TC Ltd., PO Box 130, Uxbridge, UB8 2YS, United Kingdom
Tel: +44 (0)1895 252222 - Fax: +44 (0)1895 273540
Email: info@tc.co.uk - Web: www.tc.co.uk

01895 252222

3.0 Application Methods and Equipment - RTD's

As with thermocouples, RTD outputs measuring temperature change are small - we are looking at less than 0.5 ohms per °C for an IEC standard device. However, the resulting signals are not quite as minute - 1mA energising current with a 100 ohm nominal resistance RTD sensor yields 5mV output for a change of 10°C. Move the current up to 5mA and the output is 25mV for 10°C change - at least an order of magnitude better signal strength than with thermocouples. However, bridge amplifiers (or equivalent) are still required to provide signal levels suitable for most purposes.

There are two main instruments for determining RTD sensor resistance - measuring bridges (null-balance or fixed-bridge direct-deflection), in which the supply current can vary, and potentiometers, where the current has to be known and constant. Both can use AC or DC currents, although a smooth, stable low voltage power supply is the norm.

Early measuring instrumentation relied on null balance bridges (resistive, capacitive, or inductive). In fact, balanced measuring bridges are still used extensively in laboratories where the bridge elements might be resistance decades, or tapped inductances in AC versions. Today, fixed bridge systems are more common - where the imbalance itself is a direct measure of the changing sensing resistance.

However, high accuracy can also be achieved using today's precision potentiometers, digital voltmeters and the like to measure voltage drop directly across the sensor. Stable, constant energising current circuits are available, and these tend to favour potentiometric instrumentation, particularly for industrial use. Notably, they lend themselves to high accuracy, high speed RTD sensor scanning applications.

Also, there is now a plethora of direct reading equipment covering both instrumentation types, interpolating from the quadratic resistance (and therefore voltage, if current is constant) vs temperature relationship to give a direct temperature output. The following provides some insight into methods and equipment available.

3.1 Bridge Measuring Systems - RTD's

Commercially available industrial bridge measuring systems use one of several circuit arrangements relying mainly on two versions of the Wheatstone bridge - balanced, or fixed bridge, both resistive. Incidentally, it is worth just noting that inductive ratio bridges can also be used, in which precision wound transformers are used for the ratio arms of the bridge. These can offer advantages in terms of robustness, portability and stability.

Returning to resistive bridges, whatever the circuit format selected, all bridges can be made self-balancing using servo mechanisms controlled from the balance detector. In industrial applications, the bridge is not normally balanced (by altering variable resistances). Instead, as stated above, the imbalance voltage in a fixed element bridge tends to be used as a measure of the sensor resistance - and hence of temperature.

Irrespective of bridge style, all the bridge resistors, except, of course, the sensor, are set to exhibit negligible resistance change with temperature, and in AC bridges are designed to be non-inductive. Also, bridge arm resistance errors due to sliding contacts on variable resistors (where applicable) are normally prevented by introducing these into the current supply line itself, or the balance detector circuit where they can clearly have no influence on the bridge balance.

The sensing resistor, which may well be some distance away from the bridge in industrial applications, is then attached to the bridge using copper cable - whose resistance is low compared with that of the bridge, but which will obviously vary with temperature, particularly nearer to the measurement point. When the conductors are long, or of small cross section, these resistance changes can be large enough to cause significant errors in the temperature reading. And, hence the emphasis on the wiring schemes - basically two, three or four wire - to take account of this potential problem area.

3.2 Two Wire Configuration

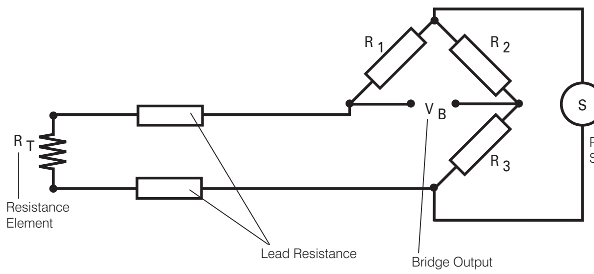

Figure 3.1: *Wheatstone Bridge with RTD in Two Wire Configuration*

The simple two wire connection shown in Figure 3.1 is used only where high accuracy is not required - the resistance of the connecting wires is always included with that of the sensor, leading to errors in the signal. In fact, a standard restriction with this arrangement is a maximum of 1 - 2 ohms resistance per conductor - which is typically about 100 metres of cable. This applies equally to balanced bridge and fixed bridge systems. The values of the lead resistance can only be determined in a separate measurement (without the RTD) therefore a continuous correction during temperature measurement is not possible.

3.3 Three Wire Configuration

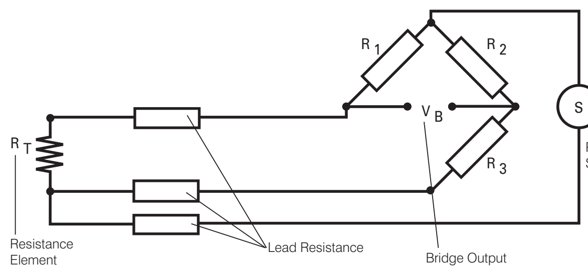

Figure 3.2: *Wheatstone Bridge with RTD in Three Wire Configuration*

A better scheme is shown in Figure 3.2. Here, the two leads to the sensor are on adjoining arms - there is a lead resistance in each arm of the bridge and therefore the lead resistance is cancelled out from the measurement. It is assumed that the two lead resistances are equal, therefore demanding high quality connection cables.This allows an increase to 10 ohms - usually allowing cable runs of around 500 metres or more, if necessary - although with the caveats pointed out in Part 1, Section 7 and Part 2, Section 10 regarding signal transmission problems.

Also, with this wiring scheme, if fixed bridge measurement is being made, compensation is clearly only good at the bridge balance point. Beyond this, errors will grow as the imbalance increases. This, however, can be minimised by using larger values of resistance in the opposite bridge arms to reduce bridge current changes.

3.4 Four Wire Bridge Configurations

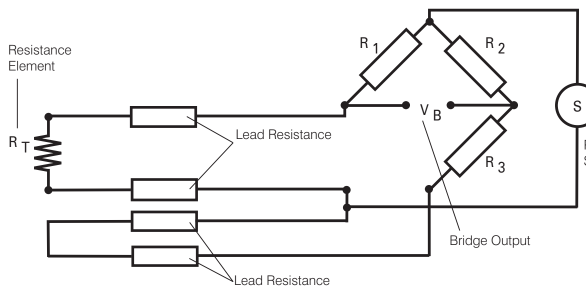

Figure 3.3: *Wheatstone Bridge with RTD in Four Wire Configuration*

Finally, the most effective method of resistance, and therefore temperature, determination is through the use of a four wire connection scheme. In Figure 3.3, a standard two terminal RTD is used with another pair of wires being carried alongside the thermometer pair, this being connected close to it. The additional loop formed is introduced into the other side of the measurement bridge, and thus the effects of the two sets of leads tend to cancel.

However, this approach is a little more costly on the copper wiring. An alternative, better version of the four wire connection scheme uses full four wire terminal RTD's, and is depicted in figure 3.4. This provides for full cancellation of spurious effects with the bridge type measuring technique. Cable resistance of up to 15 ohms can be handled with this arrangement, accommodating cable runs of around 1km. Incidentally, the same limitation as for three wire connections applies if the fixed-bridge, direct-reading approach is being used (see Section 3.3).

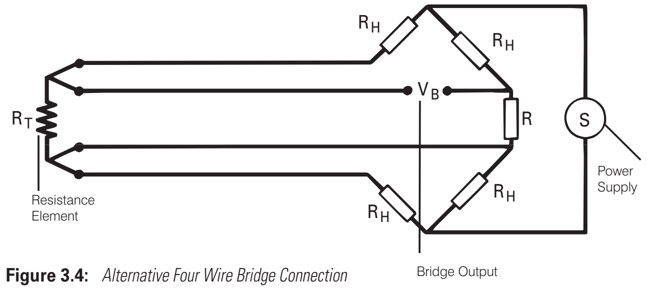

Figure 3.4: *Alternative Four Wire Bridge Connection*

3.5 Differential Temperature - RTD's

To measure differential temperatures using bridge circuitry, a second RTD is simply introduced into the bridge arm alongside the first sensor. A twin two-wire arrangement is adequate for this purpose if the cables used are both of similar resistance (Figure 3.5).

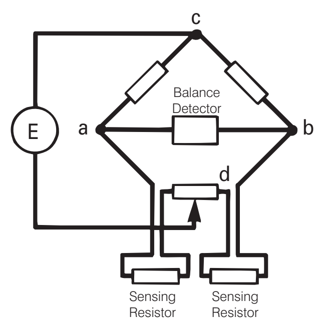

Figure 3.5: *Differential Temperature Measurement - Two Wire, Bridge Configuration*

If, however, high accuracy is required and the two sensing cable lengths, or resistances are dissimilar, then a four wire equivalent is preferable (see Figure 3.6) in which both sensors are equipped with compensating pairs (one per sensing arm of the bridge).

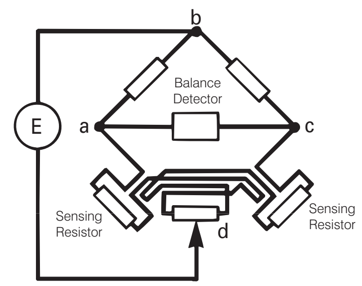

Figure 3.6: *Differential Temperature Measurement - Four Wire, Bridge Configuration*

3.6 Potentiometric Measuring Systems - RTD's

As described above, the resistance thermometer can be energised from a constant current source, and the potential difference developed across it measured directly by some kind of potentiometer. An immediate advantage is that here, incidentals like conductor resistance and selector switch contact resistance are irrelevant. The essentials for this voltage-based method are simply a stabilised and accurately known current supply for the RTD sensor (giving a direct relationship of voltage to resistance and thus to temperature) and a high impedance voltmeter (DVM, or whatever) to measure the voltage developed with negligible current flow.

So, absolute temperature can be derived as long as the current is known. Even where it is not known, if it is stable, differential resistance (and thus temperature) is provided. Also, a number of RTD's can be connected in series using the same current source. Voltage signals from each can then be scanned by high impedance measuring instrumentation.

3.7 Four Wire Potentiometric Systems - RTD's

Again, a four wire configuration is appropriate, although clearly somewhat different to that used with bridge systems. Using the configuration in Figure 3.7 the resistance of the leads has a negligible effect on measurement accuracy.

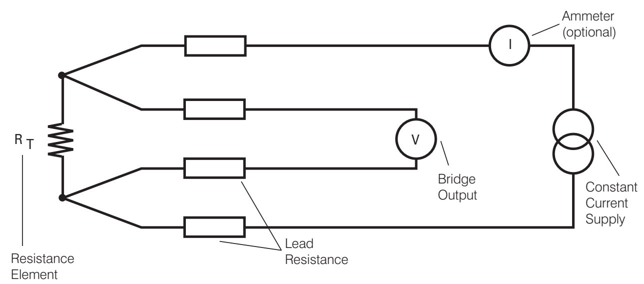

Figure 3.7: *Four Wire Sensing Arrangement*

3.8 Direct Reading Instruments - RTD's

Having looked at circuitry and measurement methods, it is time to look at the measuring instrumentation itself - detecting the null or measuring the imbalance in bridge systems, or sensing the voltage drop in potentiometric systems. The detector can, of course, take the form of a simple galvanometer - this is appropriate to balanced and fixed bridge arrangements. Deflection will indicate resistance and the scale can be configured for direct temperature reading should this be required. Sophistication can be added, with limit detectors set to provide on-off controls or alarms.

3.9 Amplifiers - RTD's

However, in general, low power electronic amplifiers, signal converters or transmitters are used. With the fixed bridge and potentiometric systems, they provide both a high input impedance and adequate power to drive more robust local or remote indicators, recorders or controllers. For null balance bridges, they are used to drive a servo system to balance the bridge, the system often forming part of an indicator, recorder or controller.

They are usually sited close to the RTD, and give the added advantage of minimising sensor cable resistance and providing a large, relatively RFI-immune signal for transmission to the signal reading instrumentation. The amplifier power supply is remote, and we're back in the realms of standard transmitter technology and 4-20mA signalling.

3.10 Potentiometric Measuring Instruments - RTD's

Then again, self-balancing direct potentiometric indicators and recorders can also be used to measure either the bridge imbalance voltage, or the direct sensor voltage drop. Constant current supply, bridge resistors, etc are all self-contained in these devices.

Continued on page 2

3.11 Digital Instrumentation - RTD's

Another more modern alternative involves either the bridge voltage imbalance, or the RTD potential drop being measured using a digital voltmeter. This clearly provides the opportunity for applying digital linearising techniques for direct temperature reading. In fact, there is a range of direct reading instrumentation today which operates more than adequately for industrial temperature measurement in ranges from -200 to +850°C.

Equipment is self-balancing, and the most straightforward comprises basically high resolution digital multimeter technology, with resistance or voltage signals being converted into direct temperature readings. The devices use linearising techniques following the RTD relationship (Part 1, Section 4) to, say, two or three orders. Linearisation is usually generalised to the RTD (as per the IEC 60751 standard quadratic expression), or specific to the sensor, with empirical calibration data taken into account.

In the former case, specifications and tolerances will be to IEC 60751 and accuracy will be to within a few hundredths of a degree. With individual calibration, accuracies to 10mK or better are available. Calibration characteristics can be provided on EAROM, which is plugged into the linearising and indicating system together with the sensor, or data can be programmed into the instrument, either directly via the front panel keypad, or remotely, with configuration performed typically in a PC and then downloaded via a serial port into the instrument.

3.12 Multi-Point Systems - RTD's

Multi-point RTD scanning instrumentation can easily be constructed using either fixed bridge or potentiometric sensing circuitry. Clearly, if selector switches are used, switch contact resistance and thermal EMF problems must be minimised, and adequate time left for the sensing and measuring circuitry to respond (this being the upper limit on frequency). Solid state switching is ideal for fast scanning. With potentiometric circuitry, this is relatively simple - the constant current source simply being switched around the sensors, along with the RTD measurement connections. In fixed bridge systems, the common voltage supply is used for all the bridges, but for multiplexing, bridge amplifiers are preferred to ease switching component duties.

Care must be taken with this direct reading equipment to ensure that the measuring current is not so great as to induce excessive self-heating (see Part 1, Section 4.2); also the current must be constant and stable such that any self-heating is reproducible.

3.13 Laboratory Style Instruments - RTD's

Figure 3.8 illustrates a simple DC potentiometric method of measurement in which the RTD is connected in series with a known standard resistor and a stable current source. A DVM can be used instead of the potentiometer, and the system lends itself to microprocessor control. Thermal EMFs are eliminated by reversing the current and the potentiometer polarity and averaging the readings.

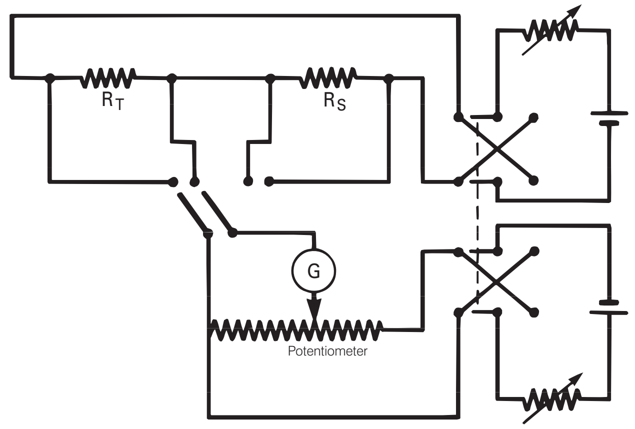

Figure 3.8: *Simple DC potentiometric method*

Alternatively, the resistance of the RTD and a variable standard resistor can be compared using a switched capacitor. A galvanometer, or similar, in one of the potential leads provides the null indication (see Figure 3.9).

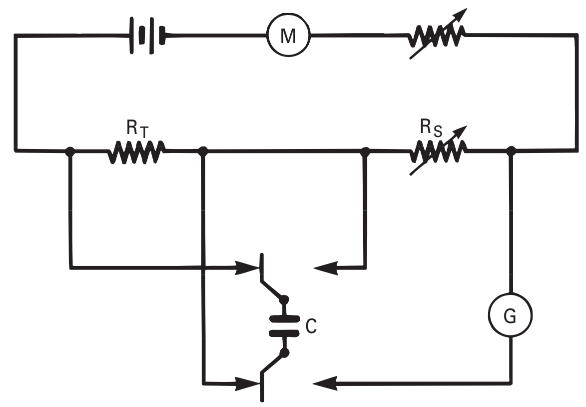

Figure 3.9: *Isolating Potential Comparator*

Beyond this, various DC bridges have been used (notable devices are the Mueller and Smith bridges), but inductive voltage dividers and ratio transformers (with their very high accuracy and stability), coupled with modern electronics (offering phase sensitive detectors and self-balancing systems) have encouraged AC measurement.

Early AC equipment included the Kelvin double bridge (mechanical coupling of the outer dividers giving the same ratio constantly) and various multi-stage transformer bridges, where lead resistance errors have been overcome by removing current flows. Modern AC bridges are self-balancing and computer coupled for direct readout of temperature using the calibration constants of the RTD concerned. Excitation frequency can be down to 25Hz such that conventional DC resistors can be used.

A modern DC bridge using ratio transformer technology is the Kusters current capacitor bridge. Here, the ratio of the currents through the thermometer and a standard resistor is measured, with the potentials across them kept equal. Bridge balancing is manual, lead resistances are irrelevant (no current flow) and automatic current reversing obviates static thermal EMF problems.

4.0 Siting Thermocouples and RTD's

An obviously important requirement with temperature sensing is that the sensor should take up the temperature of the medium it is sensing! Essentially, getting good thermal contact and thus good heat transfer without losses up the protection tube, supports, internal wires, or whatever (see Figure 4.1) is paramount.

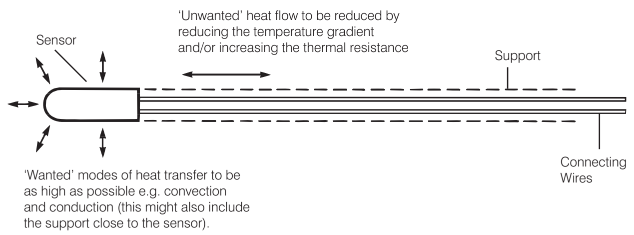

Figure 4.1: *Sensor Heat Transfer Modes*

In general, to obtain good temperature measurements you should first attend to the following three rules. Firstly, there is the question of good thermal linkage. When measuring fluids this means installation in the fastest flowing region, and arranging for the sensor to be in cross-flow if at all possible. The depth of immersion is also important and if the fluids are slow moving, external finning may be advantageous. With solids, it means inserting the sensor into a closely fitting hole, and using cements, fillers, high conductivity greases and heat transfer fluids. On surfaces, meanwhile, it means the use of pads and greases, cements and solders.

Secondly, heat flow to or from the sensor along the support and connecting wires needs to be minimised. This means reducing the temperature gradients close to the sensor, usually by providing enough sensor immersion depth (see Figure 4.2). Further improvements can be made by using pockets and supports with a high axial thermal resistance - like thin stainless steel. Additionally, when mounting either thermocouples or RTD's, you should consider using small diameter and low thermal conductivity connecting wires. Also, the leads should be in contact with the surface for some length to further reduce thermal conduction to and from the sensing point.

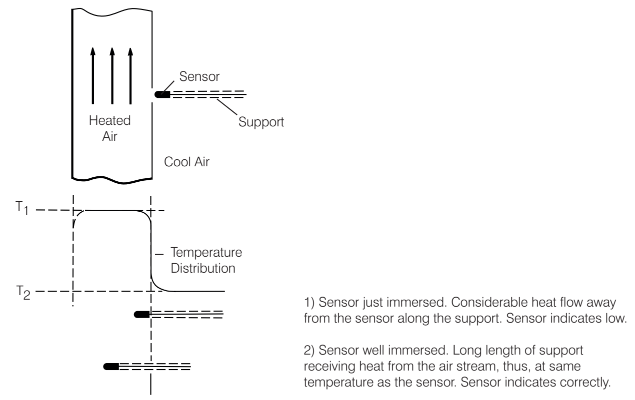

Figure 4.2: *The importance of Sensor Immersion Depth*

Finally, the mere presence of the sensor might itself affect the temperature of the medium to be measured. This is particularly the case with surface measurements, where the sensor might interrupt or modify the heat transfer process at the surface. Keeping the sensor size to a minimum, ensuring that the sensor shape conforms to that of the surface being measured (giving maximum thermal contact with minimum mechanical strain), and providing adequate insulation or isolation (to ensure that its temperature is as close to that of the surface as possible), are the best ways to proceed. Usually, attempts to reduce sensor temperature take-up errors will also reduce the temperature disturbance introduced by the sensor.

Typically for surface measurements, the sensor could be mounted on a pipe carrying fluid. If the flow and temperature differential are adequate, the internal temperature fluctuations not severe, the pipe thin enough and made of a thermally conductive material, then its outer wall temperature will be close to that of the fluid. Insulation then placed over the sensor reduces the effects of the environment, and good mounting makes this a viable measurement.

Beyond the three main considerations above, there are other points. Although good thermal contact is indeed required, a large mismatch in thermal expansion coefficients may cause strain in an RTD sensor, for example. This induces a resistance change - and errors in the measured temperature signal (see Part 1, Section 4, and Part 2, Section 6).

4.1 Heat Transfer Modes

As a background to the above, it is probably a good idea to understand a little about the mechanisms of heat transfer. Basically, the main processes are conduction, convection and radiation, and short explanations of each are provided below.

4.2 Conduction

Thermal conduction is the transfer of heat in a medium essentially due to the molecular activity within the material itself. It differs widely across the media spectrum, with metals like silver and copper being good conductors, whereas gases, like still air, are poor conductors. Thermal conductivity of materials is somewhat related to their electrical conductivity, but the near perfect electrical insulating properties of some materials do not exist in the thermal sense. This is the principal mode of heat transfer within the temperature sensor and associated pocket or thermowell assembly itself.

4.3 Convection

Convection is the mode of heat transfer between a body and a moving liquid or gas. When a fluid flows over a surface, the layer of fluid that is in intimate contact with the surface is brought to rest, there being a velocity gradient (at first rapid, then trailing off) away into the main stream of the flow. Heat transfer is then by molecular conduction across the stationary layer, and a combination of conduction and physical mixing in the body of the fluid. Temperature distribution in the fluid is related to the velocity distribution.

Forced convection refers to a fluid being circulated by mechanical means, like a pump, fan or stirrer. If the fluid moves spontaneously under the influence of gravity by heat-induced density changes, this is natural convection. Most fluid temperature sensors rely on convection heat transfer at their outer boundaries to take up the local fluid temperature.

4.4 Radiation

Any body at a temperature above absolute zero radiates energy, and so radiation heat interchange can be a consideration when installing temperature sensors. The intensity of heat radiated from the body surface is proportional to its absolute temperature to the fourth power. So the radiation interchange is a function of their temperature difference to the fourth power - and thus the effect becomes considerably more important with elevated temperatures.

Radiation intensity is also inversely proportional to the square of the distance to the receiving surface, and to the emissivity (a function of surface condition), the angle of the surface, the nature of the transmission path, and other factors. When measuring temperatures in the working space of an electrically heated furnace, heat transmission is likely to be almost entirely by radiation to both the contents and the sensor.

This phenomenon can provide unwanted heat transfer when, for example, the temperature of a relatively slow moving gas stream is being measured. The sensor temperature will be brought towards the wanted temperature of the gas by convection at the sensor boundary. If the gas is hotter than its surroundings, the sensor will also lose heat by radiation, and its temperature will thus be lowered.

Conversely, if the gas is cooler than its surroundings, the sensor will gain heat by the net interchange between the surroundings and the sensor, and its temperature will be raised above the wanted value. To reduce radiation effects of this type, the emissivity of the sensor casing can be reduced by choice of materials and their surface condition. Alternatively, shields can be fitted around the sensor to intercept the radiation.

4.5 Stagnation Temperature

As the velocity of a gas flowing over any body (and temperature sensors are no exception) increases, the temperature of the layer of gas in contact with the body begins to rise. So temperature measurement in fast moving gas flows is complicated by this dynamic heating effect. The temperature most frequently required is the free stream, or static temperature (that without the dynamic component), as opposed to the total temperature - that with the dynamic component added.

Total temperature, T_t, is usually measured, using special probes designed virtually to stagnate the gas at the sensor. From this, the static temperature, T_s, can be derived using the formula:

$$T_s = T_t / (0.5(\gamma - 1)M + 1)$$

where γ is the ratio of the specific heat of the gas at constant pressure to constant volume, and M is the Mach number. Some examples of the temperature rise due to dynamic heating in air at atmospheric pressure are: 1°C at 45 meters per second; 10°C at 145 meters per second; and 30°C at 245 meters per second.