NANMAC NOTES

Eliminate Temperature Errors Caused by Conduction

*Jacob Nanigian**

Nanmac Corp. Framingham, Mass.

Control of any heat treat process, whether basic or advanced, is only as good as the accuracy of temperature measurement. The accuracy of contact-type temperature sensors is affected by calibration, response time, and conduction.

Calibration errors are generally insignificant. Sensors can be calibrated to an accuracy of ±0.25°C (0.5°F), and standards can be calibrated to the sixth decimal place at laboratories such as MST (National Institute of Standards and Technology). Response time of sensors is very important in transient or cyclical applications, but in furnace applications, rapid transients are not usually encountered. However, the conduction phenomenon is of primary concern in furnaces because it can generate large errors in temperature measurements.

Causes of conductance errors

Conduction errors are caused by temperature gradients within the furnace and the furnace wall, and the ambient temperature outside the furnace. Since the temperature sensor is installed through the furnace wall, it creates a conductive path along which heat flows from the inside of the furnace to the exterior, thus creating an error in the observed measurement. Temperature gradients are also caused by uneven heating, poor circulation, and uneven distribution of the workload within the furnace.

To provide accurate measurement, a temperature sensor must:

- have reproducible and stable calibration properties (temperature vs. EMF and temperature vs. resistance) over the measured temperature span;
- not disturb the local temperature of the medium by its very existence; and
- have sufficiently fast response to follow temperature changes accurately.

Figure 1 illustrates the temperature profile across the wall of a heated chamber at any instant of time. In this illustration, the wall is made of a homogeneous material such as steel or ceramic. If the wall contains several materials, such as steel and insulation plus graphite or ceramic, each homogeneous material will have its own temperature profile.

Several observations can be made in connection with Fig. 1:

- Heat always flows from the hotter medium to the cooler medium.
- Heat energy is continuously absorbed by the wall at its hot side and liberated at the cold side to the cooling medium (air, water, etc.). Under steady-state conditions, the heat absorbed must be equal to the heat liberated or the wall will begin to melt.
- The temperature profile at each interface approaches exponential conditions.
- No region exhibits constant temperature over a given cross-section. Constant-temperature zones are called isotherms, and they appear only parallel to the plane of heat flow.

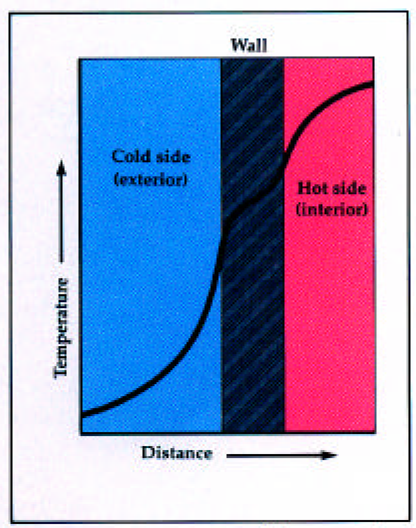

Fig. 1 — Temperature profile across a hot wall.

Thermocouples are installed by machining an appropriate hole through the wall. The thermocouple thus cuts across myriad isotherms, and creates a conductive path for heat to flow from the hot area to the cool area. The thermocouple, which in reality measures its own temperature, is constantly being cooled by this conduction.

The output of the thermocouple is always in equilibrium with the heat coming into the junction and the heat being carried away by conduction via the thermowell to the outer jacket of the furnace and the atmosphere. This is called the *stem effect.* This error is caused by the heat conduction in the wires, the insulation, and the sheath or thermowell of the thermocouple. It is impossible to predict the magnitude of this error. Even if you could determine this error at a particular temperature, it would change as the temperature changes, because thermal conductivity of all materials varies with temperature.

Therefore, the heat treater's objective should be to install a thermocouple into a furnace so that the sensing tip is always in equilibrium with the temperature of interest and, therefore, accurate measurements are made. Ideally, the sensor should be an adiabatic probe — that is, it should be thermally isolated from the wall.

Testing for conduction

We designed an experiment to determine the magnitude of errors produced by the stem effect. We used a container of hot water surrounded by a reservoir of cold water. The hot water was kept hot by an immersion-type heater; the cold water was kept cold by a simple circulating pump and cooling radiator. The temperatures in both the hot and cold reservoirs were continuously monitored by laboratory thermometers with an accuracy of ±0.25°C (0.5°F). The carbon steel hot water tank had a 12-cm (5-in.) O.D. with a wall of 1 cm (0.5-in.) thickness. Figure 2 is a schematic of the test setup.

Four thermocouples, each with a different style of thermal junction, were installed in the wall of the hot water tank and aligned flush with the inner surface of the tank. Thus, all the thermocouples were in direct contact with the hot water. All the thermocouples had iron/constantin (copper-nickel) elements, and their outputs were monitored by the same meter through a thermocouple selector switch. In addition, all thermocouples were made from the same lot of wire, and resistances were matched.

The four thermal junction styles were:

Tl — Exposed-bead weld junction

T2 — Grounded junction:
sheath welded closed and the thermal junction electrically in contact with the sheath.

T3 — Insulated junction: sheath welded closed but the thermal junction electrically isolated from the sheath. All RTDs and thermistors are similar in design to this insulated junction. The sensing element is electrically insulated and then enclosed in a metallic sheath that protects the sensing element from abuses of the environment such as corrosion, oxidation, erosion, and chemical attack.
This protection comes at the cost of reduced accuracy.

T4 — Right-angle junction:
exposed-ribbon welded junction.

Tl, T2, and T3 are conventional thermal junction styles (Fig. 2), and T4 is a right-angle unit with ribbon elements (Fig. 3).

Measurements were taken from these four thermocouples over a 16-hour period. When the hot water temperature was held at 83°C (181°F) and the cold water held at 38°C (101°F), thermocouple Tl read 78°C (173°F), T2 read 69°C (156°F) and T3 read 53°C (128°F), whereas the right-angle ribbon thermocouple read 83°C (181°F).

A temperature gradient of 40 to 50°C (70 to 88°F) was maintained over the two days in which this test was conducted. (The test took place in an exhibit hall during an ISA show.) The variations in this gradient were caused by several factors: our cooling system was not very well controlled by our simple heat exchanger — the circulating water pump and our small radiator; and, as the ambient temperature in the hall rose during the day, it caused the temperature of our cold water reservoir to rise, thus putting an additional load on our heat exchanger system. Note that the insulated junction (T3) exhibited the largest error in both absolute measurement and percent of temperature change between the hot and cold water.

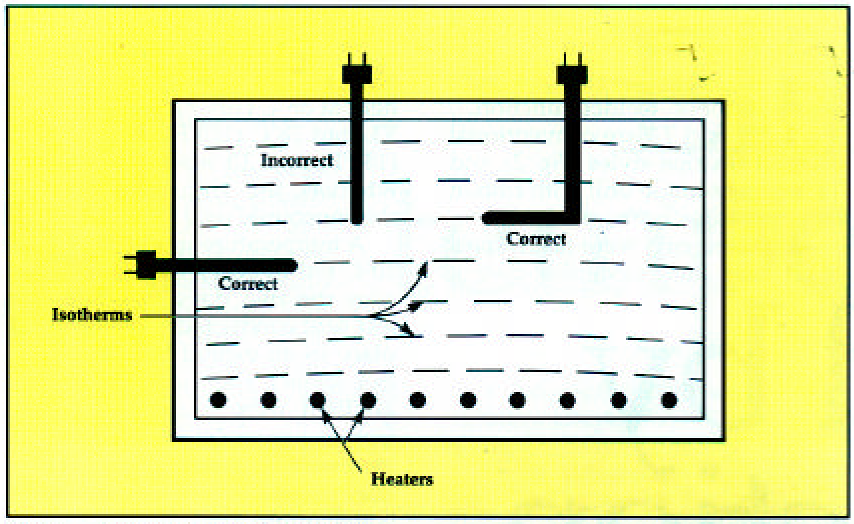

Fig. 4 — Furnace with bottom heaters.

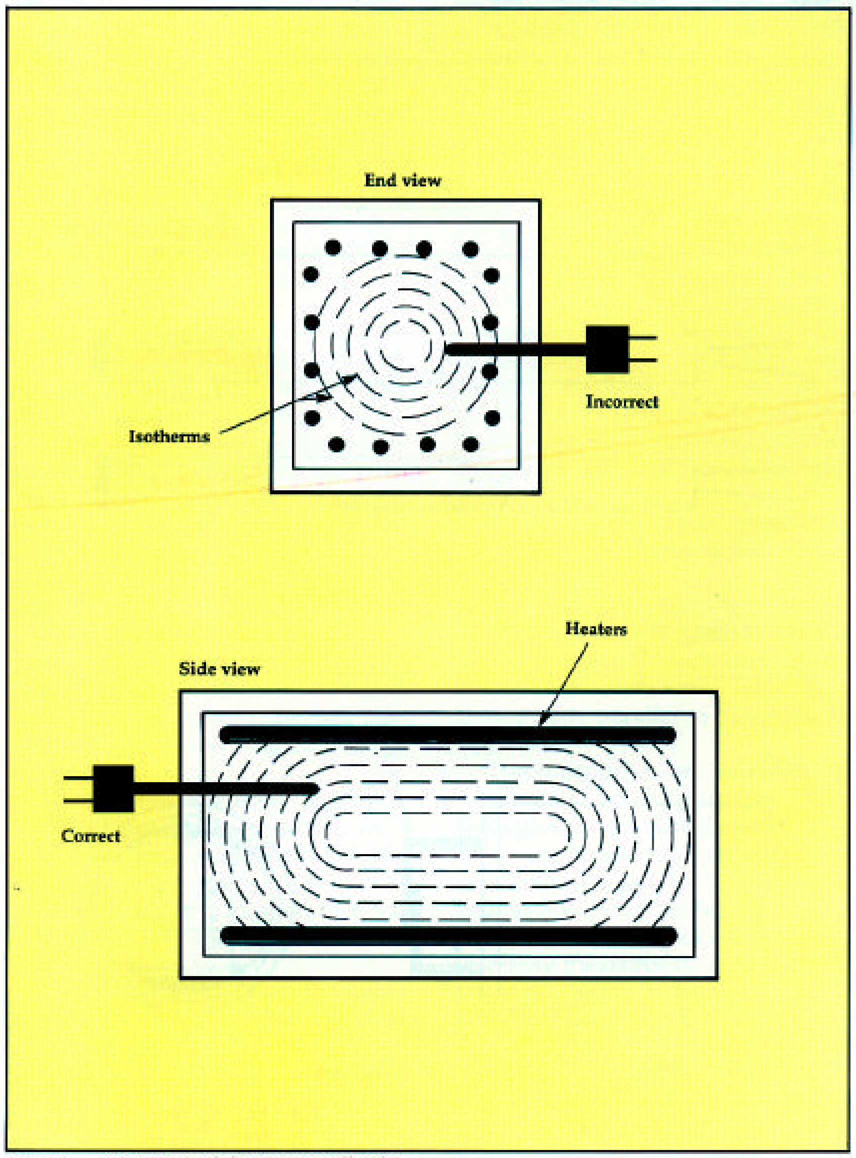

Fig. 5 — Furnace with heaters on all sides.

The right-angle ribbon sensor has a junction thickness of 0.07 mm (0.003-in.). The extension leads in the vicinity of the junction are also ribbons, and lie in the same plane as the sensing junction for a distance of at least 20 times the thickness of the junction. Thus, the sensing tip and the adjacent ribbons are parallel to the plane of heat flow, and since the ribbons on both sides of the junction are heated simultaneously with the junction, no significant error is caused by the stem effect.

To minimize the error caused by the stem effect in all sensors, this ratio of 20:1 must be maintained at the sensing tip. For example, a 3-mm (0.125-in.) round stainless steel probe must be positioned in the furnace so that it lies parallel to the plane of heat flow for 6 cm (2.5 in.) This can be accomplished by one of two methods: make a 90° bend in the probe 6 cm (2.5 in.) from its tip, or position the mounting so that the probe is parallel to the plane of heat flow.

Figure 4 is a schematic of a furnace with heating elements at the bottom. The isotherms are shown as broken lines. Figure 5 is a similar sketch showing the isotherms in a furnace with heaters on all sides. In all instances, the correct orientation requires that the thermocouple extend parallel to the isotherms for a length equal to 20 times the probe diameter. A right-angle thermocouple such as the one used in the test described above can be installed into a furnace without any 90° bends because the probe already incorporates such a bend.

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