Temperature Control FAQ #1

INSTEC Application Note
INSTEC INC.
V1.0.6

Section 1: Temperature Fundamentals

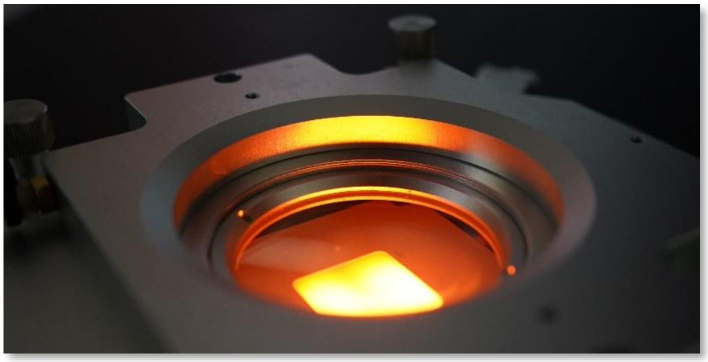


Figure 1: INSTEC high-temperature benchtop plate

Q. What is Temperature?

A. Simply put, temperature is a measure of how hot or cold something is! To be precise, however, temperature is an expression used to quantify the average kinetic energy of the molecules which comprise an object or body. The total energy in a closed system cannot be created nor destroyed, only transferred between forms. Thermal energy flows from higher temperature to lower temperature and has an incredibly wide range over several different scales.

The most commonly used scale to measure temperature is the Celsius scale (°C), which was conveniently designed to correspond to the freezing temperature of water at 0° and the boiling point of water to 100 °C. Other scales, such as the Kelvin scale or Fahrenheit scale, are simply differently mapped expressions of temperature relative to the phase change of certain materials. Ambient temperatures vary greatly based on the region and environment, but in general fall between 22-25C°.

Q. Why is Temperature Important?

A. Temperature is an incredibly important physical quality that affects the mechanical, electrical, and chemical characteristics of ALL ordinary matter in the universe. The electrical resistance of conductors can change completely, chemical reactions can vary greatly in both speed and products, and even solid steel can become soft as butter all based on temperature. Touch a piece of metal heated to 30 °C, and you will simply feel a warm piece of metal. Touch a piece of metal heated to 100 °C, and you will quickly be severely burned. Thermal effects impact virtually every application and must be considered whenever precision and accuracy are required. Because thermal effects are so important, measuring the temperature of a body and controlling the temperature of a body are essential for many applications.

Q. What is Temperature Uniformity?

A. Temperature is a measurement of the average kinetic energy of a body. In practice, this energy is not evenly distributed and must be considered at multiple locations on a given body. Anybody who has ever roasted a turkey has observed that while the outside might be crispy and cooked, the inside of the turkey can remain ice cold, even after hours in the oven. In such a case, we must consider not just the average temperature of the whole turkey, but the distribution of the temperature throughout. Temperature varies not only overall 3 dimensions but also over time as well. Uniformity over time can generally be considered as temperature stability.

A material’s ability to move heat is referred to as thermal conductivity. Materials with high thermal conductivity, such as most metals, quickly and efficiently transfer heat. Insulators with low thermal conductivity, such as glass or wood, are much slower to transfer heat. This is important because the severity of thermal gradients inside a body depends both on its thermal conductivity, and external influences such as loss that add or remove heat from the body.

The most significant sources of loss are thermal contact resistance and convection loss, however, other effects such as conduction or radiation must be considered in some specific cases. In practice, objects with high thermal conductivity will experience smaller internal temperature gradients than well-insulated materials. However, even highly thermally conductive materials will experience thermal gradients to some degree, it is only a question of how significant they will be.

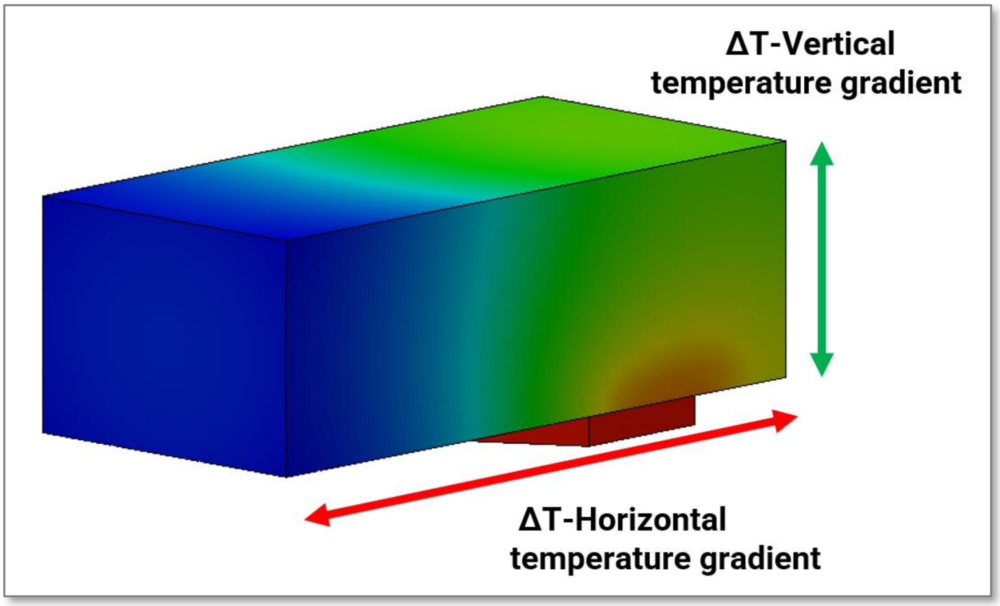


Figure 2: Dramatized temperature gradient example

Q. How do we measure temperature?

A. There are a number of different methods for precisely measuring the temperature of a body. Importantly, all of the methods listed below can easily be used to interface with digital technology for data-logging purposes, which is essential for applications requiring precise temperature control.

Thermocouple

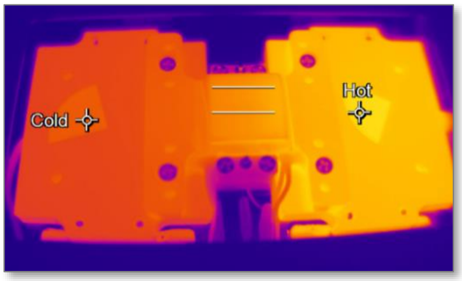
Thermocouples are reliable and versatile temperature sensors ideal for general-purpose applications. There is a selection of different types which together support a wide temperature range (-200°C to 1250°C) A thermocouple consists of a dissimilar metal junction that creates a small but repeatable voltage depending on the temperature. This voltage is measured by a volt meter, then converted into temperature. Thermocouples are not as accurate or stable as RTDs or thermistors, but have a wide temperature range and are inexpensive.

Resistive Thermal Device (RTD)

RTDs are precise temperature sensors that have a good balance of accuracy and temperature range (-200°C to +850°C). The sensor consists of a small strip of metal with a well-known resistance vs. temperature curve. This resistance is measured via an excitation current and precision voltage meter, then the resistance is converted to temperature via a simple formula. These sensors are quite accurate and stable but can be fragile and suffer from self-heating effects. RTDs are available in 2,3 and 4 wire configurations depending on the application.

Thermistor

Thermistor sensors are precise temperature sensors with a limited range (-50 ° to appx +300 °C), but very high accuracy and stability. Unlike RTDs, which are typically made from a pure metallic sample, thermistors are made from a metal oxide. Thermistors are available with either negative or positive temperature coefficients and are typically measured using only 2 wires because their resistance is intrinsically much higher than RTDs. Thermistors typically require different sensing hardware than RTDs, so they cannot serve as drop-in replacements for one another.



Infrared (IR) Imaging

IR imaging is a contactless method for measuring temperature and can be extremely useful in measuring the relative surface temperature across a body. IR imagers are available in every temperature range, but devices covering a large range often have multiple sensors calibrated specifically for different sub-ranges. IR imaging relies on the principle of thermal radiation, where all bodies emit a certain amount of radiation proportional to their temperature, and their emissivity. Emissivity is the measure of the object’s ability to emit radiation and is determined by the physical properties of the body. As the reflectivity of an object increases, the emissivity decreases. An ideal black body has an emissivity of 1, while a mirror might have an emissivity as low as 0.05. Because this property is intrinsic to the radiating body, the emissivity of the body must be known to provide an accurate IR temperature reading. An IR camera measuring a shiny metal object next to a dark metallic object could show completely different values, even if the bodies are at the same temperature. When imaging across a single body with similar emissivity across its whole surface, this error can be calibrated out and minimized, but never fully removed. Therefore, IR imaging is best used for observing the relative temperature across a body’s surface.

Q. How do we describe temperature measurements?

A. Several qualities of temperature are important to consider, including **Precision**, **Accuracy,** and **Stability**.

Precision is the refinement of measurement and is largely dependent on the measurement and hardware used. When baking a cake, precision on the scale of 10°C is generally satisfactory. Research applications can vary greatly but the difference in precision between ±1°C and ±0.05°C poses unique challenges. Instec products typically use an RTD sensor with ±0.001°C temperature measurement resolution but other sensors can be used for special cases such as high-temperature applications.

Accuracy is the difference between a measurement and the actual physical temperature. A discrepancy in accuracy can have many causes, and it is important to ask “how close do the measured temperature and actual temperature NEED to be?” A common source of inaccuracy is poor thermal contact between the heating plate and the sample. Another would be sensor calibration.

Stability is how consistent the temperature is held over time. A typical residential oven can cycle between at least ±5°C compared to or more relative to the set temperature. Instec products are generally rated to ±0.05°C stability over time when heating and ±0.1°C when using LN2 cooling. This means the temperature of our plates will be held close to the set temperature over time, but will unavoidably fluctuate to some degree. Bodies with larger thermal mass inherently tend to have higher stability.

Q. How do we control temperature?

A. Simply put, to control the temperature of a body we need to employ a four-step process:

1. Measure the body temperature
2. Calculate the error between the current temperature and desired temperature
3. Heat or cool the body to minimize the calculated error
4. Repeat steps 1-3

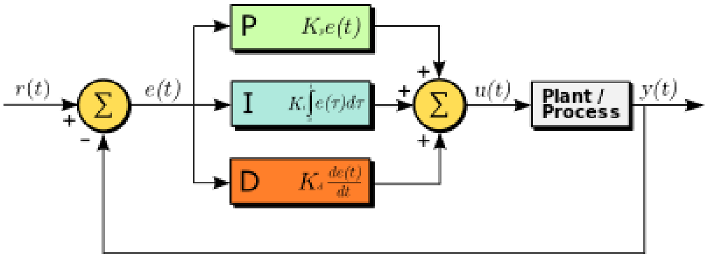
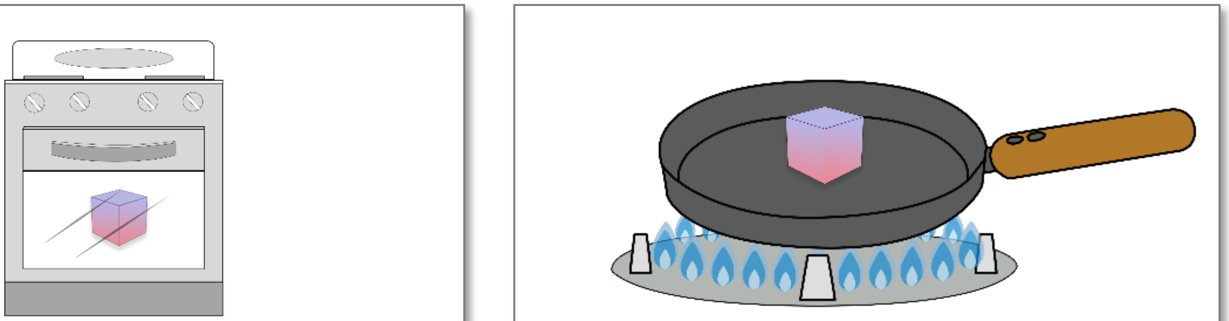


Figure 3: PID algorithm block diagram

One of the best ways to implement this 4-step process is via a PID algorithm, a control loop process that is tunable so its performance can be optimized. There are many types of PID algorithms, but in general, any well-tuned algorithm is good at reaching the desired temperature and maintaining it despite external influences.

Temperature feedback and heating/cooling response time are the keys to good temperature control. Temperature feedback needs to be quick and accurate, making contact sensors like RTDs or thermocouples a great choice. Unfortunately, these sensors must make physical contact with whatever you are trying to measure, and some samples cannot easily be measured in this way, so we have to depend on sensors embedded into objects in contact with the sample instead. Likewise, heating and cooling should be as fast as possible so that rapid transient changes in temperature can be counteracted.

Different samples require different temperature control methods, which can be classified according to the medium through which heat is added or removed from the sample. The two most practical temperature control methods that will be discussed here are Conduction and Convection. Heat transfer through radiation is also possible but is less applicable for most temperature control applications.



Convection Temperature control

The simplest and most common method of temperature control is via convection. Instead of heating or cooling the sample directly, gas or fluid is heated/cooled then circulated around the sample. This results in a very uniform temperature because the gas/fluid makes contact on most sides of the sample, but is limited in response time since both gas and fluid are generally worse thermal conductors than solid materials. It also takes more time to heat/cool the system because of the increased thermal mass, and the limited thermal conductivity of the convection medium.

Conduction temperature control

The preferred method of INSTEC INC is conduction temperature control, which uses solid matter as a heat transfer medium. Similarly to a saucepan, these systems control the temperature of a thermal block which makes contact with the sample. Heat is rapidly transferred to or from the sample through the thermally conductive thermal block, providing fast response times. One weakness of thermal block temperature control systems is that the thermal block rarely makes contact with more than one or two sides of the sample. This makes the sample vulnerable to temperature gradients, resulting in lower sample uniformity. These thermal gradients can be counteracted by using more than one thermal block, vertical insulation, or by using a hybrid combination of conduction and convection cooling.

Figure 4: Conduction vs Convection Examples

Q. What is Sensor Calibration?

A. Sensor calibration is a method to account for unique differences in positioning, assembly, and connection. For temperature sensors, two distinct calibrations are worth considering.

Isolated Sensor Calibration

When a temperature sensor is made, it must be calibrated for absolute accuracy under ideal conditions using a fixed-point reference such as ice water or the melting point of pure zinc. This calibration is designed to calibrate out unique sources of error associated with the sensor itself, and should ideally be repeated every few years or as the application requires it.

Figure 5: Basic example of sensor calibration using fixed point calibration sample(ie. Ice-water)

In-Situ Sensor Calibration

In-Situ sensor calibration is performed to account for unique sources of error associated with the usage of a sensor. Factors such as thermal contact, sample position, and environmental conditions can lead to a difference between the true temperature of a body and the measured sensor temperature. The most practical case for *In-Situ* calibration is when a thermal block is used to control a sample. *In-Situ* calibration must be used in this case to account for differences between the thermal block temperature and the sample temperature due to thermal losses and contact resistance. This type of calibration is particularly useful for conduction-based temperature control systems, as they are more prone to temperature gradients. For the highest possible accuracy, it is recommended to utilize a unique In-Situ calibration for each sample being tested.

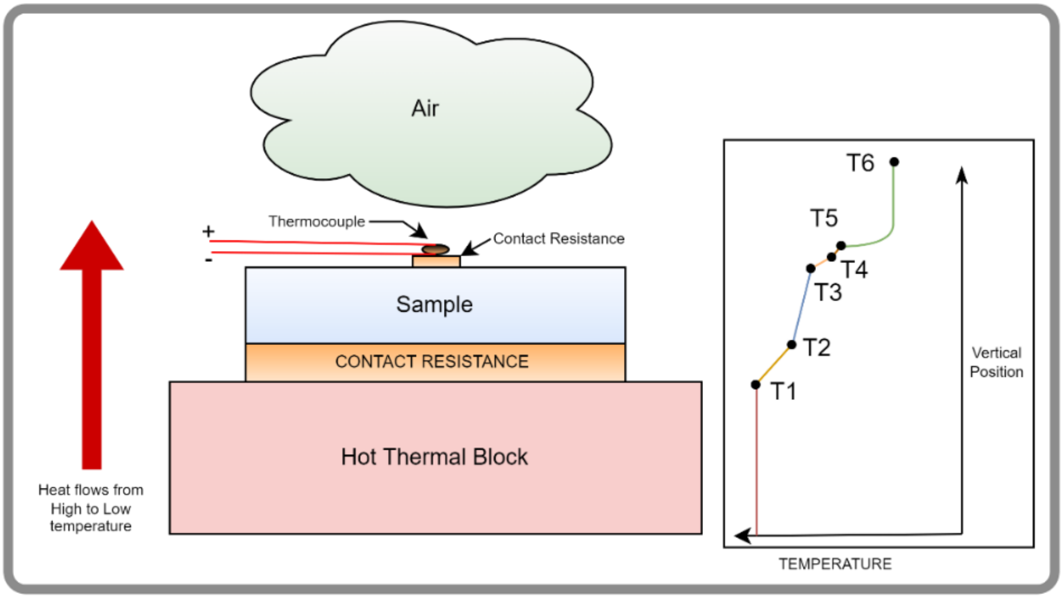


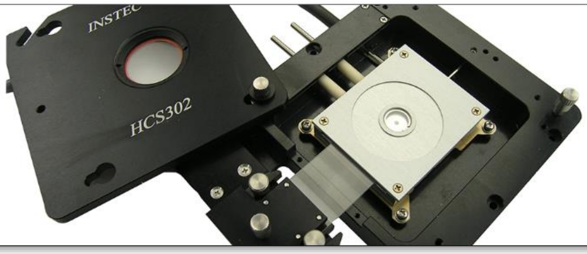
Figure 6: Visual example of vertical temperature gradients within the context of sensor calibration

Section 2: INSTEC Instrument-Specific Questions

Q. How do we avoid temperature gradients?
A. There are a number of tricks that can be used to reduce the effects of temperature gradients in temperature control, including:

1. Use a gastight cover

Using a gastight cover protects the sample from vertical temperature gradients and allows for gas-purge to prevent condensation/oxidation. INSTEC's HCP621G is a good example.

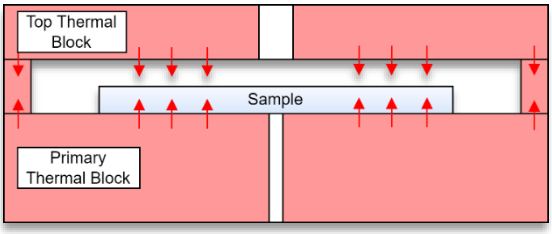


2. Use an inner lid

An inner lid affixed to the thermal block significantly improves temperature uniformity by reducing both vertical and horizontal temperature gradients. INSTEC's HCS302 is shown here fitted with an inner cover.

3. Heat from multiple sides

Using multiple thermal blocks increases system complexity and size, but offers greatly improved sample uniformity versus open faced and covered systems. INSTEC's HCS402 is designed with this in mind.

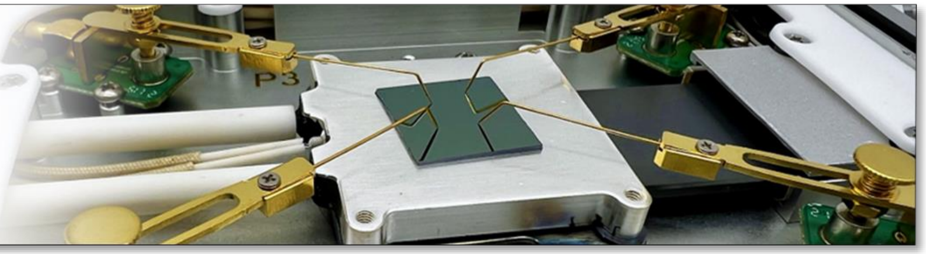


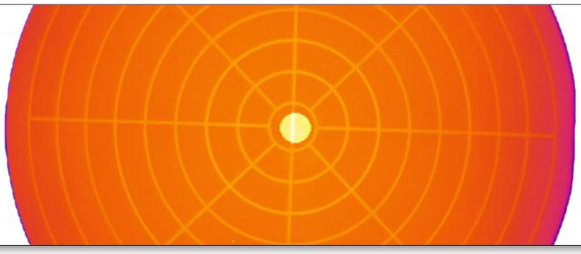
4. Maximize thermal contact

Using thermal compound, metal foils or physical force can drastically improve thermal contact, greatly improving sample temperature uniformity.

5. Carefully prepare samples

Sample preparation, including cutting samples down to size, ensuring flat and smooth surfaces, and limiting sample height as much as possible are essential for uniform temperature control





6. Be patient

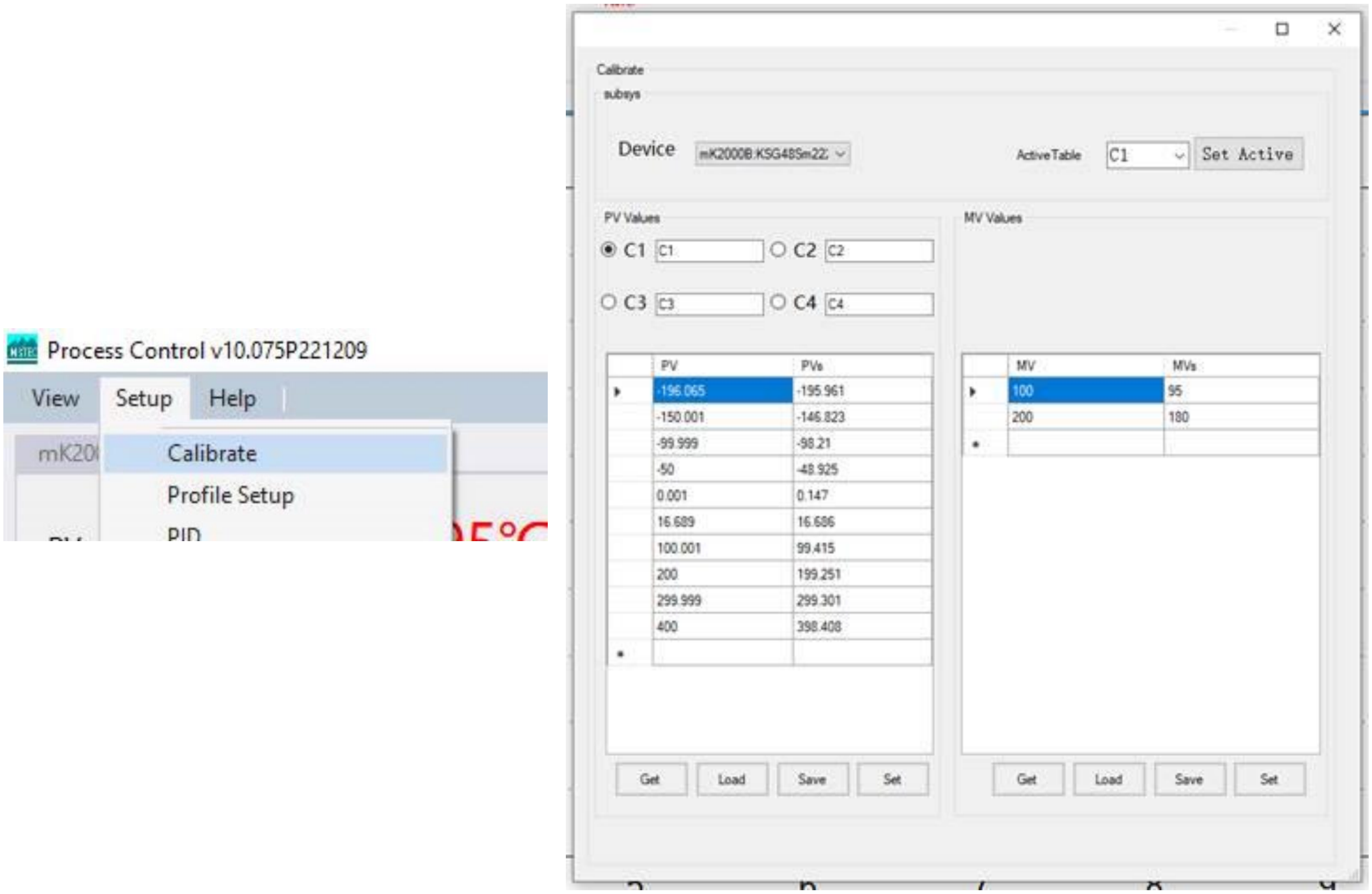
In steady state, temperature gradient effects can be measured and calibrated out of a measurement. However, transient heat transfer effects are much more severe! Be patient and let the system fully stabilize before measuring

Figure 7: Visual Infographic for temperature control best-practices

Q. How often do I need to re-calibrate my INSTEC temperature control instrument?

A. Product-specific maintenance information should be provided in the accompanying user’s manual for each INSTEC product. In general, however, INSTEC recommends re-calibrating a stage/plate/chuck once every 2 years. This re-calibration can be conducted in the field, or the system can be returned to INSTEC for an official re-calibration. Because the mK2000 supports multiple In-Situ calibration curves, it is possible to easily optimize the controller accuracy for any sample without having to rely on the INSTEC calibration. If you want to fully re-calibrate the system based on an external probe, and you trust that more than the INSTEC calibration, you can upload a new set of data that will be used to calculate new calibration parameters.

Inside the InstecApp → ProcessControl → Setup → Calibration tab, there is a tool for creating and selecting different calibration curves:



Device: mK2000B:KSG48Sm22

ActiveTable: C1

● C1 C1 ○ C2 C2

○ C3 C3 ○ C4 C4

PV	PVs
-196.065	-195.961
-150.001	-146.823
-99.999	-98.21
-50	-48.925
0.001	0.147
16.689	16.686
100.001	99.415
200	199.251
299.999	299.301
400	398.408

MV	MVs
100	95
200	180

Figure 8: InstecApp In-Situ calibration tool interface

Within this calibration tool, you can see 4 selectable fields called C1, C2, C3, and C4. Each calibration supports a PV (process Variable) which is regulated by the mK2000 and an MV (Monitor variable) which is an optional additional sensor. You can assign a custom name to each calibration field to describe its function in more detail. In the area below that, you can see the calibration data. The left column is the reading from the mK2000 without any calibration, and the value on the right is the value measured by an external temperature probe. Once the data is entered, the mK2000 uses the difference to construct a calibration curve and correct the sensor reading.

A common use case for this tool is to use an external sensor to measure the temperature inside a larger sample, then calibrate the mK2000 to reflect that temperature. For example, if the sample is a block of aluminum placed on a thermal plate with a temperature of 200°C, the internal block temperature will be some value close to 200°C, but inevitably it will be less. If you embed a sensor inside that block you can get a more accurate reading of the sample, and use that to calculate a new calibration curve that can be used by the mK2000 to provide more accurate temperature control.

Q. I measured the temperature at the surface of my INSTEC thermal plate/stage/chuck, and it does not match the temperature controller reading. Why don’t they match?

A. Precisely measuring the surface temperature of anything is quite difficult. Whether it be with a calibrated temperature probe or with IR imaging, getting an accurate reading of surface temperature requires careful consideration and technique.

All INSTEC stages/plates/chucks are carefully calibrated to accurately read the temperature at the surface of the heating/cooling block. When trying to verify this temperature reading with an external tool there are several important factors caused by heat-transfer principles which can lead to inconsistencies between the reported temperatures. If you follow all of the advice described below and are still seeing a big difference in the temperature reported by the controller and the external tool, contact support@instec.com for assistance troubleshooting the controller calibration.

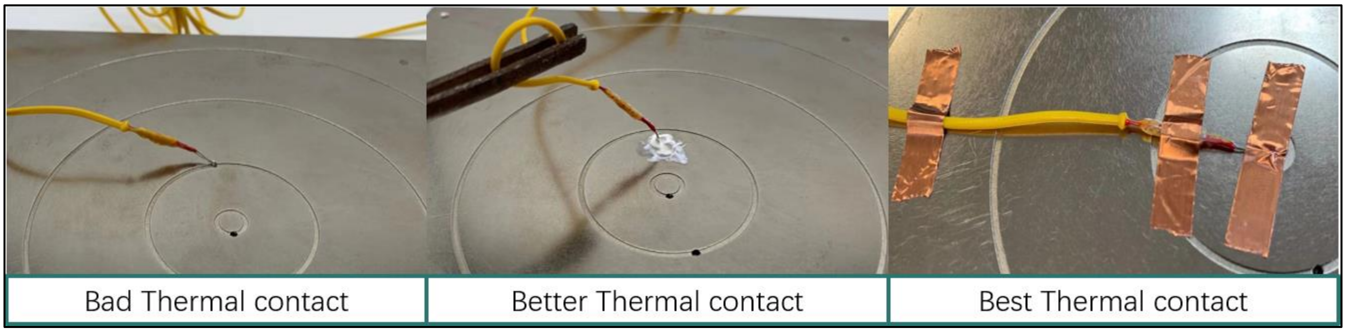
Temperature Probe Measurements:

When conducting temperature probe measurements on a flat surface like your stage/plate/chuck, poor thermal contact, and thermal leakage into the air can lead to temperature readings that are much smaller than the actual surface temperature. The quality of temperature probe measurements can be greatly improved via three simple steps:

1. Secure the probe to the surface.
   For lower temperature measurements, this can be done by securing the probe tip, and some of the lead wire, with some high-temperature tape. For higher temperatures where tape cannot be used, the best solution is to attach the probe tip to a fixture, which can then apply some downward pressure onto the surface.

2. Use a thermal compound to completely surround the temperature probe.
   Applying a dot of liquid thermal interface material (Chemplex 1381 or DOWSIL 340) to the surface, then securing the tip of the thermocouple to that dot, will greatly improve the thermal conductivity between the probe and the surface. Be sure to use a thermal compound that is both rated for the temperatures you will be measuring at, and that won't leave a huge mess once you have completed the measurement.

3. Vertically insulate the temperature probe.
   Especially in cases where thermal contact is not great, adding insulation above the temperature probe will greatly increase the accuracy of the temperature reading. Vertical insulation protects the sensor from vertical temperature gradients and increases the temperature uniformity within the sensor itself.



Bad Thermal contact | Better Thermal contact | Best Thermal contact

Figure 9: Examples of thermocouple measurement techniques. ***NOTE:*** *the “Best thermal contact” image omits vertical insulation placed above the probe. To achieve the absolute best results, this insulation should be included.*

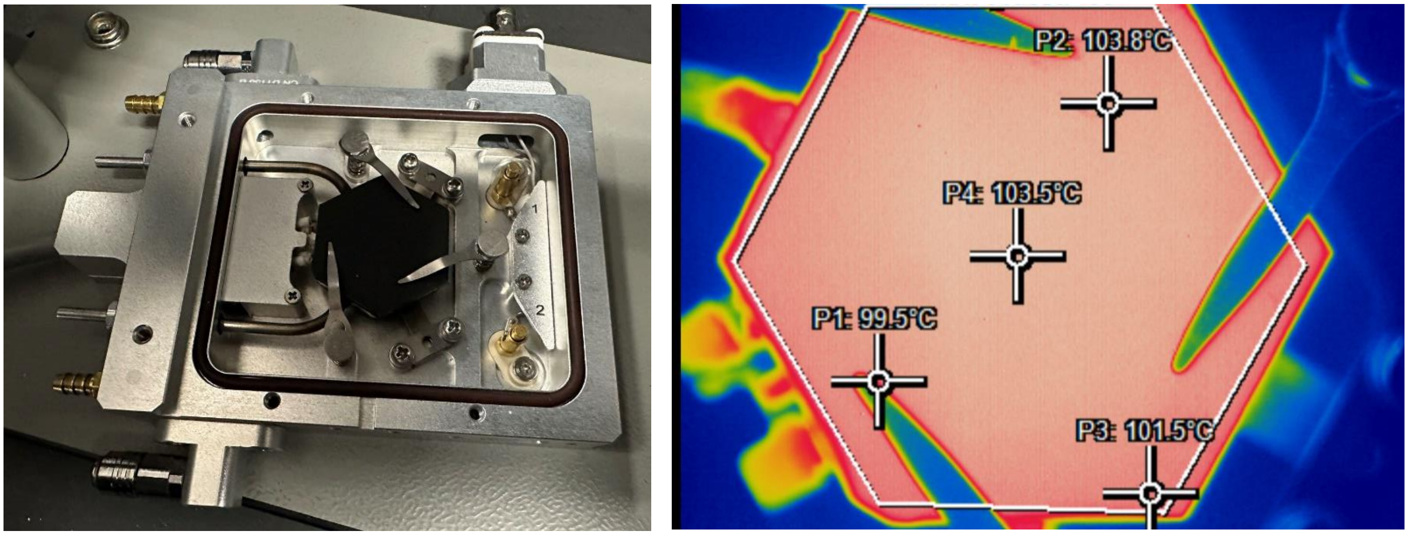


Figure 10: (Left) INSTEC HCP621G with hexagonal metal cutout secured to top surface. Cutout has been painted with high-temperature grill paint to provide an emissivity very close to 1. (Right) thermal image of HCP621G with metal cutout installed, heated to 100C.

Infrared Imaging:

When using thermal imaging techniques to measure the stage/plate/chuck temperature, the accuracy of the measurements must be carefully considered. Accurately measuring the temperature of the heating surface is fairly difficult, due in large part to the high reflectivity of the anodized coating. To account for this, it is critical to something like either black electrical tape or high-temperature grill paint, to make the stage surface as black as possible. This gives the stage surface an emissivity much closer to 1, which can be entered into the thermal imaging software to partially correct the accuracy of the temperature readings.

A great solution for reducing thermal imaging error is to paint a small piece of metal with high-temperature grill paint, then secure this piece of metal to the plate surface with some thermal interface material. With this method, it is much easier to measure the uniformity across the thermal plate, although this method does introduce some small errors due to thermal gradients, especially if the TIM is not applied well and the plate is not secured well to the thermal block.