Thermal Contact Resistance of Conductive Cloths:

Application to Hypothermia Treatment

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Overview

- Motivation for the Body Warmer Project
- Defining the Engineering Problem
- Models of Rewarming a Hypothermia Victim
- An Experiment to Measure Model Parameters
- Use of Experimental Values in the Model
- Current Status

Motivation

- ONR-STTR: Hypothermia as a threat to wounded soldiers.
- What is hypothermia?
- Treatment Options
- Objectives of STTR Project
  - ▷ Develop a device for treating injured soldier who are hypothermic
  - ▷ Use during transport from the field to primary medical facilities
  - ▷ Portable, robust system
  - ▷ Easy to operate, Effective, and Safe

What is Hypothermia?

Impending:	$36 \leq T_{\mathrm{core}} < 37\,^{\circ}\mathrm{C}$ Shivering may begin but can be overcome by activity. Fatigue and signs of weakness begin to show.
Mild:	$34 \leq T_{\mathrm{core}} < 36\,^{\circ}\mathrm{C}$ Uncontrolled, intense shivering begins. Victim is still alert and able to help self.
Moderate:	$31 \leq T_{\mathrm{core}} < 33\,^{\circ}\mathrm{C}$ Shivering slows or stops, muscles begin to stiffen. Mental confusion and apathy sets in. Speech becomes slow, vague and slurred. Strange behavior may occur.
Severe:	$T_{\mathrm{core}} < 31\,^{\circ}\mathrm{C}$ Skin is cold, may be bluish-gray in color, eyes may be dilated. Victim is very weak, may appear to be drunk, denies problem and may resist help. Gradual loss of consciousness.

Source: Web site for *Search and Rescue Society of British Columbia* `http://www.sarbc.org/hypo1.html`

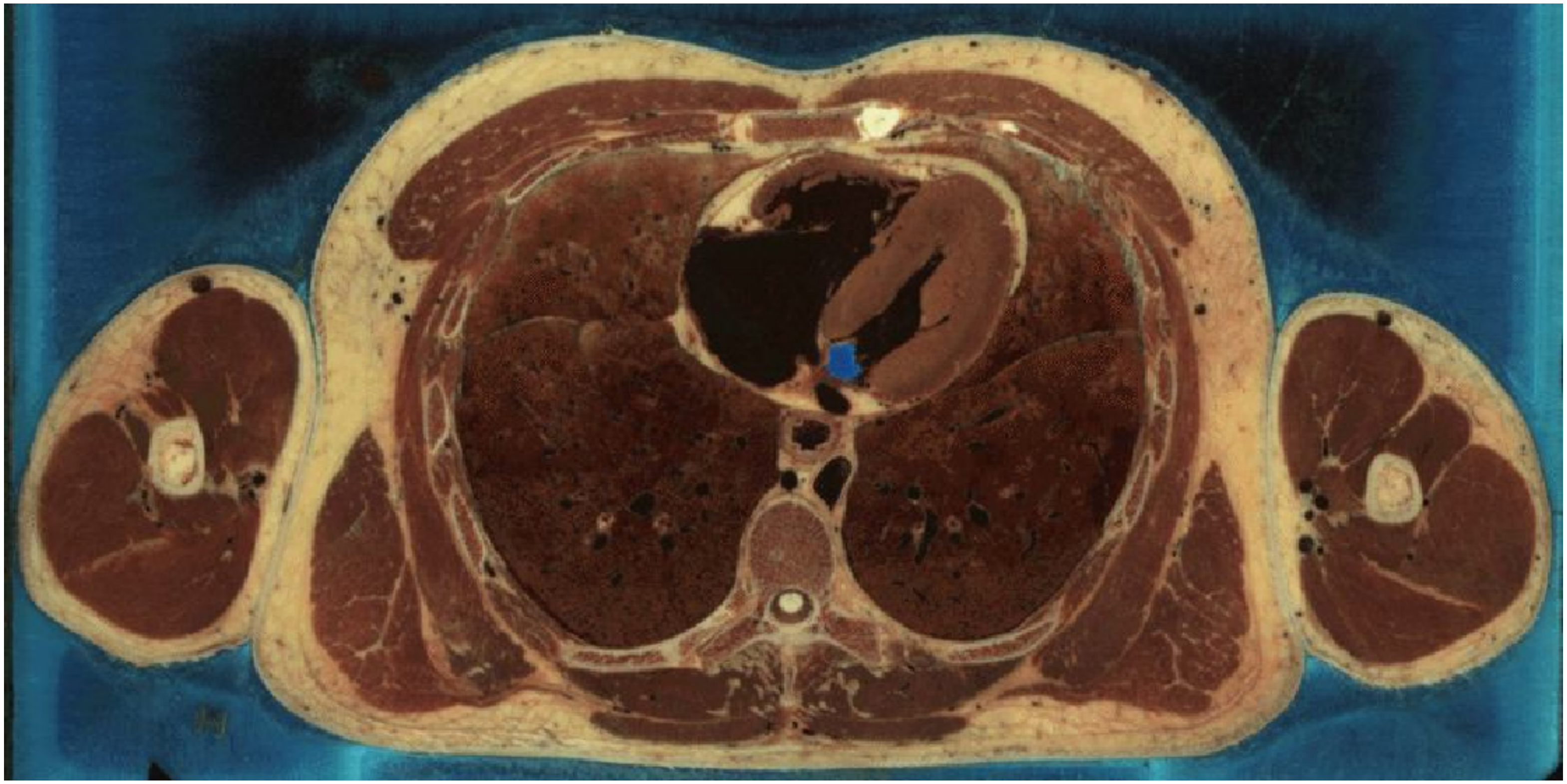
Hypothermia Treatment

- Cornell U. Medical School: *Use electric blankets*
- Niagram Mohawk Utility: *Don't use electric blankets*
- Williams et al: Ordinary blankets are just as effective as reheating systems. (*Emergency Medicine Journal*, 2005, **22**:182–184)
- Devices for preventing hypothermia in surgery patients
- Human body is complex
  - ▷ Non-uniform tissue
  - ▷ Core versus extremities
  - ▷ Vasoconstriction and vasodilation
  - ▷ Metabolic heat generation, shivering

Warning

The next slide shows a cross-section of a human body. Close your eyes if you think this image might be upsetting.

Cross-Section of Human Male Torso



From *Marching Through the Visible Man*, `http://www.crd.ge.com/esl/cgsp/projects/vm/` using data from the *Visible Human* project sponsored by the NIH, `http://www.nlm.nih.gov/research/visible/visible_human.html`. Image taken from slices of the frozen cadaver of a 39 year old convicted murderer who donated his body to science.

Existing Products

FAW: Forced-Air Warming System

- Fits in backpack
- High electrical power requirement

Operating Room Forced-Air Blanket

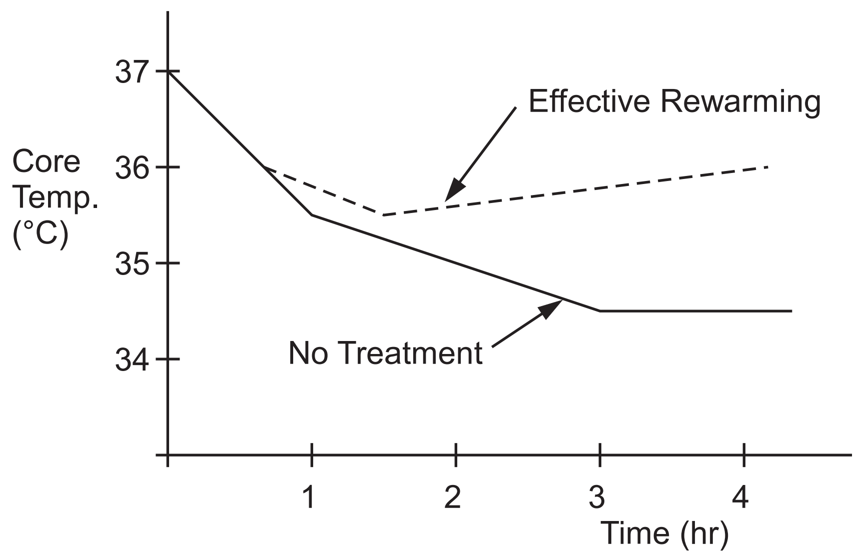
ThermoGear

ThermoGear manufactures Chillbuster^{TM}

Electrically Heated Clothing

Gerbing Vest Liner	The North Face MET5	Widder Arm Chaps
		

Core Temperature



Typical variation in core temperature for mild hypothermia due to anesthesia. The effective treatment curve (dashed line) is typical of patients with force-air warming systems or resistive heating systems.

Defining the Engineering Problem

- Use an electric blanket – it's ThermoGear's product
- Can a compact, battery-powered device deliver enough heat?
- Can we make a high heat flux blanket that does not burn skin?
- How do we organize the engineering effort?
- What are achievable goals for Phase I?

The Team

Dr. Wayne Fields, ThermoGear, Inc.

Dr. Larry Crawshaw, PSU Department of Biology

Gerry Recktenwald, Peter Tonn, Noel Tavan,
PSU Department of Mechanical and Materials Engineering

New Collaborators: Zoni Rockoff, Mr. Needham's 4th grade class

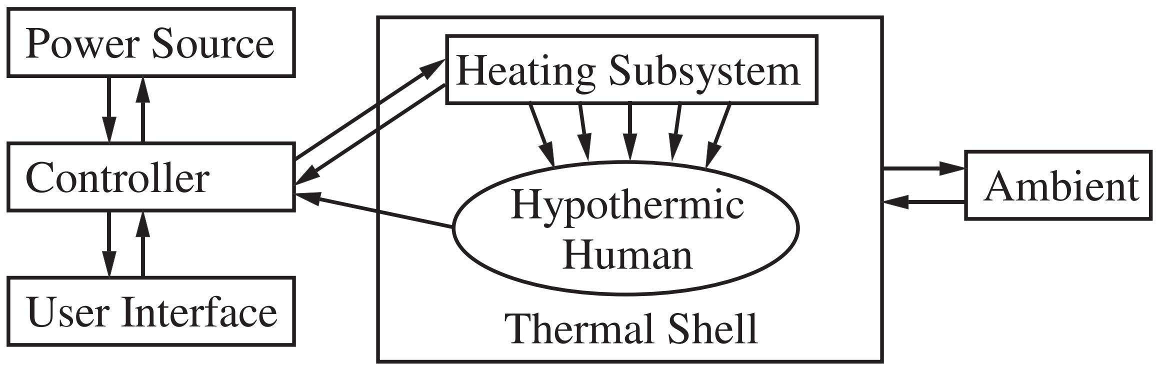
Objectives for PSU Team

- Develop ability to predict the performance of an electric resistance heating pad for use in hypothermia treatment.
- Determine whether such a device is feasible.
- Use the engineering model and data to design the prototype.

Constraints for Heater Design

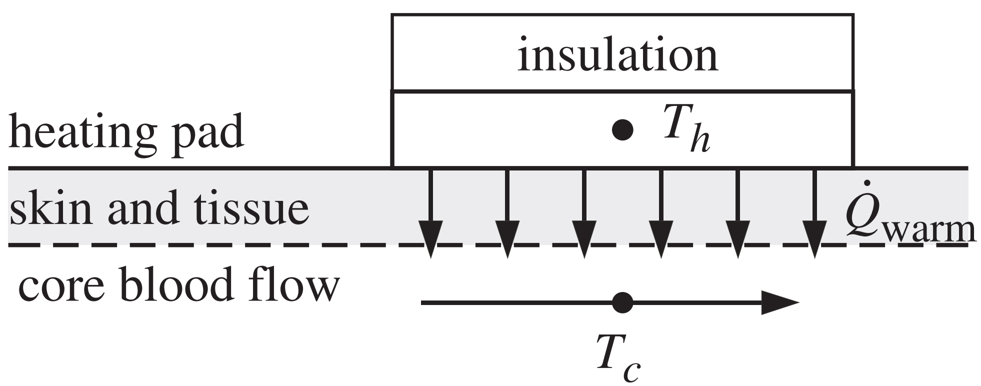
Body mass	70 kg
Body area, A	1.8 m^2
Heater area, A_h	$0.45\ \mathrm{m}^2 = A/4$
Metabolic rate	100 W
Initial core temperature	25 – 34 $^\circ\mathrm{C}$
Normal core temperature	37 $^\circ\mathrm{C}$
Maximum skin temperature	41 $^\circ\mathrm{C}$
Ambient temperature range	5 – 20 $^\circ\mathrm{C}$
Heat transfer coefficient to ambient	1 – 10 $\mathrm{W/(m^2\,{}^\circ C)}$

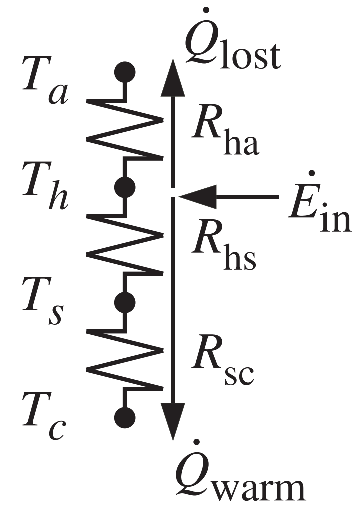
Functional Decomposition of the Device



$$\dot{E}_{\text{in}} = \dot{Q}_{\text{warm}} + \dot{Q}_{\text{lost}}$$

Heat Flow Across the Skin

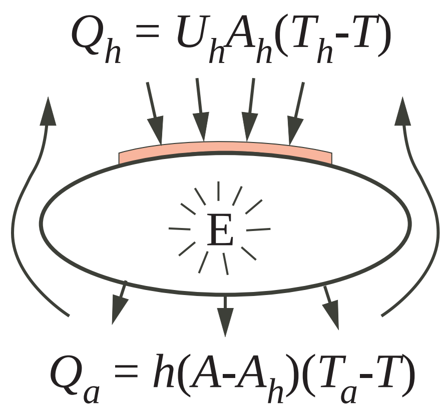




R_{hs} is the thermal resistance between heater and skin

R_{sc} is the thermal resistance between skin and body core

Modified VanDorn Model (1)



Energy balance

$$mc\frac{dT}{dt} = E + U_h A_h (T_h - T) + h(A - A_h)(T_a - T) \tag{1}$$

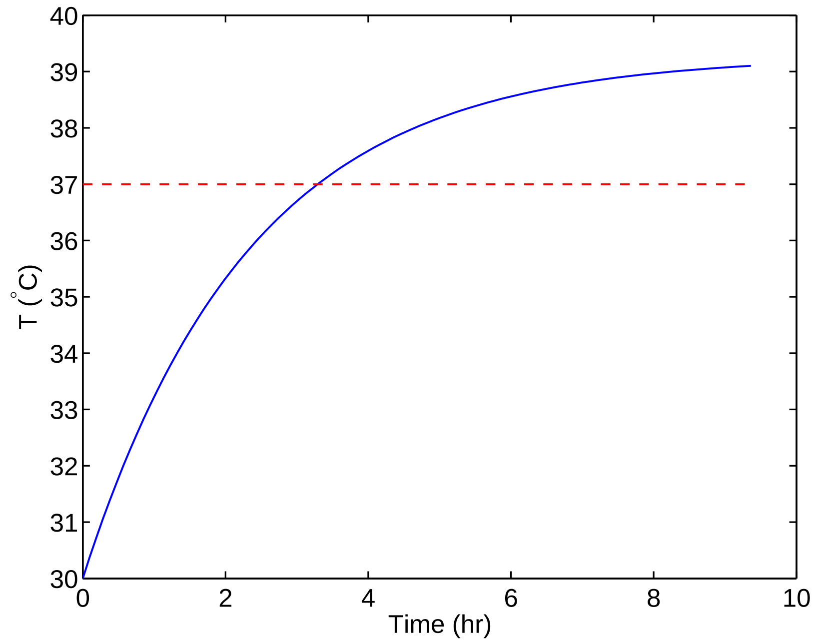
Modified VanDorn Model (2)

Analytical solution

$$T = T_{\text{ss}} + (T_i - T_{\text{ss}})e^{-t/\tau}$$

$$\tau = \frac{mc}{U_h A_h + h(A - A_h)}$$

$$T_{\text{ss}} = T_a + \frac{E + U_h A_h (T_h - T_a)}{h(A - A_h) + U_h A_h}$$



The model needs a value of U_h. Time to go to the lab.

Experiments

- What needs to be measured to determine U_h?

$$U_h = \frac{Q/A}{T_h - T_{\text{skin}}}$$

U_h depends on materials in contact and pressure (?)

- Basic design of apparatus
- Data reduction models
- Results

Practical Complications for Experiments

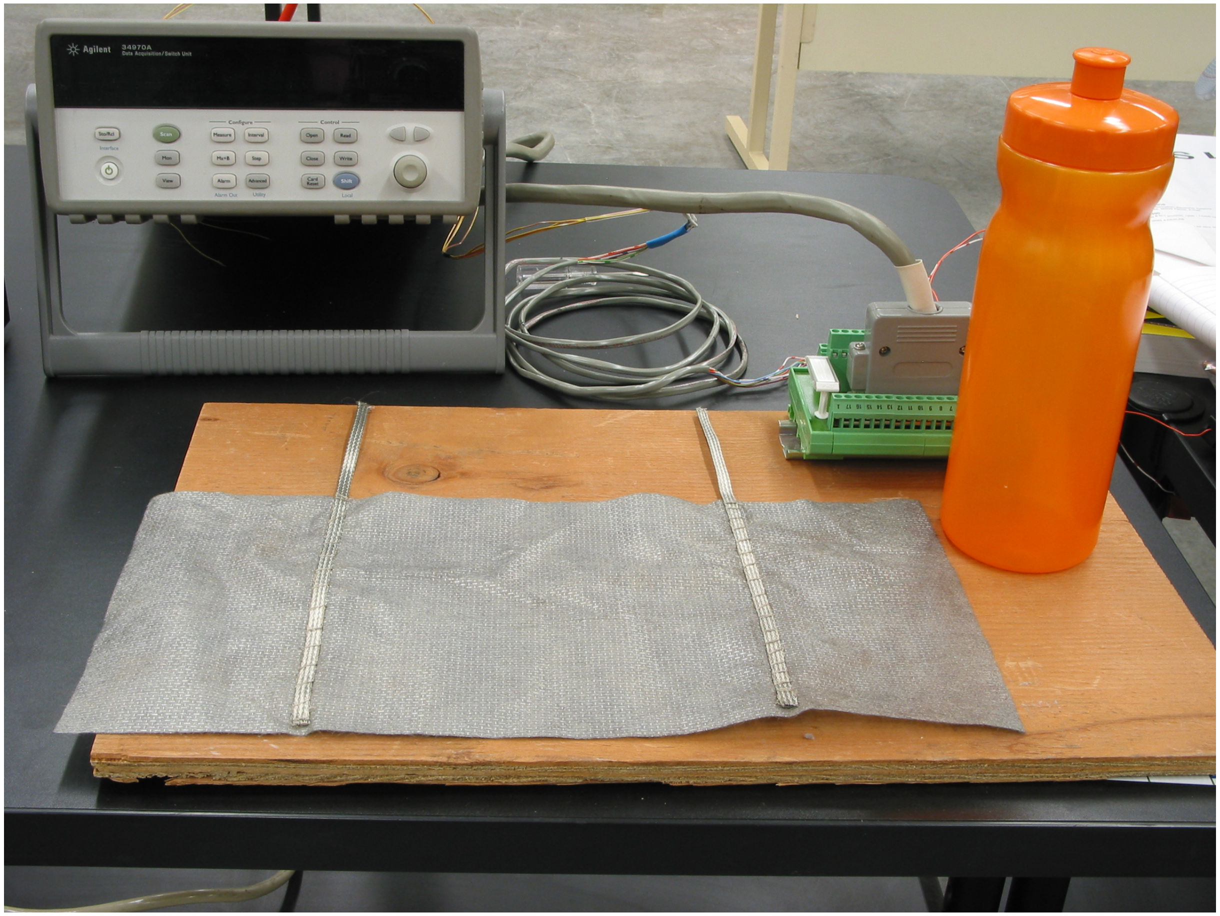
- Cloth samples need to have power supplied to them.
- How to measure cloth temperature?
- Power densities are relatively low: 5–20 W total heat transfer rate.
- Little time to design and build apparatus and make measurements.

Test Cloths

E-CT material from Gorix Ltd. of Southport, Great Britain, `www.gorix.com`.

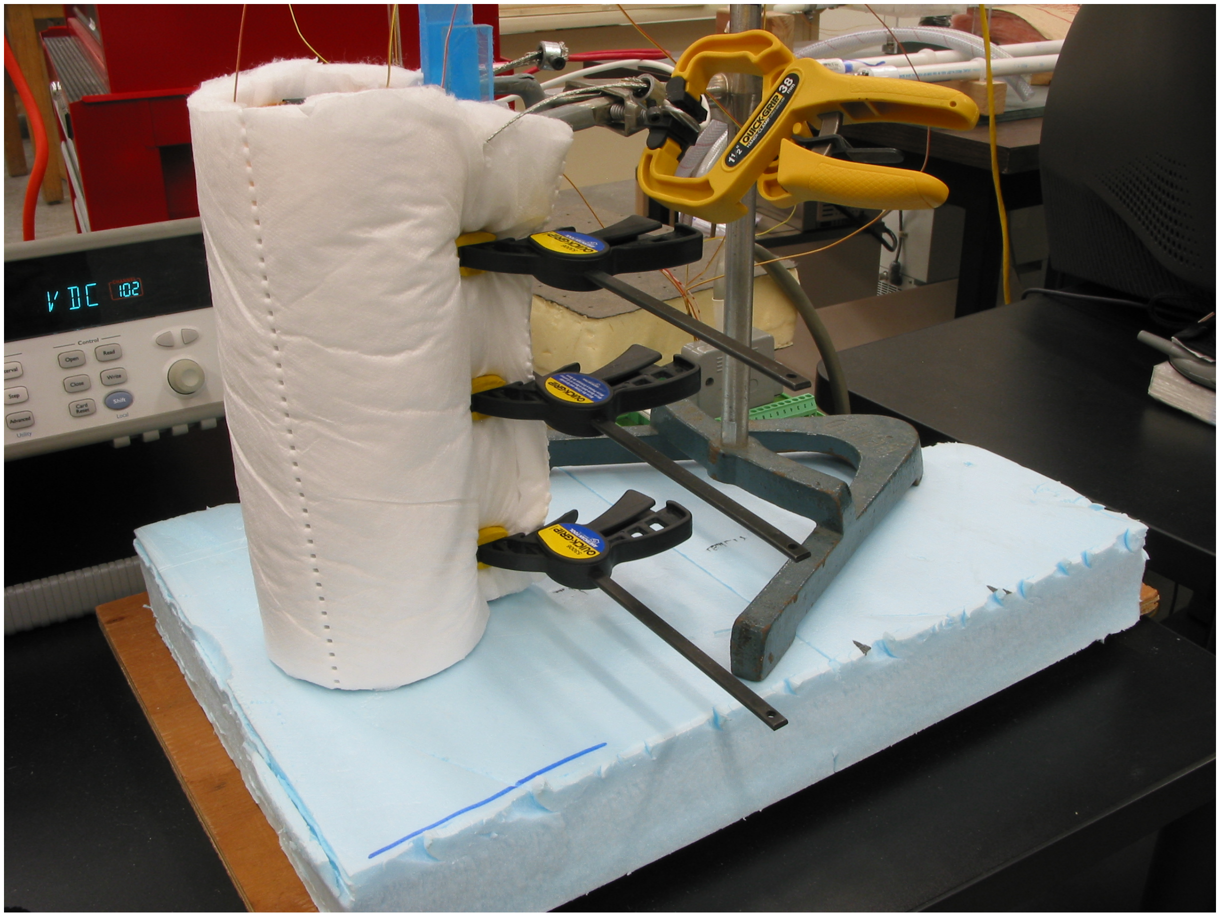
Cerex PC90615 from Sauquoit Industries, Inc., Scranton, PA, `www.sauquoit.com`.

Water Bottle Experiments (1)

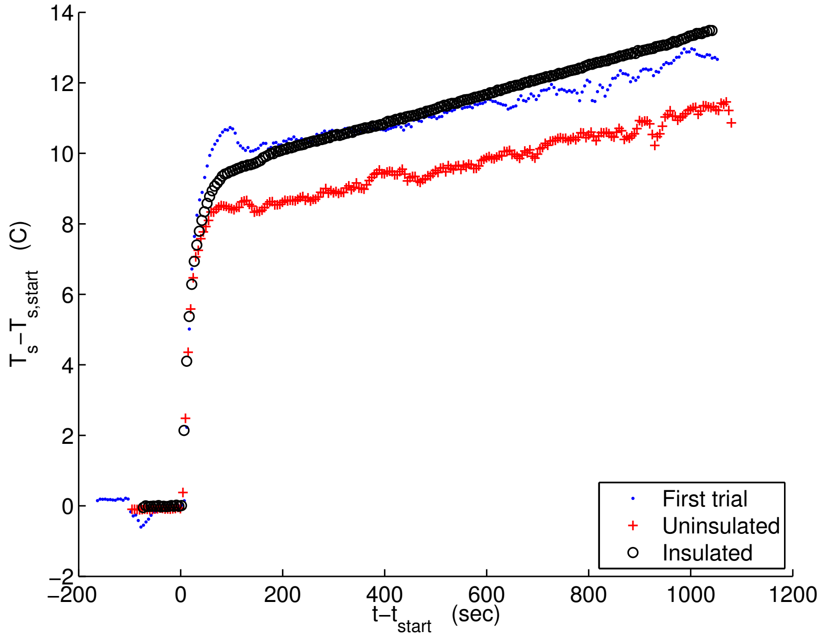


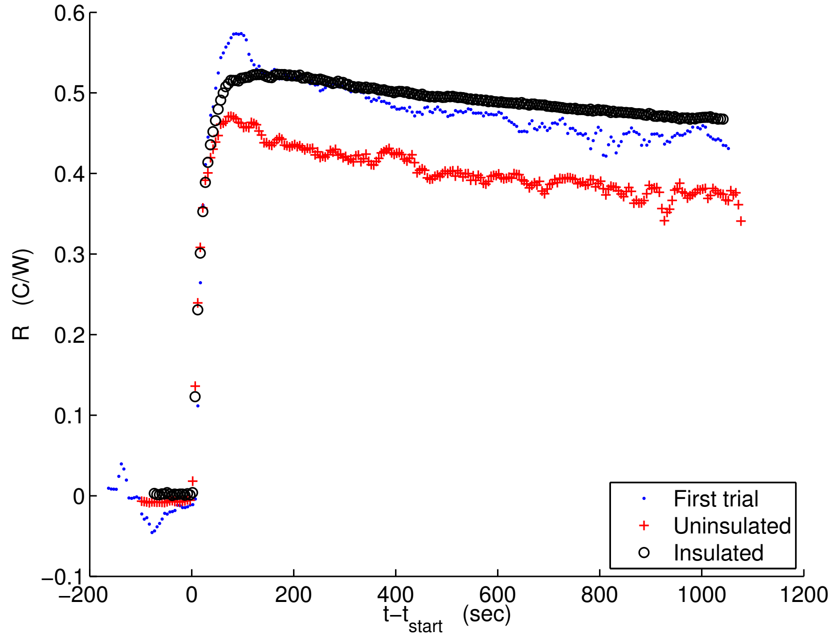
Water Bottle Experiments (2)

Water Bottle Experiments (3)

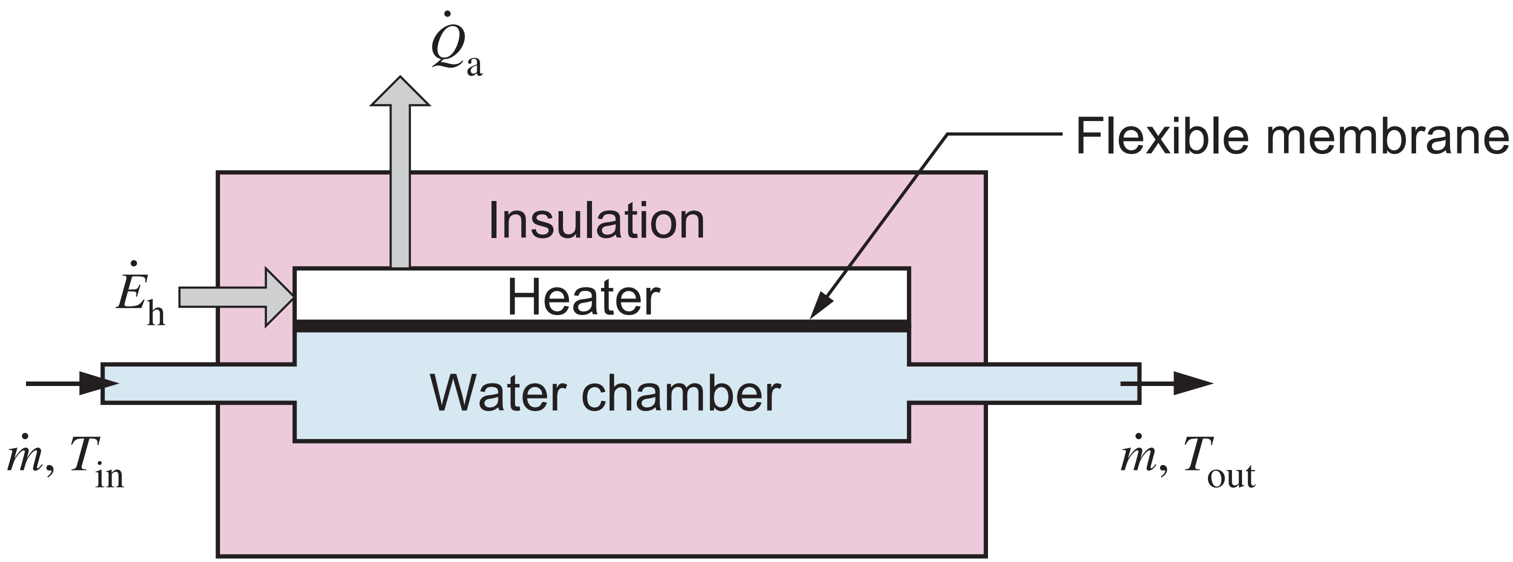


Water Bottle Experiments (4)





Conceptual Design of Test Fixture



Flexible membrane simulates skin

Thermal resistance on water side is small compared to $R_{\mathrm{hs}} = \dfrac{1}{U_{\mathrm{hs}} A}$.

Data Reduction (1)

Energy balance on the blanket

$$\dot{E}_h = Q_f + Q_a$$

Energy balance on the water

$$Q_f = \dot{m}_w c_p (T_{\text{out}} - T_{\text{in}})$$

The experiment is designed to obtain U_{hs} from

$$U_{\text{hs}} = \frac{Q_f / A}{\overline{T}_h - T_w}$$

where $\overline{T}_h$ is the average temperature of the heating pad, and T_w is the inlet temperature of the water. (Note: $\overline{T}_w \approx T_w$)

Data Reduction (2)

Problem: $T_{\text{out}} - T_{\text{in}}$ is small because power input is small. It is not possible to measure $Q_f = \dot{m}_w c_p (T_{\text{out}} - T_{\text{in}})$ accurately

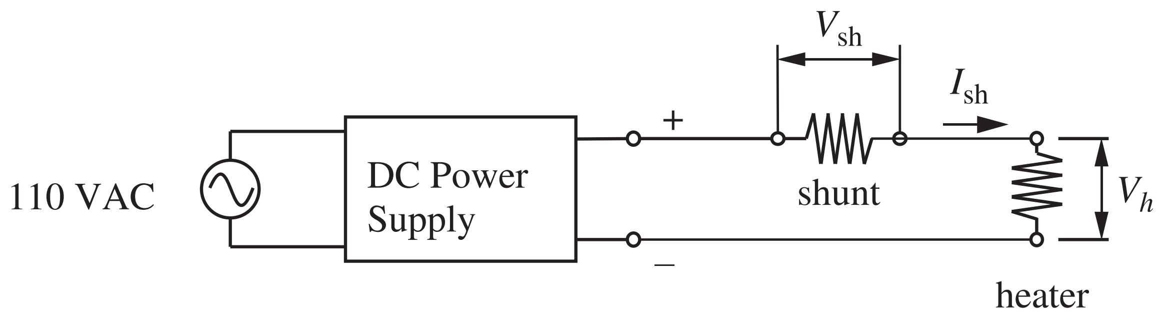
Solution: Rewrite energy balance for blanket as

$$Q_f = \dot{E}_h - Q_a.$$

Measure $\dot{E}_h$, and estimate Q_a.

A formal uncertainty analysis shows that this is a better idea.

Power Measurement



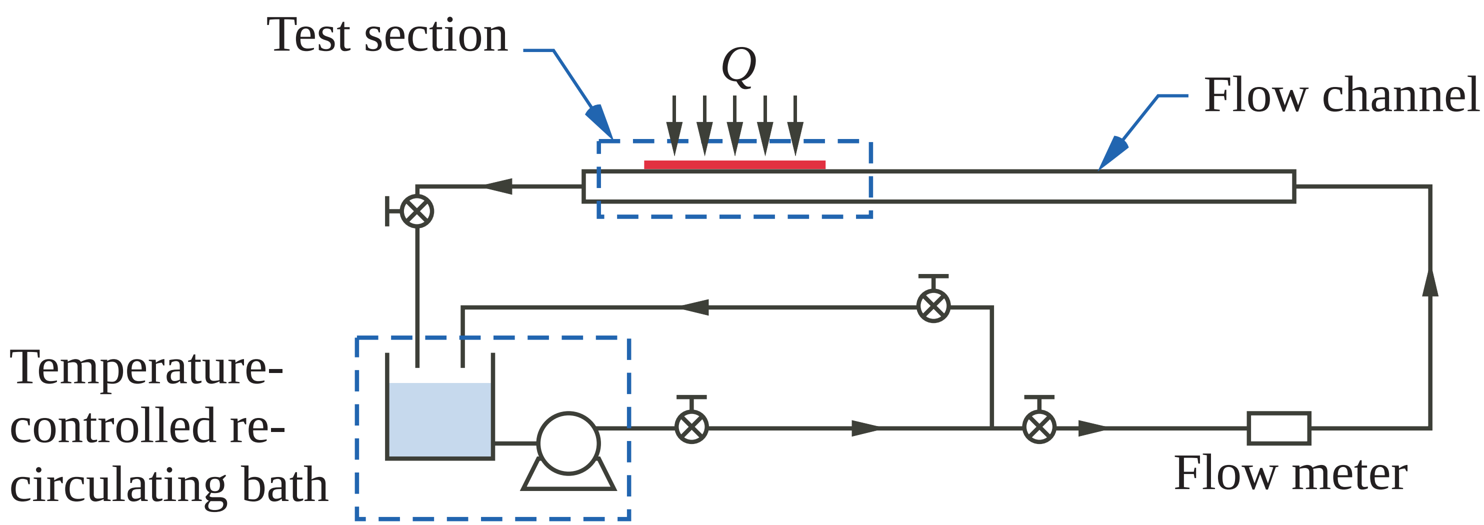
The power dissipated by the electric resistance heater is

$$\dot{E}_h = V_h I_h$$

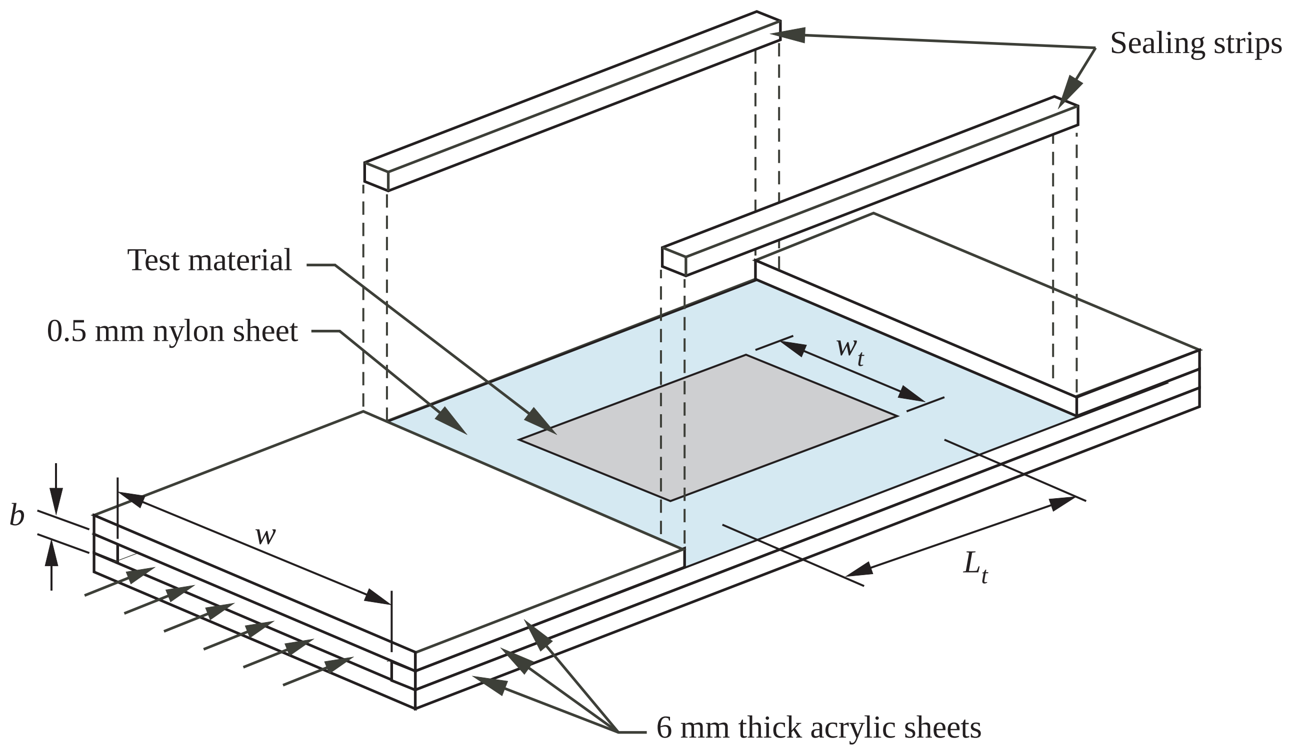
$$I_h = I_{sh} = \frac{V_{sh}}{R_{sh}}$$

$$\Longrightarrow \dot{E}_h = \frac{V_h V_{sh}}{R_{sh}}$$

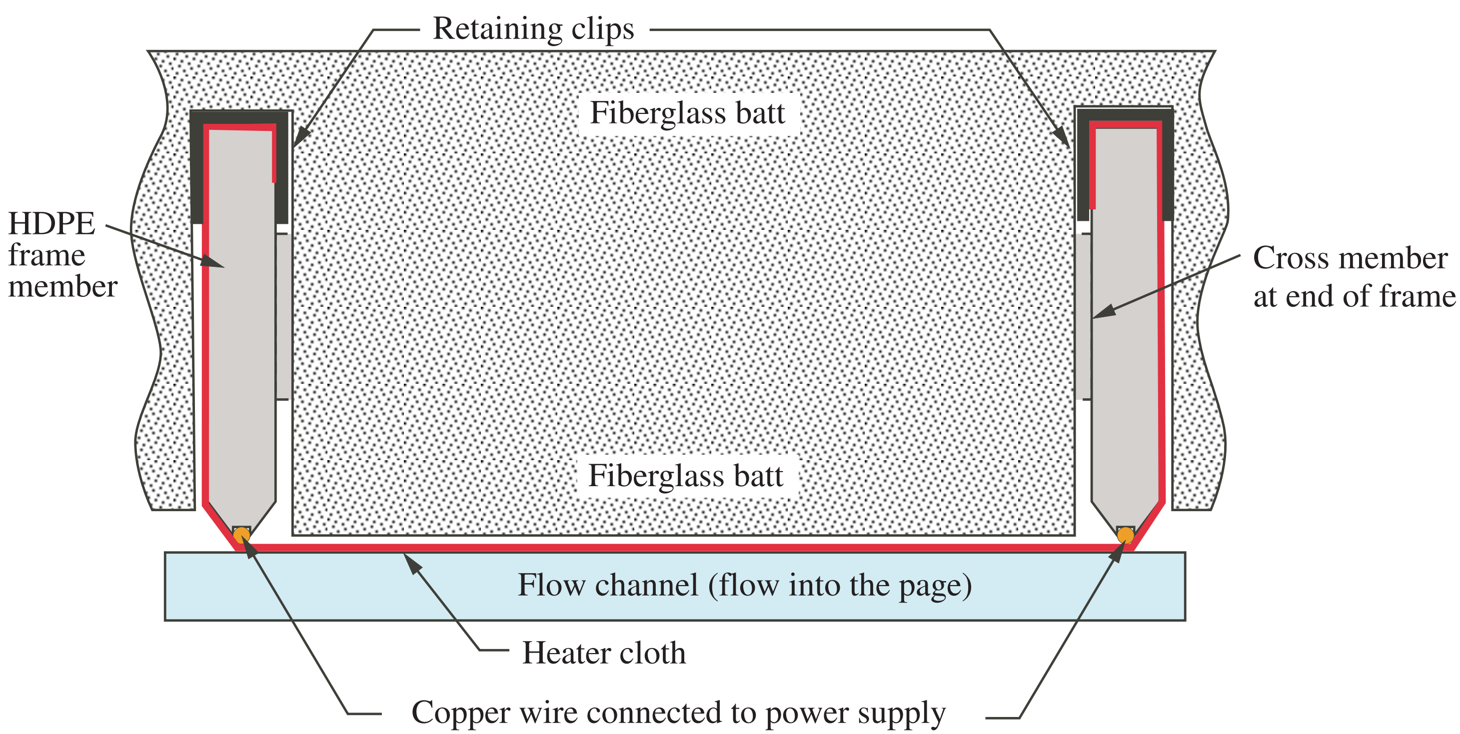
Flow Loop Schematic



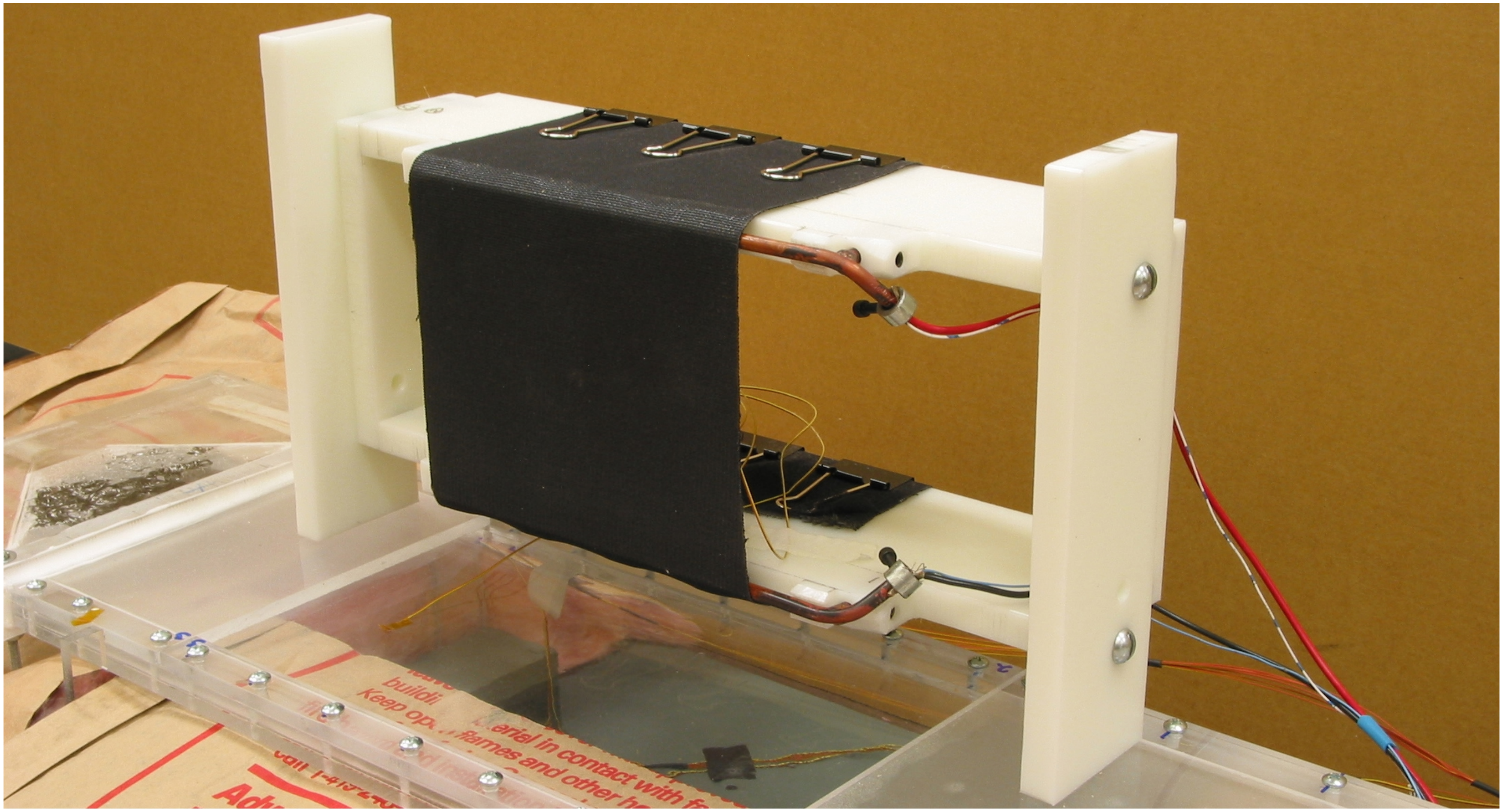
Test Section



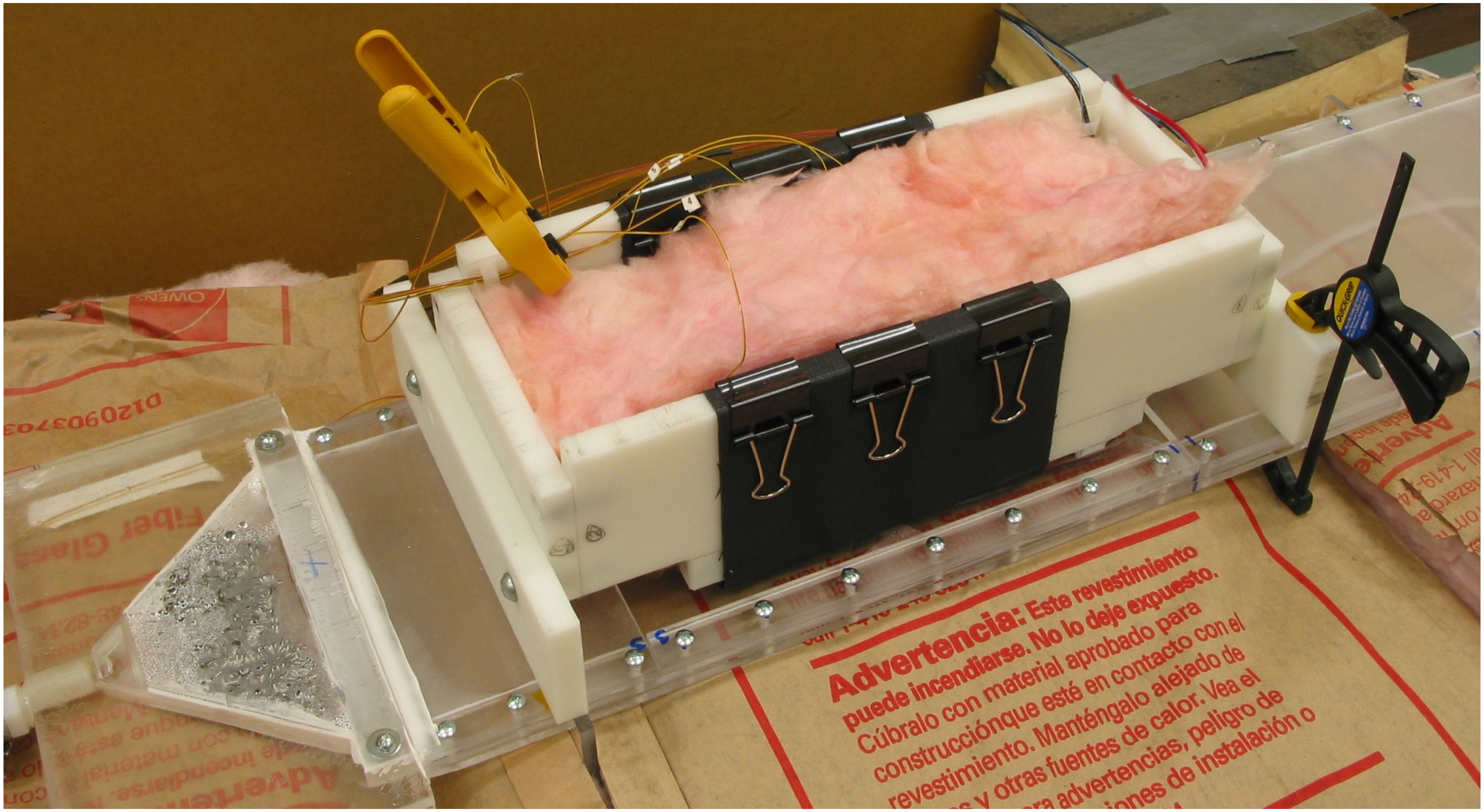
Test Fixture Version 1



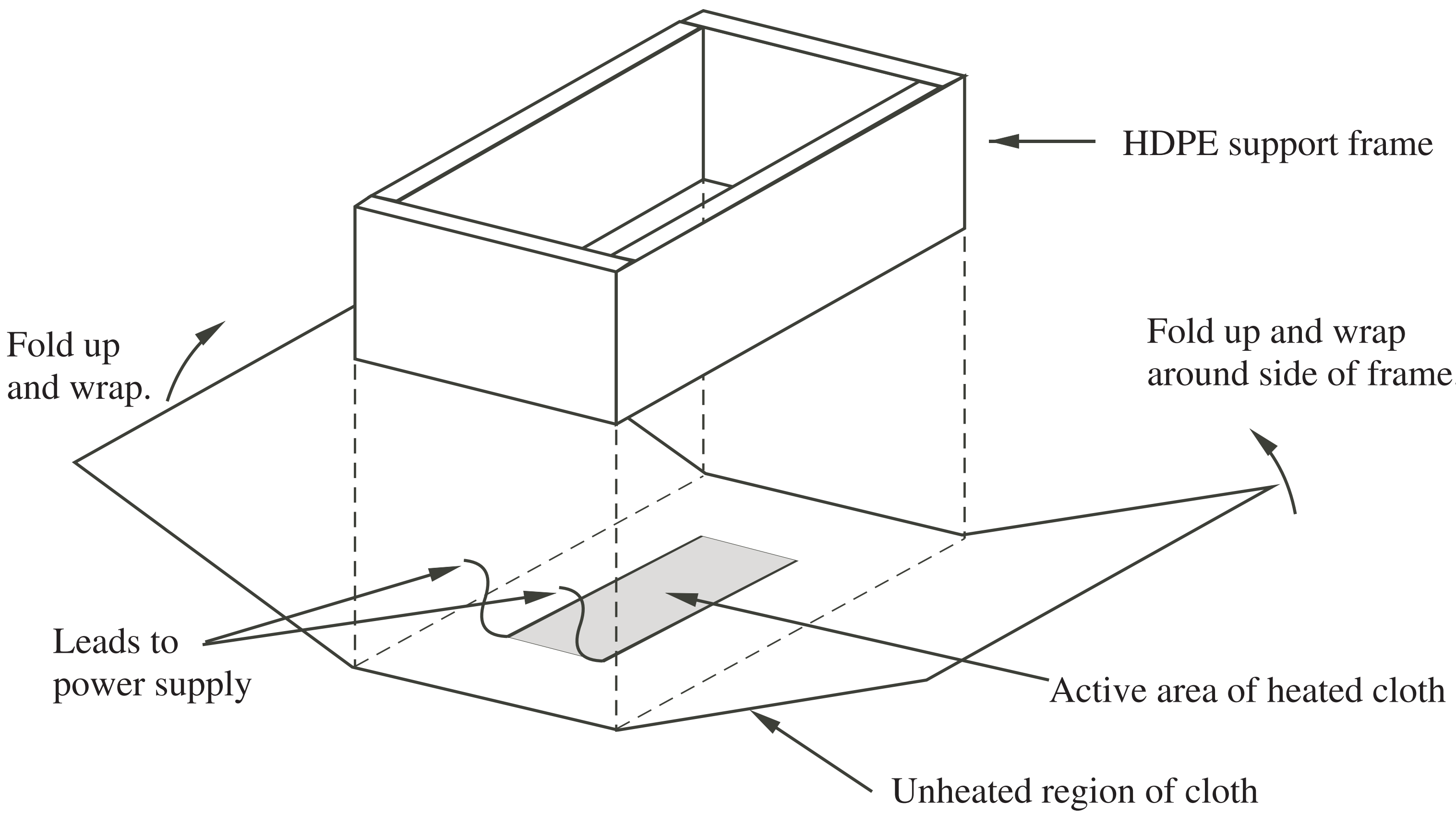
Test Fixture Version 1



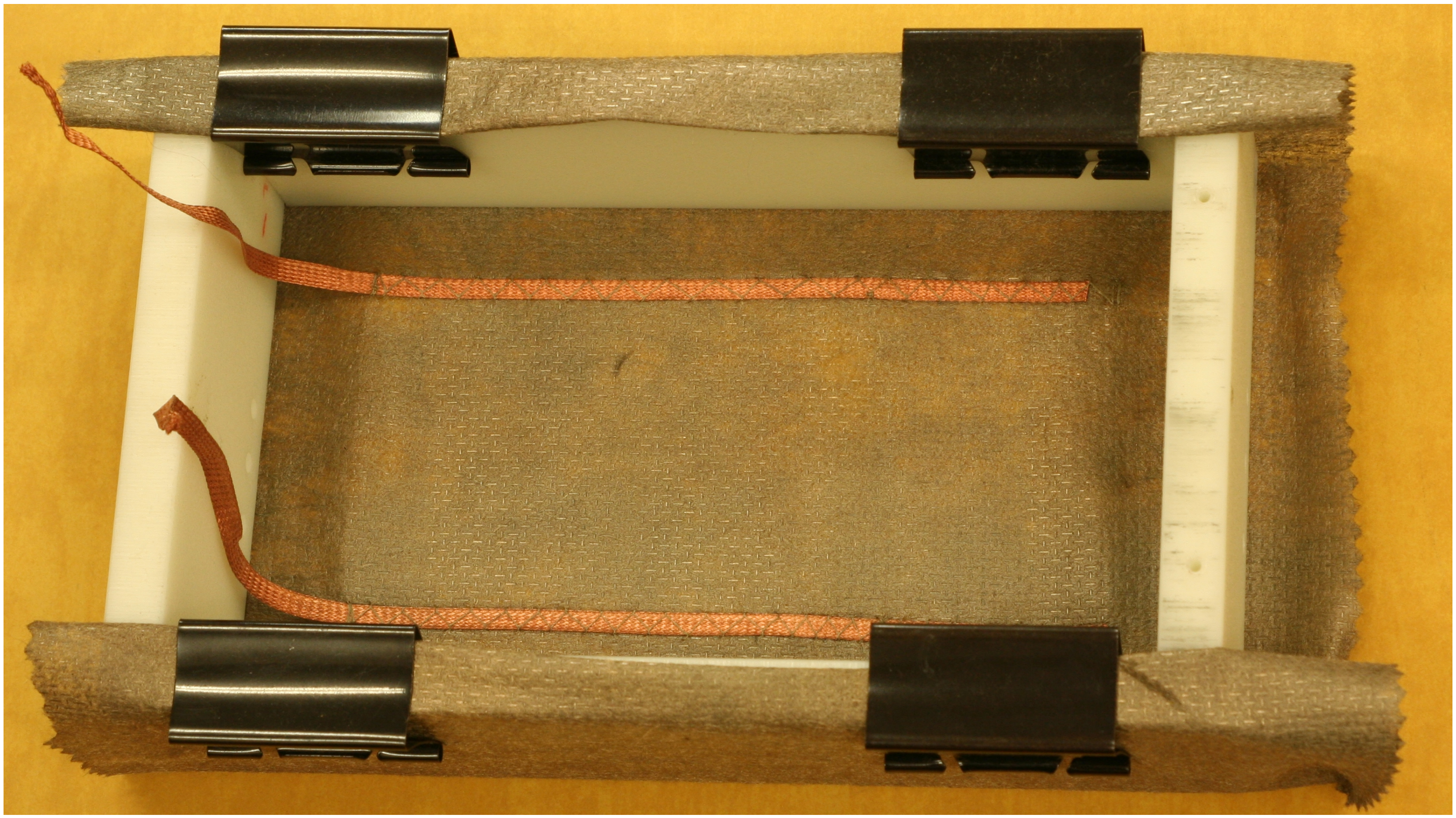
Test Fixture Version 1



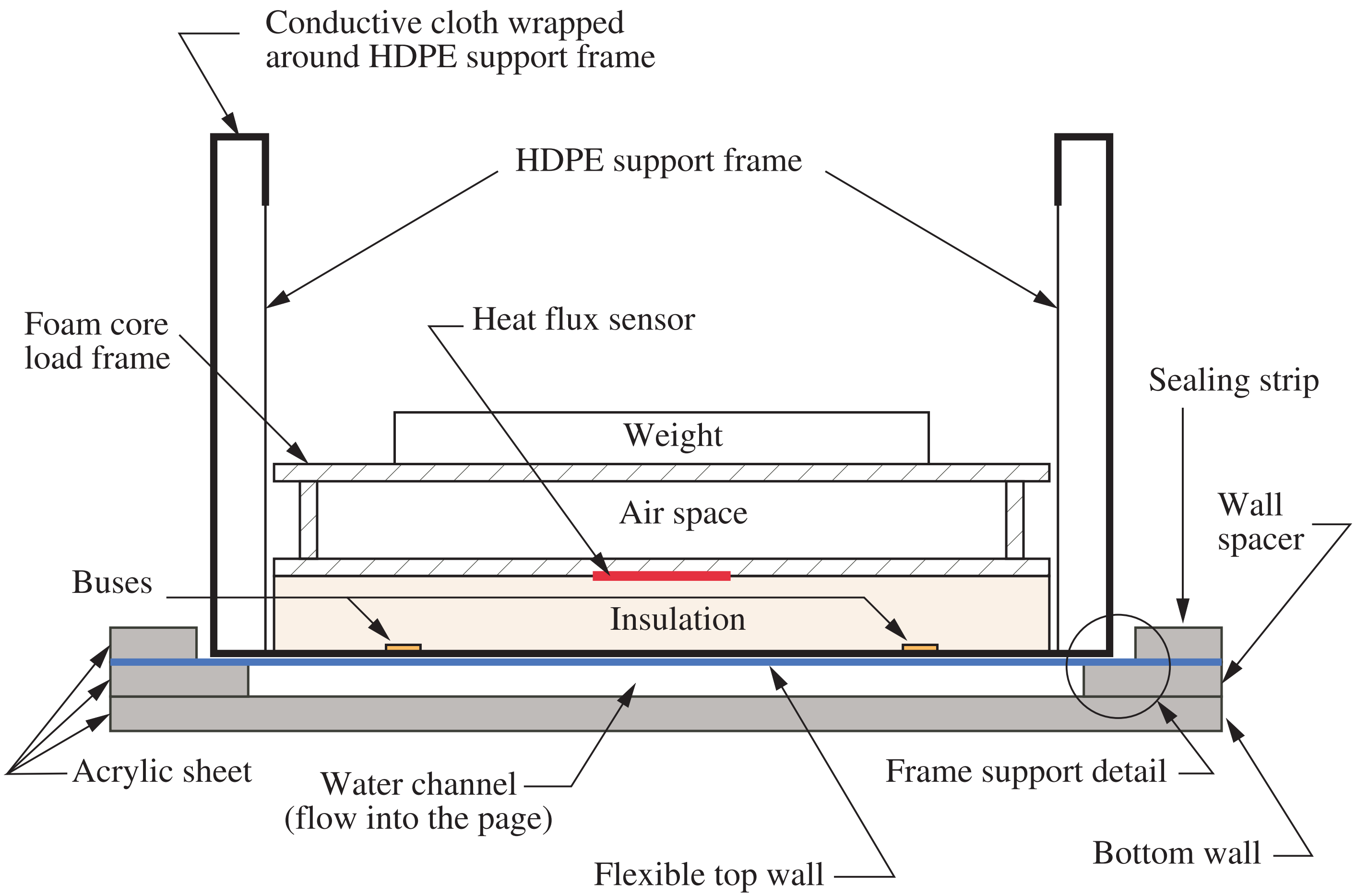
Test Fixture Version 2



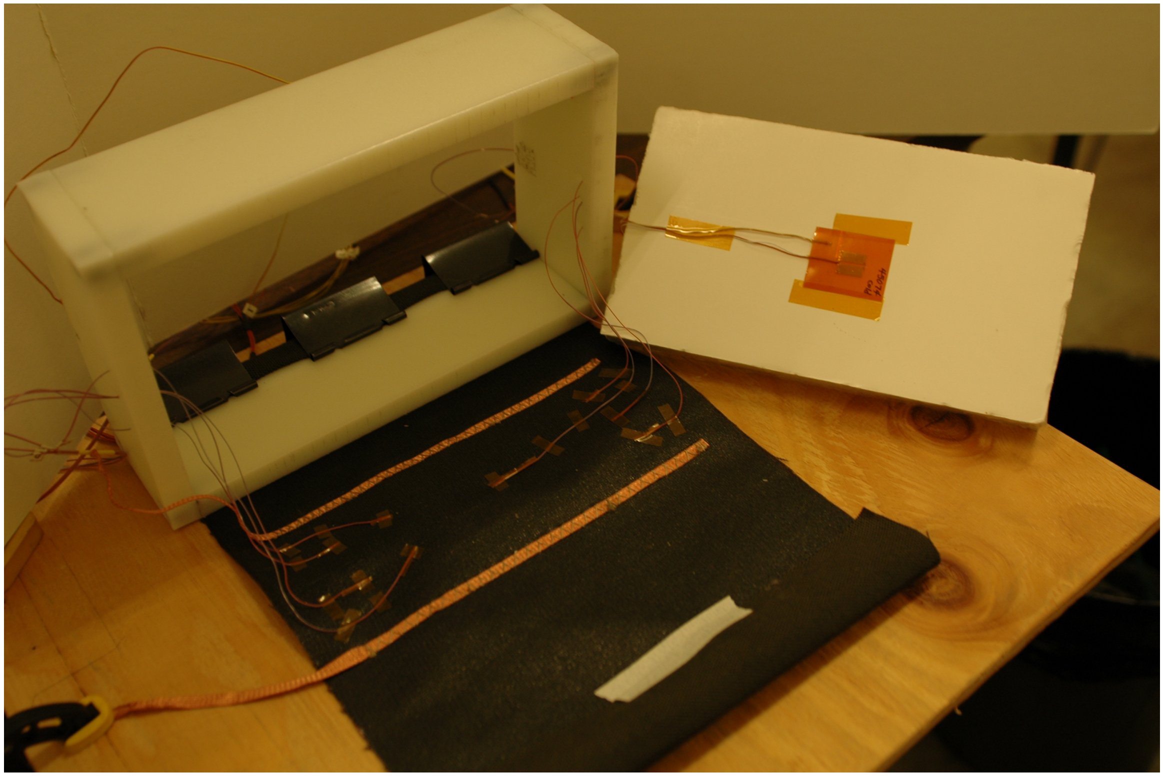
Test Fixture Version 2



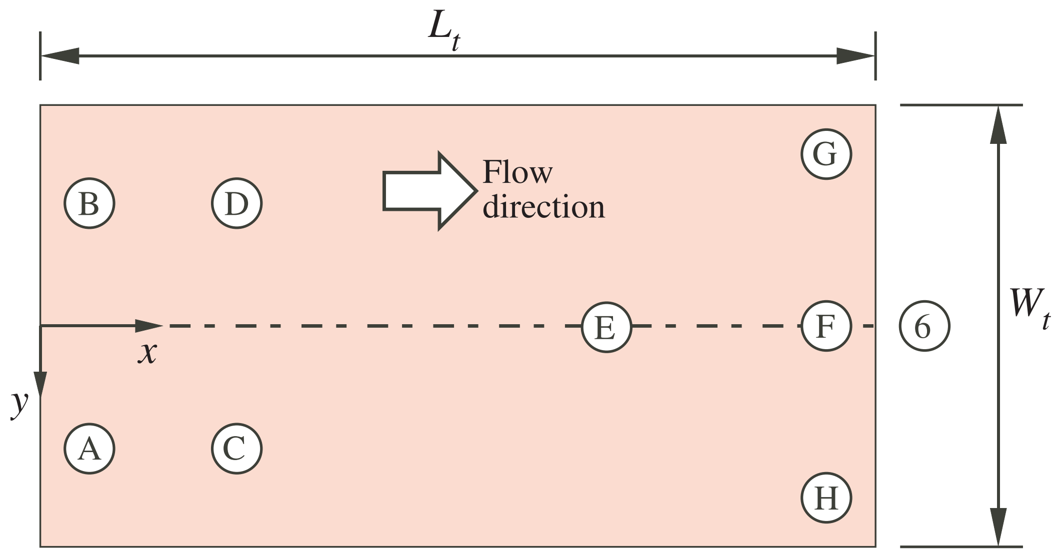
Test Fixture Version 2



Test Fixture Version 2

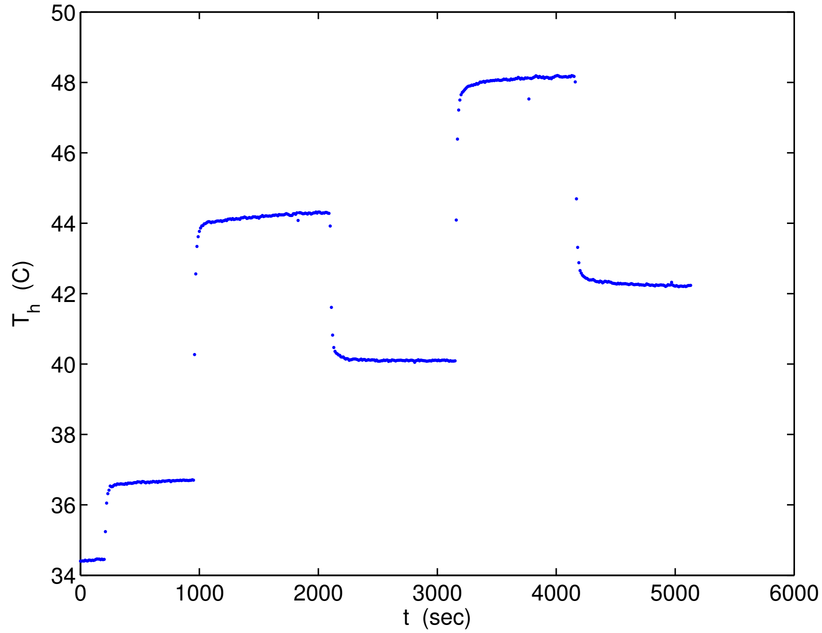


Typical Thermocouple Locations

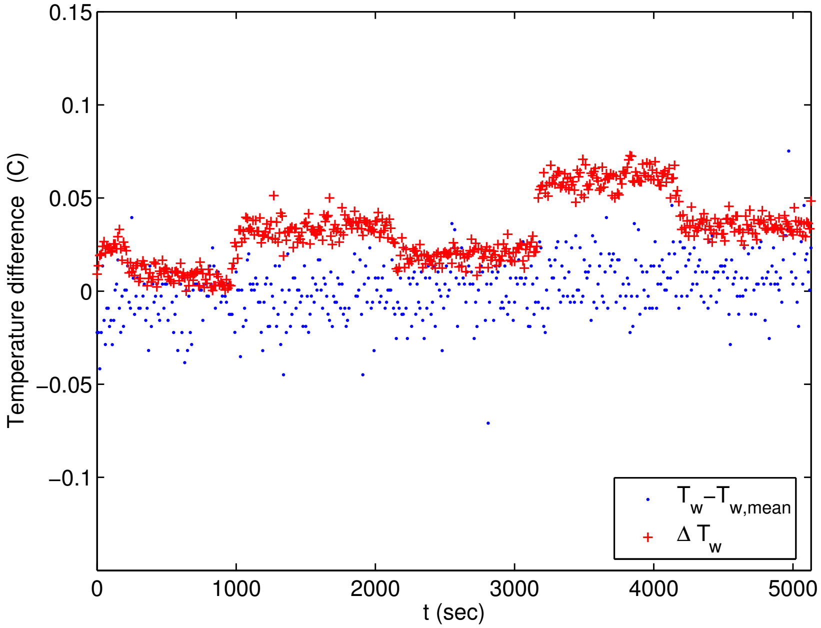


Typical Results: Average Cloth T and Water ΔT

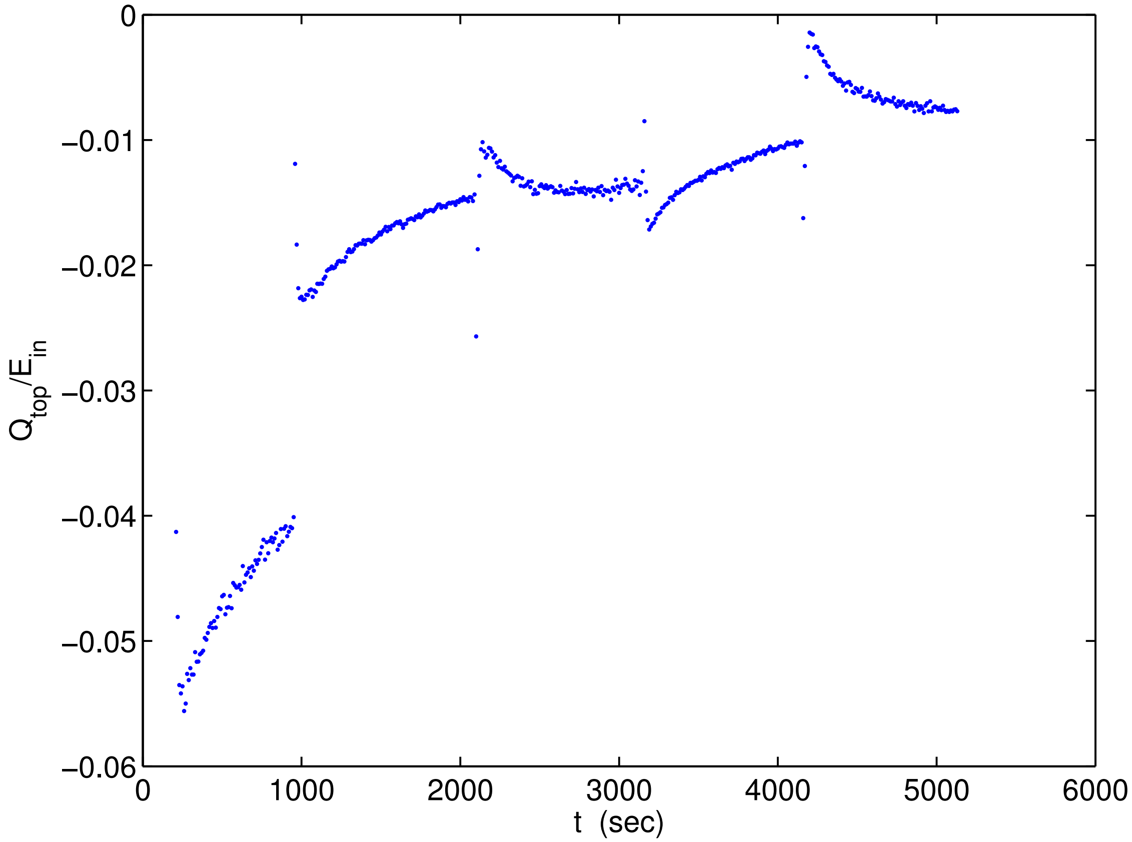
Average Heater Temperature



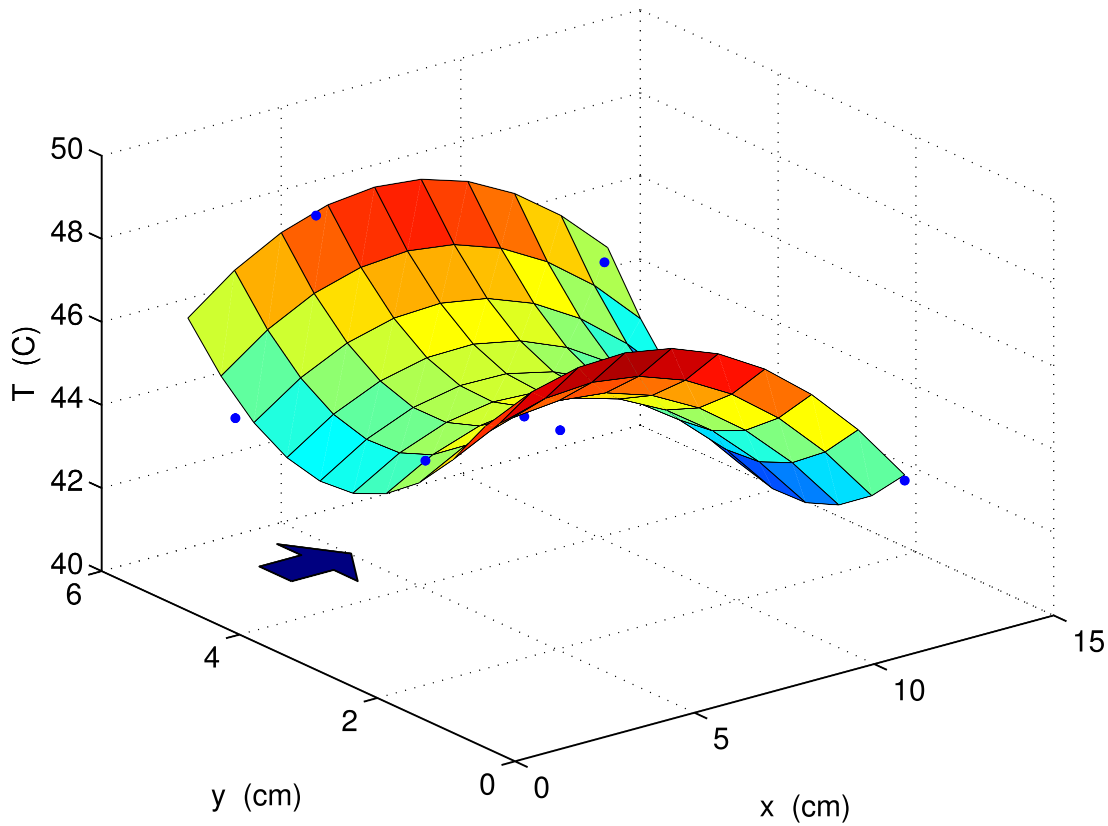
Water ΔT and $T_w - \bar{T}_w$

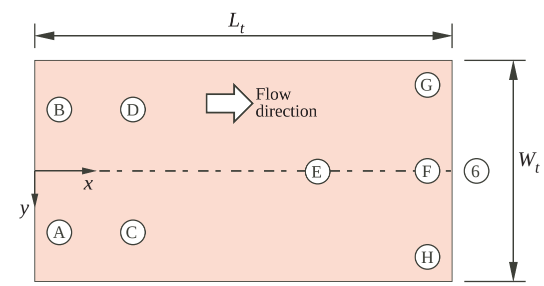


Typical Results: Top Heat Loss



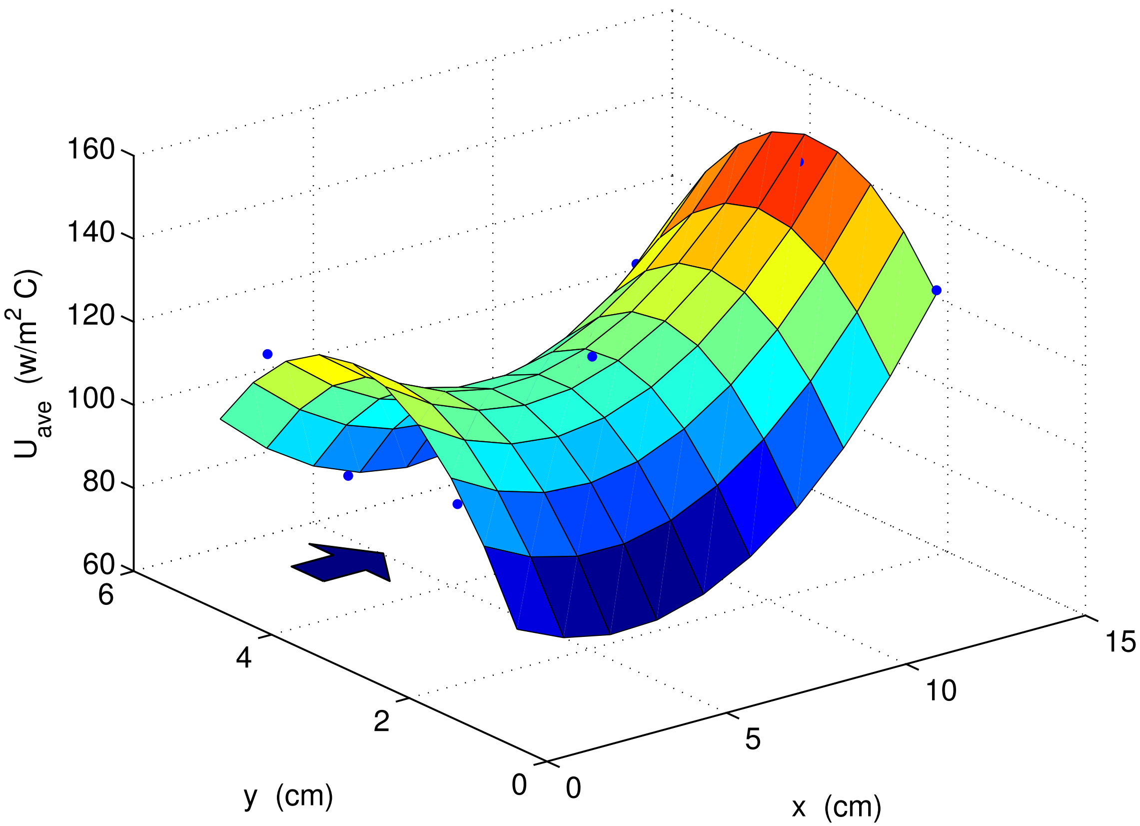
Variation of Surface Temperature

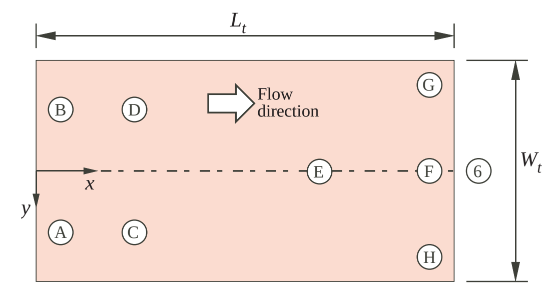




Least squares surface fit of thermocouple temperatures for Cerex cloth at 12 W.

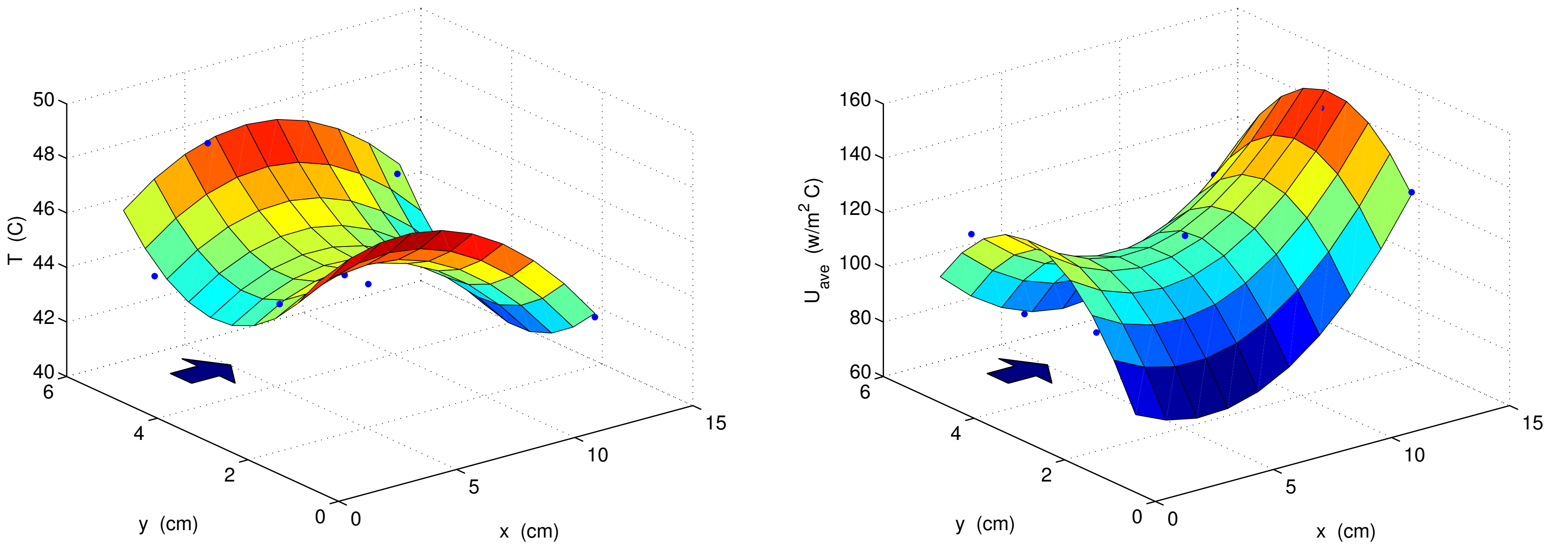
Conductance





Least squares surface fit of average local conductance for Cerex cloth.

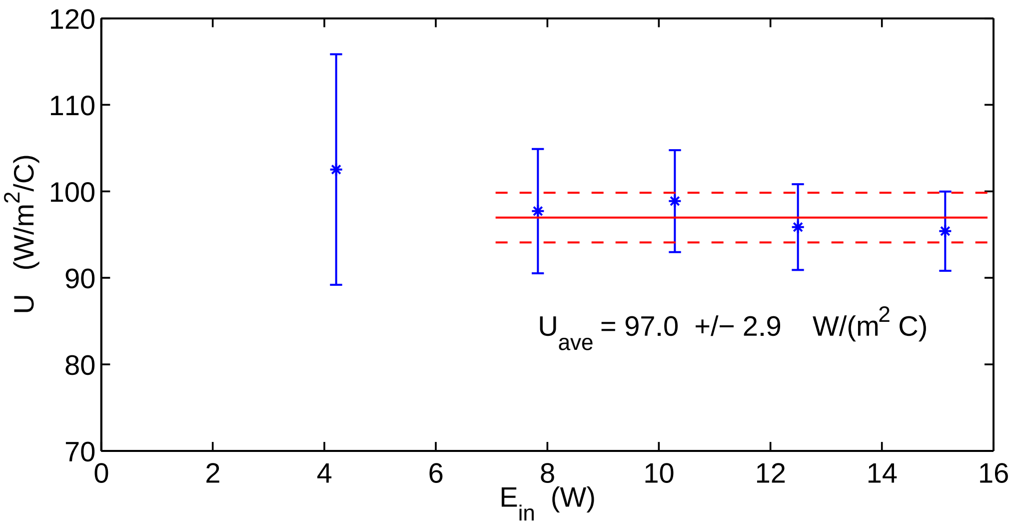
Surface Temperature and Surface Conductance



Cerex cloth: Least squares surface fit of thermocouple temperatures at 12 W and average local conductance for a range of power inputs.

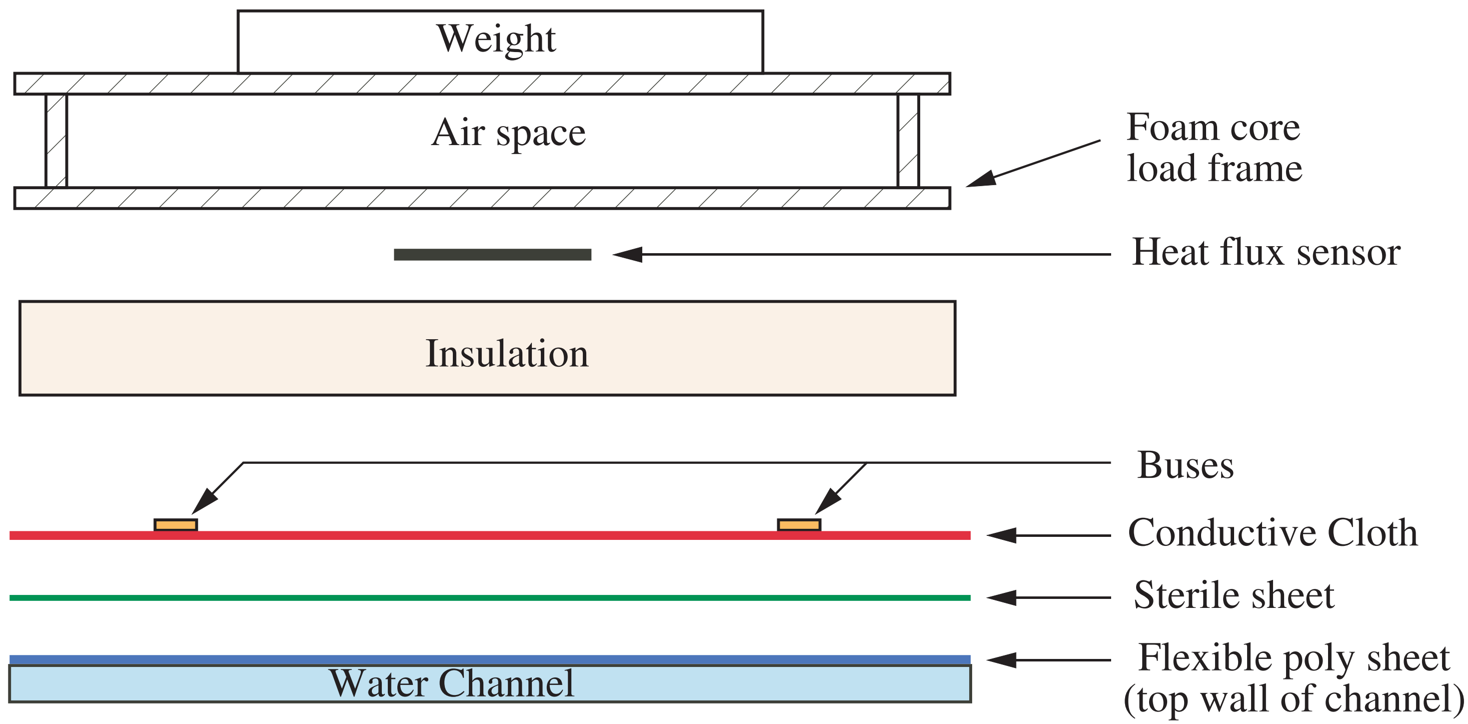
Experimental Results

Measure the cloth temperature at different power levels for each cloth configuration (cloth type, applied pressure, with or without sterile blanket). U_{hs} should be independent of power.



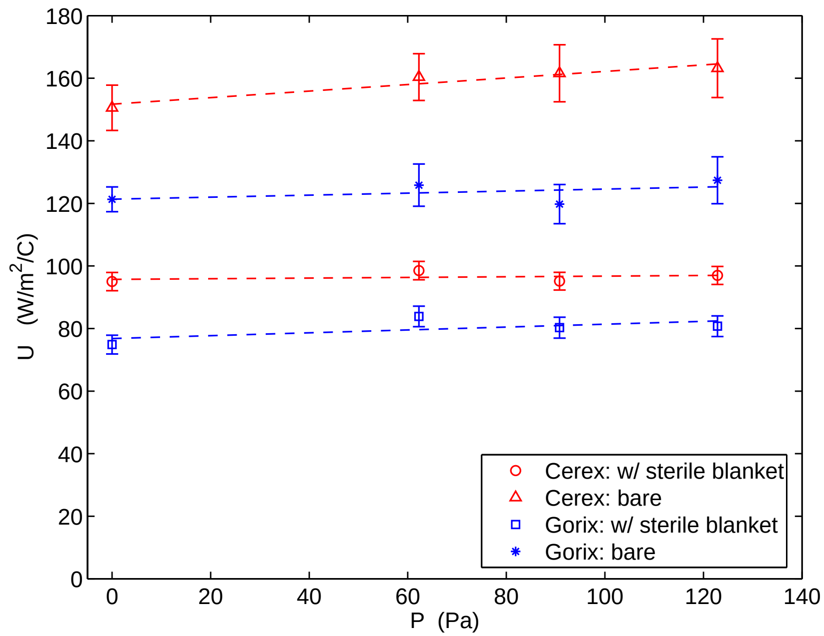
Cerex with an applied pressure of 123 Pa, and the sterile sheet between the Cerex cloth and the nylon surface on the top wall of the flow channel.

Cloth Configurations



Experimental Results

Repeat measurements for different cloth types, applied pressures, with or without sterile blanket.

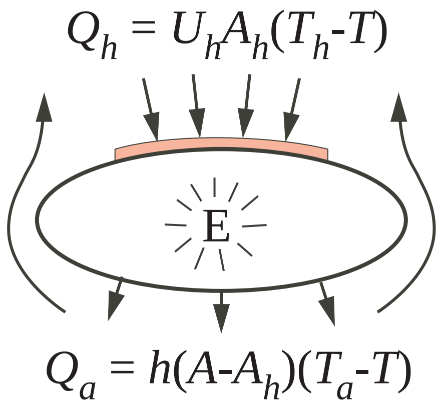


Thermal conductance ($\bar{U}$) for Gorix and Cerex materials with and without a sterile sheet between the conductive cloth and the top wall of the flow channel.

Model Predictions

- Key parameters and their ranges
- Time to rewarm
- Effect of ambient
- Power requirement
- Results

Modified VanDorn Model (Review)



$$T = T_{\mathrm{ss}} + (T_i - T_{\mathrm{ss}})e^{-t/\tau}$$

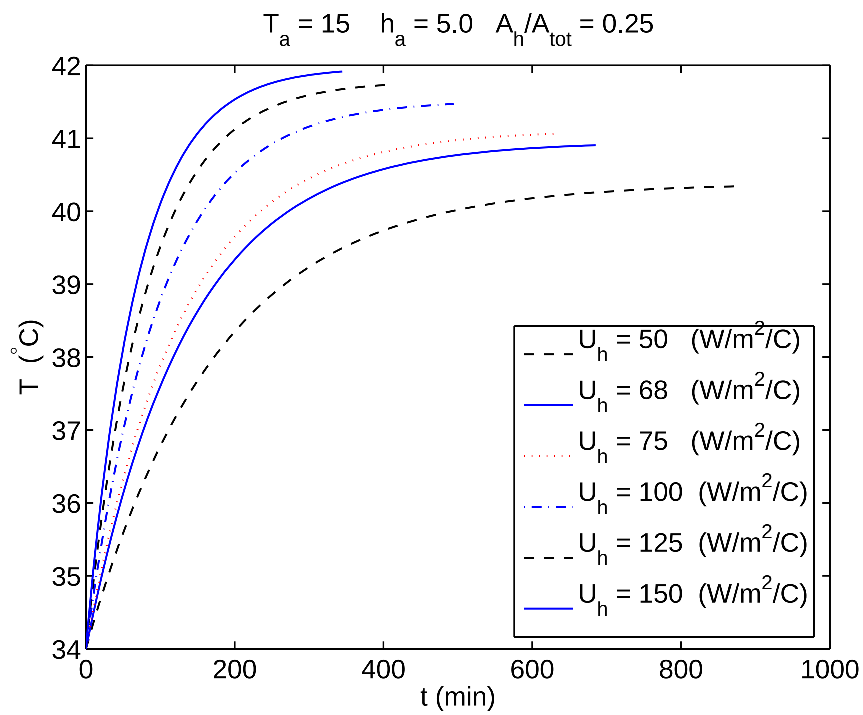
$$T_{\mathrm{ss}} = T_a + \frac{E + U_h A_h (T_h - T_a)}{h(A - A_h) + U_h A_h}$$

$$\tau = \frac{mc}{U_h A_h + h(A - A_h)}$$

Model Parameters

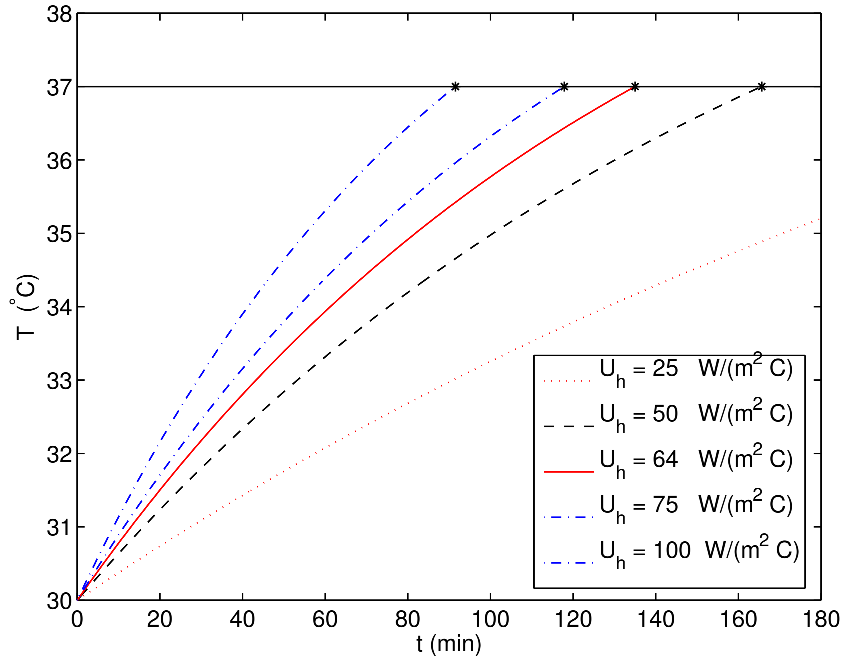
Body mass	70 kg
Body area, A	1.8 m^2
Heater area, A_h	$0.45\ \mathrm{m}^2 = A/4$
Metabolic rate	100 W
Normal core temperature	37 $^\circ\mathrm{C}$
Maximum skin temperature	41 $^\circ\mathrm{C}$
Initial core temperature	25 – 34 $^\circ\mathrm{C}$
Ambient temperature range	5 – 20 $^\circ\mathrm{C}$
Heat transfer coefficient to ambient	1 – 10 $\mathrm{W}/(\mathrm{m}^2\,^\circ\mathrm{C})$
Conductance between heater and skin	25 – 100 $\mathrm{W}/(\mathrm{m}^2\,^\circ\mathrm{C})$

Effect of U_{hs} on Rewarming Rate



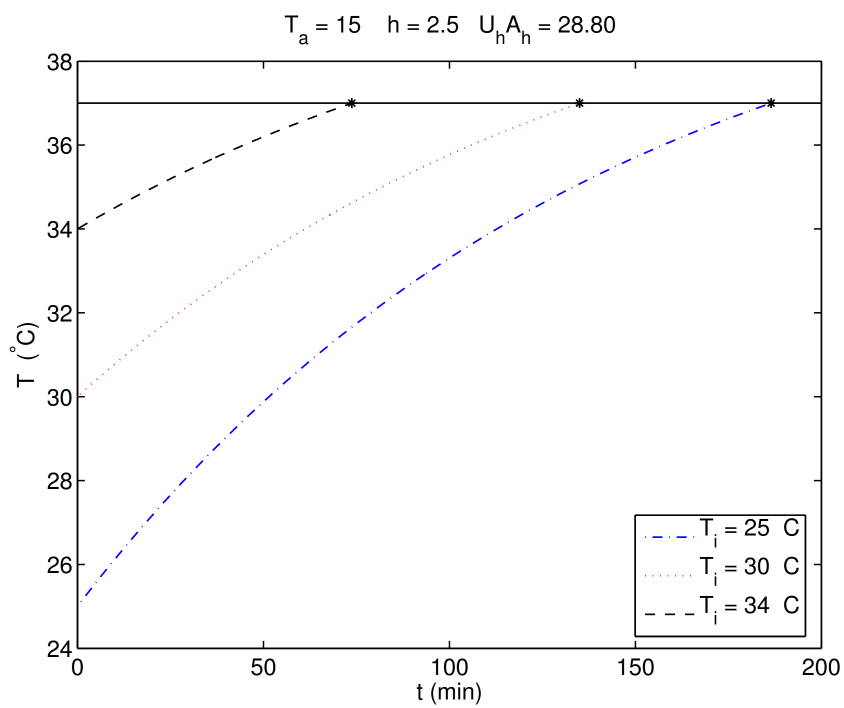
Transient rewarming response of a human as a function of conductance between heater and skin. Constant parameters: $T_a = 15\,^{\circ}\mathrm{C}$, $h = 5\,\mathrm{W}/(\mathrm{m}^2\,^{\circ}\mathrm{C})$, $A_h/A = 1/4$.

Rewarming Until Core is Restored to Normal



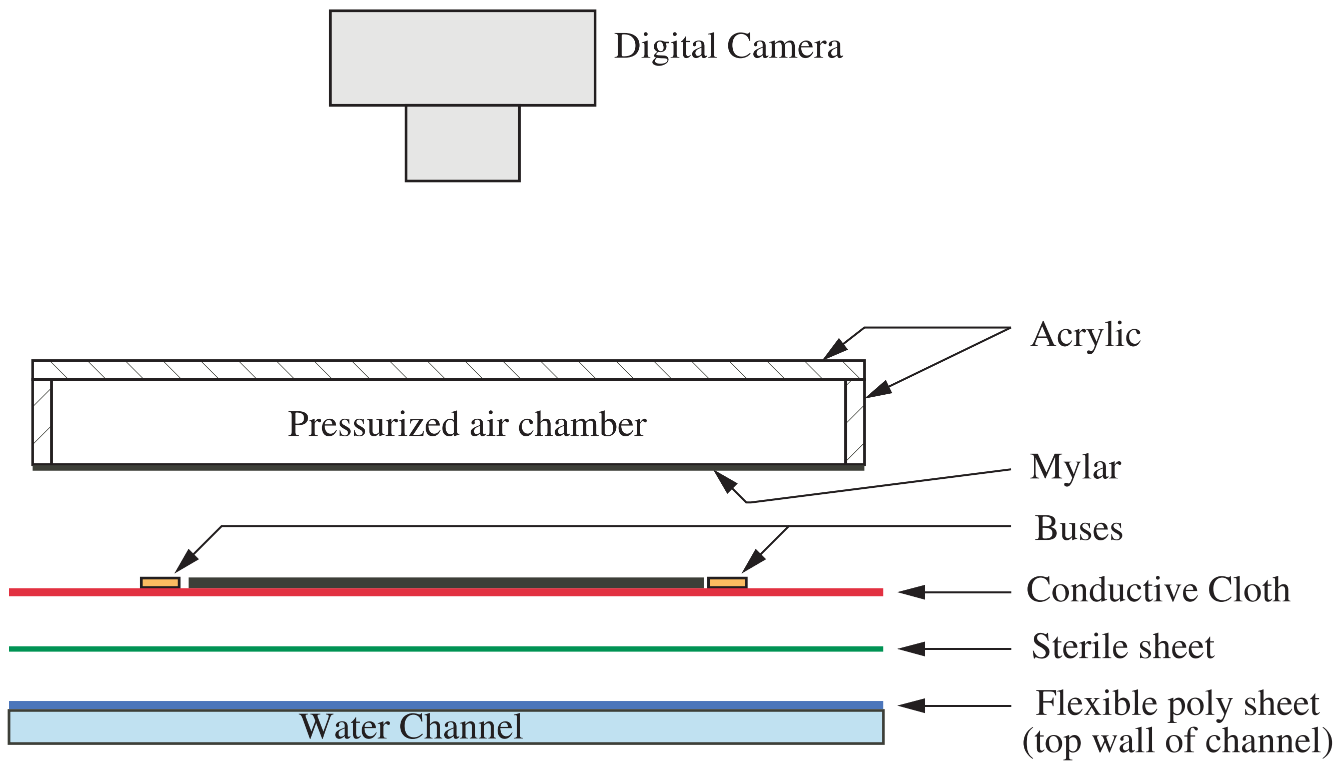
Transient rewarming response of a human as a function of conductance of the heating pad.
Constant parameters: $T_i = 30\,^\circ\mathrm{C}$, $T_a = 15\,^\circ\mathrm{C}$, $h = 2.5\,\mathrm{W}/(\mathrm{m}^2\,^\circ\mathrm{C})$.

Effect of Initial Temperature

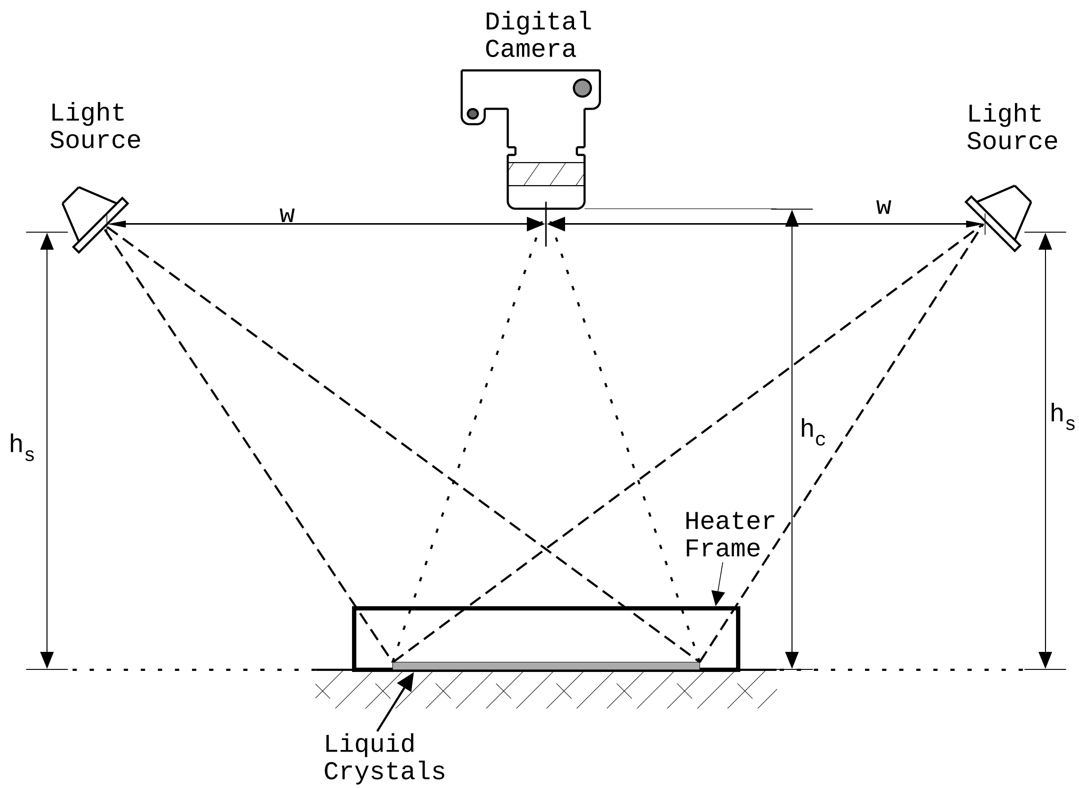


Transient rewarming response of a human as a function of initial core temperature. Constant parameters: $T_a = 15\,^\circ\mathrm{C}$, $h = 2.5\,\mathrm{W}/(\mathrm{m}^2\,^\circ\mathrm{C})$, $U_h = 64\,\mathrm{W}/(\mathrm{m}^2\,^\circ\mathrm{C})$.

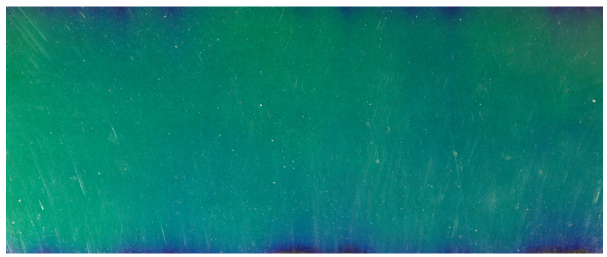
Optical Measurement with Liquid Crystal



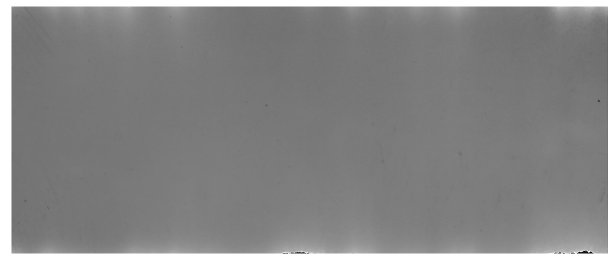
Off-axis Lighting for Optical Measurements



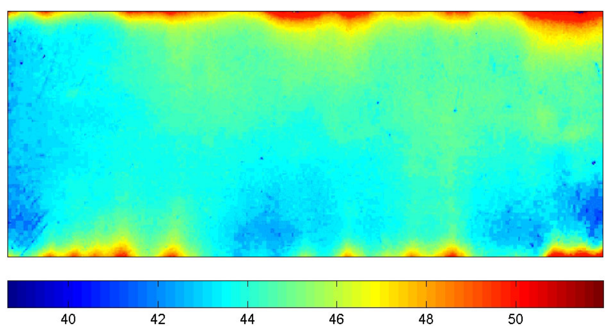
Optical Measurements of Surface Temperature



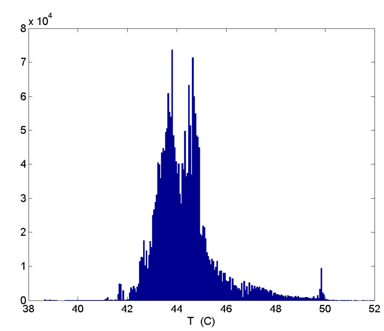
a. cropped RGB image



b. cropped hue image



c. pseudo color image



d. histogram

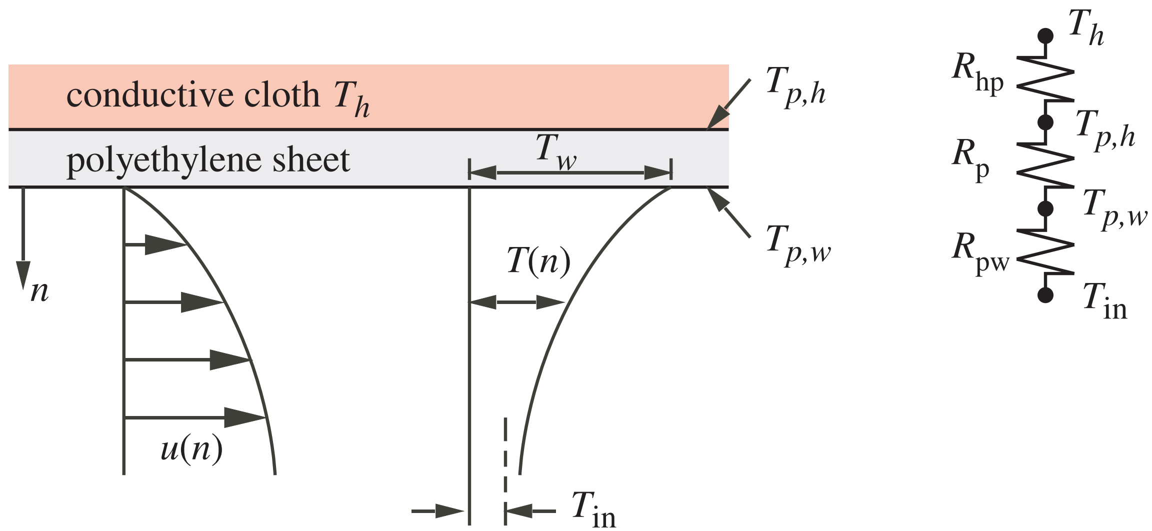
A sequence of images used to produce one data point.

Summary

- Work was not done in order presented here
- Simple model is helpful
- Need to model transient heat transfer in tissue
- Experimental data suggests that device is feasible
- Status of STTR is uncertain
- Currently Calibrating Liquid Crystal samples

Thank you

Role of Convective Resistance on Water Side



$$R_{\text{tot}} = R_{\text{hp}} + R_{\text{p}} + R_{\text{pw}}$$

Role of Convective Resistance on Water Side

The *contact conductance* is

$$U_c A = \frac{1}{R_{\mathrm{hp}}}$$

and the experiment measures

$$R_{\mathrm{tot}} = \frac{1}{UA}$$

A little algebra gives

$$U_c = \frac{U}{1 - \dfrac{U t_p}{k_p} - \dfrac{U}{h_{\mathrm{pw}}}}$$