# CHAPTER 8.3
# TRANSDUCERS FOR THERMAL QUANTITIES

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## *INTRODUCTION*

The *temperature* of a body or substance is (*a*) its potential of heat flow, (*b*) a measure of the mean kinetic energy of its molecules, and (*c*) its thermal state considered with reference to its power of communicating heat to other bodies or substances. *Heat* is energy in transfer, resulting from a difference in temperature between a system and its surroundings or between two systems, substances, or bodies. Heat energy is transferred by one or more of the following methods of *heat transfer:* (*a*) *conduction*, by diffusion through solid material or stagnant liquids or gases; (*b*) *convection*, by the movement of a liquid or gas between two points; and (*c*) *radiation*, by electromagnetic waves.

The sensing elements of temperature transducers typically act as transduction elements as well. The two most commonly used sensing-transduction elements are the *thermoelectric* element (*thermocouple*) and the *resistive* element (*resistance thermometer*). Among other sensing-transduction elements the only one that has found commercial acceptance is the *oscillating-crystal* element, essentially a quartz crystal (connected into an oscillator circuit) which has a substantial and highly linear temperature coefficient of frequency.

### Thermocouples

A thermocouple is an electric circuit consisting of a pair of wires of different metals joined together at one end (*sensing junction*) and terminated at their other end in such a manner that the terminals (*reference junction*) are both at the same and known temperature (*reference temperature*). Connecting leads from the reference junction to some sort of load resistance (an indicating meter or the input impedance of other readout or signal-conditioning equipment) complete the thermocouple circuit. Both these connecting leads can be of copper or some other metals different from the metals joined at the sensing junction. Because of the *thermo-electric effect (Seebeck effect)*, a current is caused to flow through the circuit whenever the sensing junction and the reference junction are at different temperatures. In practice, the reference junction is either held at a known constant temperature (e.g., at 0°C) or is electrically compensated for variations from a preselected temperature.

The electromotive force (*thermoelectric emf*), which causes current flow through the circuit, is dependent in its magnitude on the sensing-junction wire materials, as well as on the temperature difference between the two junctions. Commonly used wire materials are Chromel (CR) and Alumel (AL) (both registered trade names of Hoskins Mfg. Co., Detroit, Michigan), Constantan (CN, an alloy of 53 percent copper and 45 percent nickel), copper (Cu), iron (Fe), platinum (Pt), an alloy of platinum and (either 10 or 13 percent) rhodium (Rh), tungsten (W), tungsten-rhenium (Re) alloys (5 or 26 percent rhenium content is typical), nickel (Ni), and ferrous nickel alloys.

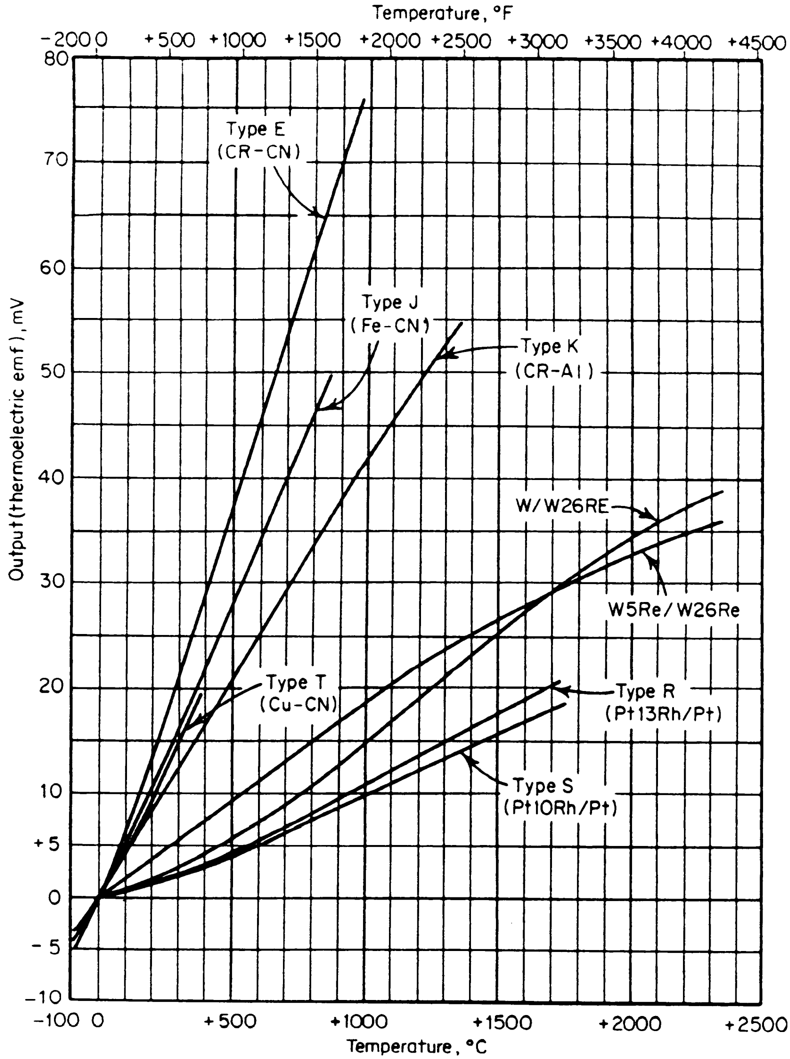


**FIGURE 8.3.1** Thermocouple output vs. temperature characteristics (reference junction at 0°C).

The characteristics of certain combinations of wire materials, such as their thermoelectric emf versus temperature characteristics, their accuracy tolerances, and wire-insulation color codes, were standardized by ANSI Standard C96.1 (which is based on ISA Recommended Practice RP1) in such a manner that materials of different brand names can be used as long as the characteristics assigned to a specific type of thermocouple are maintained.

The names of the wire materials constituting, in their combination, a thermocouple sensing junction are now listed only as typical examples. Thus typical materials of a *type K* thermocouple are Chromel and Alumel. The ANSI Standard favors the use of type-letter designations in lieu of the names of the two metals used. Figure 8.3.1 shows the thermoelectric emf obtainable from various types of thermocouples when the reference temperature is held at 0°C.

Thermopiles (see Fig. 8.3.2) consists of several sensing junctions of the same material pairs, in close proximity to each other and connected in series so as to multiply the output obtainable from a single sensing junction.

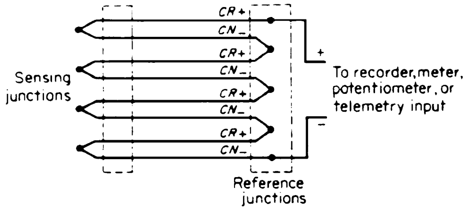


**FIGURE 8.3.2** Thermopile schematic diagram: CR-CN combination shown as example.

The isothermal reference junctions are usually also in close proximity to each other to assure an equal temperature for each reference junction.

## Resistive Temperature-Sensing Elements

Resistive temperature-sensing elements are either conductive or semiconductive. Conductive elements are usually wire-wound, sometimes made of metal foil or film. Elements wound of high-purity annealed platinum wire are best suited for most applications. Other metal-wire elements are wound of nickel or nickel alloy. Copper-wire elements are rarely used any more. Tungsten-wire elements have shown some promising characteristics but are generally considered too difficult to manufacture and too brittle to stay reliable.

A platinum-wire element has been used to define the International Practical Temperature Scale from − 183 to +630°C, and it is expected that this upper limit will be extended to the melting point of gold (+1063°C). The resistance versus temperature curve of such an element follows a well-defined theoretical relationship, making most points on the curve calculable within very close tolerances when only a few measured points have been established. Repeatabilities within about 0.01 K have been obtained at temperatures up to the freezing point of gold (1337.58 K). Semiconductive resistive temperature-sensing elements include thermistors, germanium and silicon crystals, carbon resistors, and gallium arsenide diodes. Thermistors have a nonlinear and negative temperature coefficient of resistance and an empirical resistance versus temperature relationship.

## Temperature Transducers

Temperature transducers are classified into two general categories: surface-temperature transducers, which are cemented, welded, bolted, or clamped to a surface whose temperature is to be measured, and immersion probes, which are immersed into stagnant or moving fluids to measure their temperature. The fluid can be in a pipe, a duct, a tank, or other enclosed vessel, where the immersion probe is mounted through a pressure-sealed opening. It can also be freely moving, even at almost imperceptible rates of motion, e.g., an open body of water, an outdoor or indoor atmosphere.

*Thermoelectric temperature transducers* have the same sort of sensing junction, whether they are intended for surface temperature measurement or as immersion probes. The junctions between the two dissimilar-metal wire pairs are made by butt-welding the wire ends, by crossing them and welding them, by coiling one wire end around the other, or twisting the two ends about each other, then welding, brazing, or soldering the junction, or by welding both wire ends, in very close proximity to each other, to a metallic surface or to the metallic inside of an immersion-probe tip.

For surface measurements, the junctions are soldered, brazed, or welded to a surface (if it is metallic) or cemented to it (if it is not). If it is cemented, care must be taken to have the junction in solid thermal contact with the measured surface. Taping a junction to a surface is poor practice, since even a very small gap between junction and surface can introduce considerable errors. For immersion measurements, thermocouples are often produced with an integral sheath or inserted into a sealed immersion sheath (*thermowell*).

Junctions for thermoelectric immersion probes can be grounded (metallic contact from junction to sheath or thermowell) or isolated (ungrounded). In some cases, exposed junctions, at the tip of a probe, are immersed in the fluid without use of an integral sheath or thermowell. If terminals or connectors must be used between the sensing junction and the reference junctions, the terminals as well as the *extension wires* must be made of the same types of metals as used for the junction.

*Thermocouples* are usually made from two-conductor insulated cable, rarely from reels of individual bare-wire materials. The cables have a variety of insulation, over each conductor as well as over the conductor pair, and can be shielded or unshielded. Useful for many applications is thin (2 to 10 mm outside diameter) metal-sheathed, ceramic-insulated thermocouple cable.

*Differential thermocouples* can be used when the measurement objective is to measure the temperature difference between two points. In this case the sensing junction at the other measured point replaces the reference junction. The first wire of the first junction and the second wire of the second junction must still be brought to isothermal terminals; however, it is not necessary that the temperature of these terminals be known.

## Resistive Temperature Transducers

Electrically conductive surface-temperature transducers are usually small and flat enough not to be influenced by convective heat transfer but only by conductive transfer from the measured surface. After installation they may be coated or covered to minimize any radiative heat transfer to them. The sensing element is usually a metal wire either wound around a thin insulating "card" or a coiled wire cemented to the base (see Fig. 8.3.3). Some metal-foil transducers (encapsulated or *free-grid*) are in the shape of a zigzag pattern. All designs are aimed at exposing the maximum sensing surface to the conductive heat transfer in an area of minimum size.

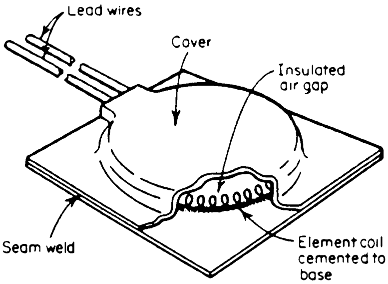


**FIGURE 8.3.3** Platinum-wire resistive surface-temperature transducer. (*Rosemount Inc.*)

Resistive metal-wire *immersion probes*, most commonly with a platinum-wire element but some-times with elements of nickel or nickel-alloy wire, are widely used for industrial and scientific fluid-temperature measurements. The probe-type transducer, illustrated in Fig. 8.3.4, has a ceramic encapsulated (coated) element in a perforated protective sheath so that it is usable for a variety of measured fluids over a wide temperature range. For applications in relatively stagnant fluids an unencapsulated (*exposed*) element is used to provide a shorter time constant. Some fluids require an element completely *enclosed* within a metallic well but with good thermal contact between well and element. The threaded mounting allows for compression sealing by means of a gasket or O ring between the housing and the mounting boss.

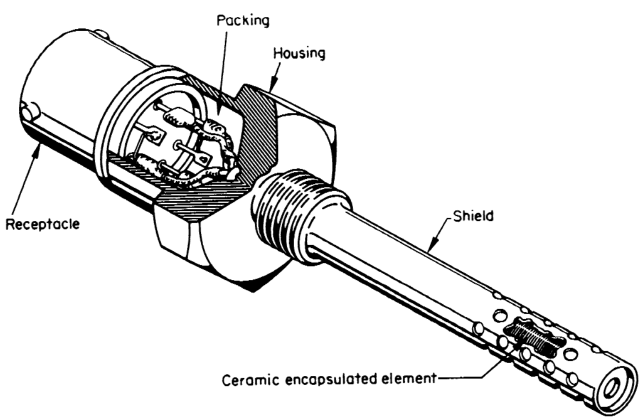


**FIGURE 8.3.4** Platinum-wire resistive immersible-probe temperature transducer. (*Rosemount Inc.*)

## Thermistors

Thermistors are used for surface-temperature as well as fluid measurements. Because of their nonlinear (essentially negative exponential) resistance versus temperature characteristics, they are particularly useful when a large resistance change is needed for a narrow range of temperature. Where a short time constant is required, a glass-coated thermistor bead, as small as 0.3 mm in diameter, can be suspended on its 0.03-mm-diameter precious-metal-alloy leads. Where somewhat more ruggedness is required, a glass-encapsulated bead about 1.5 mm around the tip and 4 mm long can be used. Excitation power must be kept low to avoid errors due to self-heating. Thermistor-type temperature transducers are available in a large variety of configurations.

## Semiconductor Thermometers

Germanium thermometers are made of germanium crystals with highly selected and controlled impurities (dopants). They are intended primarily for cryogenic temperature measurements (below –195°C). Carbon resistors have also been used for such applications, as have gallium-ărsenide junction diodes, which can be used to somewhat higher temperatures. Silicon-wafer transducers have been used for surface-temperature measurements in the range –50 to 275°C, where their resistance versus temperature characteristics are similar to those of some metal wires.

## Quartz-Crystal Temperature Transducers

Quartz-crystal temperature transducers use oscillating-crystal sensing elements in such a manner that the change of oscillator frequency with temperature is nearly linear over a range from about –50 to 250°C. They are usually furnished with associated electronics and readout equipment. This tends to limit their usability for general telemetry application without, however, detracting from their advantages in laboratory applications.

The selection of a temperature transducer is more complex than the selection of most other types of transducers. The objective is to select a design whose sensing element will attain the temperature of the measured material within the time available to make the measurement. Among primary selection criteria are, then, the characteristics and properties of the measured solid or fluid, the measuring-range limits, the required response time (time constant), and the type of excitation and signal conditioning available or intended to be used.

## Radiation Pyrometers

Radiation pyrometers are noncontacting temperature transducers which respond to radiative heat transfer from the measured surface or material. This radiation occurs primarily in the infrared portion of the electromagnetic spectrum (wavelengths between 0.75 and 1000 $\mu$m). Typical radiation pyrometers use an optical lens or mirror system (sensitive in the infrared region) which focuses the radiation on a thermoelectric or resistive (usually photoconductive) sensing element. The output of the sensing element can be correlated, by calibration, to the temperature of the measured surface. Radiation pyrometers are used primarily for high-temperature measurements (up to about 3500°C), but have also been found useful for noncontacting measurements in the medium temperature range (down to about –50°C). Some designs now use optical fibers in place of purely radiative coupling between source and instrument.

## Heat-Flux Transducers

Two basic types of transducers have been developed to measure *heat flux*, heat transfer in terms of the total amount of thermal energy (heat flux is commonly expressed in W/cm$^2$ or Btu/ft$^2$·s). The *calorimeter* provides an output proportional to convective as well as radiant thermal energy (*total heat flux*). The *radiometer* responds to radiant thermal energy (*radiant heat flux*) only. Virtually all heat-flux transducers have thermoelectric sensing elements.

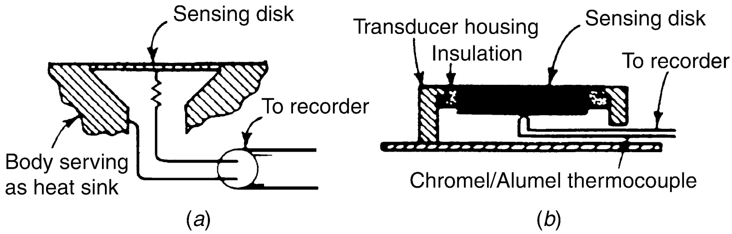


**FIGURE 8.3.5** Calorimeters: (*a*) foil: (*b*) slug.

## Calorimeters

The *foil calorimeter* (*membrance calorimeter*, Gardon gage) acts as a copper-Constantan differential thermocouple. When heat flux is received by the thin Constantan sensing disk (Fig. 8.3.5*a*), which is metallurgically bonded around its rim to a copper heat sink, the heat absorbed by the membrane is transferred radially to the heat sink. This causes a temperature difference between the center of the disk and its rim. A thin copper wire is attached to the bottom surface of the disk, at its exact center, thus forming one copper-to-Constantan sensing junction. The copper-to-Constantan contact around the rim of the disk forms the other junction. The output of the calorimeter is then proportional to the energy absorbed. When heat flux must be measured over long periods of time, the foil calorimeter can be provided with tubing and an internal flow path so that it can be water-cooled.

The *slug calorimeter (slope calorimeter)* uses a relatively thick thermal-mass sensing disk with an external high-emissivity (black) coating, which is thermally insulated from the transducer housing (Fig. 8.3.5*b*). A thin-wire thermocouple is attached to the bottom of the disk (slug), at its center. When heat flux is received by the slug, an output signal is produced by the thermocouple. The signal is proportional to the temperature rise of the slug.

## Radiometers

A typical *radiometer* is essentially a foil calorimeter with a *window* (usually of quartz or synthetic sapphire) mounted over the sensing disk so that a disk can receive radiant heat flux but no convective heat flux. The cavity formed by window, transducer housing, and sensing disk is usually sealed, but provisions for gas purging of this cavity can be made to prevent window clouding when the radiometer is to be used in a contaminating atmosphere. Radiometers can also be water-cooled. The sensitivity of a radiometer can be increased by using a differential (multijunction) thermopile instead of the two-junction differential thermocouple.

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