

# TI Designs: TIDA-01526

## ヒート・メーターおよびコールド・メーター用の高精度温度測定のリファレンス・デザイン

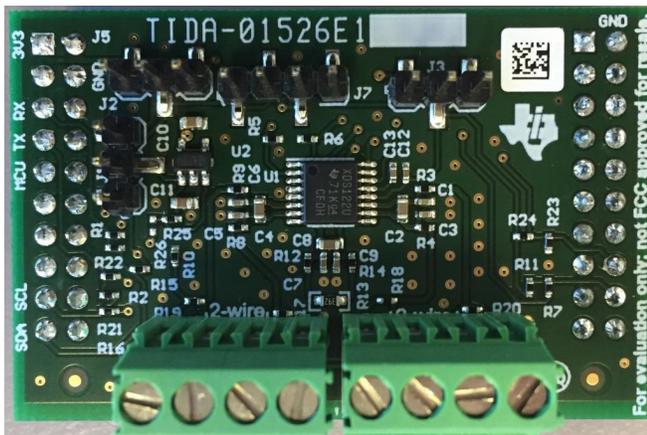


### 概要

このリファレンス・デザインでは、24ビットの低消費電力デルタ・シグマ( $\Delta\Sigma$ )アナログ/デジタル・コンバータ(ADC)を使用して、高精度の差動温度測定(DTM)サブシステムを実装します。ヒート・メーターおよびコールド・メーターのDTMサブシステムでは一般に、2線または4線式の测温抵抗体(RTD)、たとえばPT100、PT500、PT1000などが使用され、3°C~180°Cまでの水温範囲で10mKの差動温度測定精度が得られます。ヒート・メーターは欧州および中国で暖房のエネルギーに課金するため広く使用されており、コールド・メーターは中東で一般的に使用されています。このリファレンス・デザインでは、シングル・チップでコスト効率の優れた、超低消費電力のDTMシステムを実装します。このシステムを、テキサス・インスツルメンツの超音波または回転検出フロー測定サブシステムと組み合わせ、完全なヒート・メーターまたはコールド・メーターのソリューションを実現できます。

### リソース

- TIDA-01526      デザイン・フォルダ
- ADS122U04      プロダクト・フォルダ
- ADS122C04      プロダクト・フォルダ
- LP5907          プロダクト・フォルダ

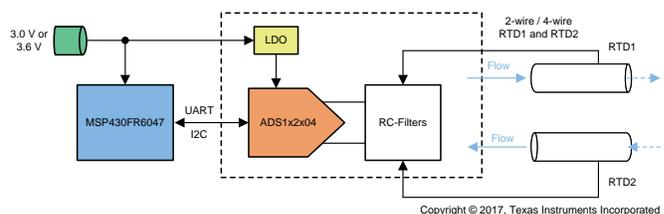


### 特長

- ヒート・メーターおよびコールド・メーターと熱計算機の温度測定サブシステムについて、RTDセンサのEN1434要件に合致
- 2つの2線式または4線式RTDで、0°C~150°Cについて絶対温度偏差が $\pm 60\text{mK}$ であり、EN1434-5:2014の $\pm 100\text{mK}$ の制限に合致
- 3つの代表的な温度測定ポイント、たとえば10°C、30°C、50°Cにおいて、各PTセンサが $\pm 700\text{mK}$ の誤差上限に合致(EN1434-5:2014)
- ADC122x04は、50 $\mu\text{s}$ のスタートアップ時間と、プログラム可能な電流ソース、ゲイン、出力データ・レートにより、電源サイクリングを使用して、非常に低い消費電力を実現
- 2つのRTDを直列に使用し、0.01°Cの分解能で差動温度測定
- 40ピンのBoosterPack™プラグイン・モジュールのフォーム・ファクタ(20ピンのBoosterPackプラグイン・モジュールと下位互換)

### アプリケーション

- 2線式または4線式PT100/PT500/PT1000を使用した住居および産業用のヒート・メーター
- 熱計算機(ユニットをフローおよび温度センサから分離)
- 産業用コールド・メーター(加熱量の代わりに冷却量を測定)
- PT100/PT500/PT1000を使用した高精度差動温度測定





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## 1 System Description

The European EN1434-1 through EN1434-6 set of standards define the technical requirements for heat meters in the European Union (EU); such devices are mandatory in many EU countries to bill for heat in multi-dwelling units. Heat meters are flow meters (usually with water) with an integrated high-precision DTM subsystem, which enables calculating the heat (or cold in cooling systems) based upon the flow volume and the temperature differential between forward (outlet) and backward (inlet) flow. Residential heat meters use 2-wire PT500 or PT1000 sensors, which are firmly integrated (soldered) inside the device and cannot be replaced in the field.

4-wire RTDs are more often for use in heat calculators, which are separate units, processing the input data from separate flow and temperature sensors. In heat calculators, the temperature sensors can be detached from the primary systems and mounted up to 15 m (2-wire RTDs) or farther away (4-wire RTDs required). The RTD sensors of the same precision class—for example Class A as in EN 60751—or the heat calculator device itself can be replaced independently from each other. This reference design has been tested in both 2-wire RTD and 4-wire RTD configurations.

### 1.1 Key System Specifications

The TIDA-01526 requirements for the DTM are derived from the system requirements of a typical EN1434 Class 1, 2, or 3 compliant heat meter.

式 1 defines the relative error, E.

$$E = \frac{V_d - V_c}{V_c} \times 100\% \quad (1)$$

where,

- $V_d$  = displayed (measured value),
- $V_c$  = correct (true) value.

The relative error limit of the temperature differential reported by the RTD pair is defined in EN1434-1:2014-02 as follows:

$$E_t = \pm \left( 0.5 + 3 \frac{\Delta\theta_{min}}{\Delta\theta} \right) \quad (2)$$

where,

- $E_t$  is the temperature error (unitless),
- $\Delta\theta$  is the temperature differential between the two RTD sensors.

EN1434 recommends  $\Delta\theta_{min} = 3 \text{ K}$  between the inlet and outlet flow as the typical starting point for accumulating (or measuring) energy.

When the temperature differential  $\Delta\theta = 3 \text{ K}$ ,  $E_t = \pm 3.5\%$  and is the largest. With an increasing  $\Delta\theta$ , the error limit goes lower, and for a temperature differential of  $100 \text{ K}$  and  $\Delta\theta_{min} = 3 \text{ K}$ :  $E_t = \pm 0.59$ .

表 1 defines the parameters for the DTM and some general system requirements. The DTM subsystem should operate over a temperature range from  $-40^{\circ}\text{C}$  to  $85^{\circ}\text{C}$  and be supplied from any primary Li-Ion battery with either 3.0-V or 3.6-V nominal voltage. The common temperature range across residential and industrial heat meters using RTD sensors spans from  $0^{\circ}\text{C}$  to  $180^{\circ}\text{C}$ .

**表 1. Key System Specifications**

| PARAMETER                                       | SPECIFICATIONS   | DETAILS                 |
|---|--|-------------------------|
| Input power source                              | One Li-Ion battery (3.0 V or 3.6 V)  | —                       |
| RTD temperature calculation                     | –200°C to +850°C look-up table with 1°C resolution implemented in the RTD temperature linearization MSP430™ MCU firmware                                 | —                       |
| RTD sensor configuration                        | 2-wire or 4-wire   | —                       |
| RTD sensor type                                 | PT100, PT500, PT1000   | —                       |
| Measurement cycle                               | Approximately 20 ms (90 SPS, turbo mode, single-shot conversion)   |                         |
| Measurement period                              | Adjustable (for example, every 4 seconds)  | <a href="#">3.1.2</a>   |
| Differential temperature accuracy (RTD1 - RTD2) | < 30 mK from 0°C to 150°C (with 2-wire PT500 and 4-wire PT1000); depends on RTD sensor accuracy (DIN Class)  | —                       |
| Power-down duration                             | Approximately 98% (for one measurement cycle of two RTD sensors per 1 second)  | <a href="#">3.2.4.3</a> |
| Average power-down consumption                  | 1 µA (LDO regulator disabled, ADS122x04 powered off)   | <a href="#">2.2</a>     |
| Average active power consumption                | Depends on the number of averaged measurements and if "chopping" is used   | —                       |
| Temperature measurement range                   | –200°C to +850°C (0°C to 150°C tested)   | <a href="#">3.2.3</a>   |
| Operating temperature                           | Limited by the battery used (LiMnO <sub>2</sub> or LiSoCl <sub>2</sub> ), as both ADS122x04 and LP5907 operate from –40°C to +125°C                      | <a href="#">2.2.1</a>   |
| Operating voltage                               | 2.8 V to 5.5 V if LP5907-2.8 LDO regulator is used or 2.3 V to 5.5 V if LDO regulator is bypassed.<br>Oil bath tests at 3.3 V and LDO regulator bypassed | <a href="#">2.2.3</a>   |
| Form factor                                     | 3.3 × 5.15 cm (40-pin BoosterPack™ Plug-in Module connectors, also compatible with 20-pin BoosterPack™ Plug-in Module)                                   | <a href="#">4</a>       |

## 2 System Overview

Heat meters are typically powered by one Lithium-based battery cell. Heat meters must operate from 6 to 12 years (or longer) depending on the ambient temperature conditions and the number of wireless communication packets transmitted during a specific time period. Therefore, a key product design consideration is the lowest power consumption.

Heat meters typically use the DTM subsystem to measure temperature every 4 seconds (or less frequently), so that the subsystem can be powered off for most of the measurement cycle. In addition to the highly accurate temperature measurement, the energy consumption of the system is limited by and battery life is extended by the ability to quickly wake from sleep mode, sample the RTD element, transmit the results to the host microcontroller unit (MCU), and return to sleep mode. The ADS122x04  $\Delta\Sigma$  ADC used in the system meets these requirements with a 50- $\mu$ s wake time, highly accurate 0.01°C temperature resolution, and a Fast-Mode Plus (1Mb) I<sup>2</sup>C communications interface.

### 2.1 Block Diagram

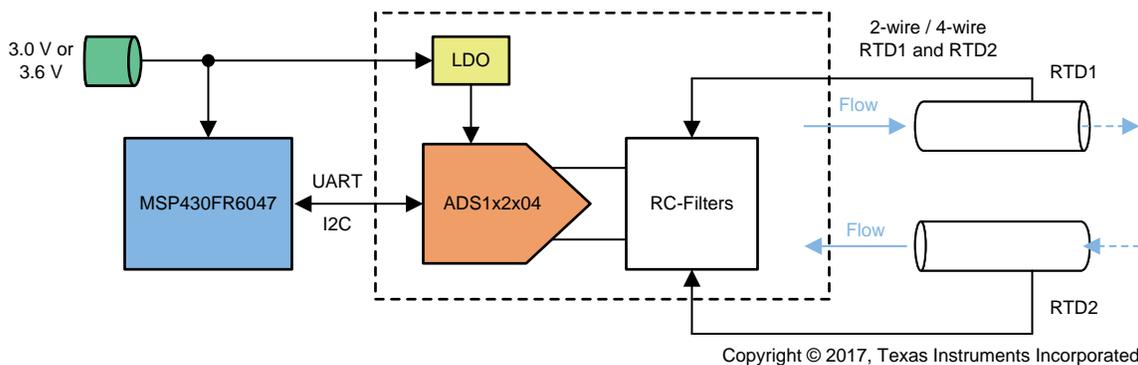


図 1. Block Diagram of TIDA-01526

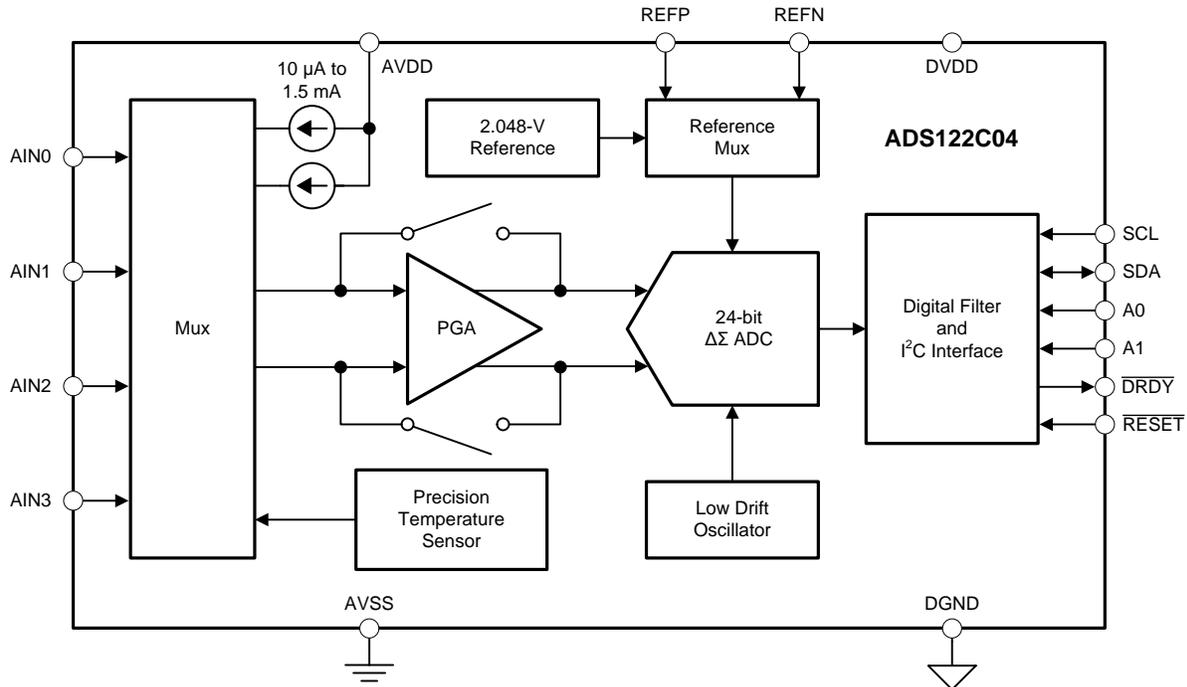
The ADS122x04 device and the LP5907 low dropout (LDO) linear regulator with the analog RC filters build the TIDA-01526, including two 4-wire terminal blocks for connecting the RTD sensors, which can be either 2- or 4-wire. Two resistors with 0  $\Omega$  each are populated by default next to each terminal block and enable 2-wire RTD connections; these resistors must be removed if using 4-wire RTD sensors.

### 2.2 Highlighted Products

#### 2.2.1 ADS122C04

The ADS122C04 is a precision, 24-bit ADC that offers many integrated features to decrease system cost and component count in applications that measure small sensor signals (see 図 2). The device features two differential or four single-ended inputs through a flexible input multiplexer (MUX), a low-noise, programmable gain amplifier (PGA), two programmable excitation current sources, a voltage reference, an oscillator, and a precision temperature sensor.

The device can perform conversions at data rates up to 2000 samples-per-second (SPS) with single-cycle settling. At 20 SPS, the digital filter offers simultaneous 50-Hz and 60-Hz rejection for noisy industrial applications. The internal PGA offers gains up to 128. Because of this PGA, the ADS122C04 is ideally suited for applications measuring small sensor signals, such as resistance temperature detectors (RTDs), thermocouples, thermistors, and resistive bridge sensors. ADC data are transferred to an external host MCU over an I<sup>2</sup>C™-compatible Interface, supporting Standard-mode, Fast-mode, and Fast-mode Plus with a 1000-kHz data rate.



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図 2. ADS122C04 Block Diagram

The change in resistance or voltage drop per 1°C temperature change is small; therefore, a high-precision ADC with a high bit count is necessary. Because of the fact that the signal of a RTD temperature sensor is practically DC, a sampling speed below 1 Hz is sufficient and can be achieved with an ADC, which measures the two RTDs sequentially, using an internal multiplexer.

Key parameters for the ADC are the standard DC parameters: offset, gain, integral nonlinearity (INL), common-mode rejection ratio (CMRR), power supply rejection ratio (PSRR), input current, and parameter drift. A relatively slow, precision ADC (usually a ΔΣ ADC), is best suited here; using a faster ADC would only increase cost and power consumption.

Another important point is that the data converter must have two differential inputs to connect two 2-wire or 4-wire RTDs, and an additional external reference input to connect the reference resistor voltage for ratiometric measurement. The digital interface to the host MCU should be as fast as possible, where serial interfaces such as serial peripheral interface (SPI), I<sup>2</sup>C, or universal asynchronous receiver-transmitter (UART) are often supported in hardware.

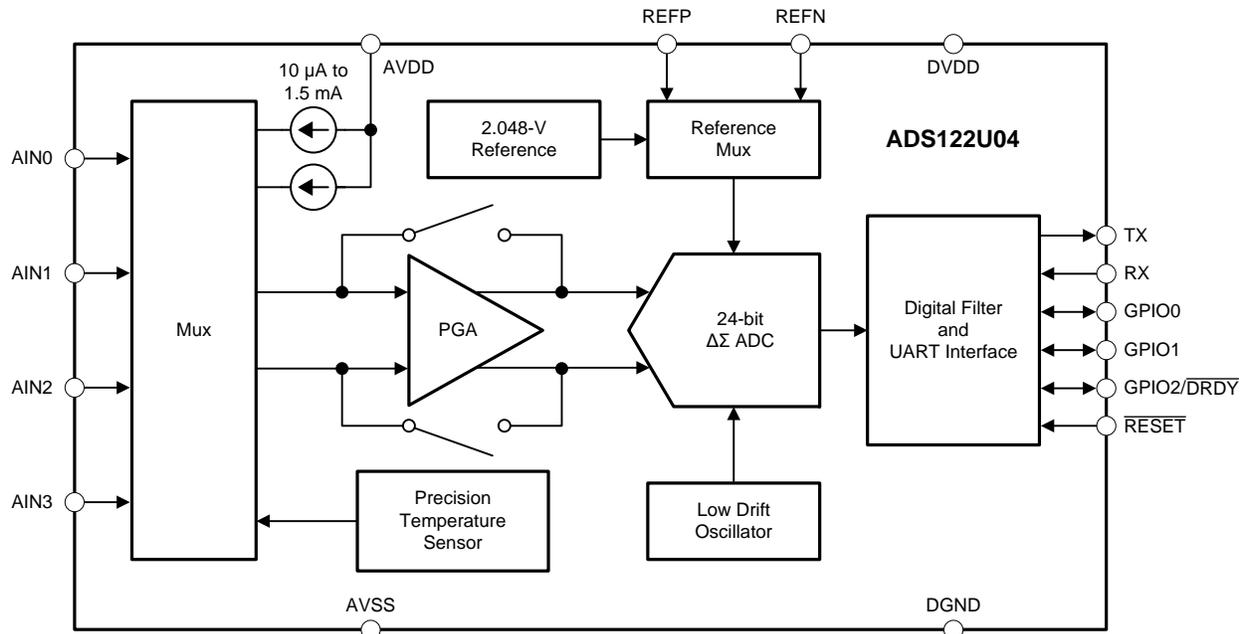
Without knowing anything about the errors introduced by the circuit and the ADC, a lower bound for the required bit count can be calculated. Assuming a perfect reference, perfect linearity, and a sensor signal that perfectly uses the ADC input range, the minimum bit count can be calculated from the required amount of discrete output values. The required temperature range from 0°C to 180°C in 0.005°C steps corresponds to 36001 steps. The 0.005°C is the acceptable resolution for each RTD sensor, thus, for the two sensors the desired 0.01°C resolution of the subsystem is achieved.

In bits, this value is equal to the logarithm  $\log_2(36001) = 15.136$  bit. In practice, the required bit count is higher because the above ideal assumptions are not achievable in a real-world application. Thus, ADCs with at least 16 bits of resolution are required; here the 24-bit ADC ADS122C04 and ADS122U04, which meet all the above requirements, were chosen.

### 2.2.2 ADS122U04

The ADS122U04 is another precision, 24-bit ADC that features a 2-wire, UART-compatible interface (see [Figure 3](#)). In applications that require galvanic isolation, this UART interface minimizes the number of digital isolation channels, thus saving cost, board space, and power.

The ADS122U04 and ADS122C04 are both offered in a leadless 16-pin WQFN or a 16-pin TSSOP package, and are specified over a temperature range of  $-40^{\circ}\text{C}$  to  $+125^{\circ}\text{C}$ . Although the two devices are not exactly pin-compatible, as they differ in the digital interface functionality, they can be still used with the same layout, as implemented in this reference design.



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**Figure 3. ADS122U04 Block Diagram**

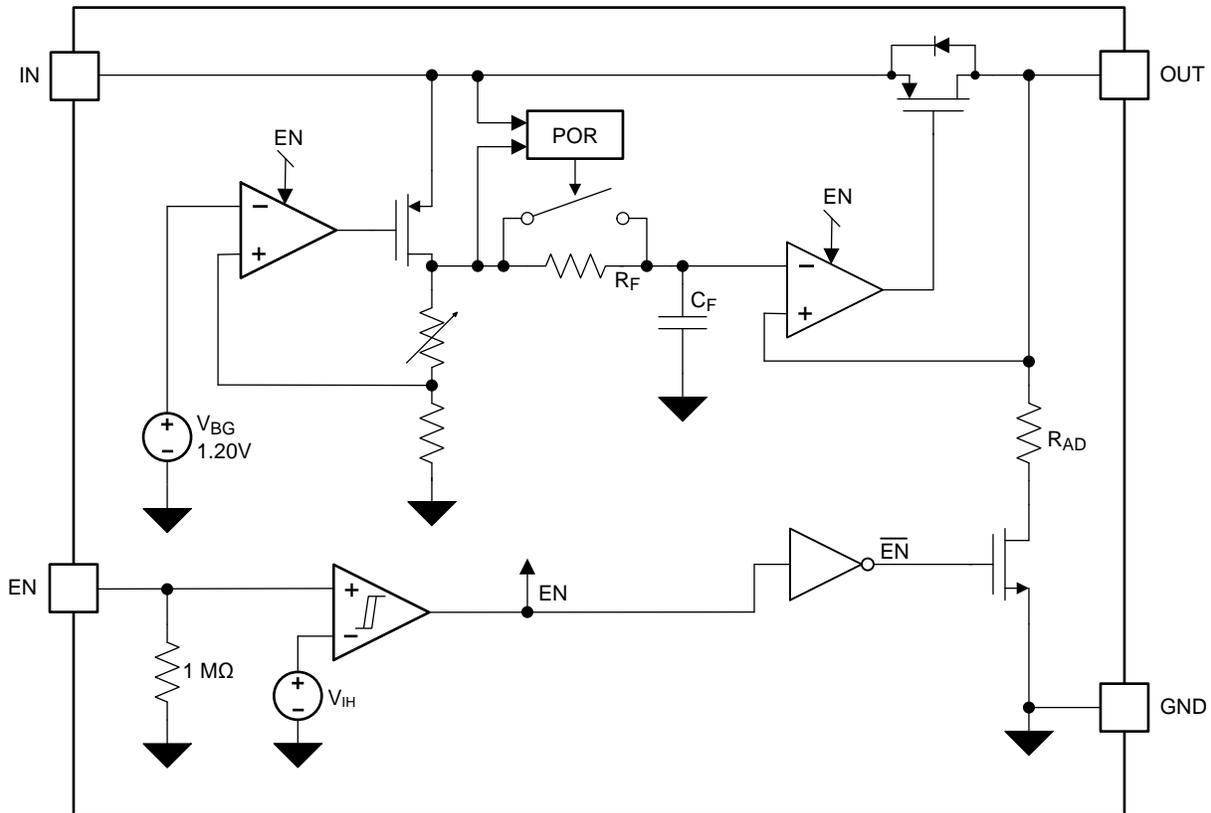
The selected devices have one differential reference input, excellent noise performance, a power consumption of only a few 100  $\mu\text{A}$  during conversion, and fast start-up time from power down. The integrated multiplexer allows for sequential sampling of the two differential input pairs, and the two integrated and programmable current sources can be routed to any of the analog pins, enabling a ratiometric configuration.

The alternative ADS1220 device offers the same data converter features and performance but with an SPI rather than the UART and  $I^2\text{C}$  interface of the ADS122x04 shown here.

### 2.2.3 LP5907

The LP5907 is a low-noise LDO that can supply up to 250-mA output current (see 図 4). Designed to meet the requirements of RF and analog circuits, the LP5907 device provides low noise, high PSRR, low quiescent current, and low line or load transient response figures. Using new innovative design techniques, the LP5907 offers class-leading noise performance without a noise bypass capacitor and the ability for remote output capacitor placement.

The device is designed to work with a 1- $\mu$ F input and a 1- $\mu$ F output ceramic capacitor (no separate noise bypass capacitor is required).



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図 4. LP5907 Block Diagram

## 2.3 Design Considerations

The required accuracy goal for the DTM subsystem in heat meters is much tighter than the best available class of RTDs. For reference, a Class DIN 1/10 RTD, also known as Class AAA, has an accuracy of  $\pm 0.03^{\circ}\text{C}$  at  $0^{\circ}\text{C}$  and  $\pm 0.12^{\circ}\text{C}$  at  $180^{\circ}\text{C}$  [1].

This inaccuracy is already worse than the required  $0.01^{\circ}\text{C}$  temperature accuracy, and adding other (nonlinear) errors in the signal processing path makes system calibration mandatory to meet the required performance.

Usually, a differential measurement requires double the precision of the individual measurements. Some errors can partially compensate or even cancel each other. This behavior is exploited in this reference design, where the ratiometric measurement approach as shown in 2.4.4 is used. The ratiometric circuit makes sure that the noise and drift of the excitation current does not have any effect on the measurement.

## 2.4 System Design Theory

### 2.4.1 RTD Overview

Resistance temperature detectors (RTDs) are typically made of a metal with predictable resistance characteristics over temperature, allowing the calculation of temperature from resistance measurement. RTD sensors offer wide temperature ranges, good linearity, and excellent long-term stability and repeatability. These properties make RTD sensors suitable for precision temperature measurement applications, such as heat meters or industrial temperature sensor transmitters.

Platinum is the most commonly used material for RTDs due to its high resistivity and long-term stability. Sir William Siemens proposed platinum as an element for RTDs in 1871. As a noble (chemically inert) metal, platinum is less susceptible to contamination, it follows a very linear resistance-temperature relationship, and is used in RTD sensors that follow the ITS-90 International Temperature Standard.

Most RTD measurement applications use an adjustable current source to excite the RTD element and create a voltage across the RTD, which is proportional to the resistance of the RTD and the excitation current. This voltage potential is fed to the inputs of an ADC, such as ADS122x04, and is amplified to a suitable level if required. The ADC converts the voltage into a digital output code that is used to calculate the RTD resistance.

Platinum RTDs are also the recommended type of temperature sensors in the document [EN1434-1 through -6](#) for heat and cold meters and also for heat calculators.

Several classes of PT sensors are available (see table regarding RTD class tolerance information in [Isolated Loop Powered Thermocouple Transmitter Reference Design](#)): tolerance Class C, Class B, Class A, Class AA, and Class AAA (also referred to as 1/10 DIN Class B).

### 2.4.2 Measurement Resolution

Many factors can influence the measurement of the RTD sensor resistance, such as external noise, non-optimized printed-circuit board (PCB) layout, component parameter variations, or even the self-heating of the sensor caused by the excitation current. The self-heating coefficient usually defines this error. In the case of flowing water, typical self-heating coefficients are approximately  $0.01\text{ K/mW}$ . The errors introduced by self-heating can be eliminated in a DTM system if both sensors are identical, equally mounted, and excited with equivalent currents. Keep the excitation current as low as possible to minimize the overall system power consumption. The self-heating error can occur for all types of RTDs, not just platinum resistors.

Within the defined temperature range from 0°C to 180°C, where heat meters mostly operate, the resistance of a PT1000 sensor varies from 1000 Ω to 1684.8 Ω, according to the ITS-90 (European Curve, Alpha = 0.00385). For the desired single RTD measurement accuracy of 5 mK, exactly 200 steps per 1°C are required. With an average 3.7-Ω increase per 1°C as per the ITS-90 table, this 5-mK step translates into a resistance change of just 0.0185 Ω at 1684.8 Ω for a PT1000, which must be detected accurately. Together with an excitation current of 250 μA, this change is equivalent to a voltage step of 4.625 μV.

For a PT500 sensor (also commonly used in heat meters), the desired resistance change is 0.00975 Ω per 5-mK change using the same 250-μA current. Instead of doubling the excitation current to 500 μA, increase the programmable gain applied inside the ADS122x04 to be more power efficient.

The input-referred noise of the ADS122x04 defines the achievable resolution of the RTD measurement and is documented in [ADS122U04 24-Bit, 4-Channel, 2-kSPS, Delta-Sigma ADC With UART Interface](#) (see Table 1 and Table 3). Because enabling the PGA adds additional current, keeping the PGA in bypass mode is more power efficient, which is the case in this reference design.

Any DC errors in the RTD measurement path relate to the accuracy of the measurement, but can be compensated for during the calibration process.

The 0.01°C accuracy is a stated design goal because this level of accuracy meets the EN1434 requirements for temperature measurement with RTD sensor pairs in heat meters.

### 2.4.3 Converting RTD Resistance Into Temperature

According to Farnicola and Iacomini, the second-order Callendar-Van Dusen equation, which is commonly used to convert the RTD resistance into temperature value, has a peak approximation error of approximately 27 mK around +80°C in a temperature range from 0°C to +200°C (Farnicola, Iacomini 2008). A more accurate interpolation function would decrease the conversion error; this function will not be linear but rather of high-order. View examples of several approximation functions [here](#): A cubic fit function provides 0.026°C precision between 0°C and +400°C. For comparison, a rational polynomial function with even more multiply steps and one division step delivers 0.015°C for the full RTD range of –200°C to +850°C.

This design uses piecewise approximation rather than the cubic or rational polynomial interpolation function to minimize energy consumption in the host MCU. The piecewise approximation is documented in and described in detail in [Small Form Factor, 2-Wire, 4- to 20-mA Current-Loop, RTD Temperature Transmitter](#), where RTD values defined in ITS-90 are used as a look-up table with steps of one degree Celsius. The associated [TIDA-00165 software](#) example shows the implementation on an MSP430™ MCU.

In [Isolated Loop Powered Thermocouple Transmitter](#), the piecewise approximation has been modified by pre-calculating the RTD look-up values into 24-bit ADC codes. An Excel sheet (based on TIDA-00189) for making this conversion for the PT100, PT500, and PT1000 sensors is included in the firmware source code of TIDA-01526.

The values of PT500 and PT1000 are generated by simple multiplication with factor 5 or 10 of the PT100 reference values.

The disadvantage of using pre-defined look-up tables is that these are less flexible than the Callendar-Van Dusen (CVD) equation and depend on the RTD resistance and gain used. Subsequently, multiple tables for PT100, PT500, or PT1000 and more MCU memory to store those are required, if multiple RTD types are supported.

EN1434-2 states that the CVD equation (defined in EN 60751) must be used for converting the resistance value into temperature. The TIDA-01526 firmware can be modified to use CVD calculations instead; in such cases, the included IQMath libraries and the Low-Energy Accelerator (LEA) subsystem of MSP430FR6047 can be used.

#### 2.4.4 Ratiometric Measurement Circuit

Any high-accuracy RTD measurement requires offset and gain calibration. Independent of the used measurement method, the RTD must be excited with a voltage or current to get a temperature proportional voltage signal.

The simplest resistance measurement approach is a 2-wire measurement, which has the disadvantage of unpredictable errors caused by the unknown resistance of the sensor cables. Achieve a significantly better precision by using 4-wire RTDs in the Kelvin connection, which is widely used in precision temperature measurements. Regardless if a 2-wire or 4-wire measurement is done, best practice is to implement a ratiometric measurement, where the reference voltage of the ADC is generated by the same current source used to excite the sensor element. This voltage generation causes all errors from the excitation current source to influence the sensor signal and the reference signal in the same way.

The ADC output,  $X$ , is given by 式 3.

$$X = \frac{V_{\text{SIG}}}{V_{\text{REF}}} \quad (3)$$

The ADC output,  $X$ , cancels the influence of the excitation source and all its errors. Another advantage of a ratiometric conversion is that excitation noise and reference noise are correlated and therefore the influence of these noise sources is also canceled and only the ADC noise stays. For additional explanations, see [The impact of voltage reference noise on delta-sigma ADC resolution](#).

Different approaches are feasible for implementing ratiometric measurements; the simplest approach is to use the supply voltage as a reference voltage. This can be done with a bridge circuit, and does not require any external precision reference. If the sensors are excited by a current source such as the one in this reference design, then the reference voltage is generated with a reference resistor in the excitation current path. However, such a reference resistor must be very precise to obtain accurate measurement results; typically resistors with 0.1% tolerance and better than  $\pm 25$  ppm/K temperature coefficient are used. The measurement circuit implemented in TIDA-01526 is a ratiometric measurement which supports 2-wire and 4-wire RTDs, and is described in [Low-Cost, Single-Chip Differential Temperature Measurement Solution With ADS1220](#).

In all cases, note that the reference voltage determines the full-scale signal of the ADC, essentially the upper bound of the input signal without clipping. To define this reference voltage, determine the optimum combination of selected gain, excitation current value, and  $R_{\text{REF}}$  for the PT500 or PT1000 sensors, which can achieve the required measurement accuracy and resolution at the lowest possible power consumption.

#### 2.4.5 Choosing Current, Gain, and $R_{\text{REF}}$ for ADS122x04

[Low-Cost, Single-Chip Differential Temperature Measurement Solution With ADS1220](#) offers optimized values for the measurement of two RTDs in series. This TI TechNote forms the base for which this TIDA-01526 reference design was established. The only minor modification between these designs is that the  $R_{\text{REF}}$  was changed from  $3840 \Omega$  to  $3900 \Omega$  with 0.1% tolerance and  $\pm 25$  ppm/ $^{\circ}\text{C}$ , which is a common resistor value and is available from multiple vendors. The default excitation current (IDAC value) of the ADS122x04 is  $250 \mu\text{A}$ , which is optimized for PT500 sensors and can be set to  $100 \mu\text{A}$  for PT1000 sensors.

##### Step 1: Determine Maximum Useable IDAC Current

First, a simple check is done to verify if the maximum voltage on REFP0 is not exceeded by the excitation current and the resistance in the measurement path.

The voltage REFP0 is calculated:

$$\text{REFP0} = \text{AVDD} - \text{IDAC compliance voltage} \quad (4)$$

Assuming  $\text{AVDD} = 2.8 \text{ V}$  with PT1000 sensors and a maximum absolute RTD temperature of  $180^{\circ}\text{C}$ :

$$\text{REFP0} = 2.8 \text{ V} - 0.9 \text{ V} = 1.9 \text{ V} \quad (5)$$

This 1.9 V sets the limit for the maximum current:

$$100 \mu\text{A} \times (2 \times 1684.8 + 3900) \Omega = 0.73 \text{ V} \quad (6)$$

$$250 \mu\text{A} \times (2 \times 1684.8 + 3900) \Omega = 1.82 \text{ V} \quad (7)$$

Check that  $1.82 \text{ V} < 1.9 \text{ V}$  and is therefore the maximum IDAC current that can be used in the ADS122x04 device.

The ADS122x04 features dual-matched programmable current sources from 10  $\mu\text{A}$  to 1.5 mA; 100  $\mu\text{A}$ , 250  $\mu\text{A}$ , 500  $\mu\text{A}$ , or 1000  $\mu\text{A}$  are supported values.

EN1434 mandates that, for resistance measurements, the selected excitation current keeps the power dissipation at or below 0.2 mW (RMS).

Therefore, for a 1685- $\Omega$  worst-case PT1000 resistance at 180°C, 100  $\mu\text{A}$  is the value to set in the ADS122x04. If calculating the RMS power over the full duty-cycle of the measurement of 1 second or longer, then all other IDAC values can be used.

For a PT500 with a 800- $\Omega$  resistance at 156°C, an excitation current setting up to 250  $\mu\text{A}$  for the IDAC is allowed, if the 0.2-mW limit is retained throughout the duration of the measurement.

If using PT100 sensors, IDAC settings of 500  $\mu\text{A}$  or 1000  $\mu\text{A}$  are also possible.

### Step 2: Select IDAC and Check if Minimal $V_{REF}$ is Met

In this step, the largest compliant IDAC value of 250  $\mu\text{A}$  from Step 1 is multiplied with  $R_{REF} = 3.9 \text{ k}\Omega$  and compared to the minimum  $V_{REF} = 0.75 \text{ V}$  of the ADS122x04:

$$250 \mu\text{A} \times 3.9 \text{ k}\Omega = 0.975 \text{ V} > 0.75 \text{ V} \text{ (which is true)} \quad (8)$$

### Step 3: Select Fastest Sampling Data Rate that Meets Target Noise Performance

The target noise performance depends on the desired temperature accuracy of 10 mK and the resistance of the selected PT sensor, which is a PT1000:

$$\text{Sensitivity}_{RTD} = \text{PT}_{\text{nominal}} \times 0.00385 \text{ } 1/^\circ\text{C} = 1000 \Omega \times 0.00385 \Omega / ^\circ\text{C} \quad (9)$$

Design goal for temperature accuracy: 10 mK

$$\text{Target input - Referred noise} = \text{Sensitivity}_{RTD} \times \text{IDAC} \times \text{Temperature resolution} / 1000 \text{ } (\mu\text{V}_{\text{RMS}}) \quad (10)$$

$$\text{Target input - Referred noise} = 3.85 \Omega/^\circ\text{C} \times 250 \mu\text{A} \times 10 \text{ mK} / 1000 = 9.63 \mu\text{V}_{\text{RMS}} \quad (11)$$

The ADS122x04 data sheet defines the input-referred noise for various parameters, such as gain level, AVDD supply voltage, PGA enabled or bypassed, turbo mode, and so forth (see [ADS122U04 24-Bit, 4-Channel, 2-kSPS, Delta-Sigma ADC With UART Interface](#), Tables 1 to 8).

If using normal mode for the data sampling, then the fastest possible rate is 330 SPS with 8.12  $\mu\text{V}_{\text{RMS}}$ ; while in turbo mode, the rate of 660 SPS with a value of 9.06  $\mu\text{V}_{\text{RMS}}$  is less than the 9.63  $\mu\text{V}_{\text{RMS}}$ .

If the target input-noise limit is set lower than 9.63  $\mu\text{V}_{\text{RMS}}$ , then decrease the sampling data rate with the 20 SPS in normal mode and 40 SPS in turbo mode delivering the lowest input-referred noise levels.

## 2.4.6 Converting ADC Output Code to RTD Resistance

Both the ADS122C04 and ADS122U04 devices provide 24-bit data in binary 2's-complement format. The positive full-scale input produces an output code of 7FFFFFFh and the negative full-scale input produces an output code of 800000h. The output clips at these codes for signals that exceed positive or negative full-scale (see the ADS122x04 data sheet). The output ADC code represents the measured  $V_{IN}$ , as in 式 12, which is usually applicable to any type of ADC.

$$V_{IN} = 1 \text{ LSB} \times \text{ADC}_{\text{CODE}} \quad (12)$$

To calculate the  $V_{IN}$ , substitute the least significant bit (LSB) in 式 13.

$$1 \text{ LSB} \left( \frac{\text{V}}{\text{code}} \right) = \frac{\text{FSR}}{2^{24}} \quad (13)$$

where,

- FSR = Full-scale range,
- Total number of possible decimal codes is  $2^{24}$ .

The FSR and the *input-referred voltage*  $V_{IN}$  have this 式 14 relationship, depending on whether any internal gain in the ADC device has been applied:

$$\text{FSR}(V) = \frac{m \times V_{\text{REF}}}{\text{Gain}} \quad (14)$$

Here,  $m$  is the reference voltage scaling factor, and as there is a differential input, which allows values from  $-V_{\text{REF}}$  to  $+V_{\text{REF}}$ , then  $m = 2$ . The gain is the specific internal gain value used and is set by the GAIN[2:0] bits in Register 0 of the ADS122x04. In addition, there are the following definitions for  $V_{IN}$  and  $V_{\text{REF}}$ , where IDAC is the current source (see IDAC1 or IDAC2 settings in Register 2) used to excite both RTD sensors and  $R_{\text{REF}}$ :

$$V_{IN} = R_{\text{RTD}} \times \text{IDAC} \quad \text{and} \quad V_{\text{REF}} = R_{\text{REF}} \times \text{IDAC} \quad (15)$$

Substituting the  $V_{IN}$  and  $V_{REF}$  values in 式 12 results in:

$$R_{RTD} \times IDAC = \frac{m \times R_{REF}}{Gain \times 2^{24}} \times ADC_{CODE} = \frac{m \times R_{REF} \times IDAC}{Gain \times 2^{24}} \times ADC_{CODE} \quad (16)$$

Dividing 式 16 by (IDAC), results in 式 17 for converting the ADC code into RTD resistance:

$$R_{RTD} \times \frac{m \times R_{REF}}{Gain \times 2^{24}} \times ADC_{CODE} \quad (17)$$

In the ratiometric measurement of TIDA-01526,  $R_{REF} = 3900 \Omega$  and gain = 1 V/V, 2 V/V. or 4 V/V (all with PGA bypass enabled), while  $m = 2$ .

#### 2.4.7 Converting RTD Resistance to Equivalent Temperature ( $T_{RTD}$ )

To decrease the error when converting the ADC code to RTD resistance with Calendar-Van Dusen equations, the piecewise linear approximation method is used as shown in the TIDA-01526 firmware code example (see [Signal Conditioning and Linearization of RTD Sensors Technical Reference](#)).

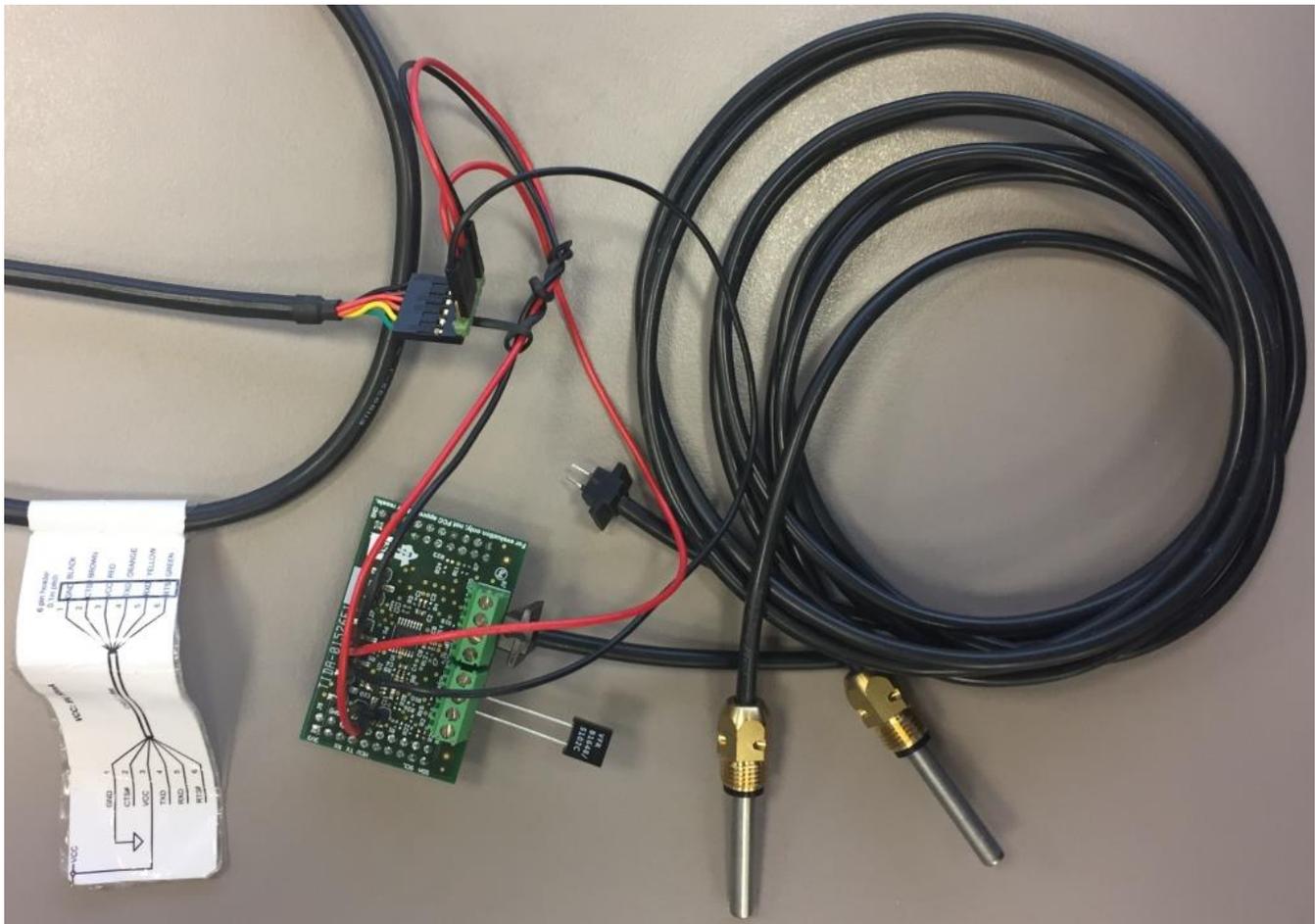
To perform the piecewise linear interpolation using these look-up tables, first compare the measured ADC code in decimal value with the ADC codes listed in the look-up table until the table value exceeds the measured value, and note the index  $n$  of the value, which is just less than the ADC code. The index  $n$  represents the integer part of the measured temperature, as the look-up table has been defined in  $1^\circ\text{C}$  steps. Then, use linear interpolation for the index  $n$  and  $n+1$  to define the fractional part of the temperature value, where fractional means the value after the decimal point.

### 3 Hardware, Software, Testing Requirements, and Test Results

#### 3.1 Required Hardware and Software

The functionality of this reference design was verified using a TTL-232R-3V3 USB-to-serial adapter cable connected to the ADS122U04 (UART) device and running an HTerm program on a Windows 10 PC.

The 6-wire USB-to-UART cable in [Figure 5](#) is connected to a PC, where the HTerm software tool is running. Several configuration files for HTerm were created to allow easy ADS122U04 register programming and ADC data read out by using mouse clicks. The reported ADC codes are output into the receive data window of the HTerm program and are copied into an Excel spreadsheet for further processing.



**図 5. High-Precision Resistor and Two 2-Wire PT1000 (USB-to-UART Cable to PC)**

A similar approach was used for converting the virtual PC com port to an I<sup>2</sup>C interface for the ADS122C04 using TI's USB2ANY tool with the USB2ANY explorer graphical user interface (GUI). USB2ANY is a TI developed multi-protocol adapter and is available as an enclosed unit from TI with the part number HPA665-001.

Slave access to the ADS122C04 was verified after correct wiring of the VDD, GND, SDA, and SCL lines between the TIDA-01526 design and USB2ANY. The resistors R21 and R22 (each with 0 Ω) must be populated for the ADS122C04 I<sup>2</sup>C interface to work correctly, or be removed if the UART interface in the ADS122U04 is used.

Read and write operations to the registers of the ADS122C04 device, as well as data transfer over the I<sup>2</sup>C bus, were verified using a [logic scope](#) with an I<sup>2</sup>C protocol decoder.

### 3.1.1 Hardware Configuration of TIDA-01526

TIDA-01526 has a few PCB populating options (see [表 2](#)), such as I<sup>2</sup>C pullup and pulldown resistors as well as 0-Ω resistors to support the I<sup>2</sup>C and UART interfaces on the TI BoosterPack Plug-in Module connectors J5 and J6.

The TX UART line from the ADS122U04 (digital output, pin 15 of the TSSOP package) is wired to connector J5, pin 5, whereas the RX UART line (pin 16 in TSSOP package) connects to J5, pin 7.

If the ADS122C04 is populated, then R21 and R22 must be soldered to connect the SDA and SCL lines to J5.19 and J5.15, respectively. Thus, the dedicated I<sup>2</sup>C interface to the host MCU can be used without changing the TIDA-01526 PCB layout. GPIO0 and GPIO1 digital lines have R5 and R6 pulldown resistors to support I<sup>2</sup>C customized address configuration. With R5 = 0 Ω and R6 = 0 Ω, the 7-bit I<sup>2</sup>C address is defined as 100 0101 or 0x45. R15 and R16 are the 4.7-kΩ pullup resistors for the I<sup>2</sup>C interface.

**表 2. ADS122x04 UART/ I<sup>2</sup>C Hardware Configuration**

| NAME              | FUNCTION  | ADS122U04 | ADS122C04 |
|-------------------|---|-----------|-----------|
| R15, R16 = 4.7 kΩ | I <sup>2</sup> C pullup resistors                                 | Remove    | Add       |
| R5, R6 = 0 Ω      | I <sup>2</sup> C address  | No effect | Add       |
| R24 = 4.7 kΩ      | RESET pullup resistor   | Add       | Add       |
| R11 = 4.7 kΩ      | DRDY pullup resistor  | Add       | No effect |
| R21, R22 = 0 Ω    | UART or I <sup>2</sup> C interface on BoosterPack™ Plug-in Module | Remove    | Add       |

The hardware design of TIDA-01526 uses the antialiasing filter design rules for selecting the required resistors and capacitors, as the section regarding *Input Filters Design* describes in [Isolated Loop Powered Thermocouple Transmitter](#).

C<sub>DIFF</sub> consists of the C2, C4, and C8 components, which are used in the filters for AIN0-1, AIN2-3, and REFP-N, respectively. C<sub>DIFF</sub> = 100 nF and is approximately 20 times larger than C<sub>CM</sub> with 4.7 nF. All C<sub>DIFF</sub> capacitors used in this reference design have a 0603 size but can be replaced with a 0402 footprint device with a 50-V or higher capability to ensure stable performance over the full lifetime and temperature range.

C<sub>CM</sub> consists of the C1 and C3, C5 and C6, and C7 and C9 components. R14, where the measurement current from the IDAC flows through, must be 0 Ω to avoid any additional resistance in the RTD measurement path.

The filter resistors have been selected to be 100 Ω each, as no significant overvoltage protection is expected with the RTDs inside a flow pipe.

The 0603-sized C11 and C10 for the LDO can be replaced with 0402-sized components if the latter meet the requirements, as per the section regarding *Output and Input Capacitors* in [LP5907 250-mA Ultra-Low-Noise, Low-I<sub>Q</sub> LDO](#).

To support 2-wire RTDs, the 0-Ω resistors R17, R19, and R18 with R20 must be populated on the PCB. If these resistors are not populated, then the designer may alternatively use two external short wires to place at the terminal blocks to make the connection between the two outer terminal pins and the inner pins, where the 2-wire RTD sensor must be placed.

For a 4-wire RTD configuration, the designer must remove (unsolder) the previously-mentioned resistors R17 through R20 from the PCB.

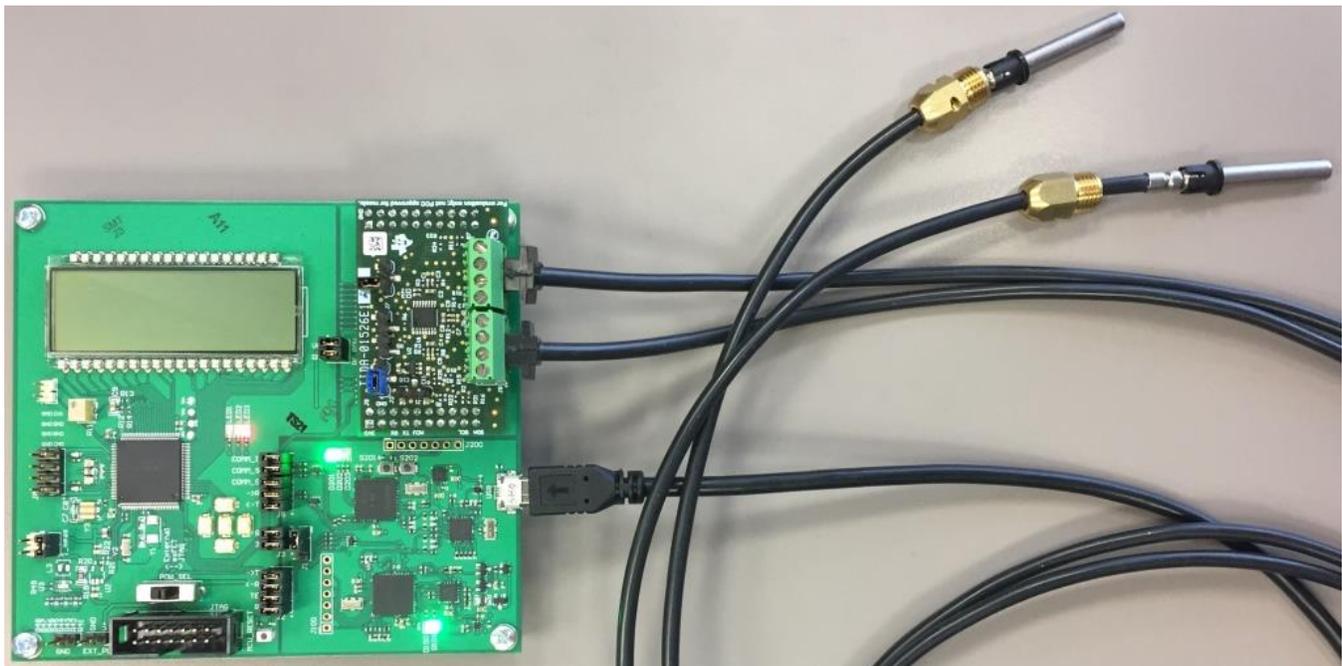
### 3.1.2 Software for TIDA-01526 and EVM430-FR6047

This reference design has been developed to work together with the EVM430-FR6047, a reference development platform used to evaluate the performance of the MSP430FR6047 for ultrasonic sensing applications, such as smart water meters (see [Figure 6](#)). Combining the highly-accurate flow measurement of the FR6047 MCU with the high-precision, differential temperature measurement subsystem of the TIDA-01526 delivers a flexible and ultra-low-power hardware platform for heat and cold meters.

The FR6047 application software is called Ultrasonic Sensing (USS) Design Center, and is available as a free [download](#). For this reference design, this software has been extended to support the UART interface on the USCI\_A3 module of the MSP430FR6047, which is wired to the extension connectors as the J5.RF\_RXD and J5.RF\_TXD lines.

The USCI\_A1 module of the MSP430FR6047 has also been configured to operate as the communication interface to the PC (using the back-channel UART of the MSP430 debugger, integrated onto the EVM).

The I<sup>2</sup>C driver for communication with the ADS122C04 has not yet been implemented in the USS Design Center.



**図 6. MSP430FR6047EVM With TIDA-01526 Mounted and Two 2-Wire PT1000 Sensors and the USB Connection to PC (UART Back-Channel Support)**

A UART driver with 115.2 kbps has been implemented and functionally verified by successfully reading and writing the ADS122U04 registers; both the electrical signals and the data transfer over the UART were verified using a logic scope.

## 3.2 Testing and Results

Testing for this reference design was done with different configurations, which are as follows:

1. Use of an off-the-shelf USB-to-UART conversion cable with the ADS122U04 and HTerm software on a PC
2. TI's USB2ANY tool for I<sup>2</sup>C transactions over a virtual COM port with the ADS122C04 and USB2ANY resource explorer GUI on a PC
3. Special firmware image for the ADS122U04EVM, which automatically collects a programmable number of *chopped* (see 3.2.1) measurements and passes them to the  $\Delta\Sigma$  ADC evaluation software GUI to log into a file
4. Firmware for the TIDA-01526 running on the MSP430FR6047EVM, as shown in [Figure 6](#), and communication to the ADS122U04 over UART interface 1, reporting raw ADC decimal codes to the PC over UART interface 2 (virtual COM port)

Calculations for converting the chopped raw ADC codes from Step 3 into a temperature value have been done using Excel spreadsheet tables with a rational polynomial function as documented in [Table 1](#), as well as using the EN1434-2:2009 second-order CVD equation with the constants A, B, and C, where C = 0 for a temperature greater than 0°C. The equation and these constants are documented in the section regarding *RTD Overview and the Callendar-Van Dusen Equation* in [Small Form Factor, 2-Wire, 4- to 20-mA Current-Loop, RTD Temperature Transmitter](#).

For power-saving reasons, the software example code in the TIDA-01526 design on the MSP430FR6047 uses the linear piecewise approximation approach, which is faster to execute because of less calculation steps than the CVD formula.

Nevertheless, if the designer prefers a CVD direct calculation, it is possible to run power efficient complex mathematic operations on the FR6047 device using the MSP430 IQMath libraries, which are provided within the TIDA-01526 software.

The firmware of TIDA-01526 is based on the software code example in [TIDA-00189](#) and is integrated into the USS Design Center software.

### 3.2.1 Offset Correction of ADS122x04

ADS122U04 offset correction can be done using the internal MUX of the ADS122x04: the AIN<sub>P</sub> and AIN<sub>N</sub> internal signals are shorted to (AVDD + AVSS) / 2 and multiple measurements (four, eight, or more) are done to determine the average offset. The latter is then subtracted from each PT element resistance measurement to obtain the offset corrected ADC code. This method of correcting offset is simple, requires no external components, and has minimal power consumption. The method does have some tradeoffs, however, as any externally-caused offsets in the signal path between the RTDs and the ADC itself are not compensated.

A more precise way to compensate for system level offset is to use the *chopping approach*, which takes two measurements: the first with normal polarity and a second with reversed polarity of the AIN<sub>x</sub> and AIN<sub>y</sub> (x = 0, 2 and y = 1, 3), which are then averaged to provide an offset compensated RTD reading.

[1-g Resolution Over 15-kg Range Sub-100-nV<sub>PP</sub> Noise Front-End Reference Design for Weight and Vibration Measurement](#) further explains the *chopping* technique, which is implemented inside the TIDA-01526 example source code. Each RTD reading reported by the ADS122U04 is actually the average of two ADC code results taken with reversed polarity. A few measurements can be done in a sequence and then averaged together to decrease noise effects; however, decreasing the noise increases the average power consumption.

Another offset is caused by the resistance of the screw contact inside the terminal block, where the PT sensor leads are connected. EN1434 states that such contact resistance must be less than or equal to 5 mΩ for a 2-wire PT100 sensor, and the resistance aging of the contact must be less than 5 mΩ.

A difference between the measured ADC code and the expected ideal ADC code will occur and corresponds to an external 0-Ω resistor connected at the input of each differential ADS channel. Multiple ADC values may be averaged, for example 8 or 16 samples are taken at 20 SPS in normal mode to decrease the impact of noise.

Each of these samples are collected as chopped to eliminate any offset which is introduced in the signal path from the terminal block, where the RTDs are mounted, to the ADS122x04 device.

For the TIDA-01526, short wires were connected to the AIN0-1 and AIN2-3 channels of one TIDA-01526 board, and after collecting 16 chopped ADC samples, the offset for the AIN0-1 channel was 54 decimal codes, while for AIN2-3 the value of 62 decimal codes was measured.

This offset is measured in advance for each of the two ADS channels and stored in the MCU non-volatile memory per each TIDA-01526. Finally, this offset (one for AIN0-1 and one for AIN2-3 channel) is subtracted or added to the chopped ADC value for each measurement on the respective AIN0-1 or AIN2-3 channels.

### 3.2.2 Gain Calibration of ADS122x04 With Precision Resistors

After the offset adjustment is done, performing the gain calibration for each ADS122x04 channel is necessary.

For this purpose, multiple 0.001% high-precision resistors with values between 0.5 kΩ and 9 kΩ were measured with a 8½ digit multimeter to obtain the exact resistor value, which is the reference  $R_{CAL}$ . Based on  $R_{CAL}$ , the expected ADC code is calculated in 式 17, and is noted as the *reference* ADC value at the temperature point. 表 3 lists the common values of interest for PT500 and PT1000.

For a PT1000 sensor, 1000 Ω corresponds to a 0°C step and approximately 1648.8 Ω are equal to 180°C.

With a two-point calibration, the gain calibration point is typically selected at (or very close to) the upper range of the application. As no precise resistors with such values were available, a parallel connection of two resistors was used: for the PT500 case, 1 kΩ and 4 kΩ in parallel (= 800 Ω) were connected to terminal block J9, while the other terminal block (J8) was shorted. Next, the configuration was mirrored to measure the values on the second channel: terminal block J9 had the 0-Ω wire connected and the two parallel resistors were mounted on J8.

For the PT1000 sensor case, 2 kΩ and 9 kΩ in parallel (= 1636.36 Ω) were connected to the J8 terminal block of TIDA-01526, while a short was used on J9. Again, multiple ADC chopped measurements were taken and averaged to give the precise ADC value at this resistance, which is named *calibration* code.

表 3. Calibration Values for PT500 and PT1000

| HIGH-PRECISION $R_{CAL}$ | PT500 (APPROX VALUES) | PT1000 (APPROX VALUES) | 8.5½ DIGIT 3458A MEASURED VALUES | GAIN CORRECTION FACTOR RTD1 | GAIN CORRECTION FACTOR RTD2 |
|--------------------------|-----------------------|------------------------|----------------------------------|-----------------------------|-----------------------------|
| 500 Ω                    | 0°C                   | -125°C                 | 499.996 Ω                        | NA                          | NA                          |
| 800 Ω                    | 158°C                 | -50°C                  | 799.989 Ω                        | 1.000300                    | 1.000293                    |
| 1000 Ω                   | 267°C                 | 0°C                    | 999.9816 Ω                       | NA                          | NA                          |
| 1500 Ω                   | 558°C                 | 130°C                  | 1499.923 Ω                       | 1.000295                    | 1.000288                    |
| 1636 Ω                   | 642°C                 | 166.8°C                | 1636.282 Ω                       | 1.000272                    | 1.000271                    |

表 3 shows several resistor values suitable either for offset or for gain calibration with PT500 or PT1000 sensors. The 0°C step (which is the minimum operating temperature as per the stated design goal) is used for offset correction; these values are either 500 Ω or 1000 Ω, depending on the RTD type used.

After adjusting the offset at these points, the gain calibration is performed. For the known external resistance from 表 3, the expected *reference* ADC code is calculated using 式 17. Subtract the 0-Ω offset from the resulting value. The resulting ADC code is divided by the measured ADC code and the ratio is the gain correction factor, as the last columns of 表 3 show.

In 式 18,  $R_{CAL}$  is the column *measured with 8.5½ 3458A multimeter* in 表 3, while  $R_{measured}$  is the ADC output code from the ADS122x04 as a resistance value, and the resulting gain factor is listed in the right column.

$$\text{Gain factor} = \frac{R_{CAL}}{R_{MEASURED}} \quad (18)$$

The values in the two right columns are almost identical, confirming the very linear behavior of the ADS122x04 signal acquisition for each channel. This gain correction factor should be applied to all measured values only after offset calibration has been performed.

These gain correction factors are stored permanently in the MSP430FR6047 as the values for *RTD1\_gain* or *RTD2\_gain*, because the factor applies only for the channel where it has been measured.

### 3.2.3 Test Setup for TIDA-01526 With RTDs

There is a difference between measuring precision resistor values, representing specific temperature points, and using standard RTDs.

The precision resistor values can verify the performance of the ADS122x04 in TIDA-01526, but they do not have the correct form factor nor the power dissipation profile of the platinum RTDs.

RTDs can dissipate heat faster because of their larger mechanical dimensions, metal enclosure, and their position being immersed in the fluid to be measured. Precision resistors have smaller physical dimensions and are usually tested on the bench with air around them.

To test the performance of the TIDA-01526 as close as possible to the final application, extensive tests have been performed using a highly-precise oil bath from Hart Instruments (model 7320) and a lab-calibrated Hart Instruments digital thermometer (model 1521). The measurements are in 10°C steps from 5°C to 150°C with additional testing at 50°C, 60°C, and 150°C.

Two different system configurations were tested. The first used a 2-wire PT500 sensor pair, which is commonly used in residential heat meters. The second configuration connected a 4-wire PT1000 sensor pair, commonly used in heat calculators. In each configuration, the PT sensor pair and the thermometer probe were submerged in the 7320 oil bath, filled with Galden HT200 silicon oil; the test setup is shown in 図 7.

The 7320 oil bath achieves temperature stability of ±6 mC with the recommended configuration settings programmed during the following tests for the HT200 oil. The TIDA-01526 device always remained at room temperature; a minimum wait time of 15 minutes elapsed while obtaining the correct temperature settling inside the oil bath before taking a new set of measurement data.

### 3.2.4 Test Results

Special test firmware for the ADS122U04EVM captured four chopped samples from each RTD sensor, called RTD1 and RTD2, and logged those into a file. The ENOB and NFB for each sampling were reported by the ADS122U04 EVM GUI and the averaged ENOB values were between 19 to 20 bits.

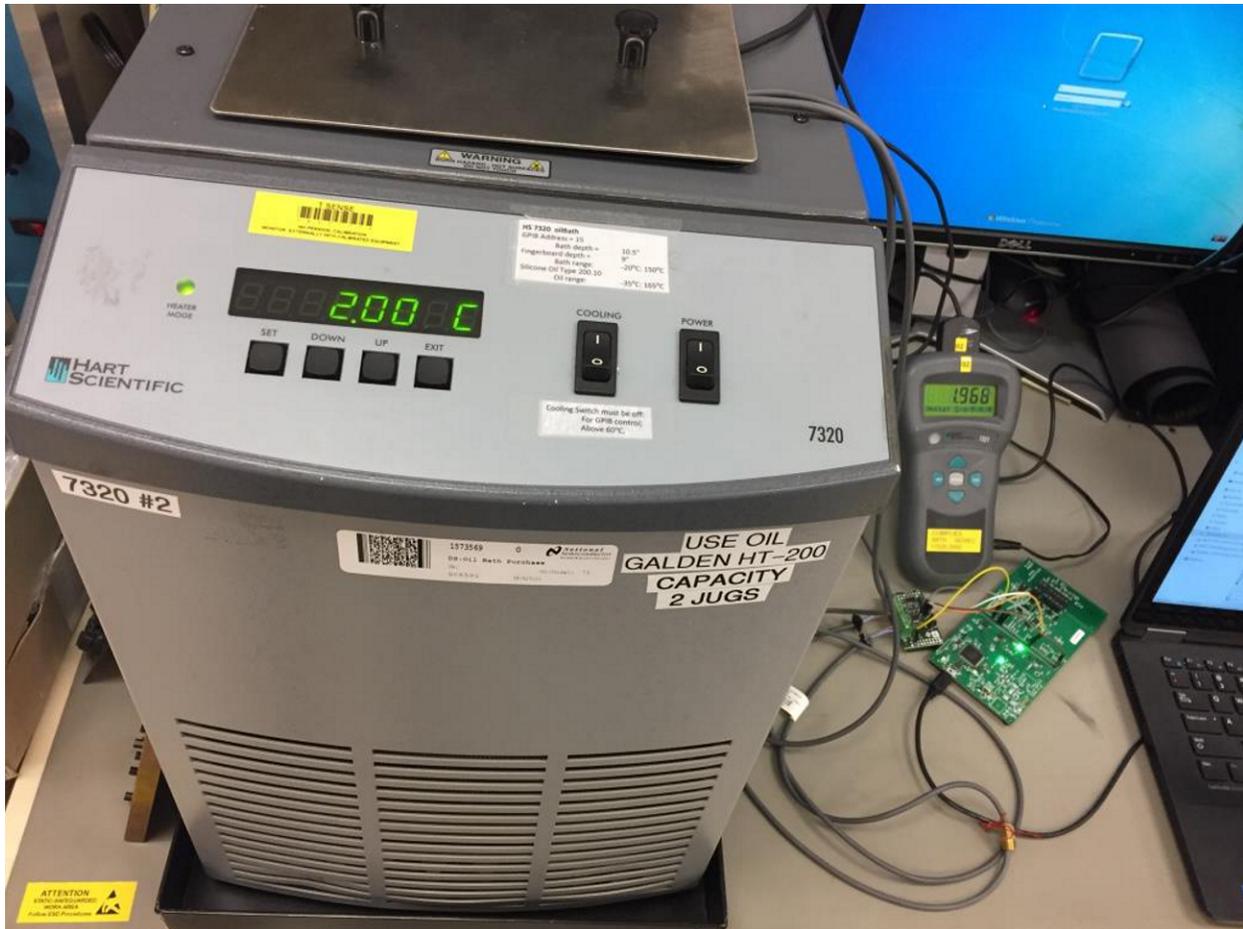


図 7. Test Setup for TIDA-01526 With 7320 Oil Bath and HART1521 Calibrated Thermometer

Conditions and parameters: Normal mode, 20 SPS, Single-shot, 3.3-V supply to the ADS122U04 from the ADS122U04EVM (LP5907 LDO is bypassed), gain = 2, PGA disabled, GPIO2 configured as output and used as DRDY.

Obtaining several calibration points for RTD1 and RTD2 lets the user adjust both offset and gain for each RTD sensor, such that the offset = 0 at the lowest measured point; in this design this is +2 °C for PT500 and +5 °C for PT1000. Next, the gain calibration is done, which is calculated based on the resistor measurement value as close as possible to the maximum operating temperature (for example at 145°C) of the application. All of this process has been done using Excel calculations based on the collected ADC data.

Each measurement contains the accumulated errors from the temperature stability inside the oil bath, the PT sensor itself, the full ADS122U04 signal measurement path, and the conversion error from resistance to temperature because of the error from the CVD equations or the alternative Rational Polynomial formula for interpolation.

### 3.2.4.1 Dual 2-Wire PT500

A pair of standard 2-wire PT500 sensors for residential heat meters were connected to the inner pins of terminal blocks J5 and J6 and inserted into the oil bath. The collected data contains all the errors for a RTD measurement, as described in the error sources topic in [Isolated Loop Powered Thermocouple Transmitter Reference Design](#).

Figure 8 shows the difference versus the absolute temperature, reported by the HART1521 calibrated thermometer, for each PT500 sensor after offset and gain calibration.

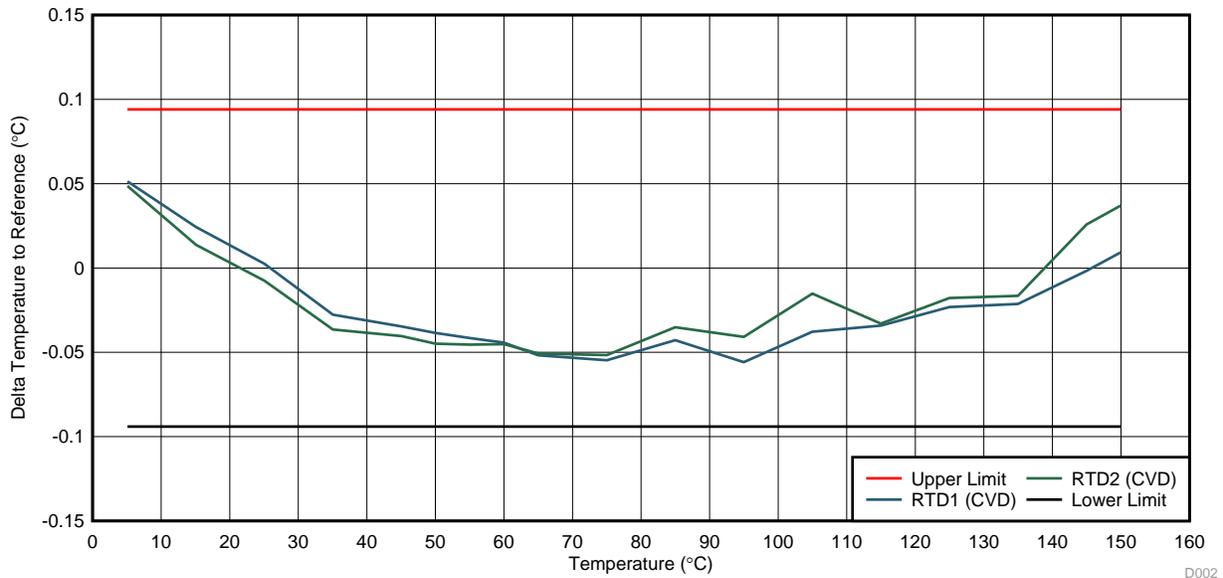
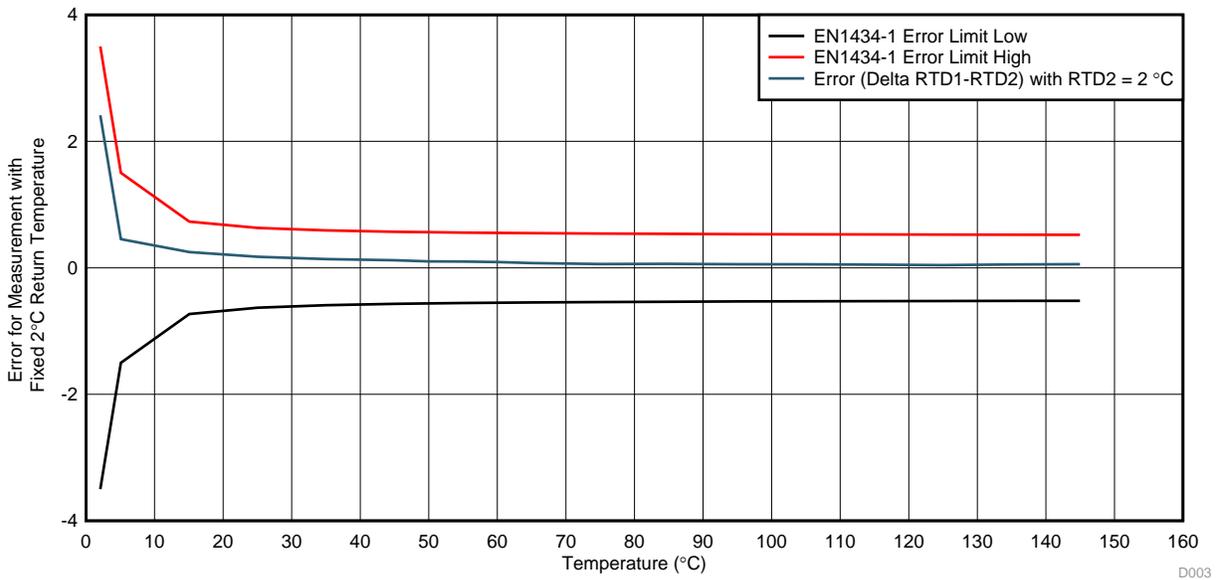


Figure 8. Absolute Temperature Accuracy of Two PT500 Sensors in 2-Wire Configuration

The red and the black lines are the limits defined by the prEN1434-5:2014-04 requirement for maximum ±100-mK error versus the absolute temperature for smart meters. Thus, the ±6 mK for the temperature instability of the oil bath 7320 model are subtracted, which result in a ±94-mK error range. The results for the TIDA-01526 design with the PT500 sensor pair are well within these limits.

Regardless of the precision for the second-order CVD equation, which has been used to convert the ADC code of ADS122U04 into a temperature value, keep the delta (or the differential temperature) between RTD1 and RTD2 as small as possible, because heat meters measure heat based upon the flow volume and the temperature difference between inlet and outlet flow and not the absolute temperature of the flow. Thus, the delta between the RTD1 and RTD2 is the important parameter.

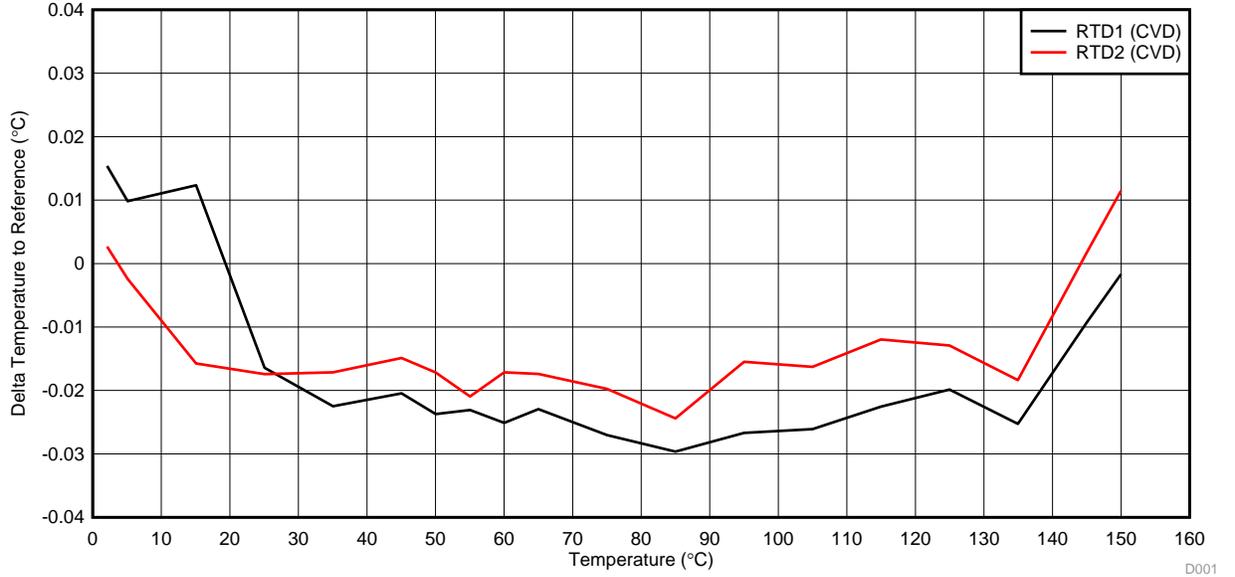
The relative temperature measurement error for the  $\Delta\theta_{MIN}$  value of 1K is shown in Figure 9.



9. Absolute Temperature Accuracy of Two PT500 Sensors in 2-Wire Configuration

3.2.4.2 Dual 4-Wire PT1000

A pair of 4-wire PT1000 sensors from a different vendor and of DIN 1/3 Class B was used for this test, see 10.



10. Absolute Temperature Accuracy of Two PT1000 Sensors in 4-Wire Configuration

Here, the difference of each PT sensor versus the HART1521 absolute reference temperature is somewhat higher than the PT500 pair, which can be attributed to the characteristic of the PT sensors themselves. Nevertheless, the performance is again well within the EN1434 limits, as explained in 3.2.4.1.

The relative temperature measurement error for the  $\Delta\theta_{MIN}$  value of 1K is shown in 11.

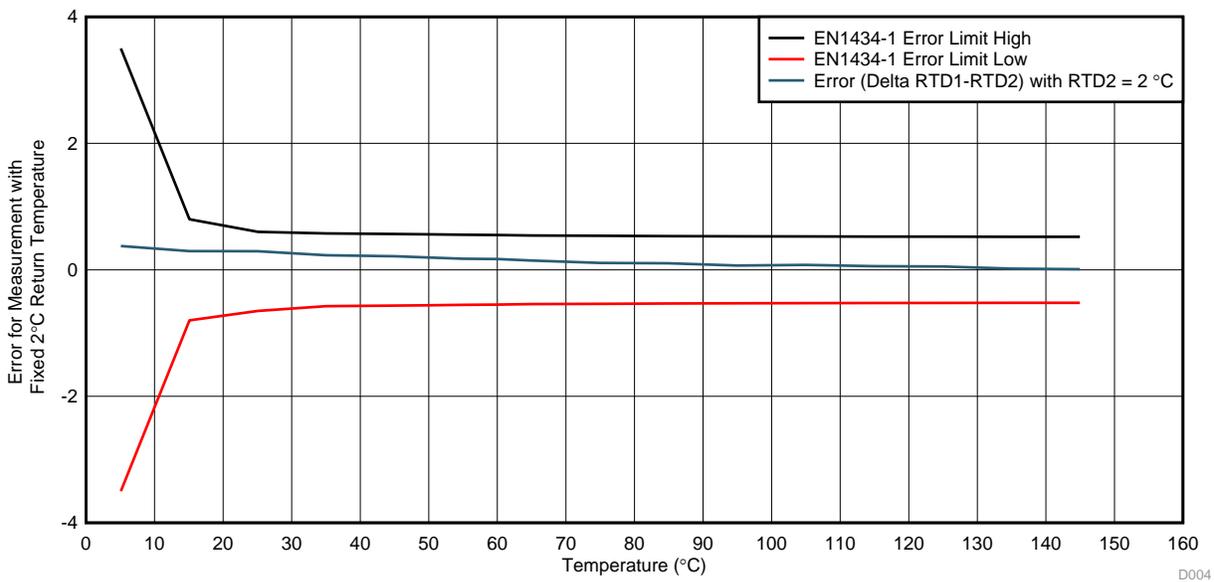


Figure 11. Relative Measurement Error With 4-Wire PT1000 Pair

### 3.2.4.3 Summary

The test results for PT500 and PT1000 sensor pairs prove that the TIDA-01526 reference design meets the requirements for a RTD sensor pair temperature measurement, as per the prEN1434-1:2014 and prEN1434-5:2014 documents. The offset and gain-adjusted temperature measurements have better than a  $\pm 60$ -mK difference to the absolute temperature, regardless if a 2- or 4-wire PT500 or PT1000 sensor pair is used.

This  $\pm 60$ -mK absolute difference is also significantly better than the limit of  $\pm 700$  mK, set in prEN1434-5:2014, when comparing each RTD sensor behavior with the ideal RTD plot using the EN 60751 CVD reference equation. The compliance with this limit should be confirmed for 3 typical temperature points, for example at 10°C, 30°C, and 50°C, which has been verified in Figure 8 and Figure 10.

In this design, the ideal RTD sensor plot has been replaced by the calibrated HART1521 reference thermometer (with an additional  $\pm 6$ -mK error for the oil bath temperature stability).

This heat and cold meter DTM subsystem is also capable of temperature measurement accuracy of 0.01°C, as explained in 2.4.5.

So, for an even better performance than what is reported in 3.2.4, set gain = 4 with turbo mode, the PGA as disabled, and a 90-SPS data rate, as recommends, because of the  $1.42\text{-}\mu\text{V}_{\text{RMS}}$  input-referred noise (listed in the ADS122U04 data sheet). This value is less than the  $2.53\text{-}\mu\text{V}_{\text{RMS}}$  value for a gain of 2 and normal mode with 20 SPS used in all the tests in 3.2.4.

In addition, the faster 90 SPS sampling rate decreases the average active time for the ADS122x04 device. Faster than 90 SPS data rates can be used depending on the required system trade-off between the ADS122x04 active time, resolution, and power consumption (see [Low-Cost, Single-Chip Differential Temperature Measurement Solution](#)).

## 4 Design Files

### 4.1 Schematics

To download the schematics, see the design files at [TIDA-01526](#).

### 4.2 Bill of Materials

To download the bill of materials (BOM), see the design files at [TIDA-01526](#).

### 4.3 PCB Layout Recommendations

The form factor has been defined by the MSP430FR6047EVM with its BoosterPack Plug-in module connectors and with the purpose of having the TIDA-01526 fit above the available PCB area. 40-pin headers have been used although only the outer 20-pin headers are electrically connected, making the design also compatible to the 20-pin BoosterPack TI LaunchPad™ Development Kits.

This reference design uses a two-layer PCB for a reduced cost design and has a maximized common analog and digital ground area below the ADS122x04, while all digital signals are routed away from the analog portion of the ADS122x04 device. Ground fill areas on the top and bottom layers are used. Multiple GND vias are placed around the analog lines to minimize noise.

Although several 0603-sized capacitors have been used, using the smaller 0402 sized capacitor is also possible to save PCB area and allow the layout to become even more symmetrical in regards to the differential signals AIN0-1 and AIN2-3.

#### 4.3.1 Layout Prints

To download the layer plots, see the design files at [TIDA-01526](#).

### 4.4 Altium Project

To download the Altium project files, see the design files at [TIDA-01526](#).

### 4.5 Gerber Files

To download the Gerber files, see the design files at [TIDA-01526](#).

### 4.6 Assembly Drawings

To download the assembly drawings, see the design files at [TIDA-01526](#).

## 5 Software Files

To download the software files, see the design files at [TIDA-01526](#).

## 6 Related Documentation

1. Temperature Controls, [RTD Element DIN Tolerance Calculator](#)
2. Texas Instruments, [Low-Cost, Single-Chip Differential Temperature Measurement Solution TechNote](#)
3. Beuth, [EN1434-1 through -6](#)
4. Texas Instruments, [The impact of voltage reference noise on delta-sigma ADC resolution blog post](#), E2E Community
5. Texas Instruments, [It's in the math: how to convert an ADC code to a voltage \(part 1\) blog post](#), E2E Community
6. Texas Instruments, [RTD Ratiometric Measurements and Filtering Using the ADS1148 and ADS1248 Family of Devices Application Report](#)
7. Texas Instruments, [Signal Conditioning and Linearization of RTD Sensors Technical Reference](#)
8. Texas Instruments, [3-Wire RTD Measurement System Reference Design, -200°C to 850°C Reference Design](#)
9. Texas Instruments, [Small Form Factor, 2-Wire, 4- to 20-mA Current-Loop, RTD Temperature Transmitter Reference Design](#)
10. Texas Instruments, [Isolated Loop Powered Thermocouple Transmitter Reference Design](#)
11. V. C. Fericola, L. Iacomini, *Approximating the ITS-90 Temperature Scale with Industrial Platinum Resistance Thermometers*, Int J Thermophys (2008) 29:1817—1827, DOI 10.1007/s10765-008-0463-4 (<https://rd.springer.com/journal/10765/29/5/page/2>)
12. [Mosaic RTD](#)

### 6.1 商標

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## 7 About the Author

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