AE3051 Experimental Fluid Dynamics

TEMPERATURE AND PRESSURE MEASUREMENTS IN A TURBINE ENGINE

Objective

This laboratory introduces the measurement of gas temperature and explores the performance of a jet engine. First, the operation and proper use of thermocouples is explored. Then, thermocouples are used to measure gas temperatures at various locations in the jet engine. In addition, engine pressures are measured with piezoresistive transducers.

NOTE: All combustion experiments are potentially hazardous. Please follow all precautions outlined in the safety section and given during the lab.

Background

Temperature Measurements

There are a number of devices used for the measurement of temperature. Most rely on the effect temperature has on some other *measurable* property of a substance. One of the oldest types is the expansion thermometer, which relies on the change in volume of a substance (usually a liquid) as the temperature varies. An example is the glass tube, mercury-filled thermometer, in which the height of the mercury column becomes a measure of temperature. While easy to manufacture, expansion thermometers are not easily implemented as small, compact electronic sensors.

Various electronic temperature sensors have been developed, including thermocouples, resistance thermometers and quartz resonance thermometers. In a quartz resonance thermometer, temperature is determined by its influence on the resonant frequency of a quartz crystal. Since frequency can be determined to great accuracy, these devices have potential for high resolution. Resistance temperature detectors (RTDs) rely on the change in resistance of a material with temperature; thus measurement of resistance is converted to a temperature measurement. There are two basic types of RTDs: metal based devices and semiconductor devices (also known as *thermistors*). While quite accurate temperature measurements can be obtained with RTDs and crystal thermometers,[*] they are usually limited to "low temperature" operation. For example, platinum resistance thermometers can operate only up to ~1000°C, while thermistors are generally limited to a few hundred degrees Celsius. Thermocouples, on the other hand, can provide reasonably accurate measurements at temperatures up to at least 2600 K with proper choice of materials.

Thermocouple Principles – Thermocouples rely on the voltage produced by a temperature difference between two junctions formed between thermoelectrically dissimilar metals (see Fig. 1). In other words, a thermocouple is simply two different types of metals, usually in the form of wires, connected together. The voltage is produced because a temperature gradient in a metal conductor also induces a gradient in electron density in line with the temperature gradient. It can be shown that the voltage produced between the two junctions of the Fig. 1 circuit is given by:

$$V = \int_0^L \varepsilon_A \frac{dT_A(x)}{dx} dx + \int_L^0 \varepsilon_B \frac{dT_B(x)}{dx} dx \tag{1}$$

where $T(x)$ is the temperature distribution along each wire, and ε is called the thermoelectric power of the material.[†] Thus it can be seen that the **voltage difference is generated throughout the length of the wires**, and is due to the local temperature gradient.

<u>When the wire is perfectly uniform in composition</u>, such that ε is not a function of position, and the two wires are connected between T_{cold} and T_{hot}, the integrals in equation (1) become,

$$V = \int_{T_{cold}}^{T_{hot}} \varepsilon_A dT + \int_{T_{hot}}^{T_{cold}} \varepsilon_B dT = \int_{T_{cold}}^{T_{hot}} (\varepsilon_A - \varepsilon_B) dT\ . \tag{2}$$

In this case, one can think of the voltage produced in a thermocouple as strictly due to the temperature difference between the junctions. It is important to remember that this holds only for the above <u>uniformity assumption</u>. In fact, some descriptions of thermocouples erroneously state that the voltage is produced "at the junction", when in fact it is produced wherever there is a temperature gradient in the metal. The thermocouple circuit that will be considered the "ideal" circuit is shown in Fig. 2. The difference between it and the circuit of Fig. 1 is simply that the voltage is "measured" at the reference junction, instead of midway through one of the

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[*]Quartz resonance thermometers and RTDs can have precisions better than 10^{-4} °C.
[†]Equal to the sum of the Thomson coefficient and temperature derivative of the Peltier coefficient for the metal.

legs of the thermocouple. Note, both points in the reference junction must be at the same temperature (*isothermal*) to be equivalent to the circuit of Fig. 1.

While any two metals with different ε can be used to produce a thermocouple,* a small number of metals (both pure and alloys) have been identified for their stability, linearity, reproducibility, and high temperature capability. Table 1 lists some common pairs of thermocouple materials, including their approximate limiting operating temperature. Some of these are sufficiently common that they are considered standards and are denoted simply by a letter. For example, a chromel/alumel† device is called a "type K" thermocouple, and it has a nearly linear temperature sensitivity (see Fig. 3). The pairs of metals listed in Table 1 were also chosen for their good temperature sensitivity, which is normally achieved by picking materials that have ε with different signs. Figure 4 shows the voltage that would be generated along a single, homogeneous wire of various materials as a function of the temperature difference between its two ends. For the type K thermocouple, the chromel and alumel alloys produce voltages of opposite sign for the same temperature gradient.

The temperature behavior shown in Fig. 4 can be used to explain what happens in a thermocouple circuit like that of Fig. 2. Consider a type-J thermocouple connected between a reference junction at T_{ref} and a junction at higher temperature, T_{probe}. As shown in Fig. 5, the voltage that would be produced is found by starting at the reference temperature, following a line with a slope equal to ε_{iron} up to T_{probe}, and then switching to a line with the slope of $\varepsilon_{constantan}$ back to T_{ref}. Thus the constantan end of the reference junction will be at a higher voltage than the iron. If the temperature at the probe junction is raised, the thermocouple voltage increases. The reason that two dissimilar materials must be used is also evident in Fig. 5. If iron was used for both legs of the thermocouple, the voltage developed in the first leg of the circuit would be canceled as the temperature drops in the other leg, i.e., we would follow the iron curve upward to T_{probe}, and then back down to T_{ref} with no net voltage induced.

While the circuit of Fig. 2 is ideal, it is usually not practical. First, thermocouple wire can be somewhat expensive. Thus it becomes costly if the measuring device needs to be located remotely from the experiment. Also, it is not uncommon to connect multiple thermocouples to

*In fact, there have been a number of applications where the operating temperature of a machinery part has been measured using the machine structure itself as part of the thermoelectric circuit.
†Chromel is a nickel-chromium alloy; alumel is a nickel-aluminum alloy

a single measurement device through some sort of switching circuit. Finally, the measurement device may have wires and connectors of its own, which effectively become part of the thermocouple circuit. Therefore, it is important to consider modifications to the ideal circuit. For example, Fig. 6 shows a circuit in which the reference junction is connected to the measurement device through copper wires. As seen in Fig. 7, the voltage difference across the device junction (V_{15}) is identical to the reference junction voltage (V_{24}) <u>if the copper wires are identical</u>, and if the <u>device connections</u> (1 and 5) are both <u>at the same temperature</u>. In this case the voltage developed in leg 1-2 is counteracted by the voltage produced in leg 4-5.

Thermocouple Referencing – So far we have explored the thermocouple voltage that is produced between a junction at an unknown temperature T_{hot} and another junction at T_{ref}. To convert the thermocouple voltage to the unknown T_{hot} requires us to know two things: 1) the change in voltage associated a given temperature change, i.e., the temperature sensitivity of the thermocouple materials, and 2) T_{ref}.

First, consider ways to determine T_{ref}. There are two basic approaches: 1) create a situation where T_{ref} is fixed by some physical condition, and 2) measure T_{ref} with another device. A known temperature can be produced using a phase point of a material, for example 0°C can easily be produced to within 0.01°C accuracy by a bath of liquid water and ice, *if the ice and water are both present and allowed to come to equilibrium* (this generally requires crushing the ice to small size and putting the mixture in an insulated container). If the reference junction (or points 2 and 4 in Fig. 6) are place in the ice bath, then T_{ref} will essentially be 0°C. It many situations, however, it is impractical to require access to ice. Therefore, a popular approach is to measure the reference junction's temperature with a thermistor or similar device that can provide accurate, absolute temperature measurements, *though at low temperatures*.

With T_{ref} known, all that remains is to convert the thermocouple voltage to temperature. Standard thermocouple materials have been extensively studied at the National Institute of Standards and Technology (NIST), and the voltage produced by a thermocouple at T_{hot} is generally reported for T_{ref}=0°C, and the values are available in tables, graphs (such as Fig. 3) or polynomial fits (see Table 2). If one is using a 0°C reference junction, then you simply look up the measured thermocouple voltage in the table (or graph or fit) and find the corresponding temperature. If you are using a different reference temperature, you must first add an offset voltage to your measured voltage. The offset is the voltage would be produced by a thermocouple at your measured T_{ref} referenced to 0°C. Electronic ice reference circuits exist to do just this, the add the proper offset voltage to account for $T_{ref} \neq 0°C$.

Gas Temperature – Strictly speaking, a thermocouple sensor measures the temperature of the thermocouple junction itself, which of course is not what we usually want to know. Rather, we wish to determine the temperature of the body in which the thermocouple is embedded. For gas temperature measurements, the "body" of interest is the gas. As shown in Fig. 8, there are two basic thermocouple probe arrangements: one in which the thermocouple junction is immersed in the gas (*unshielded probe*); and one where the junction is inside some housing material (usually a metal), and the housing is immersed in the gas (*shielded probe*). The former provides a better measure of the gas temperature and a better time response; the latter approach protects the thermocouple from damage or exposure to incompatible gases (see Table 1). For high speed flows, there are also shielded *stagnation probes*, which are designed to slow the flow down to a very low velocity before it contacts the thermocouple junction (see Fig. 8 for a simple example).

In general, the thermocouple temperature can not exactly equal the gas temperature due to heat losses. Assuming the gas is the hotter material, it will heat up the initially colder thermocouple junction. If the thermocouple had no way of losing energy, then it would eventually heat up to the gas temperature. However, the thermocouple can lose heat; either by thermal conduction from the junction down through the thermocouple wires, or by radiation. Therefore even in steady-state operation, the thermocouple will tend to be at a lower temperature than the surrounding (hot) gas in low speed flows. For high speed flows, the thermocouple temperature will also be affected by the conversion of the flow's kinetic energy to thermal energy in the region in front of the probe. Therefore in high speed flows, the thermocouple temperature will generally exceed the freestream static temperature.

Pressure Measurements

You will also be making pressure measurements in this lab with a transducer that is something like the Barocel/Baratron type transducers used in previous labs, i.e., a differential pressure is determined from the movement of a thin diaphragm exposed to the pressure difference. Instead of the capacitance based approach of the Barocel/Baratron devices, the sensors used in this lab consist of a miniature diaphragm and strain sensors composed of semiconductor material and manufactured using MEMS (Micromachined Electro-Mechanical Systems) technology. The sensors are described in more detail in a following lab.

Turbine Engines

In most cases, with the exception of civil aviation, modern aircraft are powered by turbine engines (also called gas turbines). While piston engines are efficient for low power applications, their power (or thrust) to weight ratio drops significantly as engine power increases. This makes them unsuitable for large aircraft that require high power engines. Gas turbine engines are also used in a number of other applications including marine propulsion, operating gas pipeline compressors, and most notably, the generation of electric power.

The components of a basic gas turbine system are shown in Fig. 9. Air enters the engine (through an inlet not shown) and passes through a rotating compressor that raises the air pressure. Next, the high pressure air enters the combustor where it is mixed with fuel and burned without much change in pressure. The hot products then pass through a rotating turbine that extracts work from the flow and sends it to the compressor via a rotating shaft. The exhaust of the turbine is a hot, high pressure gas. In a **turbojet**, the exhaust is expanded through a nozzle (Fig. 10), which converts the thermal energy to kinetic energy, i.e., it accelerates the gas in order to produce thrust. On the other hand in a **turboshaft** engine, the hot, high pressure gas exiting the first turbine is expanded through a following power turbine that converts the thermal energy to shaft power, which can be used to run a rotor in a helicopter engine or to turn an electric generator in an aircraft's auxiliary power unit (APU) or in a ground power station. In this lab, you will operate and perform measurements on an SR-30 turbojet manufactured by Turbine Technologies, Ltd. (Fig. 11), operating on Jet-A fuel.

Thermodynamic Analysis – The following is a brief description of the thermodynamic expressions used to analyze a jet engine.* The processes that occur in a turbine engine can be modeled, *in the ideal case*,† by a Brayton cycle. As shown in Fig. 12, the ideal compressor ($2\rightarrow3$), turbine ($4\rightarrow5$) and nozzle ($5\rightarrow e$) can be modeled as isentropic processes (constant entropy, s). The ideal combustor ($3\rightarrow4$) is modeled as a constant pressure heat addition, where the "heat" comes from burning the fuel, and the heat release rate is given by

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*A more detailed development can be found in the text for AE 4451, Hill and Peterson's *Mechanics and Thermodynamics of Propulsion*.

†Meaning each component of the engine is *reversible* and has *no heat losses.*

$$\dot{Q} = \dot{m}_f \times HV \tag{3}$$

where $\dot{m}_f$ is the fuel mass flow rate and *HV* is the heating value of the fuel (~45 MJ/kg$_{\text{fuel}}$ for most liquid jet fuels).

For the three isentropic processes, we can find a relationship between the ratios of temperature (absolute, i.e., in Kelvin or Rankine units) and pressure (absolute, not gauge pressure) across each device from the entropy state equation for a perfect gas, i.e., for an isentropic process going from state a to state b,

$$0 = s_b - s_a = \int_{T_a}^{T_b} c_p \frac{dT}{T} - R \ln \frac{p_b}{p_a} \Rightarrow \frac{p_b}{p_a} = e^{\int_{T_a}^{T_b} \frac{c_p}{R} \frac{dT}{T}} . \tag{4}$$

Assuming that the gas is also calorically perfect (c_p=constant),

$$\frac{p_b}{p_a} = \left(\frac{T_b}{T_a}\right)^{c_p/R} = \left(\frac{T_b}{T_a}\right)^{\gamma/\gamma-1} \tag{5a}$$

or equivalently for stagnation properties,

$$\frac{p_{ob}}{p_{oa}} = \left(\frac{T_{ob}}{T_{oa}}\right)^{\gamma/\gamma-1} \tag{5b}$$

where γ is the ratio of specific heats ($\gamma=c_p/c_v$).

There is also a relationship between the stagnation temperature change across the compressor and turbine. Since the turbine is used to power the compressor, the output power of the turbine should equal the power input to the compressor (assuming steady operation and no shaft losses, which are typically less than 1% of the shaft power). Therefore from conservation of energy (*and for adiabatic conditions*),

$$\dot{W}_T = \left(\dot{m}_a + \dot{m}_f\right) c_{p,T} \left(T_{o4} - T_{o5}\right) = \dot{m}_a c_{p,C} \left(T_{o3} - T_{o2}\right) = \dot{W}_C \tag{6}$$

where $\dot{m}_a$ is air mass flow rate entering the engine, and $c_{p,T}$ and $c_{p,C}$ are the (average) specific heats of the gases passing through the turbine and compressor. Similarly, the velocity at the nozzle exit can be found from

$$u_e = \sqrt{2 c_{p,N} \left(T_{oe} - T_e\right)} \tag{7}$$

where $c_{p,N}$ is the (average) specific heat of the gas passing through the nozzle, and $T_{oe}=T_{05}$ (again *assuming the nozzle is adiabatic, i.e. no heat losses)*. For the combustor, again using energy conservation, we can calculate the expected change in temperature caused by burning the fuel:

$$T_{o4} = \left(T_{o3} + f\ HV / c_{p,Combustor}\right) / (1 + f) \tag{8}$$

where f is the fuel-air ratio $\dot{m}_f / \dot{m}_a$.

If the compressor, turbine and nozzle are not ideal, i.e., they are not reversible (*but still adiabatic*), the temperature and pressure ratios across each component are related by the adiabatic component efficiencies:*

$$\eta_{compressor} = \frac{\left(p_{o3}/p_{o2}\right)^{\frac{\gamma-1}{\gamma}} - 1}{\left(T_{o3}/T_{o2}\right) - 1} \tag{9}$$

$$\eta_{turbine} = \frac{1 - \left(T_{o5}/T_{o4}\right)}{1 - \left(p_{o5}/p_{o4}\right)^{\frac{\gamma-1}{\gamma}}} \tag{10}$$

$$\eta_{nozzle} = \frac{1 - \left(T_e/T_{o5}\right)}{1 - \left(p_e/p_{o5}\right)^{\frac{\gamma-1}{\gamma}}} \tag{11}$$

Note, if the nozzle is truly adiabatic, then $T_e/T_{o5} = T_e/T_{oe} = \left(p_e/p_{oe}\right)^{\frac{\gamma-1}{\gamma}}$.

We can also define an overall thermal efficiency of a static (stationary) turbojet engine, which is given by,

$$\eta_{th} = \frac{\text{Output Kinetic Power}}{\text{Input Heat Rate}} = \frac{\left(\dot{m}_f + \dot{m}_a\right) u_e^2 / 2}{\dot{m}_f HV} \quad . \tag{12}$$

If the turbojet is ideal (<u>and</u> c_p is assumed constant throughout the engine), it can be shown that the thermal efficiency should solely be a function of the cycle pressure ratio:

$$\eta_{th} = 1 - \frac{1}{\left(p_3/p_2\right)^{\gamma-1/\gamma}} \quad . \tag{13}$$

Thus as pressure ratio of the compressor increases, η_{th} of the engine should increase.

Safety Considerations

As with any combustion experiment **safety is a primary concern**. Improper operation of the jet engine can damage the engine, and pose a hazard to those nearby. Carefully follow all the safety instructions presented during the lab concerning startup, operation and shutdown of the engine. Do not operate the engine without direct supervision by the lab technician. Do not place any part of your body, or any objects in the inlet or exhaust regions. **All students working in the lab MUST WEAR safety glasses/goggles in the lab and hearing protection when the engine is operating** (both will be supplied to you).

Preliminary

The following items must be turned in at the start of your lab session.

1. Using the information supplied in Table 2, determine the thermocouple voltage you would expect to measure if the type-K thermocouple junction was at room temperature (~74°F) and the reference junction was placed in an ice bath.
2. Bring a modified copy of the equation you developed in the earlier labs that relates dynamic pressure to velocity of a gas, and the ambient pressure and temperature. You need to **modify** the **equation** to use **dynamic pressure** in **psi** rather than mm Hg**.**

Procedure

1. Locate the electronic barometer/thermometer and record the ambient pressure and temperature.
2. Locate the type K, unshielded thermocouple probe (it has a yellow base). Connect the probe to the color-coded type K thermocouple extension wire. Then connect the extension wires to the standard electrical wire using the strip screw terminal according to the diagram of Fig. 14. Record the thermocouple voltage with the thermocouple exposed to the ambient air, and any other systems you can measure (e.g., an ice bath or boiling water).
3. Again record the thermocouple voltage with the thermocouple exposed to the ambient air, except this time raise and lower the temperature of the screw terminal junctions. You should do this: a) where the thermocouple extension wires connect to the first set of electrical wires and b) again where the first and second set of electrical wires are connected. You can also try to change the temperature of a single connector or both connectors in each junction. Record the measured voltage for each of these various cases.
4. Disconnect the extension wires from the probe, and connect the probe to the electronic ice point module (small rectangular yellow box). Connect the module to the voltmeter, and switch on the ice point module (be careful not to rotate the switch all the way to the ON

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*The efficiency compares an actual process to an isentropic one that has the same starting condition and same pressure ratio.

mark; make sure the voltage reading changes after you turn the module on). Record the thermocouple voltage with the thermocouple exposed to the ambient air and any other systems you wish.

5. Turn off the ice point module.
6. Take a tour of the turboshaft engine cutaway in the Combustion Lab foyer.
7. Familiarize yourself with the flowpath through the SR-30 turbojet engine.
8. Review the safety, startup, and engine shutdown procedures with the lab TA's and with the lab technician who will oversee the engine operation.
9. Determine the cross-sectional area of the flow where the inlet velocity is measured.
10. Ask the lab technician to start the engine (the technician may ask students to help, but the engine should be started only under the supervision of the lab technician).
11. Acquire data for *at least* 5 RPM conditions (change RPM by changing the throttle – which changes the fuel flowrate). DO NOT EXCEED 82,000 RPM. The data acquisition program will allow you to continuously monitor the engine RPM, pressures and temperatures. When you decide to acquire data at some RPM, the software will sample all the probes, and update graphs of engine conditions vs. RPM. Each time you acquire the data, the computer will pause until you are ready to return to the real-time display. **NOTE**: it will be very hard to hear while the engine is running. Make sure your group has discussed what conditions you are looking for and work out some hand signals to identify when you want to take data and when you want to return to the real-time display.
12. When you are finished, ask the technician to shutdown the engine.

Data to be Taken

1. Ambient pressure and temperature.
2. Voltages from the type-K thermocouple probe connected to the voltmeter under the different connection and temperature cases described above.
3. Cross-sectional area of the compressor inlet.
4. Values of: 1) dynamic pressure and T_2 at the compressor inlet, 2) T_{o3} and p_{o3} (gauge) at the compressor exit, 3) p_{o4} (gauge) and T_{o4} at the turbine inlet, 4) p_{o5} (gauge) and T_{o5} at the turbine exit, 5) p_{o6} (gauge) and $\sim T_{o6}$ at the nozzle exit, and 6) pressure drop (a voltage signal) in the fuel system at various RPM settings.

Data Reduction

1. Unshielded thermocouple probe temperatures reduced from the measured voltages (without heating or cooling the strip terminal junctions).
2. Air mass flowrate (from dynamic pressure at the compressor inlet).
3. Fuel mass flowrate (from fuel pressure reading and calibration, see Table 3).
4. Compressor efficiency.
5. Exit static temperature determined from the nozzle exit p_{o6} (which is measured as a gauge pressure here) and the exit stagnation temperature T_{oe}.
6. Nozzle exit velocity.
7. An estimate of the heat loss rate from gas to the nozzle (based on the difference in stagnation temperature across the nozzle).
8. Compressor and turbine powers (assuming adiabatic operation).
9. The actual engine thermal efficiency.

Results Needed for Report

1. Tables of the thermocouple voltages and reduced temperatures for the different cases.
2. Tables of the raw and reduced engine conditions at each operating RPM.
3. Plot of the compressor pressure ratio versus air mass flowrate.
4. Plot of the compressor efficiency versus air mass flowrate.
5. Plot of the heat loss in the nozzle rate versus air mass flowrate.
6. Plot of the engine thermal efficiency versus compressor pressure ratio.

Further Reading

1. Philip Hill and Carl Peterson, *Mechanics and Thermodynamics of Propulsion*, 2nd edition, Prentice-Hall, 1992.

Table 1. Some standard thermocouple materials and their properties.

Material	T_{max} °C (°F)	ANSI Type	Allowable atmosphere	Avg Output mV/100°C
Tungsten/ tungsten 26% rhenium	2320/4210	-	inert, H_2 (nonoxidizing)	1.7
Tungsten 5% rhenium/ tungsten 26% rhenium	2320/4210	-	inert, H_2 (nonoxidizing)	1.6
Platinum 30% rhodium/ platinum 6% rhodium	1820/3310	**B**	oxidizing, inert	0.76
Platinum 13% rhodium/ platinum	1770/3200	**R**	oxidizing, inert	1.2
Platinum 10% rhodium/ platinum	1770/3200	**S**	oxidizing, inert	1.0
Chromel/alumel	1370/2500	**K**	oxidizing, inert*	3.9
Chromel/constantan	1000/1830	**E**	oxidizing, inert*	6.8
Iron/constantan	1200/2193	**J**	reducing, inert, vacuum†	5.5
Copper/constantan	400/750	**T**	mild oxidizing, reducing vacuum, inert	4.0

*Limited use in vacuum or reducing environments
†Limited use in oxidizing at high temperature

Table 2. ITS-90 thermocouple inverse polynomials for type K thermocouples; two polynomial fits are listed, for separate temperature/voltage ranges. The reference junction is assumed to be at 0°C, and the polynomials are of the form, $T = \sum a_i V^i$, with T in degrees Celsius and V in microvolts.

Temperature Range	**0-500 °C**	**500-1372 °C**
Voltage Range	**0-20,644 μV**	**20,644-54,886 μV**
a_0	0.000000	-1.318058×10^{2}
a_1	2.508355×10^{-2}	4.830222×10^{-2}
a_2	7.860106×10^{-8}	-1.646031×10^{-06}
a_3	-2.503131×10^{-10}	5.464731×10^{-11}
a_4	8.315270×10^{-14}	-9.650715×10^{-16}
a_5	-1.228034×10^{-17}	8.802193×10^{-21}
a_6	9.804036×10^{-22}	-3.110810×10^{-26}
a_7	-4.413030×10^{-26}	
a_8	1.057734×10^{-30}	
a_9	-1.052755×10^{-35}	

Table 3. Calibration data for fuel flowrate.

Voltage (Volts)	Flowrate (cc/min)
1.7	175
2.2	227
2.8	255
3.0	300

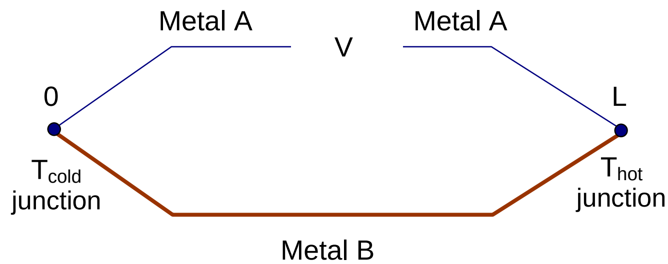

Figure 1. Simple (open) thermoelectric thermocouple circuit.

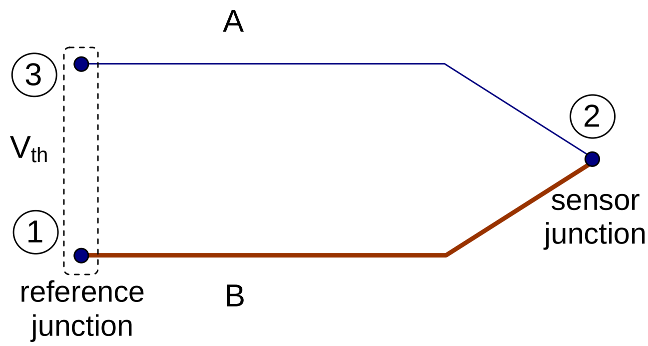

Figure 2. Ideal thermoelectric circuit, with the thermocouple voltage measured across the *isothermal* reference junction.

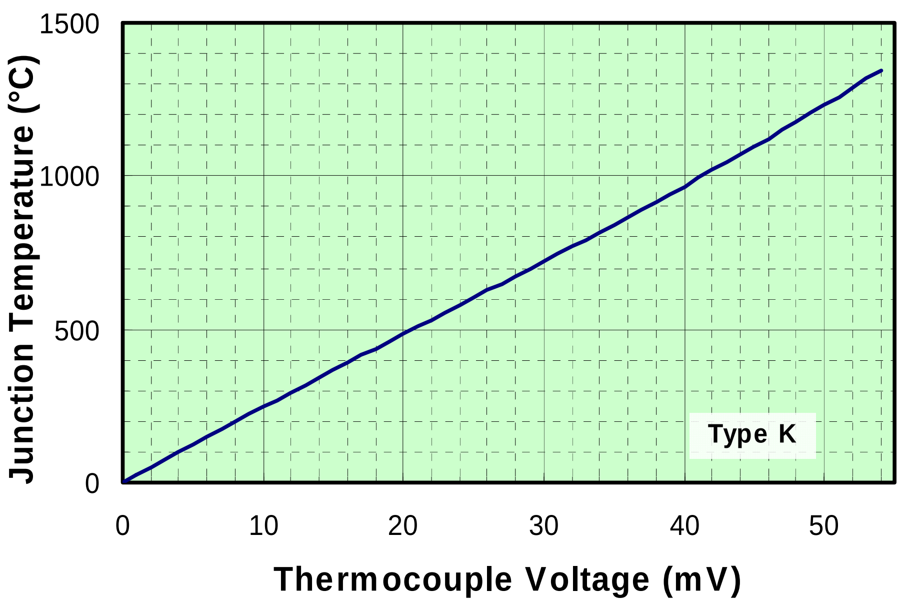

Figure 3. Sensitivity of a standard type-K thermocouple, based on ITS-90 inverse polynomial fit. The millivolt output is based on a reference temperature of 0°C.

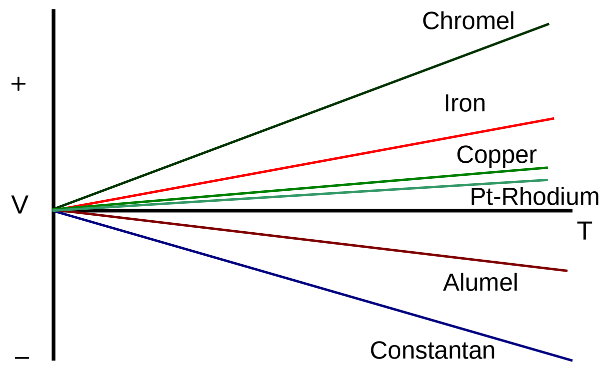

Figure 4. Voltage–temperature response for several metals.

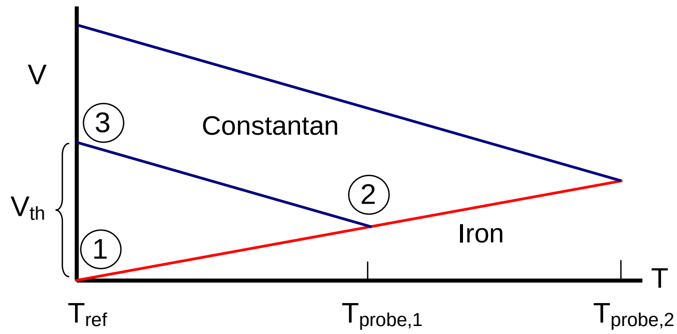

Figure 5. Development of the voltage difference across the thermocouple, V_{th}, in a thermocouple circuit, like that of Fig. 2, formed by two metals.

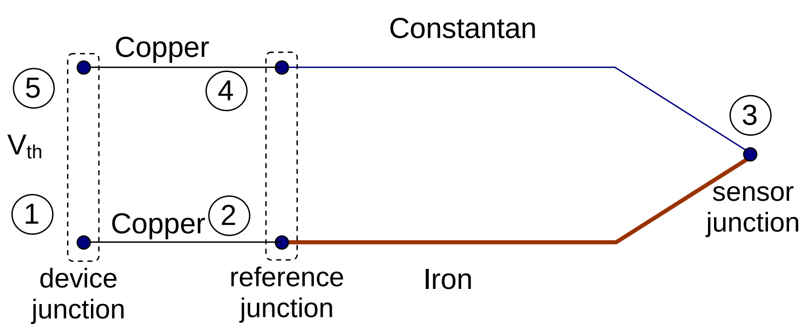

Figure 6. Modified circuit; copper extension wires connect the thermocouple to the measuring device, and the device connections are at the same temperature.

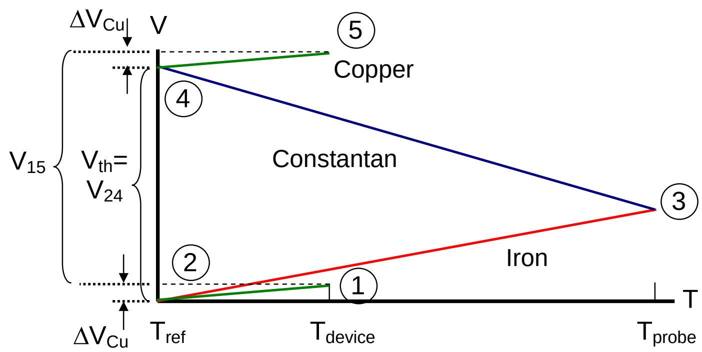

Figure 7. Development of the thermocouple voltage difference for the thermocouple circuit shown in Fig. 6. If the wires connecting points 1 to 2, and 4 to 5 are identical, and the temperatures T_1 and T_5 are the same, then the voltage measured across the device (V_{15}) is equal to the voltage that would be produced by the ideal thermocouple circuit (V_{th}=V_{24}).

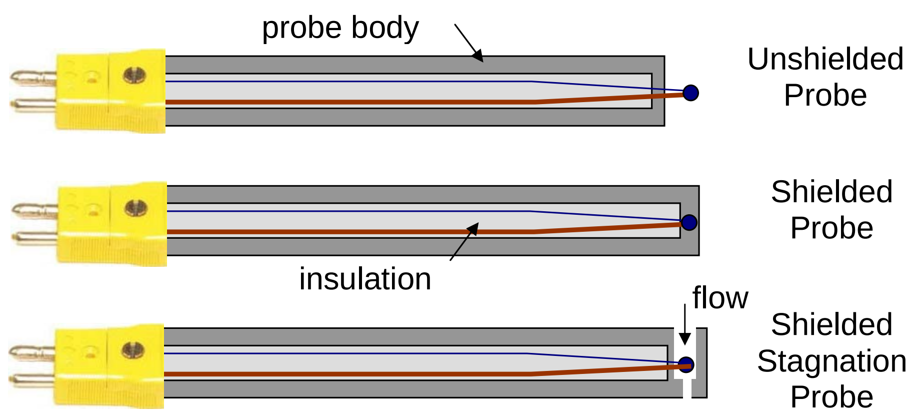

Figure 8. Examples of unshielded, shielded and stagnation thermocouple probes.

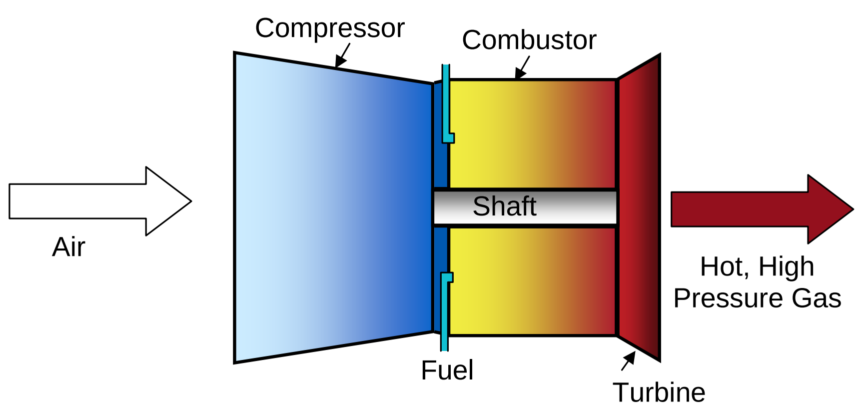

Figure 9. Basic components of a gas turbine engine.

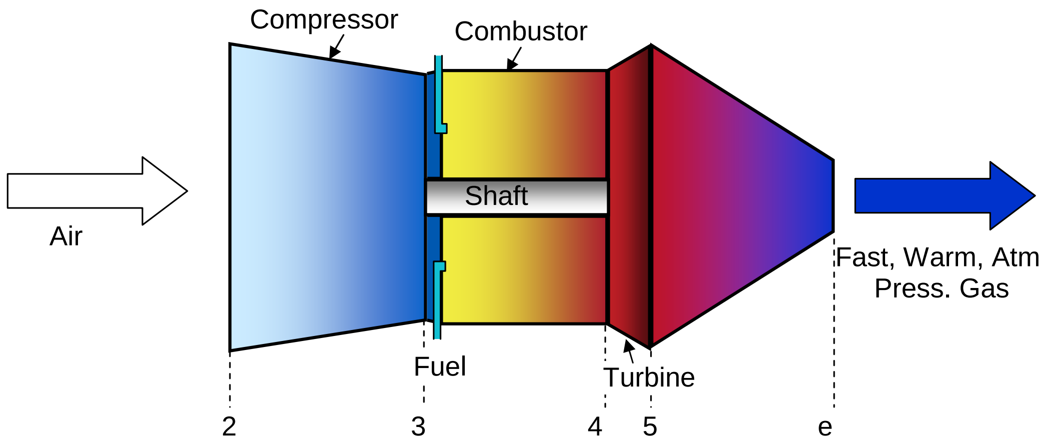

Figure 10. Basic components of a gas turbine engine.

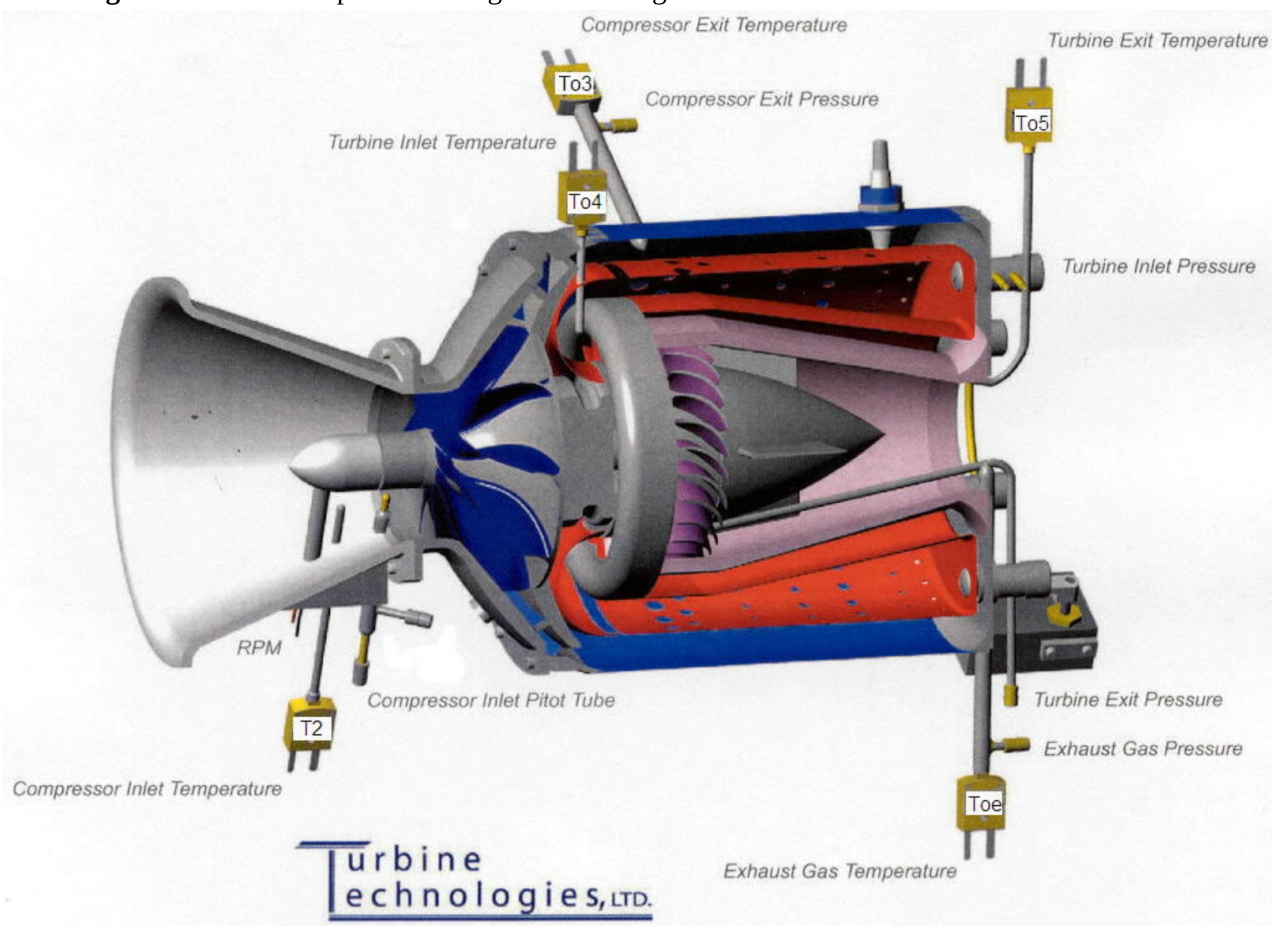

Figure 11. Schematic of the gas turbine system to be used in this lab.

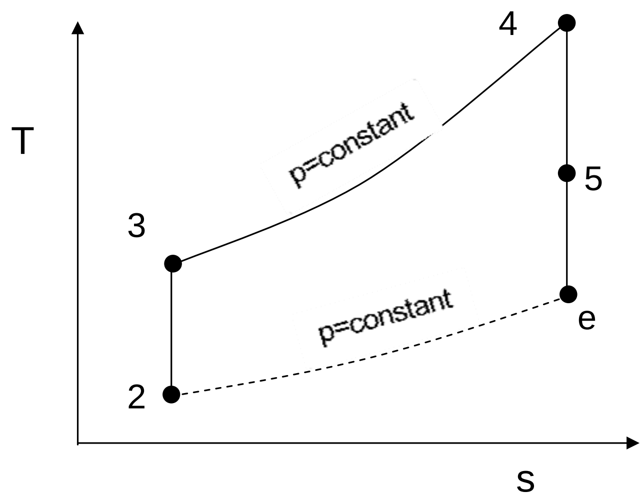

Figure 12. Ideal Brayton cycle; stations 2-e correspond to the numbering scheme shown in Fig. 10.

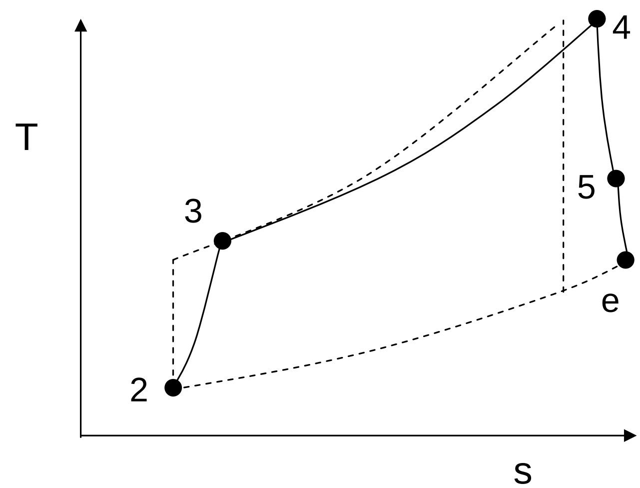

Figure 13. Turbojet cycle with nonideal components.

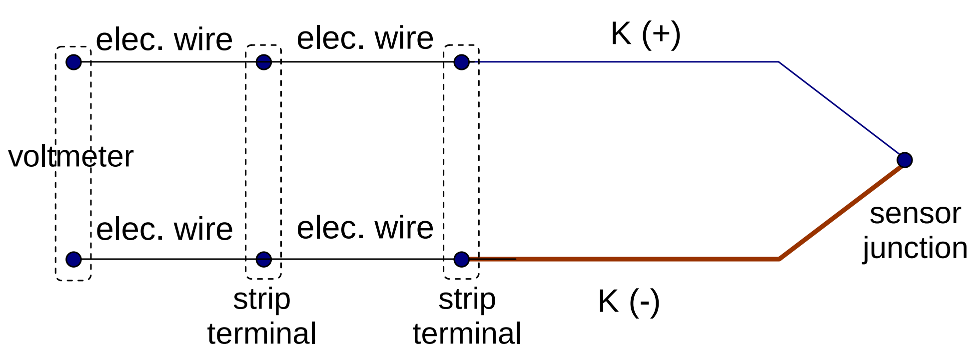

Figure 14. Thermocouple circuit to be used in this lab.