Thermocouples without tears — 2

Following on from last month's article discussing the general operation of thermocouples, this sequel describes a simple and practical thermometer/pyrometer capable of making measurements up to around 900°C. It's very suitable for measuring the temperature of small kilns or furnaces used in pottery, enamelling or heat treatment of metals.

by JIM ROWE

As I explained last month, the background to these articles was a need which arose to heat treat some home-made milling cutters, to harden them. In order to harden the cutters, which were made from "silver steel", they must be heated to about 780°C and held there for about 15 minutes. Then they must be rapidly cooled down, by quenching in water or some other liquid.

The temperature must be held at close to the correct value, or the parts won't harden properly and be ruined as soon as they're used. If they're made too hot before quenching, some of the carbon can be burned away; conversely if they're not made hot enough, the correct carbon-steel "solid solution" is not present before quenching, and the very hard Martensite crystals won't form.

The traditional way to judge the correct temperature is to go by the colour of the steel parts themselves. For example, 780°C is half-way between "cherry red" and "blood red". This may be easy for those that are very experienced, but if you're like me and only need to do it once every few months, it's surprisingly tricky. I've ruined a few cutters this way recently, and the last time it happened I decided that there simply *had* to be a better way.

There is, of course. The answer is to measure the temperature using a high-temperature thermometer, or *pyrometer.* These come in various kinds, some of which actually function by comparing the colour against a reference colour scale.

Using a type K thermocouple probe, this simple pyrometer is suitable for making measurements in kilns and furnaces up to about 900°C.

Commercial pyrometers tend to be quite expensive, and scarcely justified for casual hobby use. But it is possible to make a simple pyrometer using a thermocouple, which will do the job at surprisingly low cost.

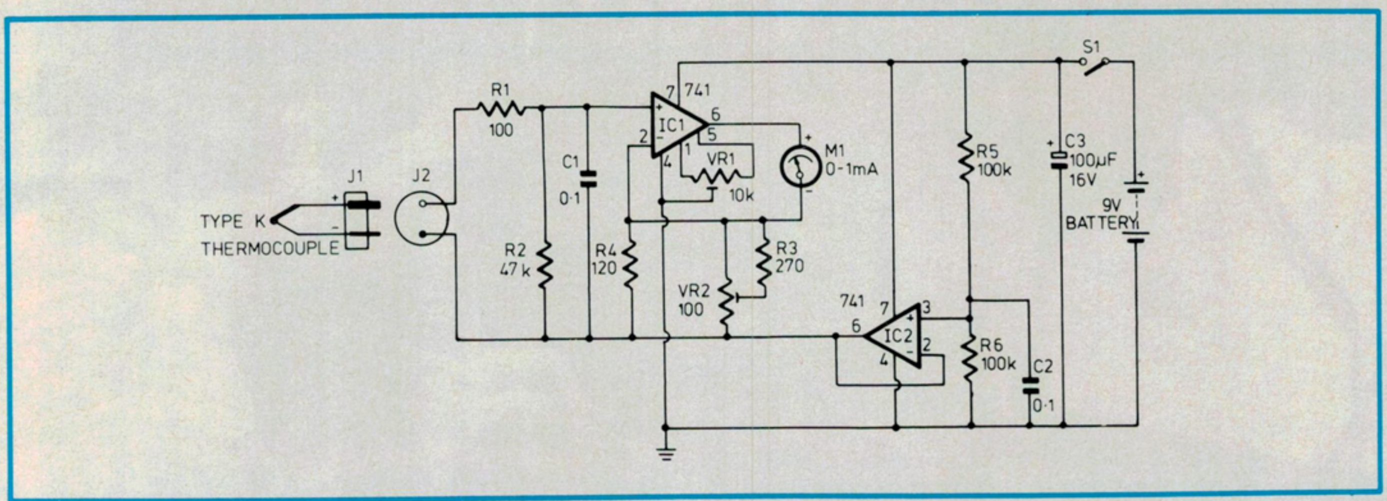
The little pyrometer to be described here uses a readily obtained type K thermocouple probe, based on a Chromel-Alumel junction. This type is currently the most suitable proposition for measurements to around 900°C, offering reasonable electrical output and stability combined with low cost. The probe I've used in the prototype unit and visible in the photographs was made to order by Richard Foot Pty Ltd, of 26-30 Tepko Road, Terrey Hills NSW 2084. It comes complete with stainless steel sheath and leads, and cost me a very reasonable $25 plus sales tax.

In a few months, it should be possible to buy similar probes based on a type N (Nicrosil-Nisil) junction, from Bell-IRH Pty Ltd of 32 Parramatta Road, Lidcombe NSW 2141. These are likely to be more stable in performance, but they're also likely to be more expensive.

For hobby work the type K probe I've used is probably more than adequate, but if you're after the highest accuracy and stability, you might well want to use a type N probe when these become available.

By the way, the little pyrometer unit described here isn't restricted to being used with a type K probe. It can be used with type N, J, or E probes, or even with the much more expensive types R and S probes with a little modification. But I should stress that it's a simple unit intended for hobby measurements, not for very demanding and critical industry applications. Hooking it up to expensive platinum-based type R or S probes would be like using a cheap pocket compass to navigate your $50,000 cruiser (if you had one!).

Basically, although my motivation for



The complete circuit for the pyrometer. As you can see, it is very simple and straightforward.

designing the unit has been for measuring the temperature of steel parts being heat treated, it should also be quite suitable for measuring the temperature of kilns and furnaces used for pottery firing and jewellery enamelling. The type K probe is capable of operating at up to about 1100°C, while one of the newer type N probes would be capable of measuring up to around 1250°C. Type R or S probes would take you even further, to around 1400°C.

As discussed last month, thermocouples produce a small DC output voltage that is proportional to the temperature difference between the "active" and "reference" junctions. This means that what we need to produce a pyrometer, apart from the thermocouple probe itself, is a means of measuring small DC voltages. In other words, a DC millivoltmeter.

Of course one solution would be to use a digital multimeter. Many of these provide a suitable low voltage range, to be sure. But they're also fairly expensive, and it won't always be feasible to press one into use — particularly if you want the pyrometer for measuring the temperature of a pottery or enamelling kiln, for significant periods of time.

Another solution would be simply to connect the thermocouple probe directly to a small moving-coil meter movement. This will work in some situations, but generally it isn't satisfactory as the output of most thermocouples is too low at the temperatures of interest. For example even the highest-output type E probe produces only about 59mV at 780°C, while the more readily-available type K probe has an even lower output, of 32.45mV at 780°C.

When you consider that the majority of moving-coil meter movements have a nominal voltage sensitivity of 100mV full scale, regardless of their current sensitivity, it's obvious that reading these low voltages with any kind of accuracy would be very difficult.

The alternative is to use a small DC amplifier circuit, as shown. This effectively converts a standard and reasonably rugged low-cost 0-1mA meter movement into a DC millivoltmeter of any suitable full-scale deflection (FSD), say 50mV to suit a type K probe.

The circuit uses a couple of low cost 741 op-amp chips, and runs from a small 9V battery. It could also be operated from a 9V DC plug-pack supply, if you needed to run it for hours on end.

Circuit description

The basic amplifier configuration is shown in Fig.1. Resistor Rf is used to generate a voltage Ef in response to the meter current Io, and since the op-amp's negative input is connected to the top of Rf, Ef becomes the negative feedback voltage.

Since the op amp has a very high open-loop gain A, it will act to ensure that Ef follows the thermocouple voltage Ei very closely. As a result, the meter current Io becomes directly proportional to Ei, and inversely proportional to Rf.

So the circuit is essentially a linear voltage-to-current converter, whose ratio is determined by Rf. By adjusting the value of this resistor we can effectively give the meter any desired sensitivity in terms of input Ei in millivolts. For example if the meter is a 0-1mA type, making Rf 50 ohms will turn it into a 0-50mV meter. Similarly a value for Rf of 20 ohms will turn it into a 0-20mV meter.

Of course this assumes that a meter that is marked "0-1mA" does give full-scale deflection when it is passing exactly 1mA. Generally this is not the case, as meters have a tolerance of between 3% and 5%. For the present purposes this can be fairly significant, as a 5% error in measuring the output of a type K thermocouple at around 800°C can correspond to an error of about 50° in temperature.

In other words, we can't really just put in a 1% precision resistor for Rf, and assume that everything will be OK. Because of the tolerance errors in meter current sensitivity, calibration is going to be necessary.

You may also recall from the first of these articles that because the output voltage from thermocouples is not a linear function of temperature, we can't easily calibrate the meter in terms of temperature. It's best to calibrate it in terms of DC millivolts, and then use the method and table given last month (Table 2) to work out the corresponding temperature.

Now let's look at the final circuit. IC1 is the basic voltage-to-current amplifier, as shown in Fig.1. A standard low-cost 741 op-amp is used, as there are no special requirements here in terms of high input impedance or output drive capability.

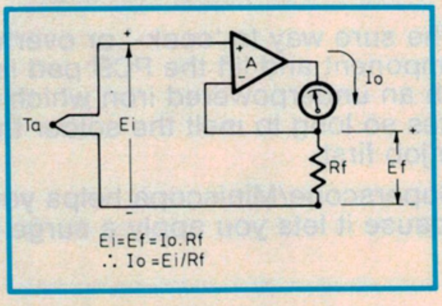
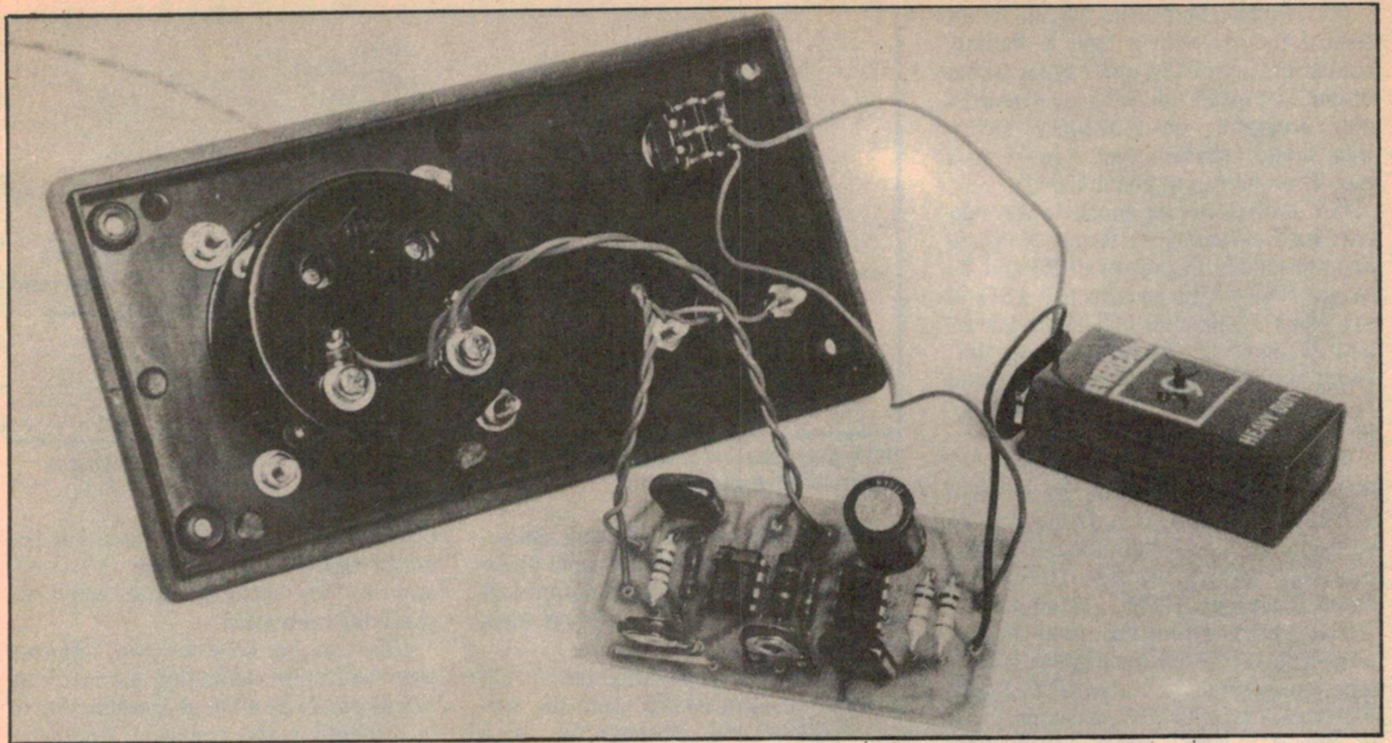


Fig.1: The basic circuit used in the pyrometer metering unit, to perform voltage-to-current conversion.



Inside the metering unit box. The small PCB mounts vertically in one of the moulded slots, between the meter and the battery.

PARTS LIST

- 1 PCB, 87t10, 62 x 31mm
- 1 plastic utility box, 41 x 68 x 130mm
- 1 0-1mA meter movement, 58 x 52mm
- 1 type K thermocouple probe (see text)
- 1 polarised 2-pin plug
- 1 matching 2-pin socket
- 1 miniature SPST or DPST toggle switch
- 1 9V battery and snap lead

Semiconductors

- 2 741 op-amp ICs, 8-pin DIL type

Resistors

1 x 100Ωs, 1 x 120Ωs, 1 x 270Ωs, 1 x 47k, 2 x 100k, 1 x 100Ω small vertical trimpot, 1 x 10k small vertical trimpot

Capacitors

- 2 0.1uF LV plastic
- 1 100uF 16VW electrolytic (PC mount)

Our estimated parts cost for this project, not counting the thermocouple probe, is $31.50. Suitable probes are available for $25 plus sales tax, as discussed in the text.

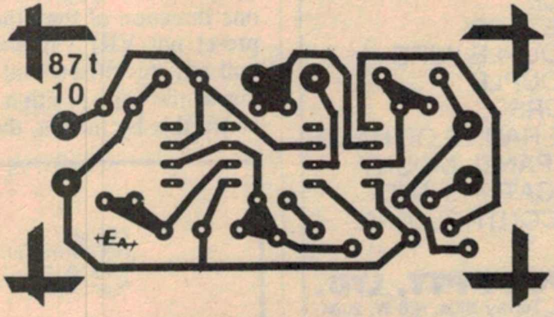
A second op-amp IC2 is used to split the 9V battery supply, in order to operate IC1 in the most linear part of its transfer curve. IC2 is connected as a unity gain voltage follower, with its input connected to a divider formed by R5 and R6. Its output is therefore midway between the two supply rails, and is used to establish the reference bias level for IC1. Capacitor C2 is to prevent any noise from being injected into IC1 via this reference line.

The thermocouple probe is connected to the input of IC1 via a simple network consisting of R1, R2 and C1. The function of R1 is to swamp out the effects of wire and connector contact resistance in the probe leads, while C1 is to bypass any RF signals which may be picked up by the leads. Resistor R2 is to prevent the input of IC1 from floating when the probe may be disconnected.

Trimpot VR1 is to allow nulling of IC1's input voltage offset, which can be as much as +/-15mV — quite small, but large enough to be significant here.

Finally VR2, R3 and R4 together make up the current feedback resistor, jointly replacing Rf of Fig.1. The idea here is to provide a resultant resistor whose value is variable over a small range, to allow adjustment which compensates for the tolerance error of the meter movement, and allows the pyrometer to be calibrated.

The circuit values shown provide a feedback resistor which can be varied from about 45 to 55 ohms — i.e., about 10% either side of 50 ohms. This should be adequate to allow the circuit to be set for an accurate 50mV FSD, with virtually any 0-1mA movement.



Here is the PCB pattern, reproduced actual size.

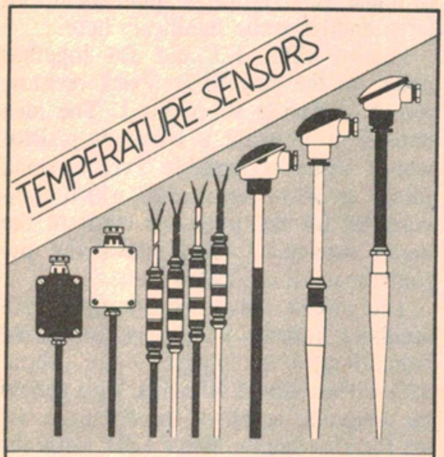
As shown, then, the circuit is intended for use with a type K thermocouple or any of the other types whose output is capable of being read reasonably accurately on a 0-50mV meter. This would include a type J probe or a type E probe (up to about 750°C).

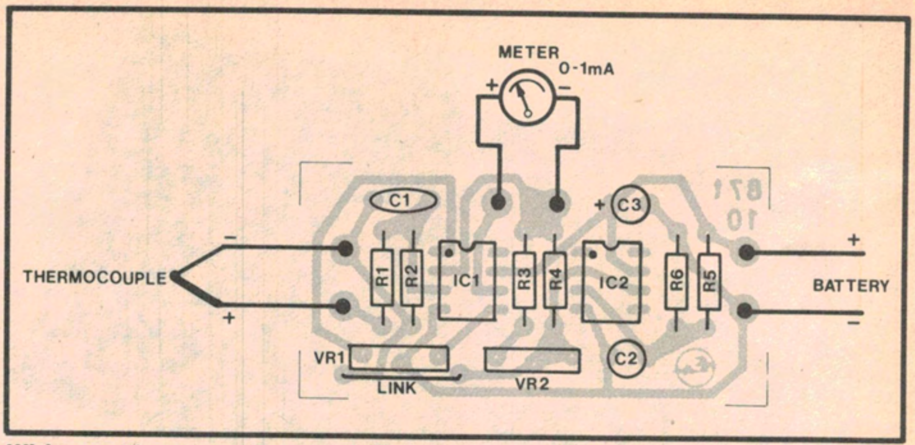
For probes having much lower output, such as the types R and S, you'd need to modify the values of R3 and R4 to give the circuit an effective FSD of say 20mV. Values of 150 ohms for R3 and 27 ohms for R4 will achieve this, giving an adjustment range from about 18.6 to 21.25 ohms (i.e., about 6% either side of 20 ohms).

The circuit is built up on a small PC board as shown, measuring 62 x 31mm and coded 87t10. This is designed to fit vertically inside a small moulded plastic jiffy box, such as the type UB3 (Dick Smith Electronics H-2853, or similar).

The meter movement used in the prototype is a small rectangular 0-1mA type, measuring 57 x 52mm (Dick Smith Electronics type Q-2010 or similar). To be honest a larger meter would allow more accurate reading, and would thus be preferable, but this would also call for a larger and more expensive case.

I used a small polarised 2-pin plug and socket, of the type where the plug has two round pins of different diameters, to connect the thermocouple probe to the metering circuit. A miniature toggle switch was used for the on-off function.





Wiring up the pyrometer should be easy using this PCB overlay and wiring diagram as a guide.

Assembly of the metering unit should be fairly straightforward using the wiring diagram and photographs as a guide. In wiring up the PCB, I suggest that you fit the resistors and single insulated link first, then the capacitors, the ICs and finally the preset pots. Just make sure that you fit the ICs and the electrolytic capacitor with the correct orientation, and watch that you to fit the two preset pots in their correct positions.

After preparing the case and mounting the meter, power switch and probe socket in position, you can add the wires to connect these to the completed PCB, and to the 9V battery snap connector.

When all is completed, you should be ready to begin setup and calibration. The first step here is to carefully adjust the meter movement's physical zero setting, with the power off, so that it does indeed correspond to zero on the scale.

Now add the battery and try turning on the power — initially without the probe connected. All that should happen is a small movement of the meter away from its physical zero position, in one direction of the other. By adjusting preset pot VR1 you should be able to null out this offset, and return its reading to the zero position again. You can verify this by turning the power on and off a few times, making sure that the meter needle doesn't move. VR1 will now be set correctly, and you'll be ready for calibration.

This can be done in two different ways: either by calibrating the metering circuit purely as a DC millivoltmeter, or by calibrating the complete pyrometer at a known temperature — perhaps against another unit of known calibration. The first approach is likely to be by far the easiest, for most people.

Here again there are are couple of possible options. If you have access to a digital voltmeter or multimeter, even briefly, the easiest plan would be to calibrate the meter against the digital meter, using a variable power supply or a battery and voltage divider combination to produce a suitable test voltage of say 50mV.

It's best to calibrate at the metering circuit's full-scale deflection, for greatest accuracy.

If you don't have access to a digital meter of any kind, or even a good analog meter to calibrate against, I can only suggest that you try the simple test circuit shown in Fig.2.

With a fresh mercury call of the photographic type, it will produce 50.5VmV when connected to the input of the pyrometer metering circuit (instead of the thermocouple probe). So when connected, it should produce a reading of just greater than FSD on the meter. If not, adjust preset pot VR2 until this is achieved.

Note that the mercury cell should be

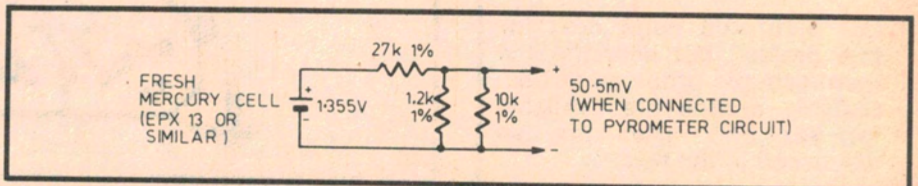


Fig.2: A simple test circuit for calibrating the metering circuit of the pyrometer.

of the type intended for photographic use, not for hearing aids. A suitable type is the Eveready type EPX-13.

The same test circuit can actually be used if you're able to calibrate the circuit against a digital meter. Here the digital meter will be able to show you any slight error in the voltage produced by the test circuit, and you can set VR2 to make the pyrometer meter read accordingly.

Having calibrated the metering circuit, you're finally ready to plug in the thermocouple probe — making sure, of course, that its leads have been wired to the plug correctly. With the unit I obtained from Richard Foot Pty Ltd, this was easy because the leads were provided with small labels marked "+" and "-".

Before closing, just a couple of tips about using the pyrometer. The first is that with thermocouple probes in a sheath, there is quite a significant thermal time constant involved. It takes a good couple of minutes, at least, before the thermocouple itself reaches a temperature close to that outside the sheath.

So if you're using the pyrometer to measure the temperature of a small kiln or furnace, the best approach is to let the thermocouple probe heat up with the kiln itself, slowly, and to stay inserted in it all of the time during which you need to make measurements. As well as allowing more accurate measurements, this will also subject the probe to fewer thermal heat up/cool down cycles — prolonging its life.

The other tip is simply to remember the correct technique for measuring temperature using a thermocouple. As explained last month, the thermocouple output voltage as measured by the meter is actually the *difference* between the Seebeck voltages generated by the active and reference junctions.

For accurate temperature measurements, then, what you need to do is make TWO measurements: one the pyrometer meter reading, and the other the ambient temperature (i.e., that of the probe cable and meter unit) using an ordinary thermometer.

Then from Table 2 given last month, or the equivalent table for the type of thermocouple probe you're using, look up the reference junction voltage which corresponds to the ambient temperature. This will allow you to work out the true active junction voltage, by simple addition: $Va = Vm + Vr$
where Va is the true voltage, Vm is the voltage measured by the meter, and Vr is the reference junction temperature as looked up from the table.

The final step is to go back to Table 2 with this corrected value for Va, and look up the true probe temperature.

It sounds a bit fiddly, and perhaps it is, but you soon get the hang of it. And in any case, it's a lot easier than trying to work out whether the colour you're looking at is blood red, cherry red, brick red or whatever!

Incidentally, if you want to check the temperature calibration of the pyrometer, this can be done by making use of the known melting points of various materials. For example pure aluminium (like that from an old saucepan) melts at 658°C, while zinc melts at 419°C. But note that for accuracy, you need to check the melting/solidifying temperature going each way (up and down), and take the average of the two.

Finally, if like me you want to know more about heat treatment of metals, I can recommend the paperbound book "Hardening, Tempering and Heat Treatment", by Tubal Cain, one of the Argus Workshop Practice Series. ⓔ