Heat Flow Meter User Guide

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Abstract

In our quest to build low-cost, insulated cooking for the global poor, we have found a lack of accessible insulation materials that suit the needs of our devices. Industrial insulation is not widely available in many parts of the world, and shipping it is exceedingly expensive. We believe we can find alternatives to industrial insulation that can be made on-site or come from accessible materials. To assess the effectiveness of different insulators, the thermal conductivity must be measured. This can be outsourced to a specialized lab for a steep price, and standard instruments for measuring very low thermal conductivity materials cost upwards of $30,000. The total cost for the materials to make our instrument (now available as a Cal Poly user facility) is less than $1,500.

Background

A heat flow meter (HFM) is a device that measures thermal conductivity, or the rate at which a substance can “move” heat when a temperature gradient is applied. The units are in Watts/Meter/Kelvin, abbreviated as W/mK. The equation used for calculating thermal conductivity is the Fourier heat equation in 1 dimension.

$$Q = kA\frac{dT}{dx}$$

Where Q is the heat flux through the substance in Joules, k is the thermal conductivity coefficient, A is the cross-sectional area of the substance, and dT/dx is the temperature gradient in the vertical direction.

The heat-flow meter is built to control or directly measure Q, A, and dT/dx. Once we have determined these values we can simply solve for k.

Overview- how this specific device works

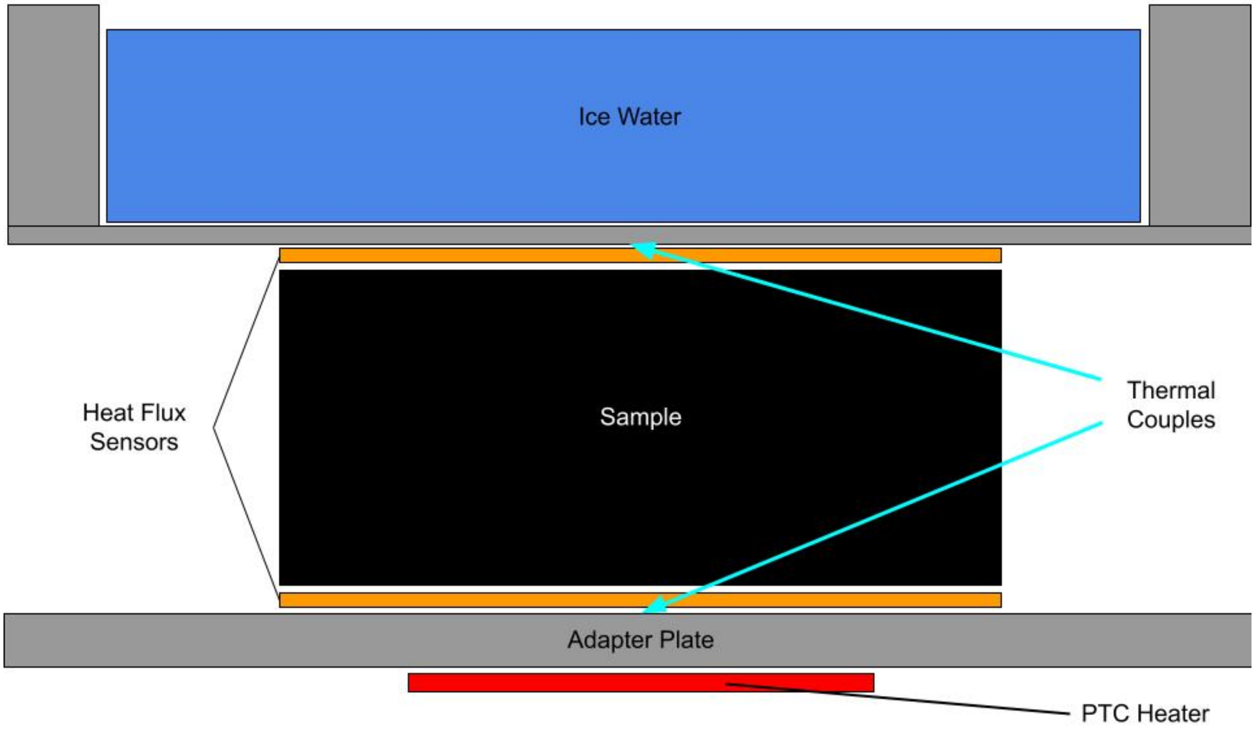

Fig. 1 HFW Schematic

For this HFM, Q and A are accounted for by the *heat flux sensors*, which output a voltage based on the heat flux per unit area as a voltage. The sensitivity of each sensor is $67.8\ \mu\mathrm{V/W/m^2}$ and $70.8\ \mu\mathrm{V/W/m^2}$, and they are labeled as such.

The sensors were custom ordered from Captec and can withstand temperatures up to 200 C. You may notice wear on the sensors, this is from some initial testing mistakes, and they show very similar results as when they were new out of the box.

Controlling the temperature gradient is where most of the margin of error lies. First, the thickness of the sample l must be measured. Second, the system must be in steady-state conditions. This is required because in steady state, we can assume that the temperature gradient is 1) only in one direction (it points from the cold plate to the hot plate) and 2) linear such that

$$\frac{dT}{dx} = \frac{\Delta T}{\Delta x} = \frac{T_{hp} - T_{cp}}{l}$$

Where T_{hp} is the temperature of the hot plate and T_{cp} is the temperature of the cold plate.

For this HFM, the hot plate is made of four 5V positive temperature coefficient (PTC) heating elements connected in parallel and glued onto an aluminum sheet using heat conduction grease. The cold plate is an ice bath in an aluminum container. Thermal couples are used on each plate to ensure that the PTCs are on and to find what temperature they settle at (they are designed to maintain a constant 100 C, but this is not always reliable).

Note: The HFM has a cooler with extra insulation on the inside- this vessel is where the experiment will be carried out. It is important to isolate the system from the ambient environment as much as possible. On the front of the cooler is a hole made for running wires into the HFM.

Operating Procedure

1. Place the PTC heating array into the cooler and run the wires out through the hole (do this for <u>all</u> wires going into the HFM.
2. Place one of the heat flux sensors on top of the PTC heating array.
3. Place the first thermal couple adjacent to the heat flux sensor and ensure good thermal contact with the PTC heating array (high temperature tape is a good option).
4. Measure and record the height of the sample, then place the sample on top of the heat flux sensor.
5. Place the second heat flux sensor and second thermal couple on top of the sample. Ensure good surface contact between the sample, thermal couple, and sensor. (Again, high temp tape is a good idea).

6. Supply a constant 5V to the PTC heating array. Use a power supply that can deliver at least 35 Watts and 7 Amps (this is how much power the PTCs will draw at first, it will drop drastically as they heat up).
7. Check that the first thermal couple and heat flux sensor are responding to the PTC array heating up. Temperature and heat flux should be increasing steadily at first.
   Note: If the heat flux sensors read negative values, it doesn't matter. The absolute value of the voltage is what we will use in the calculations since we know the direction of heat flux.
8. If all is well, place insulation on the sides of the sample to prevent any air currents from disrupting the measurements, then place the ice bath on top of the second heat flux sensor and cover the cooler.
9. At least 1 hour is recommended as a waiting time before steady-state conditions are reached. Check after about 40 min to see if the ice bath needs to be refilled. Use a scoop to take out any excess water, if needed, and then add more ice. Do not remove the ice bath container, it is important to disturb the system as little as possible.
10. Once the thermal couple and heat flux sensor readings have stopped changing rapidly (watch them for at least a minute or two), record the values T_{cp}, T_{hp}, V_{cp}, and V_{hp} (The voltages on the heat flux sensors).

Calculations

First, we convert our voltage readings to heat flux per unit area using the sensitivity of the pre-calibrated sensors.

$$Q = \frac{V}{sensitivity} = \frac{V}{67.8 \text{ or } 70.8 \times 10^{-6} \, \frac{V}{W/m^2}}$$

Remember to convert V to volts, the sensors will give a value in millivolts.

You will obtain two heat fluxes, Q_{hp} and Q_{cp}. To determine if radiative losses are significant in the experiment, check to see that Q_{hp} is at least an order of magnitude less than Q_{cp}. Ideally, V_{hp} will be so small the multimeter won't even pick it up.

From here on out, only use Q_{cp}.

Next, calculate the temperature gradient

$$\frac{\Delta T}{\Delta x} = \frac{T_{hp} - T_{cp}}{l}$$

Finally, rearrange the Fourier heat equation to give

$$k = Q\frac{\Delta x}{\Delta T}$$

Recall that Q has units of W/m^2, so the Area A is accounted for.

Uncertainty

The assumed measurement uncertainties are as follows:

Measurement	Assumed uncertainty
Height of the sample	$\pm 1\mathrm{mm}$
Voltage Heat Flux	$\pm 1\mathrm{mV}$ $\Delta Q \approx \frac{\Delta \mathrm{V}}{70\mu\mathrm{V/W/m^2}}$ $\approx 14.3\mathrm{W/m^2}$
Temperature	$\pm 0.1\mathrm{^\circ C}$
Thermal conductivity	$\Delta k = \frac{\Delta l}{2\Delta T}\Delta Q$ $= 0.07\ \mathrm{W/mK}$

These values are based on a standard multimeter with a 200mV option. The multimeter is by far the greatest source of uncertainty.

Trial Experiments

1. A rockwool sample (industrial insulation with $k \approx 0.033\ \mathrm{W/mK}$) with a height of 2.7cm was tested. The observed k-value was $0.037\ \mathrm{W/mK}$, well within the $0.07\ \mathrm{W/mK}$ uncertainty.
2. A firebrick sample (unknown thermal conductivity) with a height of 6cm was tested. The observed k-value was $0.19\ \mathrm{W/mK}$. This value is very reasonable given that firebricks can range from $0.1\ \mathrm{W/mK}$ to over $3\ \mathrm{W/mK}$. The brick was not labeled, so there is no way to track down the manufacturer, but it can be extrapolated that materials well above 0.1 W/mK can be tested. This is consistent with the literature on HFMs, which recommend that materials with conductivity up to 0.3 W/mK can be measured [1].

Fig. 2- The Rockwool Experiment

The copper plate is the heat flux sensor, the white wire is the thermal couple, and brown-gray insulation underneath is the rockwool sample.

Sources

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