2. So, the common electronic approach would be to use a DC-DC converter, with a reasonable small ripple voltage.

As the sensor heater is an ohmic resistor it would also be possible to apply a (unfiltered) PWM voltage, but this comes with certain disadvantages/risks:

- The sensor heater itself does not contain any overcurrent protection. Using e.g. a 12Vdc-rail for the PWM could permanently damage the sensor, in case of an incorrect duty-cycle. Assuming a FW controlled circuit, a duty-cycle issue could be introduced by a FW-bug.
- Accurate heater voltage/current measurement is more complex for a PWM signal, and the verification of a correct implementation is much harder.
- Risk of crosstalk / influence of the sensor cell current measurement, e.g. due to artificially high leakage currents see also section 5.2

5.2 Not recommended: large potential differences, shared ground cable for H- and S-

Heater circuit (terminal H+ and H-) and cell circuit (terminals S+ and S-) are electrical isolated. The basic sensor circuit to the right shows two floating circuits, while electronic application circuits will usually introduce an electrical connection between these circuits. Such a connection might introduce potential differences, which could cause small leakage currents between heater and cell circuit. Leakage currents might be interpreted as a sensor current and could therefore lead to a small offset-error. To minimize leakage currents (<500nA) a maximum potential difference of ± 5Vdc between heater and cell circuits is recommended.

Standard approach for minimizing the leakage current is a common ground reference for heater and sensor circuits. Common ground could also introduce issues, e.g. it is not recommended to use a shared ground cable for H- and S- and just measure the sensor current on the high side (S+). The relatively high heater current (400mA) and the small sensor current (200uA) should be routed separately as far as possible, e.g. as heater power ground and analog ground and these two grounds shall then be connected at a single point.