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BYOE: Developing a Lab-Scale Heat Exchanger Containing Phase Change Material for Hands-on Learning in Heat Convection and Thermal Energy Storage

Youngmun Lee, University of Illinois Urbana-Champaign

Youngmun Lee is a Ph.D. candidate in the Department of Mechanical Science and Engineering, University of Illinois Urbana-Champaign, where he has been studying heat transfer since August 2021. Before beginning his doctoral studies, he worked at LG Electronics after receiving his M.S. and B.S. in Mechanical Engineering from Yonsei University in 2018 and 2016, respectively.

Md Habibur Rahman, University of Illinois at Urbana - Champaign
Kyle Christopher Smith, University of Illinois at Urbana - Champaign
Dr. Blake Everett Johnson, University of Illinois Urbana-Champaign

Dr. Blake Everett Johnson is a Teaching Associate Professor and instructional laboratory manager in the Department of Mechanical Science and Engineering at the University of Illinois Urbana-Champaign. His research interests include experimental fluid mechanics, measurement science, engineering education, engineering leadership, and professional identity development.

Sanjiv Sinha, University of Illinois at Urbana - Champaign

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Keywords: Heat exchanger, Heat convection, Thermal energy storage, Hands-on learning

Abstract

Thermal energy storage (TES) systems that incorporate phase-change materials (PCMs) offer significant potential for reducing carbon dioxide emissions by capturing waste heat and enabling peak-load shifting. Among the available TES configurations, the helical coiled heat exchanger is one of the most widely studied heat exchanger. Despite its straightforward geometry, its design process remains challenging due to the complex transient behavior of PCMs. To help undergraduate students understand and address these challenges, a heat-transfer laboratory session was developed featuring a lab-scale helical coiled heat exchanger containing PCM.

The apparatus consists of a helical copper coil surrounded by PCM and enclosed within a 76.2-mm-long transparent glass cylinder, enabling direct visualization of the phase-change process. Water acts as the working fluid and flows through the copper coil with its inlet temperature and flow rate controlled by a chiller. Tubes connect the test section to the chiller, and T-valves create a bypass loop used to preheat the water to achieve a 330 K inlet temperature for the heat-exchanger loop during melting. Thermocouple probes measure the inlet and outlet water temperatures as well as the PCM temperature at mid-height. A digital flowmeter records the water flow rate. Data acquisition is performed using the InstaCal interface, and a Python script running in Jupyter Notebook records time-series temperature data in CSV format.

By varying the inlet temperature and mass-flow rate, students examine the effects of temperature gradient and Reynolds number on convective heat transfer and PCM phase-change behavior. On the fluid-flow side, they evaluate the heat-transfer rate, account for heat loss to the surroundings, and analyze heat-exchanger performance and effectiveness, including pumping power at different Reynolds numbers. For the melting and freezing of PCM, both sensible and latent heat can be assessed using temperature–time curves that reveal phase-transition plateaus. Students also quantify measurement uncertainties and identify sources of error.

Through this activity, students gain early exposure to TES and PCM technologies, which are expected to play an important role in future thermal-management and energy-system applications. Additionally, the experiment provides practical insight into forced convection, natural convection, and phase-change phenomena through hands-on experience and data analysis.

Introduction

Thermal energy storage (TES) using phase change materials (PCMs) is a promising technology due to its low cost, low carbon emission, and chemical stability. Specifically, TES is useful for managing thermal load at peak time using the stored energy [1]. This peak shaving can be achieved by the latent heat of PCMs. A large amount of thermal energy is stored at nearly constant temperature with a long phase change duration, which reduces the thermal load. Because of this characteristic benefit, TES using PCM may be used in various applications such as building thermal management [2] with incorporation of a heat pump [3], electronics cooling [4], turbine efficiency improvement [5], cooling for hypersonic vehicles [6], and satellites [7]. Despite these advantages, PCMs often suffer from degradation during thermal cycling, which has been reported in salt hydrate systems [8]. In addition, their low thermal conductivity limits their practical application [9]. To overcome this drawback, various TES configurations have been investigated. In particular, helical coiled heat exchangers have been studied widely because of the compactness and better thermal performance. However, designing such a heat exchanger requires engineering insight and knowledge due to the complicated transient behavior of PCMs [10]. Therefore, this emerging technology field demands mechanical engineering expertise in heat exchangers, as well as familiarity with TES using PCMs. To address this need, a heat transfer laboratory session featuring a lab scale heat exchanger with PCM is designed for students to conduct laboratory investigations. In this paper, the development of experimental equipment and the associated operation procedures are described. The experimental setup has so far been deployed for one semester with some promising results. Based on that experience, the instructional staff has identified certain improvements to the setup to reduce experiment time during the lab session.

Learning Objectives (Pedagogy)

This activity is designed to give students foundational experience with heat exchangers and thermal-energy-storage systems. Through direct observation of the melting and freezing of the phase-change material PureTemp 27, students gain insight into PCM thermal performance. By adjusting operating conditions such as the mass flow rate of the heat-transfer fluid, students also develop an understanding of convective heat transfer and heat-exchanger behavior.

On the practical side, the activity helps students appreciate the challenges involved in constructing an experimental setup, including leak prevention and component tolerances. Additionally, students learn to record and analyze data using freely available software and Python tools. Collectively, this experience provides valuable engineering insight and practical skills that can support future coursework and professional work.

Design of Experiment

Figure 1 shows the experimental setup used for student investigations in the heat-transfer instructional laboratory. The upper schematic shows an overall water circulation through the test section and temperature measurement locations. A closed water-circulation loop was constructed to operate a heat exchanger containing the phase-change material (PCM). Wax-based materials are known to exhibit stable thermophysical behavior with small hysteresis [11]. Motivated by this characteristic, a wax-like PCM is considered in this study. The chiller (Fisherbrand™ Isotemp™, FisherScientific) circulates water through a hose and through the copper pipe embedded in the test section. For the freezing experiment, the system operates with chilled water at 5 °C, and for the melting experiment, the water temperature is set to 57 °C. Students can investigate the heat transfer rate considering heat loss to the ambient, and thermal energy storage by PCM.

The test section consists of a transparent glass cylinder for PCM visualization, the PCM, and a copper pipe (helical shape), as shown in Figure 1. Water flows through the pipe, transferring heat to or from the PCM. We expect a large heat transfer area by the helix [12], and measurable temperature change of the water through the long path of the helix. The inlet and outlet of water are on the upper side for simple installation of the system [13]. The water mass-flow rate is measured using a digital flowmeter, and temperatures are monitored using thermocouple probes connected to a data-acquisition (DAQ) device (MCC USB-TC, Digilent). Data are sampled and recorded using the free software InstaCal. Python scripts and a Jupyter Notebook are provided to allow students to record and analyze temperature data. A complete bill of materials for the laboratory activity is included in the Appendix, along with the Jupyter Notebook data-analysis code and software-installation instructions.

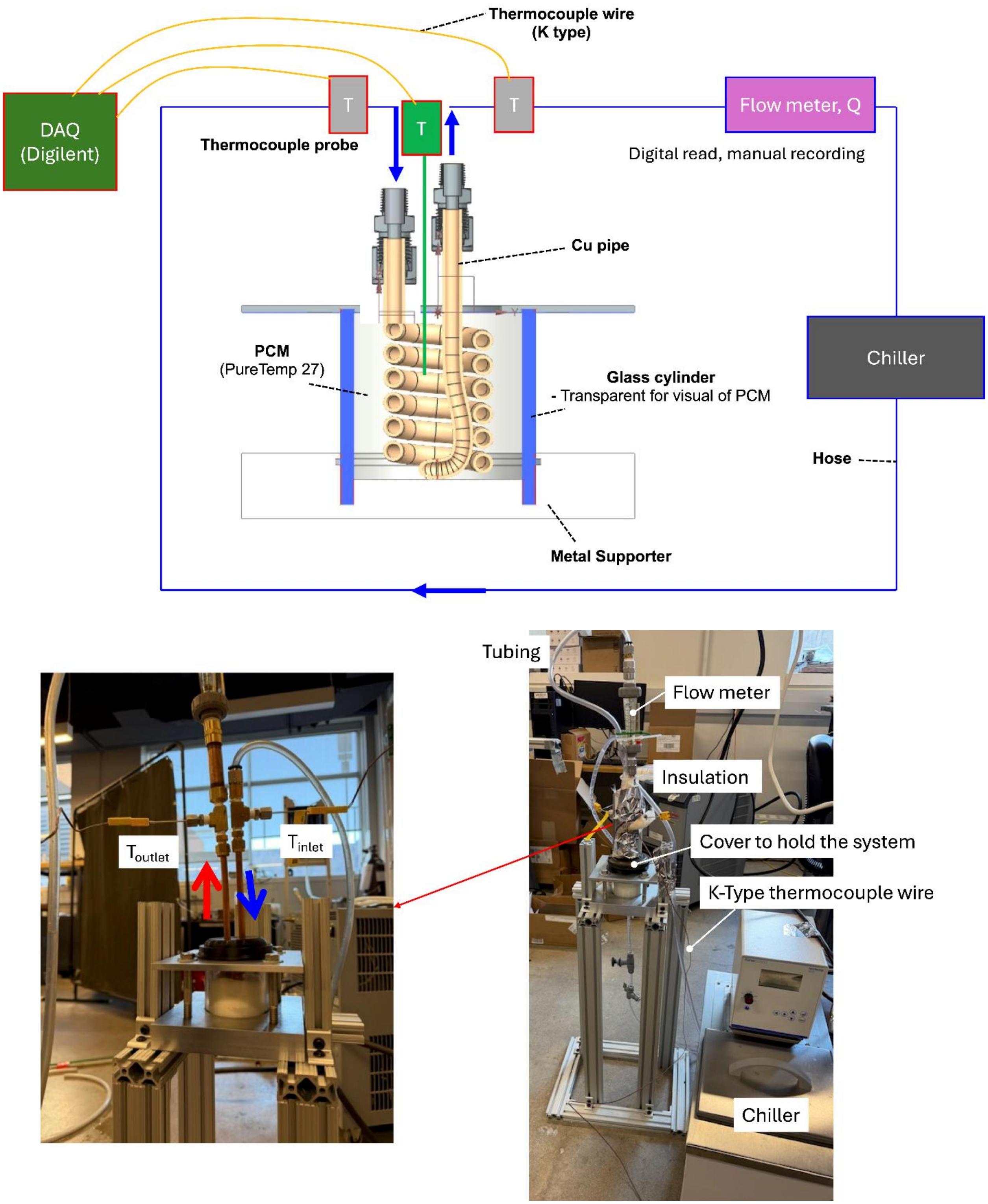

Figure 1. Experimental setup schematic (upper) and installation in the heat transfer lab (lower).

Test section

The test section consists of a 76.2-mm glass cylinder machined to length, aluminum plate with O-ring grooves, PureTemp 27 phase-change material (PCM), a helical copper pipe, a Yor-Lok fitting, a tapped aluminum plates (see Appendix), and a long bolt. Figure 2 illustrates the detailed assembly procedure. CAD drawings for the aluminum plates are provided in the Appendix. An epoxy sealant (JB Weld) was applied between the copper pipe and the bottom lid and allowed to cure for two days to ensure a complete seal. PureTemp 27 (PureTemp, LLC) was selected as the PCM because it is safe, non-toxic [14], and has been previously used in research applications [15]. Additionally, as an organic PCM, it is compatible with copper pipe, unlike some inorganic materials that may react with copper [15].

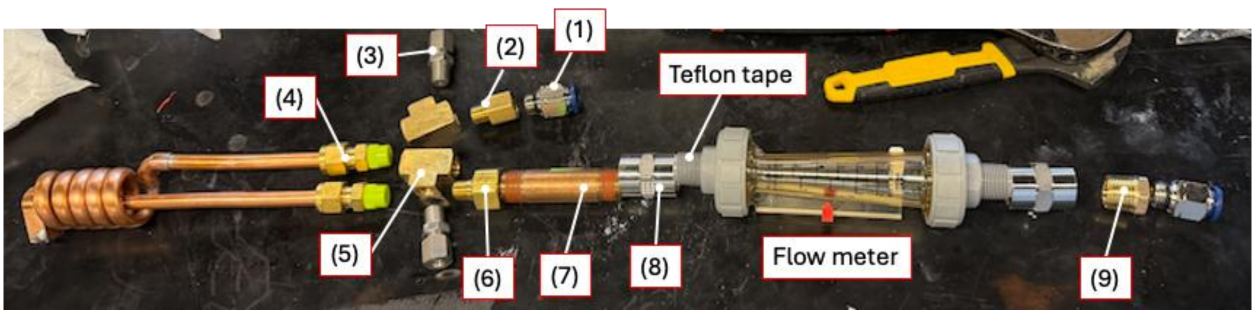

Figure 2. Assembled test section. (1) Push-to-fit tubing fitting (2) Brass Fitting Straight Reducing Adapter 1/8" Male x 1/4" Female NPT (3) RTD compression fitting (4) Yor-Lok fitting (5) Brass Fittings Tee Connector 1/8" NPT Female (6) Brass Fitting Straight Reducing Adapter 1/8 Male x 3/8" Female (7) Nipple BRASS PIPE, 3/8 X 2 1/2 (8) Straight Connector, 3/8 NPT Female (9) Brass Bushing Straight Reducing Adapter with Hex Body 3/8 Male x 1/4 Female. The teflon tape is applied.

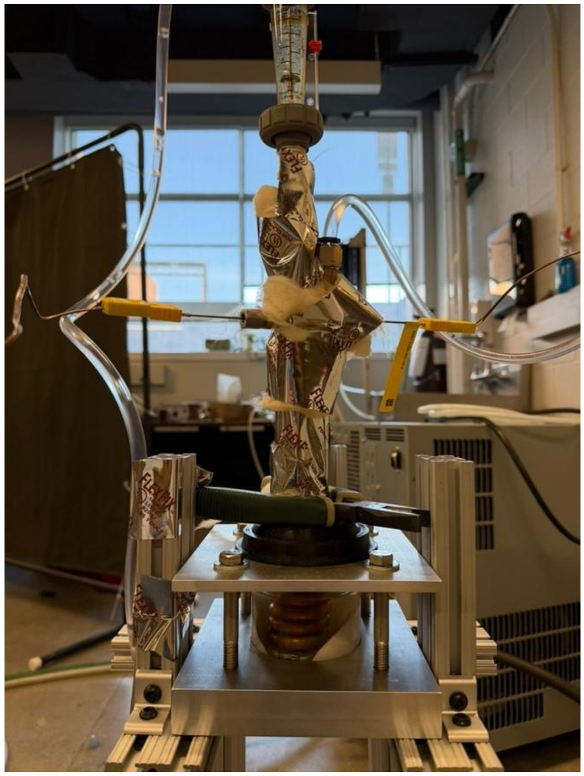

Figure 3. Heat exchanger composition. The glass cylinder (76.2 mm) is transparent for visualization of the melting and freezing of PCM. The aluminum disc is fabricated with the grooves for the O-ring. The 3D-printed upper cover has a small hole for the thermocouple probe at the center to measure the PCM temperature. The aluminum plates should be fabricated with holes and taps for fastening each other by using Mil. Spec. Hex Head Screw.

Table 1. Thermal properties of PureTemp 27 [16].

Property	**Value**	**Unit**
Melting point	27	°C
Heat storage capacity	202	$J\ g^{-1}$
Thermal conductivity (liquid/solid)	0.15/0.25	$W\ m^{-1}\ K^{-1}$
Density (liquid/solid)	860/950	$kg\ m^{-3}$
Specific heat (liquid/solid)	2630/2460	$J\ kg^{-1}\ K^{-1}$
Viscosity* (at 50 °C)	5–6	cP

*Viscosity is obtained through private communication with the supplier.

Once all parts are ready to be assembled, PureTemp 27 should be heated in an oven (about 50 °C) for a liquid phase sample preparation. Then, it is taken out of the oven and poured into the beaker at first to measure the volume of PCM (~ 160 ml). We pour the PCM into test section slowly. To ensure perfect sealing, aluminum plates are placed on the top and bottom of the glass cylinder. The hex head screw is used to secure the test section. Figure 3 shows the test section filled with PureTemp 27. We expect the students will calculate the mass of PureTemp 27 using the density of liquid phase as described in Table 1. Table 1 presents the thermal properties of PureTemp 27. Properties of other materials are not included; instead, students are encouraged to research the relevant properties of aluminum, copper, and water and incorporate them into their analyses. This approach is intended to help students develop an understanding of how thermal properties vary across different classes of materials.

Flow circulation loop

As shown in Figure 4, the flowmeter connects to a hose that attaches to the outlet straight pipe of the helical copper coil. Yor-Lok fittings are used to join the threaded T-connector to the copper pipe. An RTD compression fitting is installed at the center port of the T-connector to accommodate a thermocouple probe. The assembled test section is positioned on a jig constructed from aluminum T-slotted framing. The T-shaped valves (PVC Push-to-Connect Diverting Valve, McMaster, 3/8" OD) must also be connected to a separate loop for preheating, using the additional hose shown in Figure 5. During preheating, the chiller circulates fluid exclusively through this auxiliary loop, allowing the system to deliver a sudden increase in water temperature to the main test loop when needed.

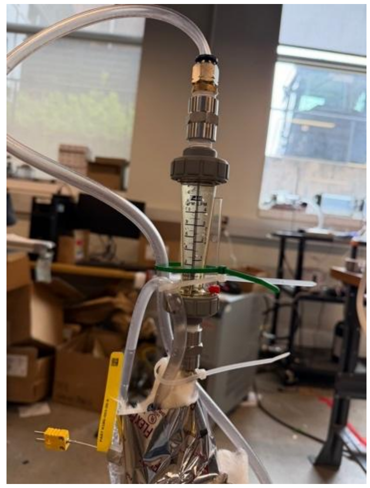

Figure 4. The flowmeter is connected using fittings sealed with Teflon tape. The flowmeter that is used to measure the flow of water through the helical copper coil. Water flows upward through the flowmeter, and flow rate should be read at the bottom plate location.

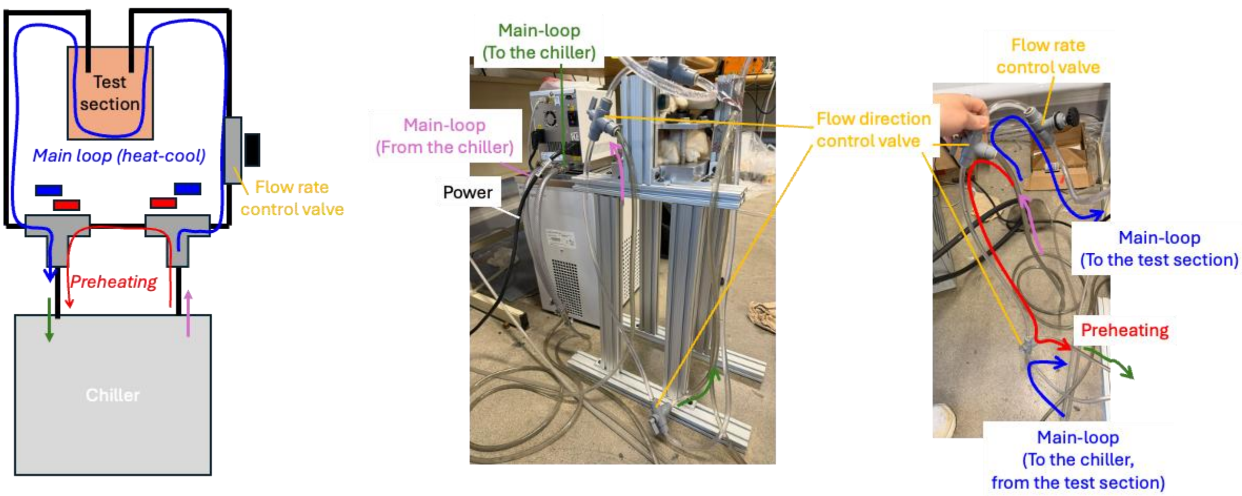

Figure 5. PVC Push-to-Connect Diverting Valve (McMaster, 3/8" OD) for flow direction control (middle) and Precision Flow-Adjustment Valve (McMaster, Push-to-Connect Fittings for 3/8" Tube OD, PVC) for flow rate control (needle valve – right image). The flow direction control valves are used to run the preheating loop and main loop. The valve should be turned completely when it changes the flow direction. The needle valve adjusts the flow rate by rotating. About 0.2 GPM (or lower) of water flow rate is recommended.

Data Acquisition

The DAQ is connected to the computer using the provided cable. The thermocouple probe and wires are attached to the DAQ by exposing the wire ends and inserting them into the designated terminals (see instructional video: https://youtu.be/2uzO0qwb2Ac?si=VHI6os1YaVeuwTS9). After all probes are connected, temperature data are recorded using Jupyter Notebook. Additional details on the data acquisition process are provided in the Appendix. Figure 6 shows preliminary temperature measurements obtained from the experimental setup using Python. Figure 7 illustrates the melting and freezing of PureTemp 27 for time.

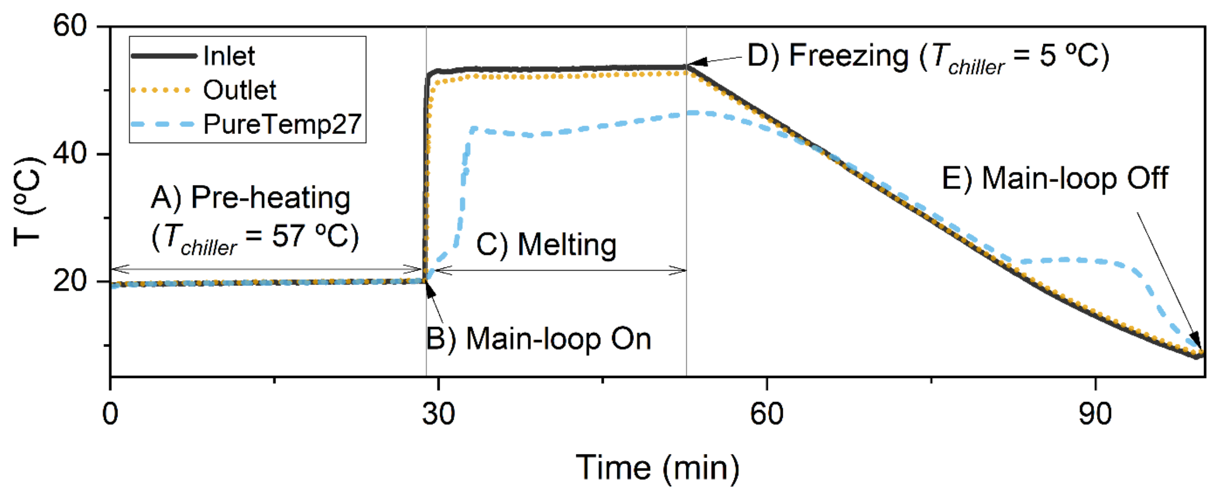

Figure 6. Temperature measurement data using Python code. A) is pre-heating period, taking around 30 mins. B) is starting point of melting by turning on the main-loop adjusting the valves. C) is melting period. D) is starting point of freezing by change the chiller temperature. E) is restoring the system to pre-heating phase by turning off the valves and changing the chiller temperature to 57 °C

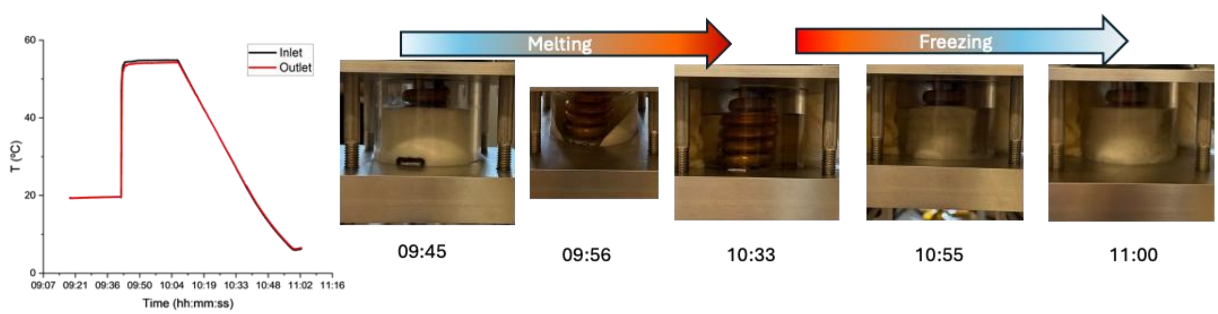

Figure 7. Melting and freezing of PureTemp 27 for time.

Operation Procedure

1) Verify that all connections are correctly installed and supply power to the chiller (while keeping the chiller turned off).
2) Check the water level of the chiller.
3) Launch the Jupyter Notebook to begin recording temperature data (detailed data-acquisition instructions are provided in the Appendix).
4) Adjust the main valves of the chiller to initiate preheating. Preheating uses only the auxiliary subloop, and no water flows through the main test loop, as shown in Figure 5. Preheating requires approximately 30 minutes.
5) Turn on the chiller and set its temperature to 57 °C for preheating. Note that the maximum temperature is 57 °C, considering PVC parts.
6) Once the chiller water reaches the set point, adjust the main valves to direct hot water to the test section. Laminar flow is recommended to achieve a clear temperature transition in the heat exchanger. Due to the short pipe length (about 640 mm), turbulent flow makes it difficult for students to determine the heat-transfer rate accurately.
7) Verify that the flowmeter is operating within the appropriate range by controlling the needle valve as illustrated in Figure 8.
8) Temperature readings can be monitored using the InstaCal software, as illustrated in Figure 6.
9) After melting is complete (indicated by the sample becoming transparent partially), reduce the chiller set temperature to 5 °C to begin the freezing process.

Figure 8. Valve control for laminar flow.

Data Analysis

From the temperature-time data shown in Figure 6, students can evaluate the energy storage by using the energy balance. The heat transfer rate is computed using the following equation.

$$\dot{Q} = \dot{m}_w C_{p,w}(T_{in} - T_{out}) \tag{1}$$

where t, $\dot{Q}$, $\dot{m}$, C_p, and T are time, heat transfer rate, mass flow rate, specific heat, and temperature, respectively. The subscript *w*, *in*, and *out* are the water, inlet, and outlet of the pipe, respectively. From Eq. (1), the time-dependent heat-transfer rate is plotted in Figure 9.

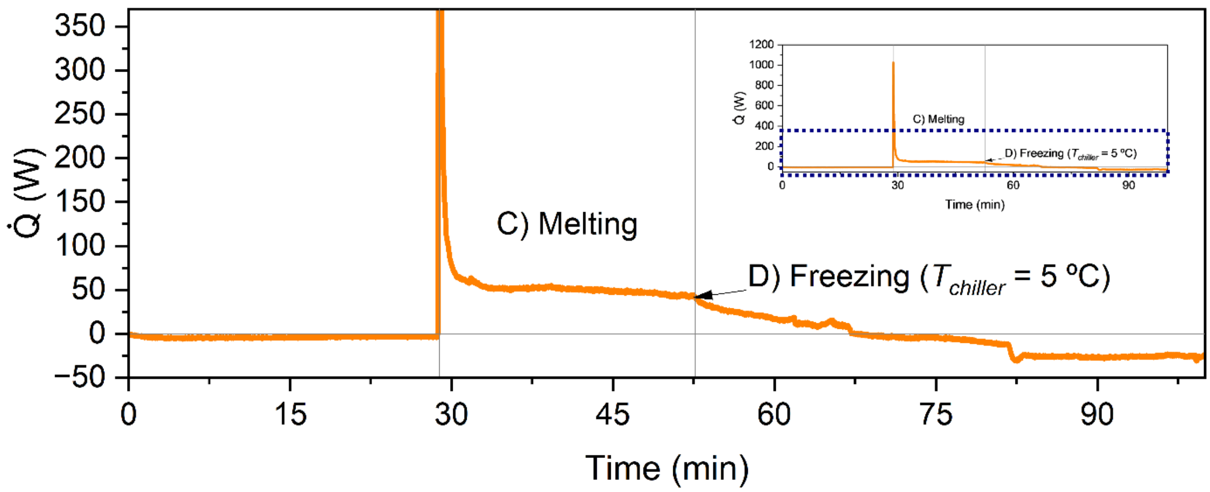

Figure 9. Preliminary data analysis. The heat transfer rate is computed by using Eq. (2).

When the main loop begins operating, a large heat-transfer peak appears due to the sudden temperature change and the substantial temperature difference between the pipe inlet and outlet. The heat-transfer rate then rapidly stabilizes. The area under the curve represents the total heat transferred from the water, which can be computed using Eq. (2).

$$\int_{t_{ini\,(main\,loop)}}^{t_{final}} \dot{Q}\,dt = \int_{t_{ini\,(main\,loop)}}^{t_{final}} \dot{m}_w C_{p,w}(T_{in} - T_{out})\,dt \tag{2}$$

The subscript *ini (main loop)*, and *final* are the initial step when the main loop begins to run, the final step when the experiment is done, respectively. A trapezoidal numerical method is used to evaluate this area. Students can then check the total amount of thermal energy stored in PCM, which is the sum of sensible heat and latent heat during heating process.

$$\begin{aligned} Energy\ stored &= Sensible\ heat + Latent\ heat \\ &= mC_{p,solid}(T_m - T_{initial}) + mC_{p,liquid}(T_{final} - T_m) + mL \end{aligned} \tag{3}$$

where *m,* and *L* are the mass and latent heat of the PCM, respectively. The mass of PCM is determined by $m=\rho_{PCM}V_{PCM}$, where ρ_{PCM} is density of PCM and V_{PCM} is volume of PCM. According to the energy balance, the heat transfer rate between the water and the PCM must equal the sum of the energy stored in the PCM, the energy absorbed by other components (such as the copper pipe, aluminum plate, and glass cylinder), and the energy lost to the surrounding air. The energy balance explains why the total heat transferred from the water to the test section is greater than the energy stored solely in the PCM as calculated from Eq. (3). Insufficient insulation contributes to heat loss and affects the thermal-energy-storage performance. This activity is intended to help students recognize the importance of proper insulation in thermal systems.

Conclusion

Students examined the heat exchanger and thermal energy storage system through the experimental setup and data acquisition code. They submitted engineering letter-style reports with phase transition images and data analysis results. Initially, we designed the straight copper pipe located in the polycarbonate tube. We found that cracks on the polycarbonate tube happened and grew. We suspected the chemical reaction between the polycarbonate and PureTemp 27, and this led us to replace the polycarbonate to glass cylinder for reliable usage. Also, we collected feedback throughout the semester by the University web service for evaluation. The primary concern was the long melting and freezing periods, and students often lacked sufficient time to complete the experiment and perform data analysis within the two-hour laboratory session. This led us to redesign the setup using the helical copper pipe for shortening the experiment time. By improving the design using the glass cylinder and helical coil, we have achieved safe setup that does not react with PCM and reduce the experiment time less than 110 minutes. Through this setup, we observe the students analyze the heat transfer rate, and suggest the total heat loss by the lack of insulation. We expect the students can explore the effect of water flow rate in phase change and thermal energy storage for future work.

Acknowledgment

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Appendix

CAD drawing for the aluminum plates

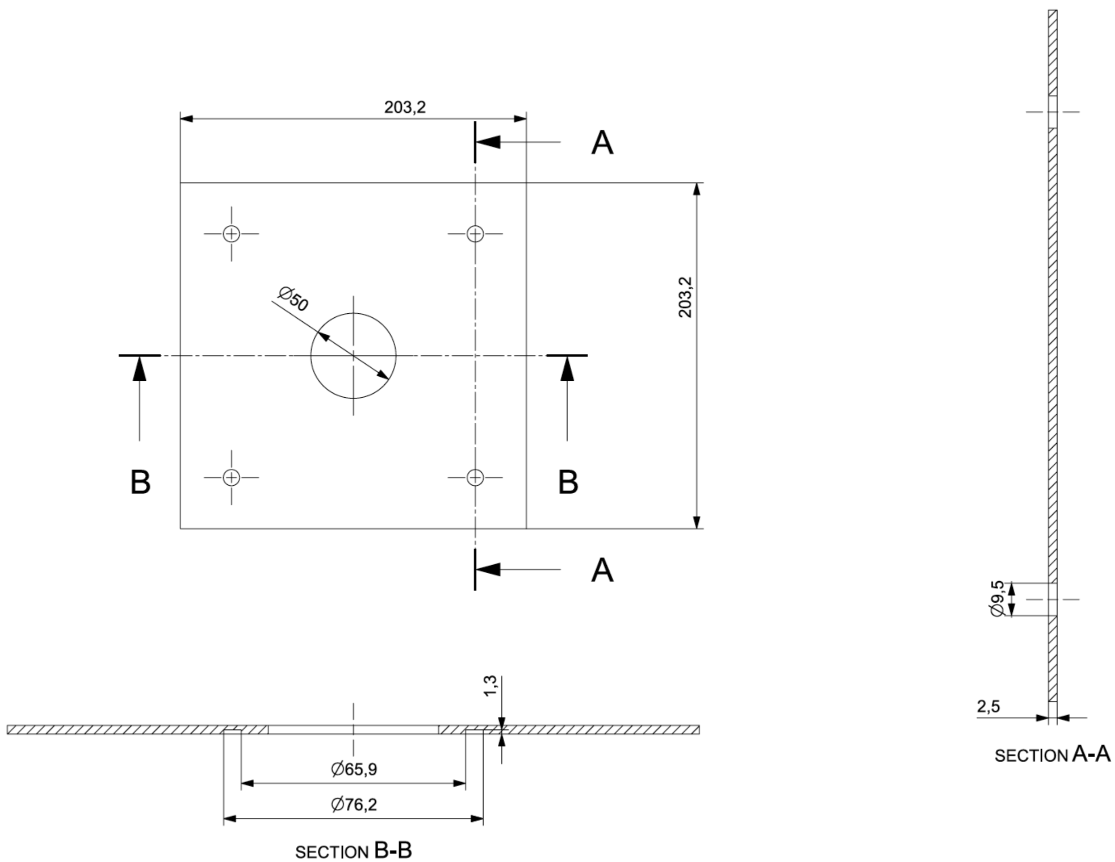

Figure A1. Aluminum plate for upper side of the glass cylinder. drawing with the hole for the thermocouple probe (1/16" diameter). The grooves for O-rings should be carefully fabricated. This drawing does not include significant tolerance.

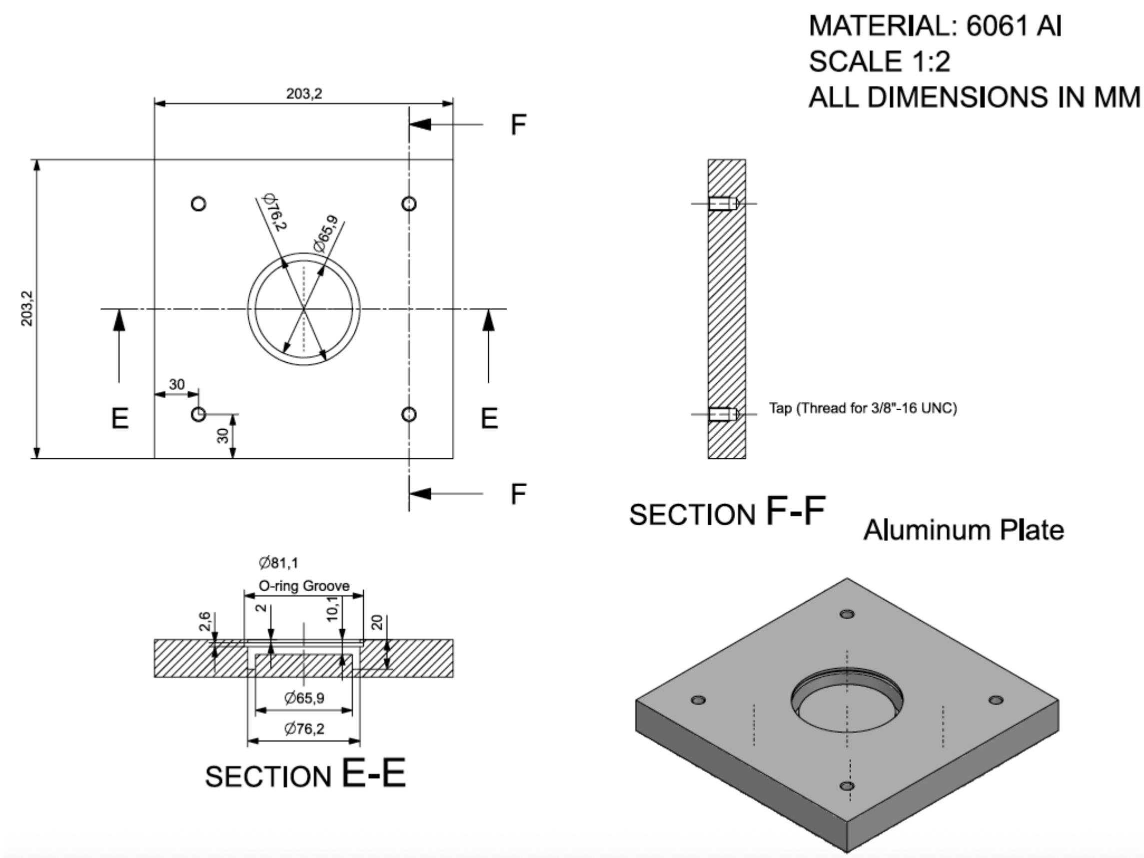

Figure A2. Aluminum plate drawing with the tap. One plate can have only hole for the long black bolt.

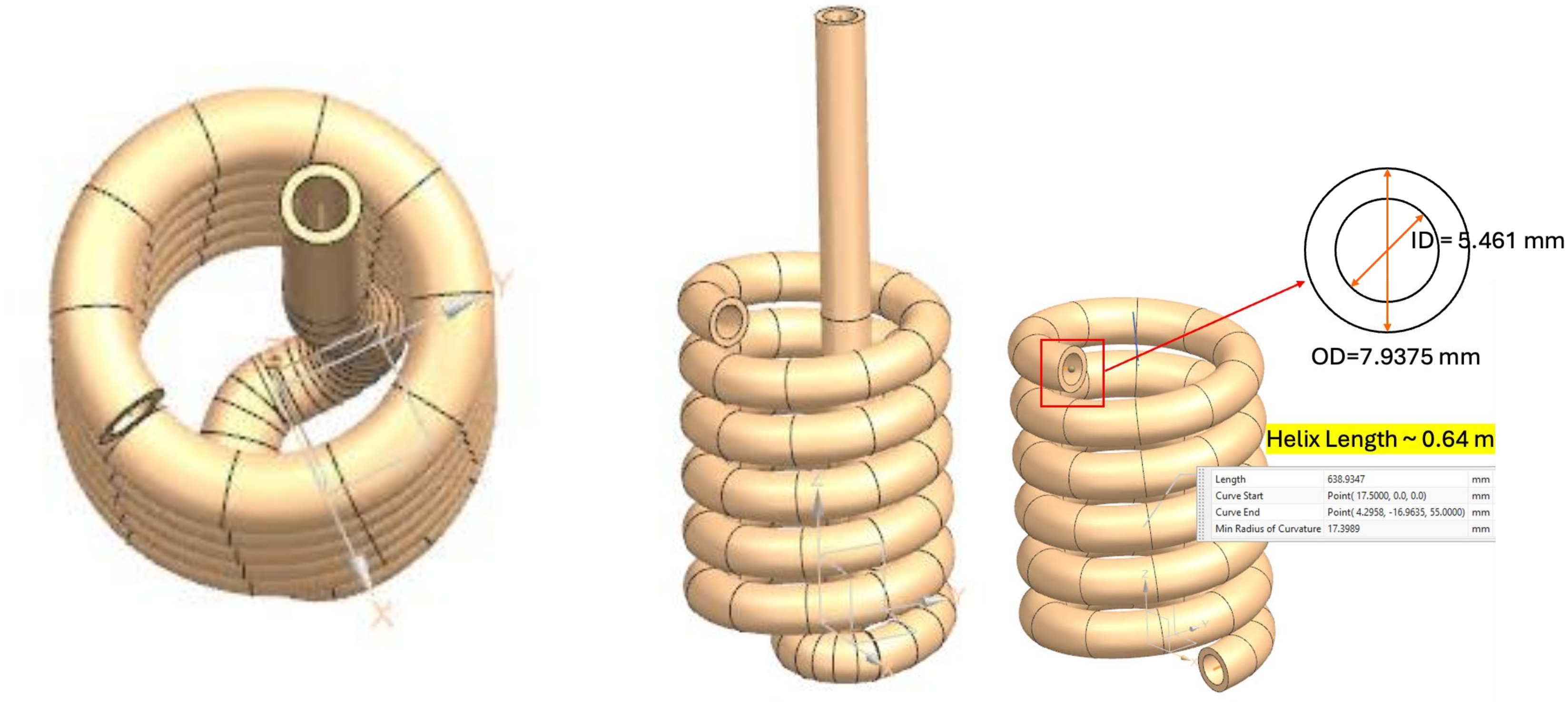

Figure A3. Helical coil drawing. Top view (left), front view (middle), and the cross section of the coil (right) of the helix. The helix information is following: IDcoil = 5.461 mm (0.215”), OD_{coil} = 7.9375 mm (5/16”), Diameter of helix = 35 mm, Pitch = 9.5 mm, Height of helix = 55 mm (~ 5.7 turns). The straight pipes are attached and brazed. Helix is created by mandril fabricated by 3D printing. The fabrication is done in University of Illinois Urbana-Champaign Aerospace Engineering Machine-Shop.

Bill of Materials

Table A1. List of major equipment for one setup.

Equipment	Company	Model #	Cost, $	Link
Chiller	FisherScientific	Fisherbrand™ Isotemp™	3300	https://www.fishersci.com/shop/products/fisher-scientific-isotemp-refrigerated-heated-bath-circulators-6-8-8-6l-115v-60hz-6/13874676?searchHijack=true&searchTerm=fisher-scientific-isotemp-refrigerated-heated-bath-circulators-6-8-8-6l-115v-60hz-6&searchType=Rapid&matchedCatNo=13874676
DAQ	Digilent	USB-TC	419	https://digilent.com/shop/mcc-usb-temp-and-tc-series-temperature-and-voltage-measurement-usb-daq-devices/?srsltid=AfmBOoq2EOFbCH2l1a5iqsCbKjlPQjXVbKVSlTPPAMsUhim9VBF8N2RQ
High-Temperature Flowmeter	McMaster	Polysulfone Fittings, 3/8 NPT Male	148.85	https://www.mcmaster.com/4400K67/
Thermocouple probe (3 EA)	McMaster	Type K	140.4	https://www.mcmaster.com/3871k493/
Thermocouple	Digikey	Type K, 1286-6069-240-003-ND	31	https://www.digikey.com/en/products/detail/digilent-inc/6069-240-003/18154811?utm_source=oemsecrets&utm_medium=aggregator&utm_campaign=buynow
Copper pipe	McMaster	5/16" OD, 0.049" Wall Thickness, Coil, 10 ft	59.18	https://www.mcmaster.com/8955K241/

PVC Push-to-Connect Diverting Valve (2 EA)	McMaster	3/8” OD	58.6	https://www.mcmaster.com/4757K62/
Precision Flow-Adjustment Valve	McMaster	Push-to-Connect Fittings for 3/8" Tube OD, PVC	31.67	https://www.mcmaster.com/7781K42/
Pressure-Rated Borosilicate Glass tube	McMaster	3" OD, 2-19/32" ID, 3" Long	44.89	https://www.mcmaster.com/1176K27/
Chemical-Resistant Viton® Fluoroelastomer O-Ring (4 EA)	McMaster	X-Profile, 3/32 Fractional Width, Dash Number 151	16.16	https://www.mcmaster.com/6540K244/
RTD compression fitting (2 EA)	McMaster	1/16" Probe OD x 3/8 NPT Male	52.1	https://www.mcmaster.com/1695N107/
Yor-Lok fitting for copper pipe (2 EA)	McMaster	Straight Adapter for 5/16" Tube OD x 1/8 NPT Male	18.86	https://www.mcmaster.com/5272K311/
Precision Extreme-Pressure 316 Stainless Steel Fitting (2 EA)	McMaster	Straight Connector, 3/8 NPT Female	56.12	https://www.mcmaster.com/48805K73/
Mil. Spec. Hex Head Screw (4 EA)	McMaster	Made in U.S., 18-8 Stainless Steel, 3/8"-16 Part Thread, 3" Long	15.68	https://www.mcmaster.com/92245A639/
Aluminum plate (thin)	McMaster	6 x 6” plate (t=0.25”)	11.72	https://www.mcmaster.com/89155K11/
Aluminum plate (thick)	McMaster	6 x 6” plate (t=1”)	37.19	https://www.mcmaster.com/89155K971/
T-Slotted Framing (Various ft)	McMaster	Double Six Slot Rail, Silver, 2" High x 1" Wide, Solid	232.58	https://www.mcmaster.com/catalog/132/2241/47065T107

T-Slotted Bracket (24 EA)	McMaster	Silver Corner Bracket, 1" Long for 1" High Rail T-Slotted Framing	190.08	https://www.mcmaster.com/47065T236/
T-Slotted Framing Bracket (24 EA)	McMaster	Silver Straight Surface Bracket, 2" Long for 1" High Rail	221.52	https://www.mcmaster.com/47065T255/
Brass Bushing Straight Reducing Adapter with Hex Body		3/8 Male x 1/4 Female	1.99	University of Illinois Urbana Champaign, MRL Store Room
Brass Fitting Straight Reducing Adapter		1/8 Male x 3/8" Female	6.58	University of Illinois Urbana Champaign, MRL Store Room
Brass Fittings Tee Connector (2 EA)		1/8" NPT Female	10.96	University of Illinois Urbana Champaign, MRL Store Room
Brass Fitting Straight Reducing Adapter (2 EA)		1/8" Male x 1/4" Female NPT	5.52	University of Illinois Urbana Champaign, MRL Store Room
Nipple BRASS PIPE		3/8 X 2 1/2	7.58	University of Illinois Urbana Champaign, MRL Store Room
Test Section Fabrication		Helical Coil Customization, brazing, Aluminum plate fabrication	1000	University of Illinois Urbana Champaign, Aerospace Engineering Machine Shop
Total			**6118.23**	

DAQ (Digilent USB-TC) software below is only available on Windows OS. The Python code is also only available on Windows OS. InstaCal is free software that is compatible with Digilent DAQ. Here is the link for download,

https://digilent.com/reference/software/instacal/start?srsltid=AfmBOorMdOWYu3YSn8uu3RMWu-2l35_iVEW-Td8h1iNG55Mf6lduschR

Once we open InstaCal, we can connect the Digilent DAQ as shown in Figure A4. To check if DAQ and thermocouple probes measure the temperature correctly, we follow some steps.

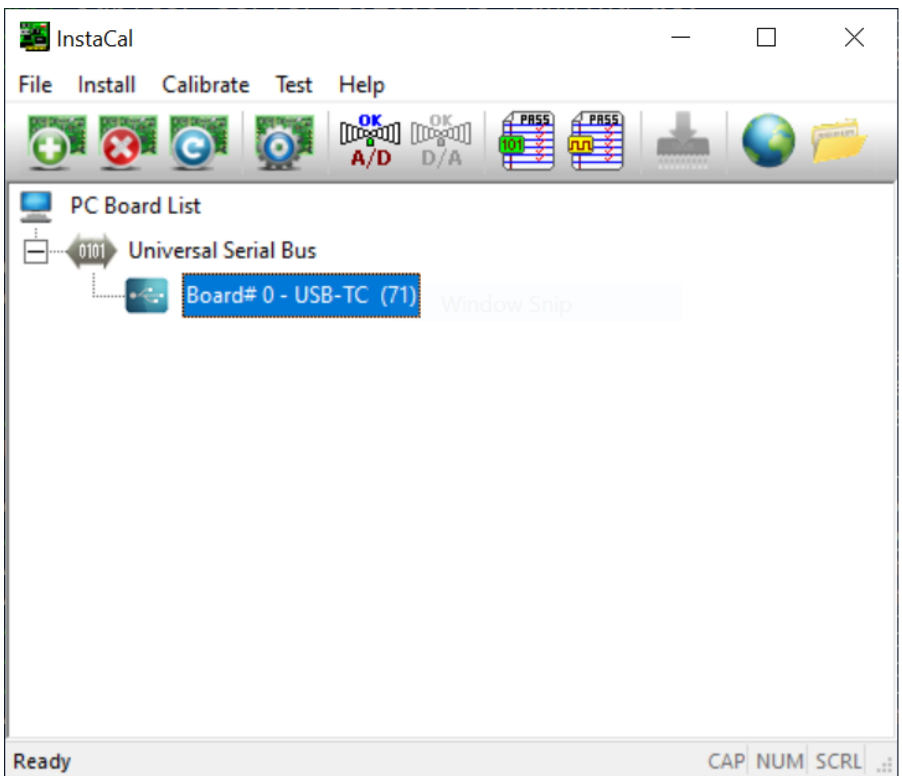

Figure A4. InstaCal interface shows the serial connection with USB-TC. The board number in this case is 0 (Board# 0). This board number should be used in the Python code otherwise the code cannot read the InstaCal signal.

1) Check the type of the thermocouple. Here, a K-type thermocouple is used (see Figure A5).

2) Check if the connection is properly done. There is a board test. If there is connection issue, then we will see wrong value such as -9999.000000. For example, Channel 1,2, and 3 are water inlet, PCM, and water outlet temperature measurement, respectively (see Figure A6).

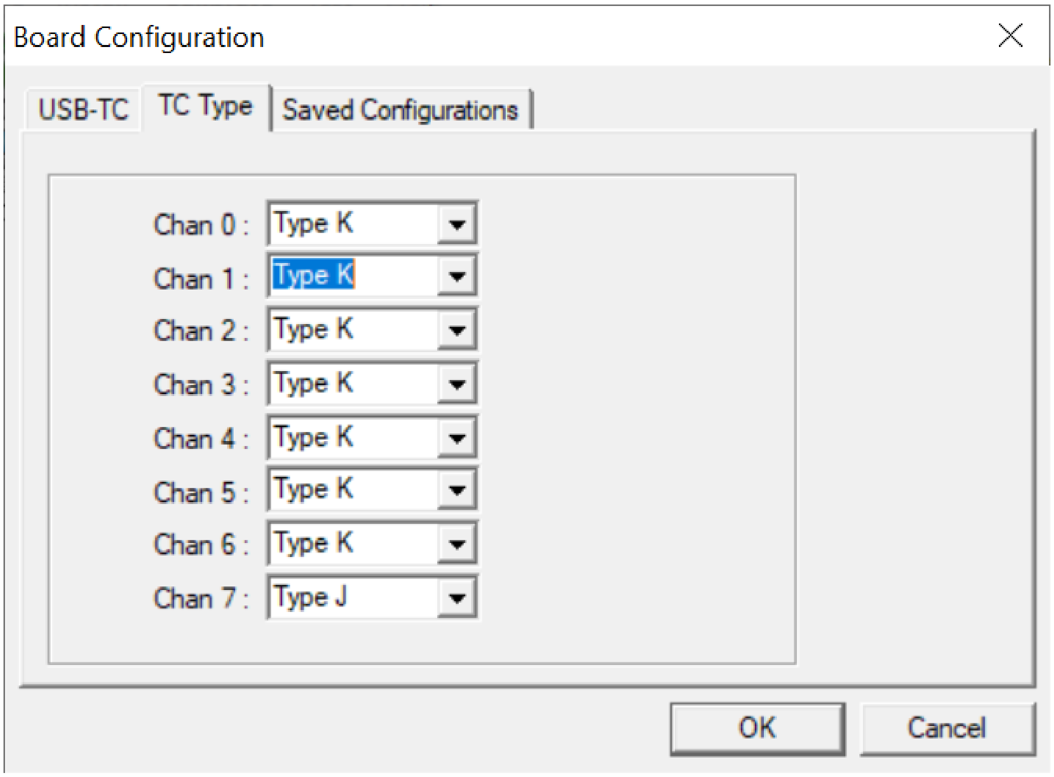

Figure A5. The TC type should be adjusted properly according to the thermocouple probe types that students use.

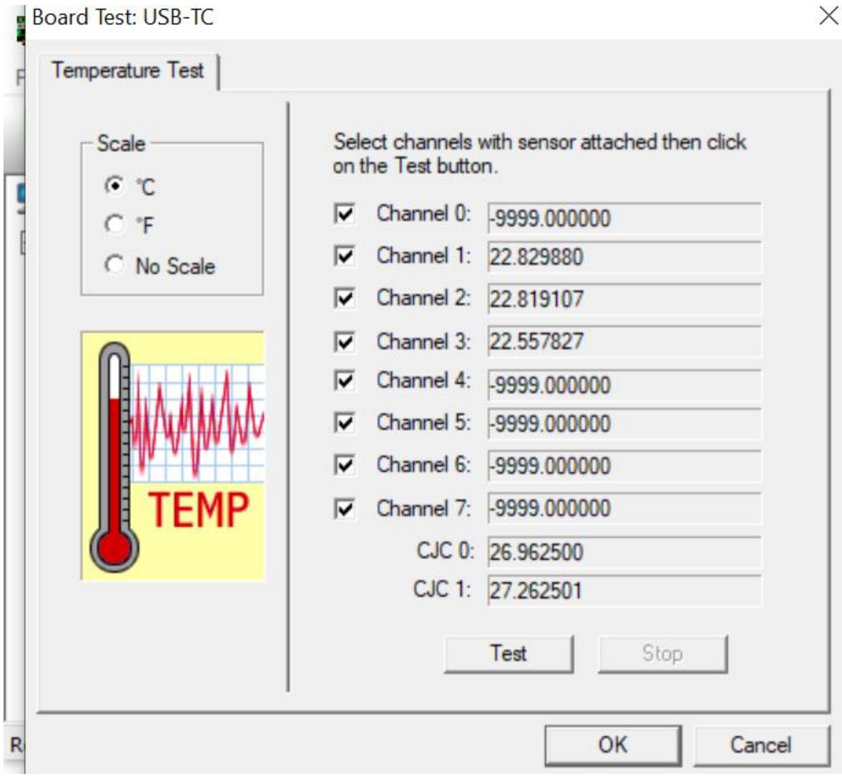

Figure A6. Once the thermocouple probe is connected to the DAQ and check the board number, students should check if InstaCal read the temperature data properly at assigned channel. Here, channels 1,2, and 3 are used. Thus, channels 0 and 4–7 show incorrect values.

Now, Python should be installed with libraries (https://www.python.org/downloads/). Then, Jupyter Notebook should be installed by following procedure.

1) Open CMD or PowerWell as Admin, and install Jupyter Notebook typing,

   pip install notebook

2) Then, run the software typing

   jupyter notebook

or

   python -m notebook

3) Now, we should have a library for MCC and here is the code to upgrade pip. Please type this code in CMD.

```
pip install --upgrade pip
```

4) Then, install the library for MCC

```
pip install mcculw
```

5) Now, use mcculw library and check the InstaCal

Data Acquisition Code in Jupyter Notebook

```
######### DAQ Reading from InstaCal and Temperature Logging with Python #########
### Author: Kubra Asena Gelisli
### Convertered to Jupyter Notebook and modified by Youngmun Lee
### Version Update by Youngmun Lee (March. 27. 2026)
### This code is developed for Heat Transfer Lab instrumentation
### Record temperature readings from thermocouples (type K)
### MCC USB-TC DAQ device configured via InstaCal.
###
### Read Me:
### Do NOT open the output CSV file in Excel while the script is running.
### Excel locks the file and will cause the script to crash during write attempts.
### To monitor the data safely during logging:
###    • Use Notepad++ or VSCode (non-blocking viewers)
###    • OR view a copied version of the CSV file

# --- Libraries ---

from mcculw import ul
from mcculw.enums import TempScale
import matplotlib.pyplot as plt
import matplotlib.animation as animation
from matplotlib.ticker import MultipleLocator
from datetime import datetime
import time, csv, os
import numpy as np

# --- Jupyter backend (widget) ---
%matplotlib widget

# --- Experiment settings ---
EXPERIMENT_NAME = "Testing local" # Put your session and group name, e.g.
ABA_Group1
timestamp = datetime.now().strftime("%Y%m%d_%H%M%S")

# --- Output CSV file ---
output_file = f"{EXPERIMENT_NAME}_temp_log_{timestamp}.csv"

# --- Config ---
board_num = 0
channels = list(range(3))  # List of channels to read. For PCM TES Lab, we use only three
channels!
interval_sec = 1           # Logging interval in seconds
total_duration_sec = None  # Set total duration or leave None for indefinite
```

```
# --- Storage ---
time_data = []
elapsed_time_data = []
temp_data = [[] for _ in channels]

# --- CSV setup (open once) ---
csv_file = open(output_file, 'w', newline='')
writer = csv.writer(csv_file)
header = ['Time', 'Elapsed_sec'] + [f'CH{i}_Temp(C)' for i in channels]
writer.writerow(header)

# --- Matplotlib plot setup ---
fig, ax = plt.subplots(figsize=(9, 5))
lines = []
color_list = plt.rcParams['axes.prop_cycle'].by_key()['color']

for i, ch in enumerate(channels):
    (line,) = ax.plot([], [], label=f'T{ch}', color=color_list[i % len(color_list)])
    lines.append(line)

ax.set_xlabel("Elapsed Time (sec)")
ax.set_ylabel("Temperature (°C)")
ax.set_title(f"Real-Time Temperature Monitoring — {EXPERIMENT_NAME}")
ax.legend(loc='upper left', bbox_to_anchor=(1.02, 1), borderaxespad=0)

temp_text = ax.text(
    1.02, 0.75, '', transform=ax.transAxes,
    fontsize=10, verticalalignment='top',
    bbox=dict(boxstyle='round', facecolor='white', alpha=0.7)
)
plt.subplots_adjust(right=0.75)
#plt.tight_layout()

# --- Initial x-axis locator ---
ax.xaxis.set_major_locator(MultipleLocator(60))  # Show initial tick every 1 minute

# --- Start time ---
start_time = time.time()

# --- Main update function for animation ---
def update_plot(frame):
    current_time = time.time()
    elapsed_time = round(current_time - start_time, 2)

    # Stop condition
```

```
if total_duration_sec and elapsed_time > total_duration_sec:
    print("Logging complete.")
    ani.event_source.stop()
    csv_file.close()
    return

timestamp_now = datetime.now().strftime("%H:%M:%S")
time_data.append(timestamp_now)
elapsed_time_data.append(elapsed_time)

temps = []
for ch_index, ch in enumerate(channels):
    try:
        temp = ul.t_in(board_num, ch, TempScale.CELSIUS)
    except:
        temp = float('nan')
    temps.append(temp)
    temp_data[ch_index].append(temp)
temp_strings = [
f"T{ch}: {temps[i]:.2f} °C" if not np.isnan(temps[i]) else f"T{ch}: NaN"
for i, ch in enumerate(channels)
]
temp_text.set_text("\n".join(temp_strings))
# --- CSV writing ---
writer.writerow([timestamp_now, elapsed_time] + temps)
csv_file.flush()

# --- Update plot lines ---
for i, line in enumerate(lines):
    line.set_data(elapsed_time_data, temp_data[i])

# --- Autoscale y-axis, x-axis grows with elapsed time ---
ax.relim()
ax.autoscale_view(scalex=False, scaley=True)
ax.set_xlim(0, max(elapsed_time + 10, 60))  # Expand x-axis gradually

# --- Dynamic x-axis tick interval based on elapsed time ---
if elapsed_time < 20 * 60:          # 0 - 20 minutes
    tick_interval = 60              # 1-minute ticks
elif elapsed_time < 60 * 60:        # 20 - 60 minutes
    tick_interval = 5 * 60          # 5-minute ticks
elif elapsed_time < 120 * 60:       # 1 - 2 hours
    tick_interval = 15 * 60         # 15-minute ticks
else:                               # >2 hours
    tick_interval = 30 * 60         # 30-minute ticks
```

```
    # --- Generate tick positions including first tick at 0 ---
    max_time = elapsed_time_data[-1] if elapsed_time_data else 0
    ticks = np.arange(0, max_time + tick_interval, tick_interval)
    ax.set_xticks(ticks)

    return lines

# --- Start animation ---
ani = animation.FuncAnimation(fig,update_plot,interval=interval_sec * 1000,blit=False)
plt.show()

# --- Manual stop function ---
def stop_logging():
    print(">>> Logging stopped by user.")
    ani.event_source.stop()
    csv_file.close()

### Now, create another line, and put the code below to stop recording and plotting.
```

```
# When you want to stop recording and plotting, please run this cell
stop_logging()
```

Data Analysis Code in Jupyter Notebook

```
######### Heat Transfer Rate Calculation based in Integral in T-t with Python #########
### Author: Youngmun Lee
###
### This code is developed for Heat Transfer Lab Heat Exchanger with PCM
### Compute heat transfer rate using recorded temperature data
###

# First load the temperature-time plot

# Import Libraries
import pandas as pd
import matplotlib.pyplot as plt
import matplotlib.dates as mdates

# Load CSV
filename = "FILE NAME.csv" # You should put the saved file name correctly
df = pd.read_csv(filename)

# Convert Time column to datetime
df["Time"] = pd.to_datetime(df["Time"], errors="coerce")


# Plot
plt.figure(figsize=(10,5))
for ch in df.columns[1:]:
    plt.plot(df["Time"], df[ch], label=ch)

plt.xlabel("Time")
plt.ylabel("Temperature (C)")
plt.title("Temperature vs Time (Put the data & time)")


# Time format: Hours, Minutes, Seconds
plt.gca().xaxis.set_major_formatter(mdates.DateFormatter("%H:%M:%S"))
plt.gca().xaxis.set_major_locator(mdates.AutoDateLocator())

plt.xticks(rotation=45)
plt.grid(True, linestyle="--", alpha=0.7)
plt.legend()
plt.tight_layout()
plt.show()
```

From the code above, the students will see the temperature-time curve. Now, students apply water properties and experimental conditions to calculate the heat transfer rate using Eq. (1-3).

```
import numpy as np

# Water properties: Students should check it and modify
rho = 997 # Density, kg/m3
mu = 0.001002 # Viscosity, Pa s
k = 0.6062 # Thermal conductivity, W/mK
Cp = 4180 # Specific heat, J/kgK

# Parameter and nondimensional number
GPM = 0.2 # Water flow rate, Gallon per min (Students should put what they measured)
m = (GPM*3.78541/60)*0.001*rho # Water mass flow rate, kg/s
D_flowmeter = 0.0107968 # Flow meter diameter, m (Students should update this)
Vin = m/(rho*0.25*np.pi*((D_flowmeter)**2)) # Inlet velocity, m/s
Re = rho*Vin*D_flowmeter / mu # Reynolds number at inlet
Pr = mu*Cp/k # Prandtl number at inlet

print(f"Density       = {rho} kg/m³")
print(f"Viscosity     = {mu} Pa·s")
print(f"Conductivity  = {k} W/m·K")
print(f"Specific heat = {Cp} J/kg·K")
print(f"Mass flow rate = {m:.6f} kg/s")
print(f"Diameter      = {D_flowmeter} m")
print(f"Inlet velocity = {Vin:.6f} m/s")
print(f"Re = {Re:.6f}")
print(f"Pr = {Pr:.6f}")
```

Once students run the code above, they will see the printed list as below. This list will be useful for them to use Python code as a tool to compute various thermo-fluid parameters such as Reynolds number or Prandtl number. For a given information, they will see the water flow can be regarded as transition flow.

Density = 997 kg/m³

Viscosity = 0.001002 Pa·s

Conductivity = 0.6062 W/m·K

Specific heat = 4180 J/kg·K

Mass flow rate = 0.018870 kg/s

Diameter = 0.0107968 m

Inlet velocity = 0.206730 m/s

Re = 2220.881714

Pr = 6.909205

With this information, students finally compute the heat transfer rate using the following code directly.

```
df.columns = df.columns.str.strip()
print("Columns:", df.columns.tolist())

df = df.rename(columns={
    df.columns[0]: "Time",   # A column
    df.columns[1]: "Tin",    # B column (Inlet)
    df.columns[2]: "Tpcm",    # C column (PCM)
    df.columns[3]: "Tout"    # D column (Outlet)
})

df["Time"] = pd.to_datetime(df["Time"], errors="coerce")
for c in ["Tin", "Tout"]:
    df[c] = pd.to_numeric(df[c], errors="coerce")


# Calculate heat transfer Q = m * Cp * (CH01 - CH03)
df["Q"] = m * Cp * (df["Tin"] - df["Tout"])
print(df[["Time", "Tin", "Tout", "Q"]].head()) # Check the value shortly


# Q - Time plot
plt.figure(figsize=(10,5))
plt.plot(df["Time"], df["Q"], label="Q = m·Cp·(Tin - Tout)")
plt.xlabel("Time")
plt.ylabel("Heat transfer Q (W)")
plt.title("Heat Transfer vs Time")
plt.gca().xaxis.set_major_formatter(mdates.DateFormatter("%H:%M:%S"))
plt.gca().xaxis.set_major_locator(mdates.AutoDateLocator())
plt.xticks(rotation=45)
plt.grid(True, linestyle="--", alpha=0.7)
plt.legend()
plt.tight_layout()
plt.show()
```

```
# t rearrangement
df = df.sort_values("Time")  # sorting the data vs time
df["Time_sec"] = (df["Time"] - df["Time"].iloc[0]).dt.total_seconds()  # Initializaiton, t_ini =
0 s
df["dt"] = df["Time_sec"].diff().fillna(0)  # time difference

# We use a trapezoidal method to compute a cumulative heat transfer, J
# trapezoidal rule: dQ_i = (Q_i + Q_{i-1})/2 * dt_i
Q_values = df["Q"].values
dt_values = df["dt"].values
dQ_trap = np.zeros_like(Q_values)
dQ_trap[1:] = 0.5 * (Q_values[1:] + Q_values[:-1]) * dt_values[1:]

# summation of each dQ_trap
Q_total_trap = np.sum(dQ_trap)
print(f"Total heat transfer (trapezoidal) = {Q_total_trap:.2f} J")

# Store the computed values
df["dQ_trap"] = dQ_trap
df["Q_cumulative"] = np.cumsum(dQ_trap)

# Plotting

plt.figure(figsize=(12,6))
plt.plot(df["Time"], df["Q_cumulative"], label="Cumulative Q (trapezoidal)")
plt.xlabel("Time")
plt.ylabel("Cumulative Heat Transfer (J)")
plt.title("Cumulative Heat Transfer vs Time")
plt.gca().xaxis.set_major_formatter(mdates.DateFormatter("%H:%M:%S"))
plt.gca().xaxis.set_major_locator(mdates.AutoDateLocator())
plt.xticks(rotation=45)
plt.grid(True, linestyle="--", alpha=0.7)
plt.legend()
plt.tight_layout()
plt.show()
```