Process Control
Series 6090

Temperature Process and Heat Exchanger

Course Sample

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e-mail: did@de.festo.com

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Safety and Common Symbols

The following safety and common symbols may be used in this manual and on the equipment:

Symbol	Description
⚠ DANGER	**DANGER** indicates a hazard with a high level of risk which, if not avoided, will result in death or serious injury.
⚠ WARNING	**WARNING** indicates a hazard with a medium level of risk which, if not avoided, could result in death or serious injury.
⚠ CAUTION	**CAUTION** indicates a hazard with a low level of risk which, if not avoided, could result in minor or moderate injury.
CAUTION	**CAUTION** used without the *Caution, risk of danger* sign ⚠, indicates a hazard with a potentially hazardous situation which, if not avoided, may result in property damage.
	Caution, risk of electric shock
	Caution, hot surface
	Caution, risk of danger. Consult the relevant user documentation.
	Caution, lifting hazard
	Caution, belt drive entanglement hazard
	Caution, chain drive entanglement hazard
	Caution, gear entanglement hazard
	Caution, hand crushing hazard
	Notice, non-ionizing radiation
	Consult the relevant user documentation.
⎓	Direct current

Safety and Common Symbols

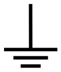
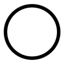
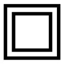
Symbol	Description
	Alternating current
	Both direct and alternating current
	Three-phase alternating current
	Earth (ground) terminal
	Protective conductor terminal
	Frame or chassis terminal
	Equipotentiality
	On (supply)
	Off (supply)
	Equipment protected throughout by double insulation or reinforced insulation
	In position of a bi-stable push control
	Out position of a bi-stable push control

Table of Contents

Table of Contents

Table of Contents

Table of Contents

Table of Contents

Table of Contents

Preface

The growing use of process control in all types of industry comes from the need for a fast, low-cost means of production with better quality, less waste, and increased performance. Process control provides many other advantages, such as high reliability and precision at a low cost. Taking advantage of computer technology, controllers are more efficient and sophisticated than ever. To successfully operate and troubleshoot process control systems, effective training on process control systems is essential.

The curriculum using the Process Control Training System, Model 6090, is divided into three courses that respond to the various training needs in the field of instrumentation and process control. All three courses use water as the process medium.

The main objective of the basic course is to teach the operating principles, measurement and control of pressure, flow, and level processes. In addition, students gain valuable experience tuning closed-loop processes using the most frequently encountered industrial methods. Only basic equipment (Model 6090-1) is required for this course, but the industrial pressure, flow, and level add-on (Model 6090-5) can be used to complement the learning experience.

The second course is similarly designed but concentrates on temperature processes. In addition to the basic equipment, the temperature add-on (Model 6090-2) is necessary. An industrial heat exchanger add-on (Model 6090-4) is optional.

The third course is structured like the first two, but focuses on pH processes. This time, the basic equipment and the pH add-on (Model 6090-3) are mandatory.

Processes can be controlled using the Process Control and Simulation Software (LVProSim) or an optional PID controller. The exercises in the manual have been written to be compatible with two different types of control signals: 4-20 mA and 0-5 V. The experiments are performed using the I/O interface of the LVProSim controller with 4-20 mA signals. However, they can also be accomplished with other PID controllers and previous versions of the LVProSim I/O interface.

We invite readers of this manual to send us their tips, feedback, and suggestions for improving the book.

Please send these to did@de.festo.com.

The authors and Festo Didactic look forward to your comments.

About This Manual

Manual objectives

When you have completed this manual, you should be able to:

- explain the concepts of energy, temperature, and heat flow.
- identify heat transfer processes.
- understand the physical principles behind temperature measurement devices.
- read and understand flow diagrams and wiring diagrams.
- perform temperature measurements.
- characterize temperature processes in the heating and cooling modes.
- perform control on a temperature process in the heating or cooling mode.

Safety considerations

Safety symbols that may be used in this manual and on the equipment are listed in the Safety and Common Symbols table at the beginning of the manual.

Safety procedures related to the tasks that you will be asked to perform are indicated in each exercise.

Make sure that you are wearing appropriate protective equipment when performing the tasks. You should never perform a task if you have any reason to think that a manipulation could be dangerous for you or your teammates.

Prerequisite

As a prerequisite to this course, you should have read and completed the exercises in the manual titled *Pressure, Flow, and Level Processes (*P/N 87996-00).

Systems of units

Units are expressed using the International System of Units (SI) followed by units expressed in the U.S. customary system of units (between parentheses).

To the Instructor

You will find in this Instructor Guide all the elements included in the Student Manual together with the answers to all questions, results of measurements, graphs, explanations, suggestions, and, in some cases, instructions to help you guide the students through their learning process. All the information that applies to you is placed between markers and appears in red.

Accuracy of measurements

The numerical results of the hands-on exercises may differ from one student to another. For this reason, the results and answers given in this manual should be considered as a guide. Students who correctly performed the exercises should expect to demonstrate the principles involved and make observations and measurements similar to those given as answers.

To provide answers to the exercises of this manual, tests were performed at an ambient temperature of approximately 21°C (70°F). At higher temperatures, the observations and measurements made by the students may differ markedly from those given as answers, due to a decrease in the amount of thermal energy transferred to the ambient air.

The instructor should be familiar with process measurement and control to recognize erroneous results. It is advised that a complete run-through of each exercise be included in the instructor's preparation for class.

The training system can be controlled by using the included Process Control and Simulation Software (LVProSim) or with a trend recorder and any other conventional PID controller compatible with 4-20 mA or 0-5 V signals. For the sake of simplicity, the exercises in the Student Manual Temperature Process Control and their solutions have been written for a controller that works with 4-20 mA signals, which is the case of the LVProSim controller. If a controller that works with 0-5 V signals is used, the instructor should adapt the exercises in consequence prior to their beginning by the students.

Sample

Extracted from

Instructor Guide

Thermal Energy Transfer in Temperature Processes

EXERCISE OBJECTIVE

In this exercise, you will become familiar with the concept of heat and the mechanisms by which it transfers from one system to another.

DISCUSSION OUTLINE

The Discussion of this exercise covers the following points:

- Heat
  Heat units.
- Heat transfer mechanisms
  Conduction. Convection. Radiation.
- Specific heat
- Latent heat

DISCUSSION

Heat

Looking at the number of expressions and idioms using the word *heat*, one may think that heat is a well-defined term and that no ambiguity floats around it. Unfortunately, expressions can be misleading when looking at what heat is from the thermodynamic point of view.

The word **heat**, as we will use it, means energy in transit. It is the energy transferred (across a boundary) between two systems due to a temperature difference. Therefore, from the thermodynamic perspective, energy cannot be qualified as heat if it does not cross a boundary. This may seem a little bit abstract, but the following example will help to clarify the definition.

Figure 2-27 shows our starchy friend, the potato, in various situations to illustrate heat transfer. First, the potato, at room temperature, is resting on a kitchen counter (Figure 2-27a). Since the potato is at the same temperature as the air in the room, there is no temperature difference, thus no **heat transfer**. If the potato is placed in a hot oven (Figure 2-27b) at 175°C (350°F), there is a temperature difference of about 150°C (280°F) between the potato and the air in the oven. Therefore, there is heat transfer from the hot air to the potato. In this case, the skin of the potato is the boundary between the hot air and the potato flesh. Once the potato is perfectly cooked, it is put back on the counter (Figure 2-27c). This time, the potato temperature is higher than the room temperature. Hence, the heat transfer is now from the potato to the air and environment.

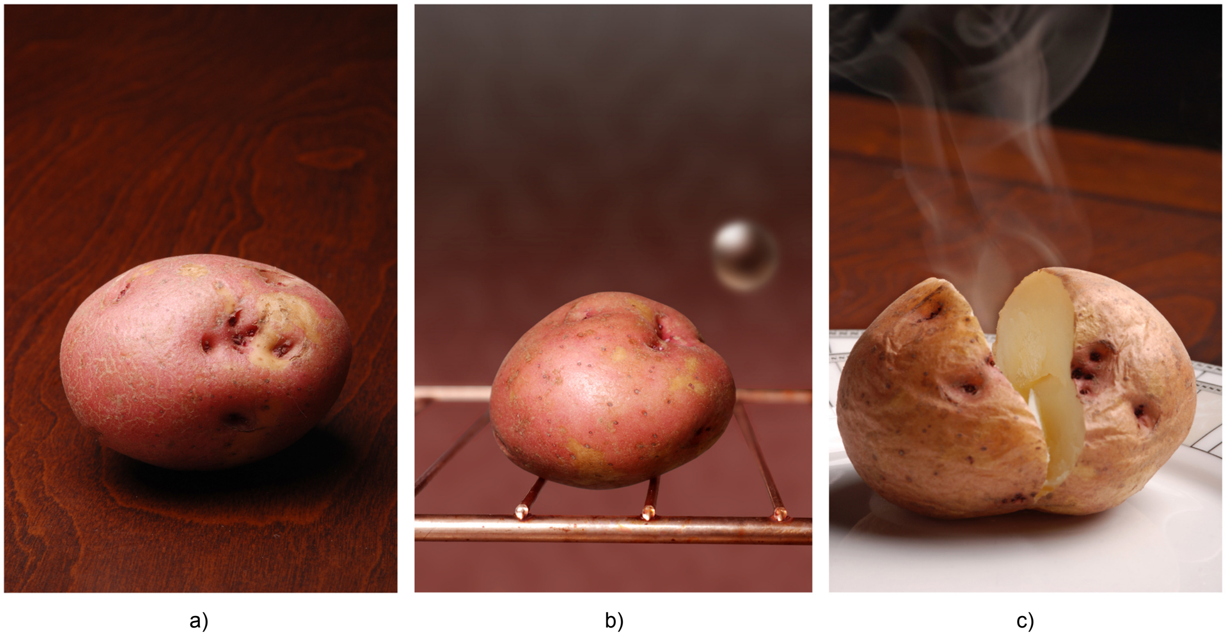

a) b) c)

Figure 2-27. Potato heat.

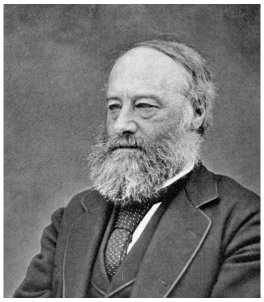


Figure 2-28 James Prescott Joule.

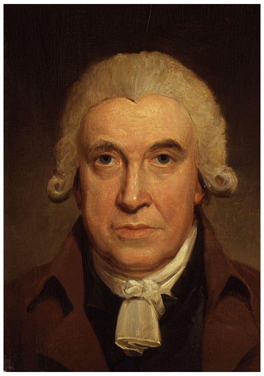


Figure 2-29. James Watt.

Heat units

It was once thought that heat was a kind of fluid, called the caloric, which was poured from a hot body to a cold body. This idea came from the calorie theory of Antoine Lavoisier (1743-1794), a French chemist. Although the idea of the caloric proved to be false, the name stuck and a unit, the **calorie**, was named after it. A loose definition of calorie (cal) is the energy required to increase the temperature of one gram of water by one degree Celsius[12]. Another unit for heat is defined similarly in the U.S. customary system of units—it is the **British thermal unit** (BTU or Btu), which is the amount of energy required to increase one pound of water by one degree Fahrenheit. Both of these units are still widely used in the world of instrumentation and process control. However, for research and science, the SI unit of joule is favored. The **joule**, symbolized J, was named after the British physicist James Prescott Joule (1818-1889). It has dimensions of $kg{\cdot}m^2/s^2$ (ML^2T^{-2}). The joule can be defined as the ability to perform mechanical work on a system. That is, one joule is the work done on a system by a 1 N force which displaces the system by one meter in the direction of the force. All of these units refer to the concept of energy.

Heat is defined as a change of the energy of a system – a flow of energy from one system to another. Consequently, the units used to express heat directly refer to the time-change of energy. In the SI system, the derived unit of watt is employed to quantify a flow of energy (or power): 1 W = 1 J/s. As an example, if our hot potato is left on the counter as in Figure 2-27c, a heat exchange of 10 W could happen at some point in the cooling process. This would simply mean that 10 J of energy are exchanged from the potato to the air every second at that time. The unit of power or heat transfer, the watt, was named in honor of the Scottish engineer James Watt (1736-1819). In the U.S. customary system of

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[12] The calorie used in nutrition for the amount of energy in food is in fact a kilocalorie (1000 calories).

units, Btu/h (Btu per hour) is the norm to quantify a heat exchange. For example, a barbecue could be rated for 50000 Btu/h. This would mean that such a BBQ is able to transfer up to a maximum of 50000 Btu to its content every hour. Be careful though: advertisements and even technical papers too often quote the heat-exchange capacity of devices in Btu whereas the proper units should really be Btu/h to be meaningful.

Heat transfer mechanisms

Having defined heat, we can take a look at the different mechanisms of heat transfer. This aspect is particularly important since no system can be totally isolated so that there is no heat transfer with its surrounding environment. There are three fundamental mechanisms of heat transfer: conduction, convection, and radiation. These exchange mechanisms are described below.

In practice, all three heat transfer mechanisms can be at work simultaneously, even though their relative magnitude may vary greatly.

Conduction

Conduction is probably the type of heat transfer we understand most intuitively. When holding a mug of hot chocolate in your hands, for example, heat is transferred by conduction from the mug to your hands. Since the mug is hotter than your hands, the “mug” molecules have a mean kinetic energy higher than the molecules of your body. A portion of this energy is transferred to your body when the more energetic molecules and atoms of the mug collide with the less energetic molecules of your hand.

Conduction is not an instantaneous process; it takes time for the energy to transfer from one body to another or even to distribute evenly within an object. Some materials, like metals, are good thermal conductors while others are bad conductors and can be used for thermal insulation.

To further illustrate the principle of conduction, let us look at what occurs when a blacksmith puts a metal rod in the hot fire of his furnace (Figure 2-30). The molecules, atoms, and particles in the furnace are much more energetic than those in the metal rod. By colliding with the tip of the rod, they transfer energy to the atoms in the rod and make them vibrate more violently than they were before. The excited atoms in the tip of the rod transfer a part of their energy to neighboring atoms which, in turn, do the same with their neighbors. This process allows heat to be transferred from the hot tip of the rod to the cool extremity. The color of the rod is a good indication of the conduction process. The hot tip of the rod is yellow, the color then fades to red, and finally to black, indicating cooler temperatures.

Figure 2-30. Metal rod in the fire of a furnace.

The rate at which the temperature varies with the position along the rod is called the **temperature gradient** (dT/dx). In the simplified case of an insulated rod (shown in Figure 2-31), the rate of energy transfer by heat due to conduction can be written as:

$$\frac{dQ}{dt} = -\kappa A \frac{dT}{dx} \tag{2-17}$$

where dQ/dt is the rate of energy transfer by conduction

κ is the thermal conductivity, a constant

A is the cross-sectional area of the rod

dT/dx is the temperature gradient[13]

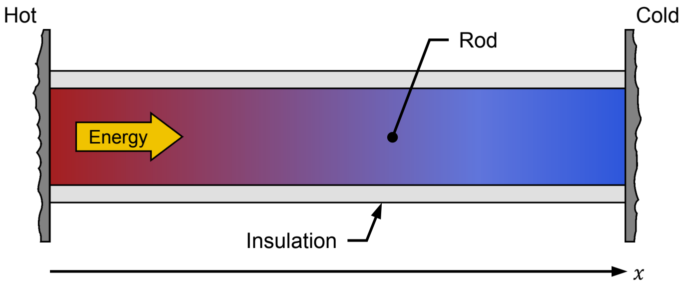

Figure 2-31. Conduction in an insulated rod.

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[13] A mathematical gradient points in the direction of the maximum rate of change. Hence, in the case of the temperature, it points from the cooler region to the hotter region. In order to obtain a positive rate of energy transfer (from the hotter to the cooler region), a negative sign is added to the equation.

From Equation (2-17), we see that the higher the **thermal conductivity** of a substance, the higher the **rate of energy transfer**. Table 2-8 gives the thermal conductivity of different substances. In general, metals are good conductors, while gases are poor conductors of heat.

Table 2-8. Thermal conductivities.

Substance	Thermal conductivity (W/m·°C)
Diamond	2300
Copper	400
Iron	80
Lead	35
Ice	2
Glass	0.9
Water	0.6
Rubber	0.2
Helium	0.14
Wood	0.08
Air	0.024

Convection

When energy is transferred in a solid, the atoms within it stay around their equilibrium position. But in a liquid or a gas, atoms move more freely than in a solid and heat is transferred by the movement of these atoms. This is the **convection** process.

The coffee mug example of Figure 2-32 features two examples of heat transfer by convection. First, someone placing his hand above the mug would clearly feel the hot air rising from the mug. Second, when the liquid at the top of the mug is exposed to cool air, it cools down. This creates a temperature difference between the liquid at the top of the mug and the liquid at the bottom of the mug. Because the cooled liquid has a higher density, it drops toward the bottom of the mug, while hotter liquid rises to the top. This is called natural convection by opposition to forced convection which occurs when a fluid is forced to move (with the use of a fan for example).

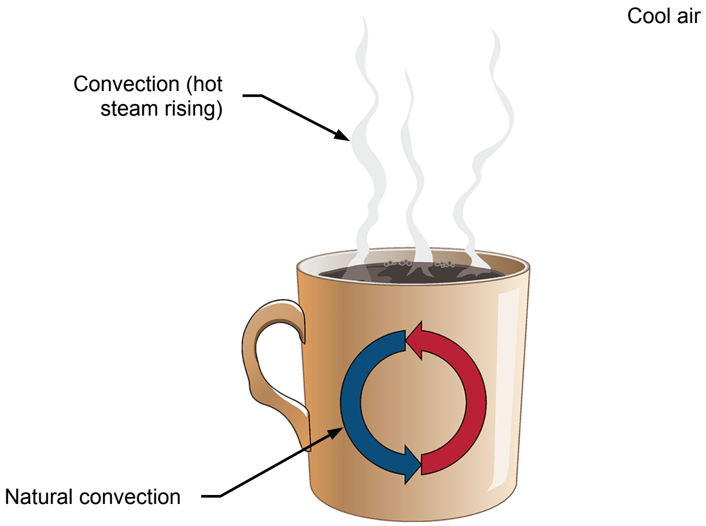

Figure 2-32. Convection mechanisms in a mug of coffee.

To put it briefly, when heat transfers by convection, energy is transferred by the movement of the atoms in the fluid, not through collisions of the atoms in the lattice of the material, as it is the case for conduction.

Radiation

The last heat transfer mechanism presented in this section is **radiation**. Unlike heat transfer by conduction or convection that require the presence of a solid or a fluid, radiation does not require a medium to transfer energy. All substances radiate energy in the form of electromagnetic waves. These electromagnetic waves carry energy away from the substance. You are already familiar with some types of electromagnetic radiation. Visible light, radio waves, and microwaves are all examples of electromagnetic radiation. Figure 2-30, presented earlier, also exhibits an example of radiation. The hot tip of the rod emits electromagnetic waves in the form of visible light. However, most of the electromagnetic waves emitted by the objects around us are not visible light, but infrared light which our eyes cannot perceive. Energy emitted by a body in the form of infrared light can be detected using a thermographic camera, as shown in Figure 2-33.

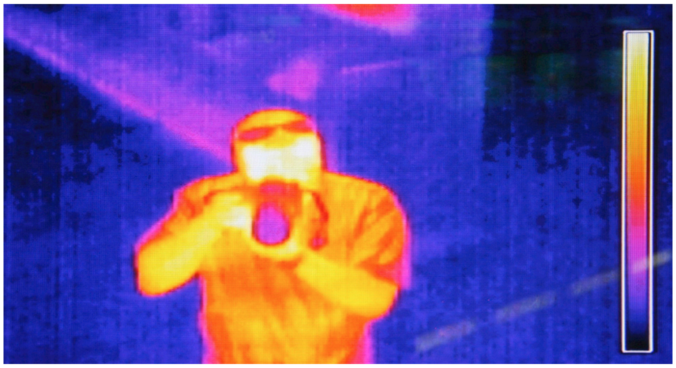

Figure 2-33. Image taken using a thermographic camera.

The rate at which a body radiates energy is given by the **Stefan-Boltzmann law**:

$$\frac{dQ}{dt} = e\sigma AT^4 \tag{2-18}$$

where e is the emissivity of the substance, a dimensionless constant

σ is the Stefan-Boltzmann constant, σ = 5.67×10^{-8} W/(m^2·K^4)

A is the area of the radiating body

T is the absolute temperature of the body (in K)

The **emissivity** of a substance is a coefficient whose value lies between 0 and 1. It is interesting to note that the emissivity is equal to the **absorptivity** of the substance. Therefore, a substance that is good at emitting radiation is also good at absorbing radiation. A bright metallic sheet has a low emissivity and absorptivity index (usually below 0.1), while a dull black surface has a high index (above 0.9). This is why it is better to wear pale clothes (i.e., with low emissivity and absorptivity) in hot weather since they absorb less heat than dark clothes. This is also why thermos bottles are made of bright stainless steel. Table 2-9 gives the values of the emissivity constant for various substances.

Table 2-9. Emissivity of various substances.

Substance	Emissivity
Polished brass	0.03
Aluminum foil	0.04
Polished stainless steel	0.08
Mild steel	0.20-0.32
Sand	0.76
Plastic	0.91
Black silicone paint	0.93
Asphalt	0.93
Water	0.95-0.96
Ice	0.97

The fact that a good emitter is also a good absorber must be taken into account when considering the net energy absorbed and emitted by an object through radiation. For an object at temperature T_1 whose surrounding environment is at temperature T_2, the net rate of energy radiated (or absorbed) by the object is given in Equation (2-19).

$$\frac{dQ}{dt} = e\sigma A(T_1^4 - T_2^4) \tag{2-19}$$

Again, we see that if the temperature of the object is the same as the temperature of its surrounding environment (i.e., $T_1 = T_2$), the body is in thermal equilibrium with its environment and no net energy is exchanged.

Specific heat

Different substances absorb heat differently. Therefore, if the same quantity of energy is transferred to two different substances, their temperature will not rise by the same amount. For a body of mass m, the quantity of energy ΔQ required to raise the temperature of the body by ΔT is given by Equation (2-20).

$$\Delta Q = mc_p\Delta T \tag{2-20}$$

In this relationship, c_p is the **specific heat** of the material. When using the SI units, c_p is expressed in J/(kg·K). The specific heat is a measure of how sensitive a substance is to the addition of energy. A substance with a high specific heat needs a lot of energy before its temperature rises by one degree compared to a substance with a low specific heat. For a given body, $C = mc_p$ is the **heat capacity** of this particular body. The heat capacity is the amount of thermal energy a body must gain in order for its temperature to rise by one degree at a given temperature and pressure. Table 2-10 gives the specific heat of various substances.

Table 2-10. Specific heat of various substances at room temperature (unless specified).

Substance	Specific heat J/(kg·K)
Lead	130
Gold	130
Copper	385
Iron	450
Aluminum	900
Silicon	700
Wood	1700
Ice (at $T = -10°\text{C}$)	2100
Water	4190

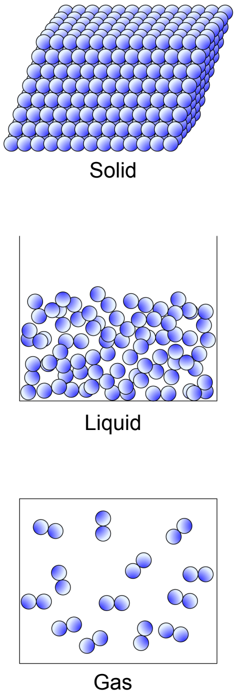

Figure 2-34 States of matter.

Be aware that the specific heat of a substance varies with its temperature. However, if ΔT is small, the specific heat can usually be approximated as a constant. Note that in the U.S. customary system of units, $c_p = 1$ Btu/(lbm·°R) for water at room temperature.

Latent heat

Matter can take the form of several states. These states are known as the physical states or the states of matter. The first three states of matter are well known because we experience them in everyday life. They are the solid, the liquid, and the gaseous states (Figure 2-34). The "other" states are not of interest for now, since they only occur in extreme physical conditions. When a substance is heated or cooled, it can undergo a change of its state called **phase change**. When a substance undergoes a phase change, its physical properties such as density also change. A substance can also keep the same state (the solid state for example) but nevertheless experience a phase change if the internal structure of the solid changes.

In a phase change, the internal energy of a substance changes, but its temperature stays the same. The energy absorbed or lost by the substance allows breaking or creating bonds between atoms and molecules. For example, water boils at 100°C (212°F). As long as the water is boiling, its temperature will stay the same. However, the continuous addition of energy breaks the bonds between the water molecules and takes them apart until they are so far from each other that they no longer are a liquid but a gas. The quantity of energy required to produce a phase change for a mass m of a substance can be expressed as:

$$\Delta Q = mL \tag{2-21}$$

The constant L is called **latent heat**; it is a property of the substance and depends on the type of phase change. For a given substance, the latent heat for fusion (solid to liquid) is not the same as the latent heat for vaporization (liquid to gas). Figure 2-35 shows a graph of the temperature of a sample of water as a function of the energy added. The two flat portions on the graph at 0°C (32°F) and 100°C (212°F) correspond to the phase change from solid to liquid and from liquid to gas respectively.

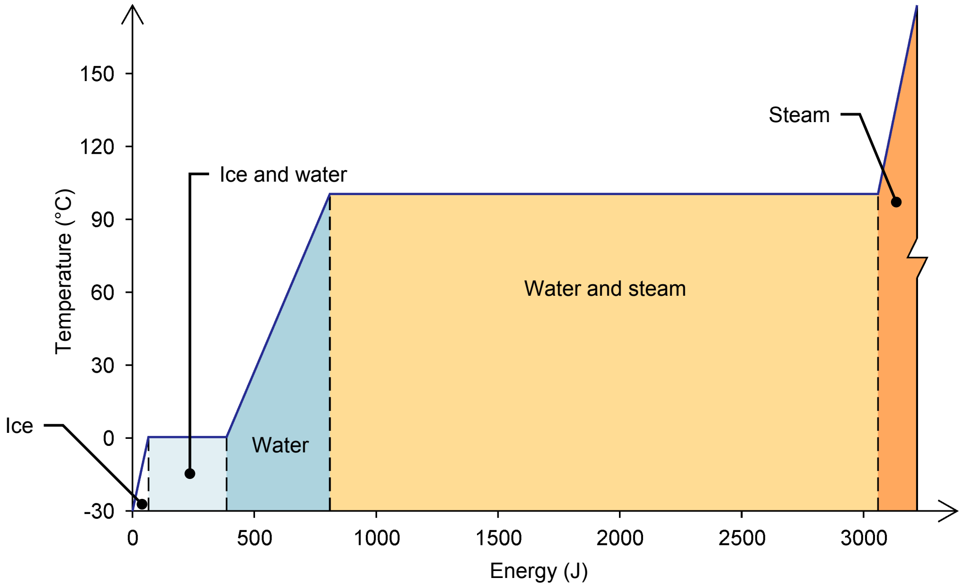

Figure 2-35. Temperature change as a function of energy added to water.

PROCEDURE OUTLINE

The Procedure is divided into the following sections:

- Set up and connections
  Preliminary setup. Calibration of the temperature transmitters. Purging air from the components downstream of the column. Placing the system in water recirculating mode.
- Measuring temperature at equilibrium
  Thermal energy transfer calculations.
- Ending the exercise

PROCEDURE

Set up and connections

Preliminary setup

1. Connect the system as shown in Figure 2-36, Figure 2-37, and Figure 2-38. Do not perform the connections shown in blue in Figure 2-38 yet; this would compromise the calibration procedure performed later.

   The controller TIC1, placed in the manual mode, will manage the electrical power applied to the heating element of the heating unit. You will manually control the rotational speed of the fans of the cooling unit.

   The controller FC1, placed in the manual mode, will regulate the drive of the pumping unit remotely. If you prefer, you can also control the pump speed locally with the drive keypad.

   Connect the four thermocouple probes to transmitters TT1 to TT4 of the thermocouple temperature transmitter module. Insert the thermocouples in the following pressure ports:

   - TT1: Heating unit inlet
   - TT2: Heating unit outlet
   - TT3: Cooling unit inlet
   - TT4: Cooling unit outlet

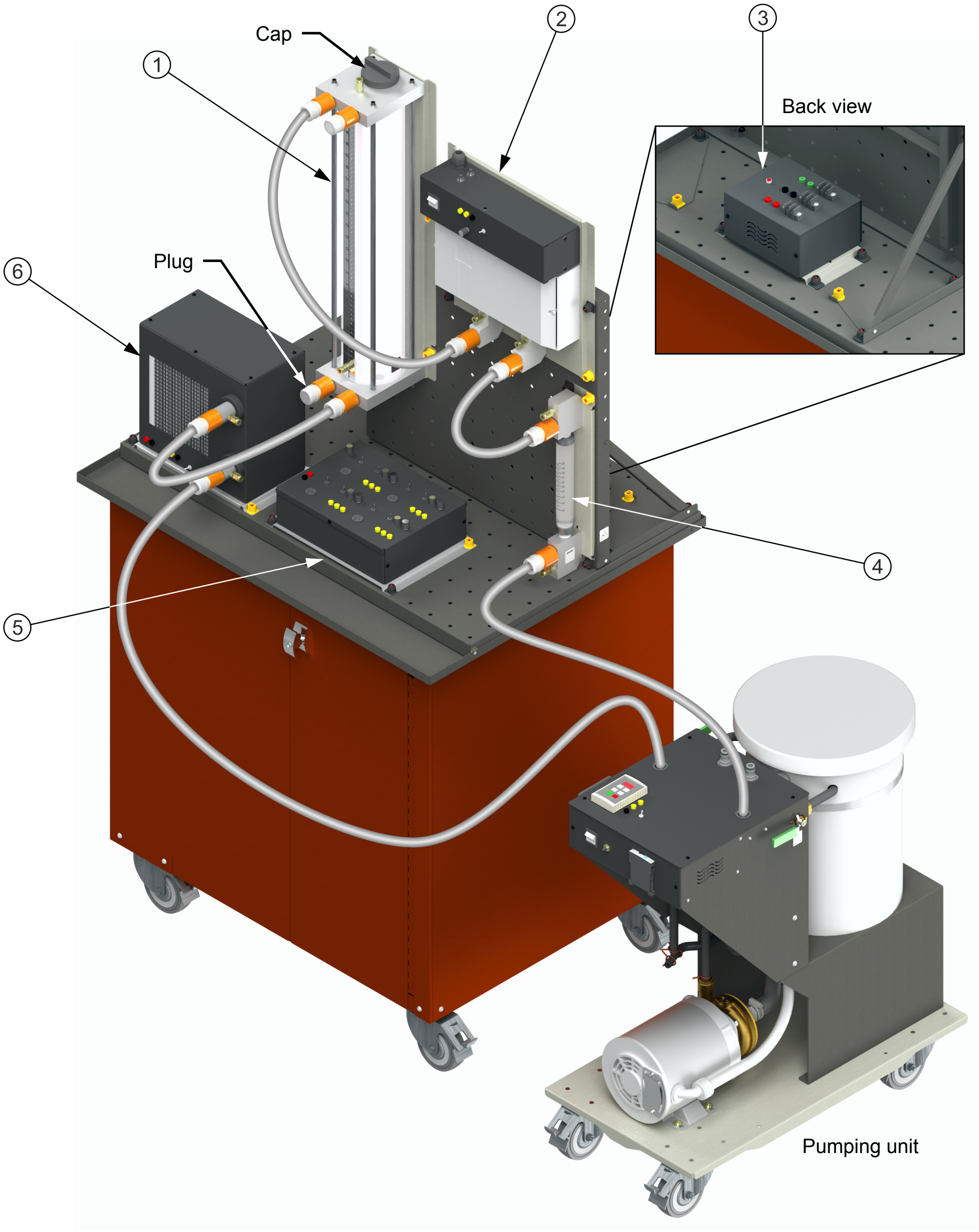

Figure 2-36. Setup - Thermal energy transfer in a temperature process.

1 - Column	4 - Rotameter
2 - Heating unit	5 - Thermocouple temperature transmitter module
3 - Power supply	6 - Cooling unit

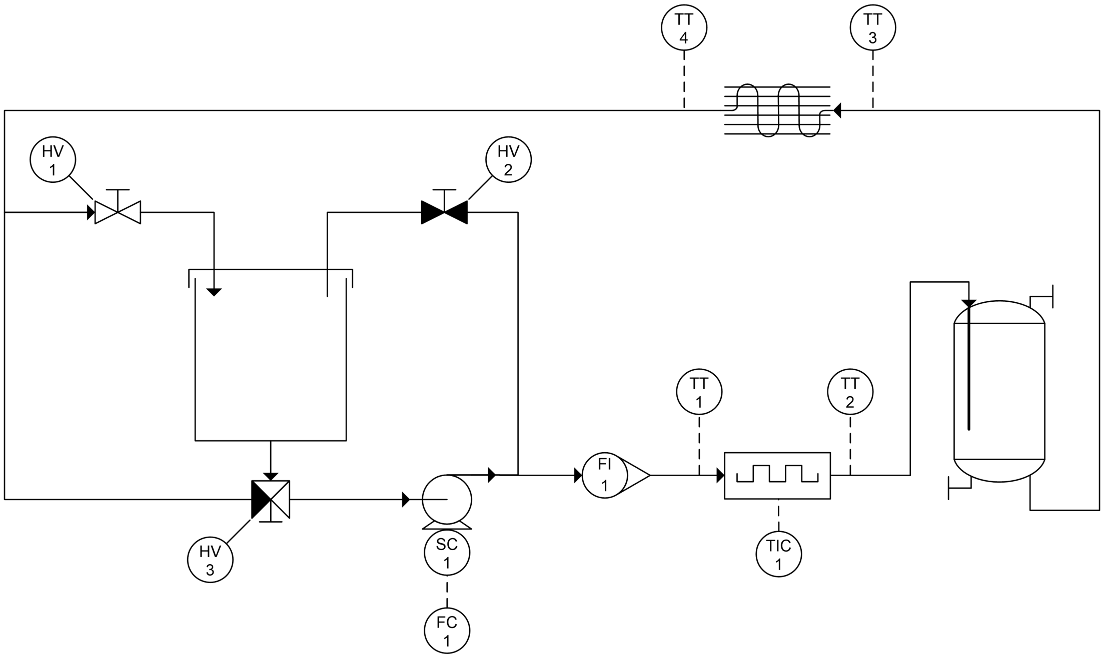

Figure 2-37. Flow diagram - Thermal energy transfer in a temperature process.

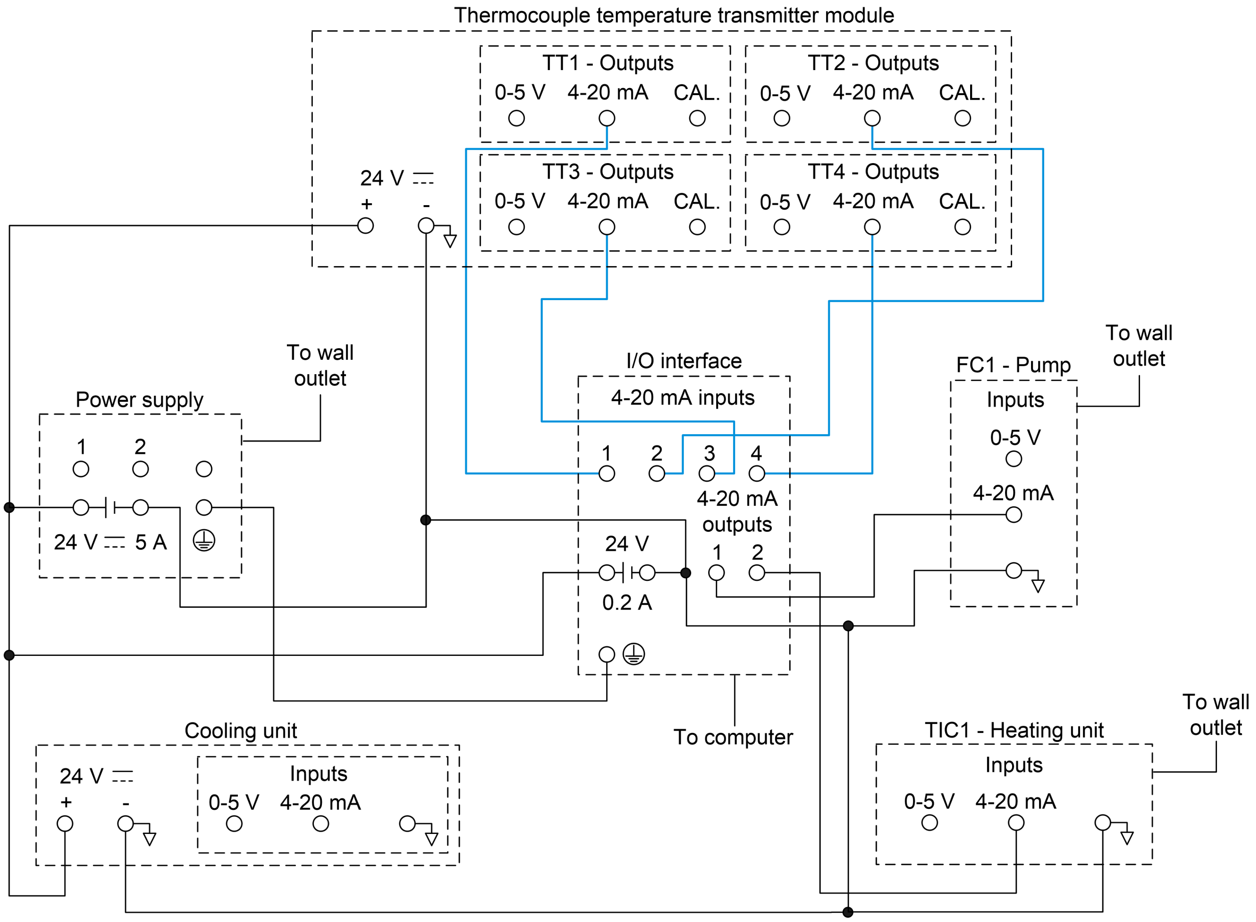

Figure 2-38. Wiring diagram - Thermal energy transfer in a temperature process.

2. Adjust the equipment to the settings shown in Table 2-11.

Table 2-11. Equipment settings.

Equipment	Knob or switch	Setting
Heating unit	S1	1
Cooling unit	S1	2
	Manual control knob	Fully counterclockwise
	S2	↑↑
All four thermocouple temperature transmitters	INPUT	CAL. SOURCE
	CALIBRATION	VARIABLE
	ZERO	MAX.
	SPAN	MAX.

3. Make sure controller TIC1 is in the manual mode. Set the output of this controller to 0% (4 mA).

4. If you control the pump remotely, make sure controller FC1 is in the manual mode. Set the output of this controller to 0% (4 mA).

5. Turn on the power supply. This powers up the I/O interface, the cooling unit, and the thermocouple temperature transmitter module. Leave the pumping unit and the heating unit off.

CAUTION

Never power up the heating unit in the absence of water flow through this unit. Failure to do so might cause the heating unit to wear out prematurely.

Calibration of the temperature transmitters

6. Calibrate the output of each of the four thermocouple temperature transmitters so that the output signal goes from 0% to 100% (4 mA to 20 mA) when the probe temperature simulated by the calibration source is increased from 25°C to 55°C (77°F to 131°F).

   Use the method outlined in steps 8 through 12 of the procedure of Ex. 2-1 for calibration of the outputs of the transmitters.

7. Once the four thermocouple temperature transmitters are calibrated, set the INPUT switch of each transmitter to THERMOCOUPLE.

   Connect the 4-20 mA output of transmitters TT1, TT2, TT3, and TT4 to inputs 1, 2, 3 and 4, respectively, of the I/O interface (blue connections in Figure 2-38).

Purging air from the components downstream of the column

8. On the column, make sure the cap is tightened firmly and the plugs are in place (one at the bottom and one at the top).

9. Verify that the reservoir of the pumping unit is filled with about 12 L (3.2 gal) of water and that the baffle plate is properly installed at the bottom of the reservoir.

10. On the pumping unit, adjust valves HV1 through HV3 using Table 2-12.

Table 2-12. Valves settings.

Valve	Position
HV1	Open
HV2	Closed
HV3	Fully clockwise[14]

11. Turn on the pumping unit. Adjust the parameters of the drive to either local or remote mode depending on the way you want to control the speed of the drive.

12. Press the Run button on the drive keypad to start the pump.

13. Set the variable-speed drive of the pumping unit to maximum speed (with the buttons on the keypad or with LVProSim).

14. Allow the level of the water to rise in the pressurized column until it stabilizes at some intermediate level. This forces air out of the components downstream of the column.

Placing the system in water recirculating mode

15. On the pumping unit, close valve HV1. Then set valve HV3 for directing the full return flow to the pump inlet (turn handle fully counterclockwise).

16. Open valve HV2 in order to decrease the water level in the column to 7.5 cm (3 in), then close this valve.

17. Remove the cap to depressurize the column.

18. Adjust the variable-speed drive of the pumping unit until you have a flow rate of about 2 L/min (0.5 gal/min).

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[14] To direct the full reservoir flow to the pump inlet

Measuring temperature at equilibrium

19. Plot the output signal of each thermocouple temperature transmitter (TT1 through TT4 in Figure 2-37) on the trend recorder. See below for detailed instructions.

LVProSim

Figure 2-38 shows how to connect the computer running LVProSim to the pump and temperature transmitter. Follow the steps below to plot the four transmitter output signals in the software. Configure each thermocouple to read a temperature between 25°C and 55°C (77°F and 131°F).

For each channel, press the Set Channels icon in the LVProSim menu bar and, in the Set Channels window, configure the four channels as detailed below.

- Enter the name you want to give to the channel in the Label section.
- Select Temperature as the type of measured variable.
- Select Celsius (or Fahrenheit) as the measurement unit.
- Enter 25°C (77°F) in the Minimum value field and 55°C (131°F) in the Maximum value field. These values correspond to 4 mA and 20 mA signals respectively.

From the Settings menu, change the sampling interval to 200 ms. Add all four channels to the curves list and press the play button in the menu bar to start recording data.

20. On the cooling unit, set the manual control knob slightly past the mid position.

21. Turn on the heating unit and set the output of controller TIC1 to 100% to apply the maximum electrical power to the heating element. Allow the signals from the four temperature transmitters to increase on the trend recorder.

If the ambient temperature is lower than 25°C (77°F), the transmitter signals will remain at 0% of the span for some time before they start increasing on the trend recorder, since the minimum temperature they can detect has been adjusted to 25°C (77°F).

22. Once the temperature at the outlet of the heating unit, measured using the temperature transmitter TT2, has reached about 90% of the span (52°C or 126°F) on the trend recorder, readjust the output of controller TIC1 to stabilize the temperature at 52°C (126°F).

You might also have to adjust the speed of the fan on the cooling unit if you perform the experiment in a warm or cold environment.

Record the output level of controller TIC1 required for the temperature at the outlet of the heating unit to stabilize at about 90% of the span.

TIC1 controller output level:__________ % of span.

At an ambient temperature of 21°C (70°F), the output of controller TIC1 must be set to about 73% in order for the temperature at the outlet of the heating unit (TT2 signal) to stabilize at 90% of the span. This is highly dependent on the speed of the fans of the cooling unit and the room temperature.

23. Once the temperature at the outlet of the heating unit is stable, the signals from the other temperature transmitters should also be stable, indicating that the process is in a state of thermal equilibrium.

Record the temperatures measured by TT1 through TT4 at equilibrium in the table below.

Table 2-13. Temperatures measured by TT1 through TT4 at equilibrium.

Transmitter	Temperature
TT1 (heating unit inlet)	
TT2 (heating unit outlet)	
TT3 (cooling unit inlet)	
TT4 (cooling unit outlet)	

The temperatures measured by the thermocouples once at equilibrium are approximately:

Temperatures measured by TT1 through TT4 at equilibrium (room temperature of 21°C [70°F]).

Transmitter	Temperature
TT1 (heating unit inlet)	45.6°C (114.1°F)
TT2 (heating unit outlet)	51.7°C (125.1°F)
TT3 (cooling unit inlet)	48.2°C (118.9°F)
TT4 (cooling unit outlet)	46.2°C (115.2°F)

Your results may differ from those presented above.

However, the students should be able to explain where the maximum temperature should occur (outlet of the heating unit) and where the minimum temperature should be found (somewhere between the outlet of the cooling unit and the inlet of the heating unit).

24. Set the output of controller TIC1 to 0%.

25. Set the variable-speed drive of the pumping unit for minimum speed.

CAUTION

Even if the heating unit is protected against overheating, electrical power should not be applied to the heating element in the absence of water flow through this unit. This means that the manual control knob of the unit should be turned fully counterclockwise or that the current or voltage applied by the controller to the control input terminals of the unit should be minimum (4 mA or 0 V) in the absence of water flow. Failure to do so might cause the heating unit to wear out prematurely.

26. Turn off the pumping unit, the heating unit, and the power supply.

Thermal energy transfer calculations

27. Based on the temperatures recorded in Table 2-13, calculate the rate at which thermal energy is being gained or lost by the water as it flows through the heating unit, through the cooling unit, and through the components (column and hoses) between these two units. Refer to Equation (2-2) on page 30.

Assume the mass density of the water to be 1000 kg/m^3 (62.42 lbm/ft^3), and the specific heat capacity of the water to be 4.19 J/g·°C (1.00 Btu/lbm·°F).

Heat flow through the heating unit (ΔT = TT2 – TT1):

Heat flow through the cooling unit (ΔT = TT4 – TT3):

Heat flow through the components (column and hoses) between the heating unit outlet and the cooling unit inlet (ΔT = TT3 – TT2):

- Heat flow through the heating unit (ΔT = TT2 – TT1)

SI units

$$q = \rho \dot{V} c_p \Delta T$$

$$= 1000\,\frac{\mathrm{g}}{\mathrm{l}} \cdot \frac{2\mathrm{l}}{\mathrm{min}} \cdot \frac{1\ \mathrm{min}}{60\ \mathrm{s}} \cdot 4.19\,\frac{\mathrm{J}}{\mathrm{g{\cdot}°C}}(51.7°\mathrm{C} - 45.6°\mathrm{C}) = \ 852\ \mathrm{W}$$

U.S. customary units

$$q = \rho \dot{V} c_p \Delta T$$

$$= 62.42\,\frac{\mathrm{lbm}}{\mathrm{ft}^3} \cdot 0.5\,\frac{gal}{\mathrm{min}} \cdot \frac{1\ \mathrm{min}}{60\ \mathrm{s}} \cdot 1\,\frac{\mathrm{Btu}}{\mathrm{lbm{\cdot}°F}} \cdot \frac{1\ \mathrm{ft}^3}{7.48\ \mathrm{gal}}(125.1°\mathrm{F} - 114.1°\mathrm{F})$$

$$= 0.765\ \mathrm{Btu/s}$$

- Heat flow through the cooling unit (ΔT = TT4 – TT3):

SI units

$$q = \rho \dot{V} c_p \Delta T$$

$$= 1000\,\frac{\mathrm{g}}{\mathrm{l}} \cdot \frac{2\mathrm{l}}{\mathrm{min}} \cdot \frac{1\ \mathrm{min}}{60\ \mathrm{s}} \cdot 4.19\,\frac{\mathrm{J}}{\mathrm{g{\cdot}°C}}(46.2°\mathrm{C} - 48.2°\mathrm{C}) = \ -279\ \mathrm{W}$$

U.S. customary units

$$q = \rho \dot{V} c_p \Delta T$$

$$= 62.42 \frac{\text{lbm}}{\text{ft}^3} \cdot 0.5 \frac{gal}{\text{min}} \cdot \frac{1\ \text{min}}{60\ \text{s}} \cdot 1 \frac{\text{Btu}}{\text{lbm·°F}} \cdot \frac{1\ \text{ft}^3}{7.48\ \text{gal}} (115.2\text{°F} - 118.9\text{°F})$$

$$= -0.257\ \text{Btu/s}$$

- Heat flow through the components (column and hoses) between the heating unit outlet and the cooling unit inlet (ΔT = TT3 – TT2):

SI units

$$q = \rho \dot{V} c_p \Delta T$$

$$= 1000 \frac{\text{g}}{\text{l}} \cdot \frac{2\text{l}}{\text{min}} \cdot \frac{1\ \text{min}}{60\ \text{s}} \cdot 4.19 \frac{\text{J}}{\text{g·°C}} (48.2\text{°C} - 51.7\text{°C}) = -489\ \text{W}$$

U.S. customary units

$$q = \rho \dot{V} c_p \Delta T$$

$$= 62.42 \frac{\text{lbm}}{\text{ft}^3} \cdot 0.5 \frac{gal}{\text{min}} \cdot \frac{1\ \text{min}}{60\ \text{s}} \cdot 1 \frac{\text{Btu}}{\text{lbm·°F}} \cdot \frac{1\ \text{ft}^3}{7.48\ \text{gal}} (118.9\text{°F} - 125.1\text{°F})$$

$$= -0.431\ \text{Btu/s}$$

28. According to the results obtained in the previous step, is the rate at which thermal energy is gained through the heating unit approximately equal to the rate at which thermal energy is lost through the cooling unit and through the components between the heating unit outlet and the cooling unit inlet? Explain.

The rate at which thermal energy is transferred by the heating unit to the fluid (852 W [0.765 Btu/s]) is approximately equal to the rate at which thermal energy is lost through the cooling unit (279 W [0.257 Btu/s]) and through the components in-between (489 W [0.431 Btu/s]), which gives a sum of 768 W (0.688 Btu/s). This is a difference of approximately 10%.

29. Does the water lose thermal energy as it flows through the components between the heating unit outlet and the cooling unit inlet? If so, where does this energy go?

Yes, a certain loss of thermal energy may be measured, as it is the case here, between the heating unit outlet and the cooling unit inlet. This is due to the transfer of thermal energy from the water to the walls of the hoses and column by conduction and forced convection and by the transfer from the walls to the surrounding air by conduction and natural convection. This energy goes into the surrounding air which is warmed up.

Ending the exercise

30. Open valve HV1 of the pumping unit completely and let the water in the column drain back to the reservoir.

31. Disconnect all leads from the training system. Remove from the work surface the power supply, the temperature transmitter, and any electrical equipment not included in the water loop.

32. Disconnect the hoses. Return all leads, hoses, and components to their storage location.

CAUTION

Hot water may remain in the hoses and components. The training system is not equipped with dripless connectors, so be careful not to allow water to enter the electrical components and their terminals upon disconnection of the hoses.

33. Wipe off any water from the floor and the Process Control Training System.

CONCLUSION

In this exercise, you measured the temperature of the water at various points of a temperature process in thermal equilibrium. This allowed you to determine the rate at which thermal energy was gained or lost by the water as it flowed through the circuit components.

You saw that the rate at which thermal energy was gained by the water was approximately equal to the rate at which thermal energy was lost by the water. This occurred because the process was in thermal equilibrium.

A fundamental function of temperature process control is to act on the thermal equilibrium of the process in order to maintain the temperatures within predetermined limits, as will be seen in Unit 4.

REVIEW QUESTIONS

1. What does "heat capacity" mean?

The heat capacity is the amount of thermal energy a body must gain in order for its temperature to rise by one degree, at a given temperature and pressure.

2. Calculate the amount of thermal energy that a mass of 1 kg (2.205 lbm) of water must gain in order for its temperature to rise by 1°C (1.8°F), given a specific heat capacity of 4.19 J/g ·°C (1.00 Btu/lbm ·°F).

SI units: $E = 1000\ \text{g} \cdot 4.19 \frac{\text{J}}{\text{g}\cdot°\text{C}} \cdot 1°\text{C} = 4190\ \text{J}$

U.S. customary units: $E = 2.205\ \text{lbm} \cdot 1.00 \frac{\text{Btu}}{\text{lbm}\cdot°\text{F}} \cdot 1.8°\text{F} = 3.969\ \text{Btu}$

3. What does "thermal equilibrium" mean in the context of a temperature process?

Thermal equilibrium is a state in which the temperatures in a process remain constant as the energy gained is equal to the energy lost by the process.

4. What happens to the heat flow gain in the heating unit if the electrical power is increased? What happens with the outlet temperature (assuming the inlet temperature stays constant)?

The heat flow to the water will increase and the output temperature will rise.

5. What happens to the temperature of the water in the column if the heating unit is turned off, with the rest of the system operating as before?

The temperature of the water in the column will decrease until it reaches the ambient temperature due to the action of the cooling unit and the heat losses occurring in the pipes.

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