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# Thin Film Gauges and Coaxial Thermocouples for Measuring Transient Temperatures

## General

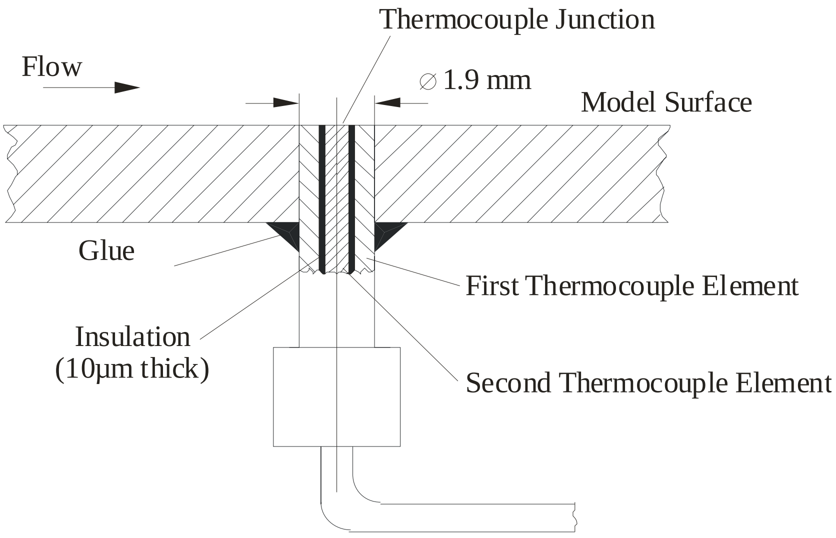
The gauges described in the following allow the measurement of highly transient surface temperatures, as e.g. they are typical for testing wind tunnel models in impulse facilities, the change of the cylinder wall temperature during one cycle of a piston engine, all types of industrial applications, and research-oriented work where the registration of highly transient temperatures is of importance. The response time of the gauges has been proven to be in the range of microseconds. It is important to note that this strongly depends on the dynamic capabilities of the electronic equipment (amplifier, A/D conversion, etc.) of the measuring line which usually limits the achievable response time.

Of course, the gauges are also suitable to measure constant temperatures with time, but their superior field of application is given by transient measurements. Given by the physics, for highly transient processes the output of all gauges represents the time-dependent temperature of its measuring part which in this case may significantly deviate from the temperature of the gauge-surrounding heating or cooling environment. For example, in a piston engine a flush wall-mounted temperature gauge registers with its typical response time the variation of the cylinder wall temperature and not the variation of the average gas temperature within the cylinder. The measured time-dependent surface temperature of the gauge and its known thermal properties allow to recalculate the time-dependent heat flux from the heating environment onto the gauge which caused the temperature change of the gauge. This is accomplished by the theory of heat conduction into a semi-infinite body. The design of the gauges is such that during a typical time period of about 10 ms, the requirements of a body of semi-infinite thickness are fulfilled. The direction of the deduced heat flux is perpendicular to the measuring surface of the gauge.

In general, thin film gauges are much more sensitive than thermocouples. They allow to measure surface temperature changes in the order of 0.1 K and heat fluxes as small as 0.5 W/cm$^2$. Thermocouples are one order of magnitude less sensitive, but due to their design they are very robust, easy to operate and able to withstand harsh environmental conditions and extremely high heat fluxes. In certain conditions, the evaporated or sputtered thin metallic film of thin film gauges may be destroyed e.g. by the impact of small particles carried by the flow or by too high heat fluxes which cause too high thermal stresses in the film resulting in its destruction. Therefore, for determining relatively low heat fluxes in clean environmental conditions thin film gauges are recommended, whereas for high heat fluxes in harsh conditions coaxial thermocouples represent the better choice.

## Coaxial Thermocouple

Coaxial thermocouples of type E (chromel/constantan) and type K (chromel/alumel) are available for different standard sizes (length, diameter). The special feature results from its unique design, where one thermocouple element is swaged over the second element with an electrical insulation in between with a typical thickness of about 10 µm. The thermocouple allows a mounting through the wall which is important for the accurate measurement of a rapidly changing surface temperature. For some applications the wall temperature is of direct interest. In this case the probe material should have thermal properties (ρck-value) which match those of the surrounding wall as nearly as possible. This is not a necessary requirement for determining convective heating rates by performing a fast surface temperature measurement with the help of a coaxial thermocouple. Usually the thermocouple is fixed in the wall by gluing at the rear part of the element. Installation by a thread is also possible which is recommended for higher operating temperatures.

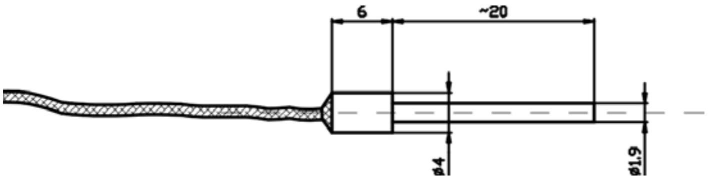


Principle setup and possible installation of a coaxial thermocouple

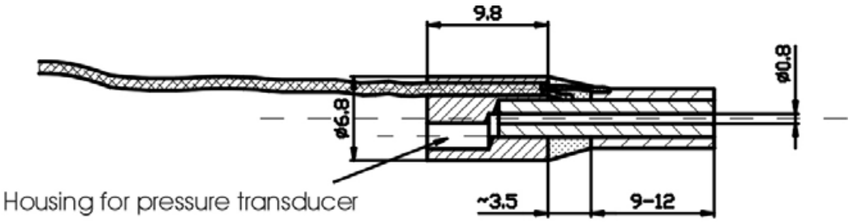
Of course, installation is also possible in a ‚blind‘ hole in the test wall to measure the internal material temperature at a known location. There is no electrical insulation necessary between the thermocouple and the surrounding wall.

Usually, the thermocouple junction is simply formed by grinding its front surface with sandpaper. The micro-scratches generated by this process form the active junction of the thermocouple and therewith, it represents a very small amount of active mass resulting in a short response time. The grinding of the front surface allows to perfectly fit it into curved walls, i.e. in this case no steps or gaps between the thermocouple and the wall surface disturb the measurement. This method of forming the thermocouple junction makes the gauge very robust and suitable for the application in harsh environmental conditions. As example, the impact of high speed particles transported by a fluid has in general no influence on the operation of the thermocouple. In case of a failure, grinding of the front surface again activates the thermocouple.

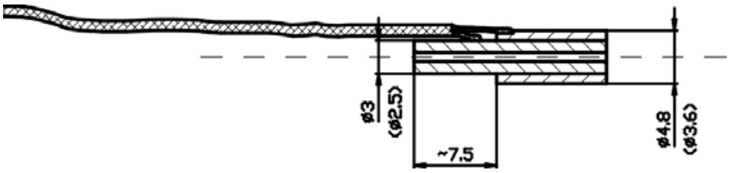
For special applications, like measurements in reactive media, the front surface of the thermocouple can be covered by a vacuum-deposited metallic coating of one to two microns thickness. Usually, Chromium is best suited for this coating, but depending on the application other coating materials are possible.



Standard model KL

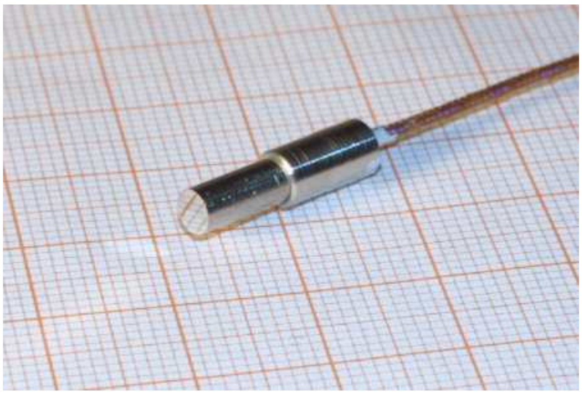


Model MI with adapter for pressure measurement



Model MI without adapter

Model KL



Model MI without pressure tap

Model MI without pressure tap,

Model MI with pressure tap, adapter

with thread for installation and pressure transducer installed

| Thermocouple | Outer diameter [mm] | Pressure tap | Length of active part [mm] | Overall length [mm] |
|---|---|---|---|---|
| KL | 1.9 | no | 20 | 26 |
| MI with adapter | 4.8 | yes | 12 | 25 |
|  | 3.6 | yes | 12 | 26 |
| MI without adapter | 4.8 | possible | 12 | 20 |
|  | 3.6 | possible | 12 | 20 |

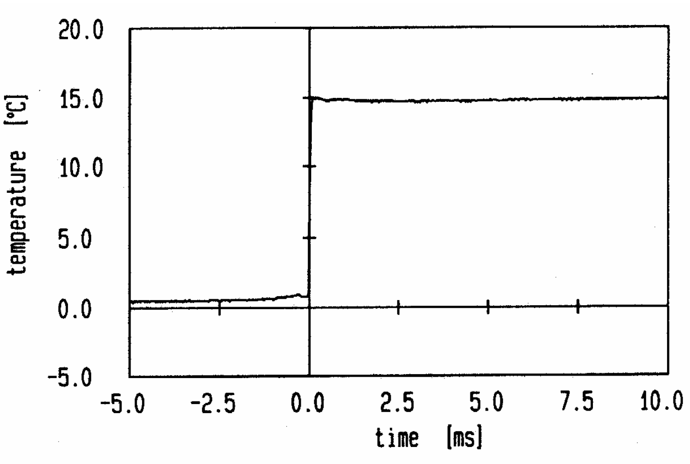
On request, the thermocouple design can be modified in order to meet special customer requirements.

The standard diameter of the thermocouple model KL amounts to 1.9 mm. Its length typically amounts to 20 mm, but it can be adapted to the customer‘s requirements. At its rear a sleeve of 4 mm diameter protects the wiring connection to the thermocouple.

In many applications it is a special desire to perform a surface temperature measurement in parallel to a pressure measurement at nearly the same position. For this purpose, the models MI are equipped with a pressure tap drilled through the central part of the thermocouple. This pressure tap is connected at its rear end via an adapter to a commercial pressure transducer. Typically, the diameter of the tap amounts to 0.8 mm (other diameters are possible), where the outer diameter of the active thermocouple can be 3.6 mm or 4.8 mm, respectively. These dimensions have been chosen by the semi-infinite principle of heat conduction in order to fulfill typically the operational requirements of an impulse facility; i.e. during a maximum measuring time of 10 ms the temperature measurement is not disturbed by radial heat fluxes emerging from the pressure tap or the junction between the wall and the outer thermocouple element. These elements have been tested in a shock tunnel, and no difference in the temperature as well as pressure signal was recognized compared to those of single thermocouple and pressure gauges.

## Calibration

For heat flux determination the thermodynamic property ($\sqrt{\rho c k}$ -value) of the thermocouple has to be known. This value is calibrated individually for each gauge using the contact method. This is based on the familiar heat diffusion problem which arises when two semi-infinite bodies suddenly come into contact, yielding for a certain period of time a constant contact temperature which depends on the two initial temperatures of the two bodies and their $\sqrt{\rho c k}$ -values. The figure below shows the fast temperature rise from the initial temperature of the thermocouple to the constant contact temperature by dipping a cold thermocouple into a hot liquid.

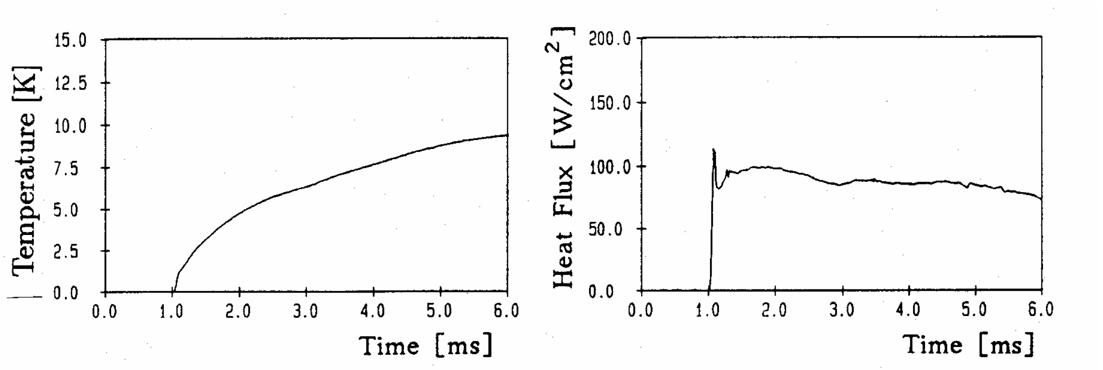


Signal of temperature rise by fast dipping
of a coaxial thermocouple into a hot liquid

The temperature sensitivity of the manufactured thermocouple is chequed regularly. It is found to be identical to published standard data for the corresponding types (E and K) of thermocouples.

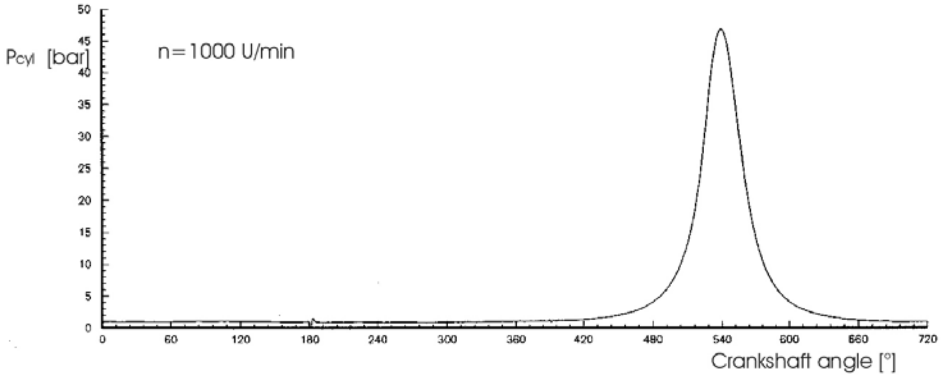
## Examples of Application

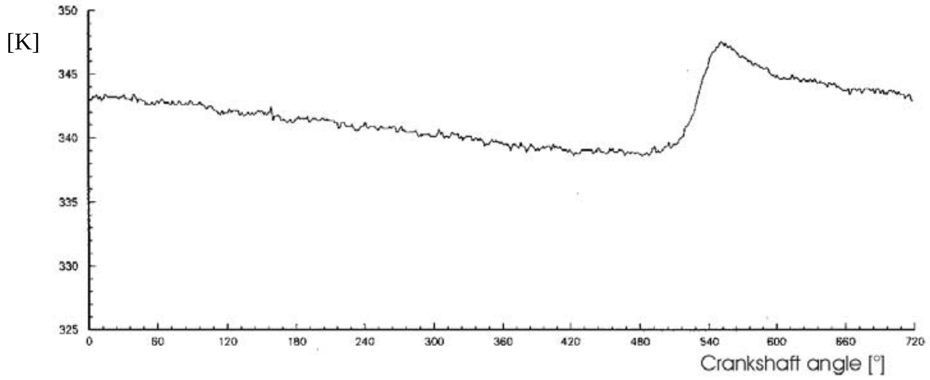
The following figure shows a temperature signal of a coaxial thermocouple installed into a wind tunnel model tested under hypersonic flow conditions in a shock tunnel. From the temperature signal and the calibrated thermal properties the convective heat flux is deduced.



In this case, the flow starts at t = 1 ms, and the continuous temperature rise of the model surface due to the convective heat flux generated by the flow is obvious. The stepwise rise of the heat flux signal at the beginning of the flow nicely depicts the capability of this technique to resolve heat flux variations at a very high time resolution in the order of microseconds.

For research purposes coaxial thermocouples have been used to measure the temperature variation of the inner cylinder surface of a driven piston engine. The figures below show the pressure inside of the cylinder and the cylinder surface temperature as function of the crankshaft angle (rate of resolutions 1000 min$^{-1}$) of a driven engine for research purposes. It is seen that, as expected, the temperature signal follows the pressure signal without any obvious time delay.





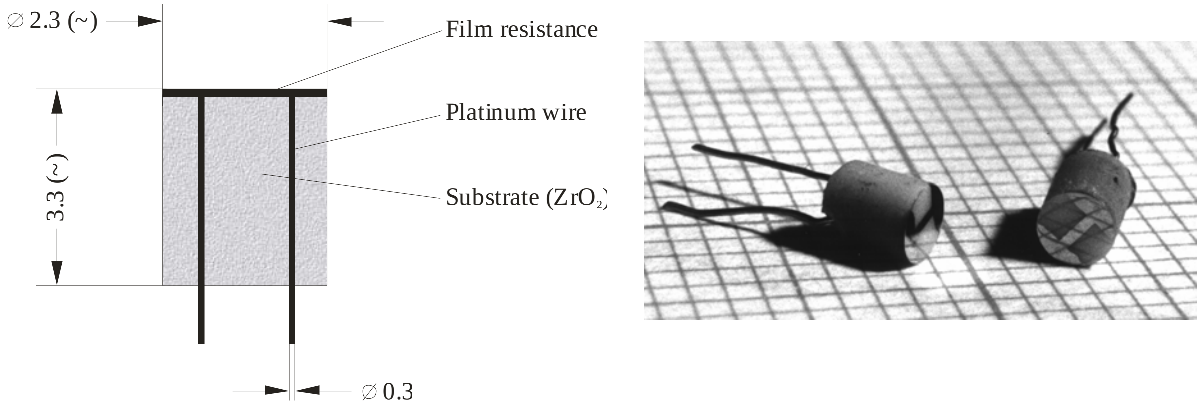
In a typical industrial application coaxial thermocouples are used to measure the surface temperature of welding dies of a machine welding thin plastic films. In this case, the surface temperature represents an important parameter for controlling the welding process. Since a high number of cycles per unit time is desired, the surface temperature measurement has to be very fast and the thermocouple has to be very robust to withstand the high numbers of loadings.

## Thin Film Thermometer

The thin film thermometer consists of a ceramic substrate (zirconium oxide) on which a thin nickel or platinum film is deposited by means of sputtering. This gauge is superior for applications which require a very high sensitivity of the measurement. Surface temperature changes in the order of 0.1 K can be measured with a response time in the range of micro-seconds. For surface temperatures larger than 320 K the dependence of the calibration factors on the temperature has to be taken into account. The gauge is not suited for hard environmental conditions, where e.g the impact of high energetic particles may cause the destruction of the film.

The typical diameter of the gauge amounts to 2.3 mm with a length of 3.3 mm. Two platinum wires are imbedded by sintering into the substrate. At its rear ends wires for electrical power supply and for registrating the resistance change of the thin film during the measurement process are fixed by soldering. This technique drastically reduces the problems associated with establishing the electrical contact to the thin film by thin leads along the outer cylindrical surface of the substrate.

During operation the thin film thermometer has to be supplied by a constant current in the range of 7 ma to 10 ma. The transient surface temperature of the substrate as it occurs during the measurement causes a voltage change across the thin film which is a direct measure for the substrate surface temperature. Within the theory of thin film thermometers it is assumed that the thin film has no influence on the substrate surface temperature.



Setup of the sensor and completed sensors

If $R_0$ is the ohmic resistance of the thin film prior to the measurement, by heating it changes its resistance according to

$$R = R_0(1+\alpha \cdot \Delta T_S) \ ,$$

where α characterizes its temperature sensitivity. This yields a voltage change which is directly proportional to the time dependent change of the surface temperature

$$\Delta T_S(t) = \frac{\Delta u(t)}{IR_0\alpha} \ .$$

For each gauge, the calibration of its temperature sensitivity as well as the thermal property $\sqrt{\rho ck}$ are performed individually. Installation into the testing body can be done by gluing or by an adapter. Constant current sources or special amplifiers with integrated current supply are available on request.

### Determination of the heat flux from the temperature signal

The determination of the heat flux from the temperature signal is based on the theory of one-dimensional heat conduction into a semi-infinite body as it is described in many standard text books. It is based on the assumption that during the measuring time the heat pulse penetrating into the sensor for ideal conditions does not influence the temperature of the sensor at its rear end. The formula given below holds for the coaxial thermocouple as well as for the thin film thermometer as long as the principle of a semi-infinite body is valid. From this, the maximum-recommended measuring time for the thermocouple amounts to 20 ms, whereas the thin film thermometer allows 100 ms. This only holds if the gauge is used to determine heat fluxes. For the measurements of steady or very slowly varying temperatures no upper limit exists concerning the measuring time.

The one-dimensional heat conduction theory yields the following relation between the surface heat flux $\dot{q}_s$ and the surface temperature signal T(t)

$$\dot{q}_s(t) = \frac{\sqrt{\rho c k}}{\sqrt{\pi}} \left[ \frac{T(t)}{\sqrt{t}} + \frac{1}{2} \int_0^t \frac{T(t) - T(\tau)}{(t-\tau)^{3/2}} d\tau \right] .$$

For data evaluation this expression can be transformed to

$$\dot{q}_s(t_n) = \frac{2\sqrt{\rho c k}}{\sqrt{\pi}} \sum_{i=1}^{n} \frac{T(t_i) - T(t_{i-1})}{(t_n - t_i)^{1/2} + (t_n - t_{i-1})^{1/2}} .$$

This expression is valid under the assumption that for $t_0 = 0$ the temperature is set to $T(t_0) = 0$, i.e. the temperature in the formula given above represents the temperature difference of the gauge registered during the measurement with respect to the initial temperature. The heat flux signals shown above have been deduced by this formula.

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