Plastics Manufacturing Systems Engineering
A Systems Approach

Sample Chapter 3:
Heating and Cooling
3 Heating and Cooling

An actuator is a device that uses power to change a process state in accordance to a provided control signal. As shown in Figure 3-1, actuators are usually placed between the controller and the process. Many actuators are often used in a single plastics manufacturing system to produce heating, cooling, flow, pressure, rotational motion, linear motion, etc. In most processes, the power delivered by these processes is on the order of kilowatts while the power delivered by the control signal is on the order of milliwatts. Because of this discrepancy, actuators usually require an external power source in parallel with the control signal to fulfill the commanded process changes. In the next section, common specifications for actuators are discussed. Afterwards, the chapter describes the design and operation of common heating and cooling systems used in plastics processing.

![Actuators in plastics processing](image)

### 3.1 Specifications

Figure 3-1 indicates that there are many different types of actuators used in plastics processing machinery. Even so, the various actuators share many of the same specifications that should be considered when purchasing or operating this equipment including power output, linearity, consistency, efficiency, mean time between failures, failure mode, cost, and operating requirements.
3.1.1 Power Output

The primary function of an actuator is to produce a change in the process according to a specified control signal. In general, the process will respond more quickly when the actuator has greater power output. Consider the following examples:

- rise time for barrel or sheet temperatures as a function of heating power;
- available screw torque as a function of motor;
- maximum continuous melt or air flow rates a function of pump power;
- maximum melt pressure as a function of hydraulic cylinder size, and others.

The vast majority of actuators receive their power from electrical utilities delivering a voltage with an alternating current (AC). For example, actuators such as hydraulics, pneumatics, and DC motors are respectively powered by hydraulic pumps, pneumatic compressors, and motor controllers that are provided AC power.

Many actuators used in plastics manufacturing processes have a power output on the order of kilowatts. To avoid drawing excessive current\(^1\), plastics processing machinery often relies upon three phase power with high supply voltages. Table 3-1 provides the two most common electrical power distribution standards [51]. The electrical utility generally transmits high-voltage (thousands of Volts) to regional power distribution stations where it is transformed to three-phased power with lower voltages. Table 3-1 indicates that there is a fairly broad range of voltages that can be supplied within a single specification. The variations are most often due to the voltage drop across the transmission lines between the power distribution station and the end user. However, the electric utility might provide varying voltages intentionally to balance power demand and availability. As such, plastics process machines should be robust with respect to variances in the delivered voltage.

Table 3-1: Electrical Power Standards

<table>
<thead>
<tr>
<th>Type of power</th>
<th>North America 60 Hz</th>
<th>Most elsewhere 50 Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single phase (line to neutral)</td>
<td>110–120 V</td>
<td>220–240 V</td>
</tr>
<tr>
<td>Two phase (two lines)</td>
<td>199–217 V</td>
<td>380–415 V</td>
</tr>
<tr>
<td>Three phase (three lines)</td>
<td>220–240 V</td>
<td>440–480 V</td>
</tr>
<tr>
<td>Transformed three phase</td>
<td>440–480 V</td>
<td>N/A</td>
</tr>
</tbody>
</table>

\(^1\) High electrical currents are undesirable due to inefficiency of power transmission. Power dissipation, \(P\), is equal to \(I^2R\), where \(I\) is the delivered current and \(R\) is the resistance of the transmission lines. As such, the power loss in the electrical supply lines can be reduced by moving to high supply voltages with less current.
In North America, each phase is provided at a nominal 115 V AC. Most other countries supply a line voltage of 230 V AC, which results in lower current usage and less transmission waste. The average voltage across two lines is 208 V in North America and 400 V elsewhere. Three phase power is 230 V in North America and often 460 V elsewhere. Many plastics processing machines are designed for 440–480 VAC power because of its widespread availability outside North America as well as its higher operating efficiencies. As such, step-up transformers are often used in North America to provide this power. It is important when specifying an actuator that the correct electrical service is available. For example, a heater may be designed for three phase 230 VAC service. This heater will only deliver 80% of its rated power with two of the three phases connected, and only 25% of its rated power with the heater connected between a single 115 VAC phase and ground.

It may seem that more power is always better, but this is not necessarily the case. There are at least three significant constraints that limit the maximum amount of actuation power that should be specified in a plastics manufacturing system. First, higher actuator power requires compatible machine designs with respect to the connected machine components. For example, a larger motor capable of providing higher output torque requires stronger gearing for power transmission as well as a stronger plasticizing screw. Similarly, higher melt pressures require larger barrel/nozzle wall thicknesses and higher quality materials. Second, higher actuator power can actually provide a lower level of control due to poor control resolution. For example, higher heating power may provide a faster rise time but actually greater temperature variations due to an infrequent duty cycle in the controller. Third, higher power actuators tend to be larger and more expensive while incurring additional hidden costs associated with connected subsystems.

### 3.1.2 Actuator Efficiency

After rated power, the performance of an actuator is often rated with respect to its efficiency, linearity, and repeatability. The efficiency, \( \epsilon \), is defined as the ratio of useful power provided to the process, \( P_{\text{process}} \), to the total power consumed by the actuator, \( P_{\text{actuator}} \):

\[
\epsilon = \frac{P_{\text{process}}}{P_{\text{actuator}}} \quad 3-1
\]

While actuation efficiencies of 100% are desired, the actuation efficiencies will vary significantly with the type and design of actuator. For example:

- a heater band may be 80% efficient due to the air and heat convection around the outside of the band;
- a radiant heater may be 50% efficient due to misdirected radiation, air convection, and undesired heat conduction in a thermoforming process;
- an electric motor may be 90% efficient due to resistance in its windings and friction of internal bearings; and
- a hydraulic cylinder may be 90% efficient due to the viscosity of the hydraulic fluid and friction between the seals and the cylinder bore.
All these examples are fairly high; efficiencies for cooling systems are much lower since they are limited by the second law of thermodynamics and the Carnot efficiency [52]. In general, efficiency improves with the quality of the actuator design and construction. The decision to adopt a more efficient actuator should consider the purchase cost, usage costs, and other factors such as size, longevity, etc.

### 3.1.3 Linearity

Linearity is a highly desired property of actuators, as an actuator with perfect linearity would provide power output in exact proportion to the control signal. Yet, many actuators have significant non-linearities due to the governing physics. For instance, the heat output from a heater is proportional to the square of the applied voltage. More generally, nonlinearity is often evidenced by actuators due to hysteresis and saturation as shown by the bold curve plotted in Figure 3-2.

Many actuators provide no response at low control signals. There are several reasons for this “null zone”. One common reason is internal static friction within the actuator. For instance, hydraulic cylinders may utilize very tight seals between the piston and the cylinder bore. A significant hydraulic pressure might be required to overcome this static friction before the piston provides any force or movement [53]. Alternatively, the mechanical design may require internal motion before any external actuation is evidenced. Examples of actuator hysteresis due to mechanical design include backlash or slop in gears or lead screws as well as the overlap between a spool and a fluid port in a control valve [54]. Other actuators may present hysteresis due to the purposeful electrical design of the controlling circuit. For example, an electric motor may not respond until a significant non-zero voltage is provided. This design

![Figure 3-2: Actuator non-linearities](image-url)
ensures that no motion is mistakenly provided due to erroneous fluctuations about a zero control voltage [55].

At higher levels of the control signal, the actuator response can exhibit saturation and a plateau of the output power [56]. This behavior may be evidenced due to the mechanical and electrical design of the actuator. For instance, the torque provided by a DC motor will decrease with motor speed due to the development of back EMF. Given an applied load, the output motor speed is often limited at higher control signals. As another example, a nozzle heater may provide increasing temperatures with the control signal. However, the nozzle temperature will reach some maximum temperature even with 100% heater power due to heat loss from the nozzle to nearby machine components and the environment. Still, other actuators may present saturation due to the purposeful electrical design of the controlling circuit.

### 3.1.4 Consistency

Short and long term consistency is also a potential issue with actuators. Figure 3-3 presents the degradation in power output as a function of time. When an actuator is first placed in operation, there are sometimes minor variations between the control signal and the actuator output. The level of variation is not normally problematic but can lead to cycle-to-cycle inconsistencies in the manufacturing process. After a significant amount of time, such as 5,000 hours of continuous use, the actuator output may exhibit the same short term variation on a cycle-to-cycle basis. It may be difficult to observe any significant long term degradation in the actuator output from its new state. After a long period of time, however, the actuator output can degrade significantly such that the actuator can no longer provide its rated output [57]. The actuator may also exhibit greater short term variation on a cycle-to-cycle basis.

![Figure 3-3: Actuator short and long term repeatability](image_url)

Figure 3-3: Actuator short and long term repeatability
Perhaps surprisingly, the linearity and repeatability of actuators are actually less important than they are with sensors. The reason is that most actuators are controlled via a feedback loop from the process sensors. If the sensors are inconsistent, then the process controller is blind with respect to the true process state and will provide inconsistent performance. If the actuators provide inconsistent behavior, however, the controller will sense the errors in the process and so provide additional control energy to adjust the actuation and thereby correct the process. For example, degradation in a heater’s output according to Figure 3-3 would be automatically compensated for via the controller by supplying a higher control voltage or turning the heater on for a longer period of time. Still, actuator repeatability is desired to provide the most consistent product on a cycle to cycle basis, batch to batch basis, and especially on a machine to machine basis.

3.1.5 Failure Rate and Mode

The failure of a single machine actuator will often cause the shut down of the plastics manufacturing process. Unlike process sensors, machine actuators can be expensive and so spare actuators may not be stocked by the plastics manufacturer. Furthermore, actuators are more tightly integrated with adjoining systems and require more time to disconnect and reconnect electrical and mechanical attachments. Given that a typical plastics processing machine has several heaters, one or two motors, several cylinders, and other actuators, it becomes clear that actuators must have a long lifetime as typically measured by the mean time between failures (MTBF).

The definition and magnitude of the mean time between failure varies with the type of actuator. For example, a heater may have an MBTF of 10,000 hours while a pneumatic cylinder may have an MBTF of 10,000,000 cycles. Given that a plastics processing machine uses multiple actuators, the expected failure rate for the machine is [58]:

$$\lambda_{\text{machine}} = 1 - \prod_{i=1}^{n} (1 - \lambda_i)$$  \hspace{1cm} 3-2

where \( n \) is the number of actuators and \( \lambda_i \) is the failure rate of the \( i \)-th actuator defined as:

$$\lambda_i = \frac{1}{\text{MBTF}_i}$$  \hspace{1cm} 3-3

The number and selection of machine actuators should be specified to provide a reasonable uptime percentage without significant unplanned downtime. The definition of “reasonable” will vary with the expectations of the end-user.

**Example 3-1:** A blow molding process has five heaters with an MBTF of 10,000 hours, two motors with an MBTF of 20,000 hours, and eight pneumatic cylinder with an MBTF of 10,000,000 cycles. If the blow molding process has a cycle time of 20 s, estimate the failure rate of the machine.

**Solution:** The MBTF of the cylinder is first converted to number of processing hours based on the number of cycles.
3.1 Specifications

\[ \text{MBTF}_{\text{cylinder}} = 10,000,000 \text{ cycles} \times \frac{1 \text{ Hr}}{3600 \text{ s/Hr}} \times \frac{20 \text{ s/cycle}}{1 \text{ Hr}} = 55,600 \text{ Hr} \]

The failure rates for the heaters, motors, and cylinders are then:

\[
\begin{bmatrix}
\lambda_{\text{heater}} \\
\lambda_{\text{motor}} \\
\lambda_{\text{cylinder}}
\end{bmatrix}
= \begin{bmatrix}
\frac{1}{\text{MBTF}_{\text{heater}}} \\
\frac{1}{\text{MBTF}_{\text{motor}}} \\
\frac{1}{\text{MBTF}_{\text{cylinder}}}
\end{bmatrix}
= \begin{bmatrix}
1 \times 10^{-4} \text{ Hr}^{-1} \\
5 \times 10^{-5} \text{ Hr}^{-1} \\
1.8 \times 10^{-5} \text{ Hr}^{-1}
\end{bmatrix}
\]

Given that there are five heaters, two motors, and eight cylinders, the failure rate of the blow molding machine is then estimated as:

\[ \lambda_{\text{machine}} = 1 - (1 - \lambda_{\text{heater}})^{\text{heaters}} \cdot (1 - \lambda_{\text{motor}})^{\text{motors}} \cdot (1 - \lambda_{\text{cylinder}})^{\text{cylinders}} \]

\[ \lambda_{\text{machine}} = 1 - (1 - 1 \times 10^{-4})^5 \cdot (1 - 5 \times 10^{-5})^2 \cdot (1 - 1.8 \times 10^{-5})^8 = 7.4 \times 10^{-4} \text{ Hr}^{-1} \]

The mean time between failure for the machine is:

\[ \text{MBTF}_{\text{machine}} = \frac{1}{\lambda_{\text{machine}}} = \frac{1}{7.4 \times 10^{-4} \text{ Hr}^{-1}} = 1350 \text{ Hr} \]

If the machine is operating 120 hours per week, a machine failure due to an actuator should be expected every 11 weeks. Most of the failures will be due to the heaters since there are multiple heaters and the heaters have the lowest MTBF. The plastics manufacturer may wish to invest in heaters with a higher MBTF or otherwise stock some spare heaters.

The failure rate is important, but the failure mode of the actuator should be considered as well. Specifically, machine designers and process engineers should seek actuators that fail in a "fail safe" manner without injury to personnel or damage to the machinery [59]. Some modern actuators have built-in diagnostics to indicate the imminent failure of an actuator [60]. In other cases, the failure of an actuator will simply cause the actuation of the process to cease. The machine controller will then detect and attempt to correct the resulting variance in the associated process sensors by updating the control signal to the failed actuator. Since the actuator has failed, however, the controller will be unable to correct the process and subsequently trigger an alarm.

### 3.1.6 Cost

In a competitive marketplace, higher cost actuators should deliver improved performance. As such, there is typically a trade-off to be made in actuator selection between cost, failure rate, repeatability, efficiency, and power output [61]. Many plastics manufacturers will select actuators based on an assessment of the total life cycle cost. A relatively simple life cycle cost assessment would model the actuator’s total hourly cost, \( \kappa_{\text{life}} \), as a function of the actuator’s mean time between failure, MTBF, purchase cost, \( C_{\text{purchase}} \), hourly operating cost, \( \kappa_{\text{operating}} \), and any costs associated with downtime, \( C_{\text{downtime}} \):

\[
\kappa_{\text{life}} = \frac{C_{\text{purchase}} + C_{\text{downtime}}}{\text{MTBF}} + \kappa_{\text{operating}} \tag{3.4}
\]
In the above equation, the purchase and downtime cost due to failure are divided by the MBTF to provide an amortized cost of the actuator’s purchase and failure. The operating cost is estimated as:

$$k_{\text{operating}} = \frac{P_{\text{process}} \cdot k_{\text{electricity}}}{e}$$  

This analysis does not considering the potential costs or savings due to changes in yields with an actuator, though these could also be calculated as part of the hourly operating cost.

Example 3-2: A plastics manufacturer is considering upgrading from mica to mineral insulated (MI) band heaters with a diameter and width of 20 cm. At an average power output of 500 W, the $200 mica heater has a MTBF of 4,000 hours. An MI band heater costs $270, but is expected to require only 480 W and have a MTBF of 8,000 hours in the same application. Estimate the hourly operating costs for the two heaters.

Solution: The hourly operating cost depends on the cost of electricity. Assuming 0.12 $/kWHR, the hourly operating cost for the mica heater is:

$$k_{\text{operating}} = 0.5 \text{ kW} \cdot 0.12 \$/\text{kWHR} = 0.06 \$/\text{Hr}$$

Neglecting downtime cost, the life cycle operating cost of the mica heater is:

$$k_{\text{life \ mica}} = \frac{C_{\text{purchase}} + C_{\text{downtime}}}{\text{MBTF}} + k_{\text{operating}} = \frac{200 + 0}{4000 \text{Hr}} + 0.06 \$/\text{Hr} = 0.115 \$/\text{Hr}$$

The same analysis can be repeated for the MI band heater, with the result that:

$$k_{\text{life \ MI}} = \frac{C_{\text{purchase}} + C_{\text{downtime}}}{\text{MBTF}} + k_{\text{operating}} = \frac{270 + 0}{8000 \text{Hr}} + 0.48 \text{kW} \cdot 0.12 \$/\text{kWHR} = 0.091 \$/\text{Hr}$$

The MI band will result in a net cost reduction of $0.019 or 17% per hour, mostly due to the longer MTBF. Given the average savings rate, the payback period (time to recoup the added cost) is:

$$\text{Payback Period} = \frac{\text{Added cost of investment}}{\text{Savings rate due to investment}} = \frac{270 - 200 \$/\text{yr}}{0.11 - 0.091 \$/\text{Hr}} = 3,700 \text{Hr}$$

This analysis indicates that MI band heaters provide a net cost savings, with a payback period of 3,700 hours or about 8 months in a production plant operating 120 hours per week. The decision to adopt mica or MI band heaters will vary across plastics manufacturers depending on their application’s technical and economic needs.

3.1.7 Operating Requirements

Actuators are primarily rated by power output, but operating requirements must also be considered. Specifically, plastics manufacturing processes can be located in plant environments that are hot, humid, dirty, or wet. Operating requirements will vary according to the type of actuator. For example, it may seem obvious that:
• a heater will have a maximum temperature;
• a hydraulic or pneumatic cylinder will have a maximum operating pressure;
• an electric motor will have a maximum current, and so on.

It is less obvious is that these actuators will have additional operating requirements. For example, hydraulic and pneumatic cylinders often have a maximum operating temperature or velocity to avoid degradation of the included seals. Electric motors will also have maximum operating temperatures associated with degradation of the magnets and other components. Humidity and contamination can also be a significant factor to actuator performance and longevity. Humidity can cause accelerated corrosion in electrical devices. Contamination in air or hydraulic fluids can cause wear in the control valves and seals; contamination in power transmissions can cause surface wear and premature failure in the actuators and their driven systems. Because the operating environment is such a significant issue, the National Electrical Manufacturers Association (NEMA), American National Standards Institute (ANSI), and the International Electrotechnical Commission (IEC) publish standards and application guides that are highly relevant to the design and end use of actuators and their associated controls, wiring, and enclosures [62]. Table 3-2 provides some of the most common NEMA standards that are used with respect to motors, heaters, electrical enclosures, and other actuators [63]. Actuators frequently require supporting subsystems to operate effectively, such as fans, heat exchangers, cooling jackets, mechanical couplings, electrical connectors, hydraulic fittings, and others. To ensure inter-component reliability, NEMA, ANSI, IEC, and other standards organizations have additional standards that govern the physical configuration, mechanical design, materials properties, and electrical characteristics of associated devices [64]. As such, the machine designer or process engineer should consider the total systems cost and replacement strategy when selecting an actuator for a given application.

Table 3-2: Common NEMA Standards

<table>
<thead>
<tr>
<th>NEMA type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A general purpose design for dry, clean, well-ventilated, indoor applications. Intended to protect against dust, light, indirect splashing, and accidental human contact.</td>
</tr>
<tr>
<td>4</td>
<td>A watertight design that provides protection against windblown dust and rain, splashing water and hose directed water from any angle. However, not designed to be submerged.</td>
</tr>
<tr>
<td>7</td>
<td>A design suitable for a hazardous location in which flammable gases may be present in the air in quantities sufficient to produce explosive or ignitable mixtures; the design will withstand the pressures resulting from an internal explosion.</td>
</tr>
<tr>
<td>9</td>
<td>A design suitable for hazardous locations to prevent the entrance of dust, carbon black, and other particulates. Enclosed heat generating devices such as motors and electronics must not cause reach excessive temperatures.</td>
</tr>
<tr>
<td>12</td>
<td>A design suitable for industrial use to prevent the entrance of hydraulic or cooling fluids, dust, fibers, filings, etc. Designs are often not ventilated and rely on synthetic gaskets for sealing.</td>
</tr>
</tbody>
</table>
3.2 Heating

There are many different types of heaters used in plastics processing, but most share a similar set of specifications including: maximum operating temperature, temperature uniformity, power density, compactness, packaging options, mean time to failure, and cost. Of these specifications, the maximum operating temperature is perhaps the most critical specification since it immediately limits the range of processing temperatures that can be achieved as well as the heater’s failure mode and time to failure. Figure 3-4 plots the expected mean time to failure as a function of operating temperature for a mica heater band. The heater band is expected to provide a long operating life with little degradation at different operating temperatures until a specified maximum temperature. At higher temperatures, the heater’s components will tend to oxidize and thereby reduce the heater’s lifetime [65]. For this reason, the appropriate heater selection is important to provide an economic and technically feasible process.

The most common heaters used in plastics manufacturing processes are next discussed. Heater specifications will vary greatly with the processing application [66], so readers are encouraged to work with application engineers of heater suppliers to determine appropriate heaters in plastics processing applications. Some applications will demand high power density as measured by Watts of heating power per unit surface area of the heater; power densities vary significantly (by a factor of four or more) with the underlying heating technology. Other applications will place emphasis on geometric compactness with respect to availability of lengths or diameters as well as the minimizing the thickness of the heater. Advanced heating technologies are also available. Some suppliers provide a host of options related to mechanical and electrical connections including integrated temperature sensors. In some applications, temperature uniformity is vital and suppliers can provide heaters with different power densities as a function of position within the heater.

![Figure 3-4: Heater temperature-time failure behavior](image-url)
3.2 Heating

3.2.1 Conduction Heaters

Band heaters are widely used for barrel and nozzle heating in injection molding, extrusion, and blow molding. The construction of a heater [67] is provided in Figure 3-5. In this design, a resistive wire consisting of a nickel/chrome alloy (often referred to as "nichrome") is wrapped around an electrically insulating support member. Nichrome has a melting point of around 1400 °C, a maximum operating temperature of 1200 °C, and an electrical resistivity of 0.0001 Ω cm. Nichrome's resistivity is approximately ten times that of steel and 50 times that of aluminum. Nichrome's high resistivity and operating temperature enable nichrome wire to be used directly as a heating element by applying a voltage across its length.

In the design of Figure 3-5, mica sheets are provided around the wrapped nichrome wire for electrical insulation. The mica sheet is essentially a form of paper composed of muscovite mica fibers. Mica sheets are widely available in different thickness and widths with end use temperatures of 500 to 700 °C. The heat conducting shell provides an enclosure for the mica and wound nichrome wires. In this design, the heat conducting shell is formed by sheet stamping and bending. The shell may be formed of different materials such as mica, aluminum, or stainless steel. The material and design of the outer shell often determines the heater's end use temperature, corrosion resistance, and failure mode.

Mica heaters are among the most common used in plastics manufacturing since the design is not only compact and low cost, but also scalable to different sizes and power densities. Table 3-3 compares a few specifications for mica and other heaters commonly used in the plastics industry. The design of mineral insulated heater bands is quite similar to that of the mica band of Figure 3-5; the primary difference is the substitution of higher temperature mineral insulator for the mica sheet. Some mineral insulated heaters have a thicker outer insulating sheet to direct heat to the inside of the heater band and thereby improve energy efficiency. The design of the ceramic knuckle heater is quite different. In this design, ceramic

![Figure 3-5: Typical band heater construction](image-url)
Heating and Cooling spaces (knuckles) are intermittently spaced around the heater band with electrically insulated wires threaded through holes in the ceramic spacers. Cylindrical band heaters are widely used for heating cylindrical machine components such as bands and nozzles from their outer surfaces. For machine components with substantially flat surfaces, plate heaters of similarly construction are available. Alternatively, machine components such as extrusion dies can be internally heated via cartridge heaters placed in provided holes. The design of a cartridge heater is shown in Figure 3-6. A nickel/chrome resistive wire is wrapped around a ceramic cylindrical support. The wound heater assembly is then surrounded by magnesium oxide insulation and a protective outer sleeve. To provide the most effective heat transfer between the heater cartridge and the machine component, the corresponding hole should be drilled and reamed to the nominal diameter of the heater cartridge.

Cartridge heaters have several significant advantages compared to heater bands. First, cartridge heaters have much higher power densities, typically 60 W/cm² though this higher power density is necessary since heater cartridges have much smaller surface area than heater bands. Second, heater cartridges are protected by the surrounding machine component and so are less prone to failure due to unintended abuse. Third, heater cartridges have higher operating temperatures than heater bands and plates; they are also relative inexpensive with respect to purchase cost per unit of heating power. Finally, heater cartridges heat the machine components internally and so will provide higher heating efficiency than external heaters that may lose a significant portion of their heat to the surrounding environment. The value of this last advantage is somewhat decreased by the poor temperature uniformity across the machine component provided by heater cartridges.

Table 3-3: Specifications of Common Heaters

<table>
<thead>
<tr>
<th>Specification</th>
<th>Mica heater</th>
<th>Mineral insulated</th>
<th>Ceramic knuckle</th>
<th>Heater cartridge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum operating temperature (°C)</td>
<td>480</td>
<td>760</td>
<td>760</td>
<td>900</td>
</tr>
<tr>
<td>Power density (W/cm²)</td>
<td>9</td>
<td>40</td>
<td>7</td>
<td>60</td>
</tr>
<tr>
<td>Typical thickness (mm)</td>
<td>4</td>
<td>4</td>
<td>12.5</td>
<td>10</td>
</tr>
<tr>
<td>Purchase cost (US$/kW)</td>
<td>70</td>
<td>100</td>
<td>100</td>
<td>50</td>
</tr>
</tbody>
</table>

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Figure 3-6: Typical cartridge heater construction
When temperature uniformity or compactness is vital in a plastics application, the heating element may be more tightly integrated with the machine element. For example, Figure 3-7 shows that typical heater sheath wire, widely used in the industry, consists of resistive wires surrounded by an insulating material and semi-rigid protective sheath. This heater sheath wire can be placed into a helical groove to provide a compact nozzle design with excellent temperature response and uniformity [69]. A protective strip is then wrapped around the heater to protect the heater sheath wire. For extra protection and to provide a uniform external appearance, the entire nozzle assembly may be brazed or otherwise encapsulated.

Recently, thick film heaters have also been used in plastics machinery. The term “thick film” refers to films with a thickness above 0.02 mm, which can be made by a direct deposition process such as screen or ink jet printing. As shown in Figure 3-8, a dielectric layer consisting of a ceramic or glass is provided on the substrate to provide electrical insulation. A resistive layer is then printed to provide the desired heating density across the substrate; the power density of the heater can be controlled by changing the layout and resistance of the deposited heaters. Using this approach, high power densities and thermal uniformity have been reported [70]. An outer dielectric layer may also be provided to prevent damage during installation or operation.
The designs of Figure 3-7 and Figure 3-8 may be applied to a variety of processing applications including non-cylindrical geometries with good results. The best approach, however, is highly dependent on the application requirements. For example, the thick film heater of Figure 3-8 could have been directly applied using the nozzle as the underlying substrate. However, this approach could be more costly to the nozzle’s supplier given potential disposal of defects during heater production as well as the nozzle’s end-user who may need to replace a failed heater. If the heater is directly integrated with the machine component as in Figure 3-7, then the end-user would need to replace the entirety of the component due to just the failure of the heater.

In all these conductive heating technologies, the heater presents a nearly constant electrical resistance, $R$, to the electrical circuit. A time varying voltage, $V$, is supplied typically varying between 0 and a few hundred volts. The generated heating power is:

$$ P = \frac{V^2}{R} $$  \hspace{1cm} 3-6

Ohm’s law may be applied to find the electrical current, $I = \frac{V}{R}$, passing through the heater. In many or most applications, the maximum heating power occurs on the initial process start-up. As such, the required heating power, $P_{\text{Required}}$, is often well estimated by the required heating energy, $E_{\text{Required}}$, divided by the desired initial heating time, $t_{\text{Required}}$, of the machine component(s) being heated:

$$ P_{\text{Required}} = \frac{E_{\text{Required}}}{t_{\text{Required}}} $$  \hspace{1cm} 3-7

The required heating energy is estimated as:

$$ E_{\text{Required}} = \rho \cdot V \cdot C_P \cdot (T_{\text{process}} - T_{\text{initial}}) $$  \hspace{1cm} 3-8

where $\rho$, $V$, and $C_P$ are the density, volume, and heat capacity of the machine component and $T_{\text{initial}}$ and $T_{\text{process}}$ are the initial and processing temperatures.

**Example 3-3:** An extrusion die measures approximately 20 cm on a side. Specify the heater power required to provide a processing temperature of 250 °C with an initial heating time of 15 minutes.

**Solution:** The density and heat capacity of AISI 4130 steel are respectively 7850 kg/m$^3$ and 525 J/kg°C. Assuming an initial temperature of 20 °C, the required energy is:

$$ E_{\text{Required}} = 7850 \text{ kg/m}^3 \cdot (0.2 \text{ m})^3 \cdot 525 \text{ J/kg°C} \cdot (250 °C - 20 °C) = 7.6 \cdot 10^6 \text{ J} $$

Given a heating time of 15 minutes or 900 s, the required heating power is:

$$ P_{\text{Required}} = \frac{E_{\text{Required}}}{t_{\text{Required}}} = \frac{7.6 \cdot 10^6 \text{ J}}{900 \text{ s}} = 8.4 \text{ kW} $$

There are two likely approaches for heater selection in this application. One approach is to use four heating plates on the outside faces of the extrusion die. The heating power density of the plates would then be:
The required heating power density of 5.3 W/cm² is within the capabilities of conventional mica heaters as listed in the specifications of Table 3-3. In fact, this application is likely well matched since the heaters would probably be somewhat smaller than 20 cm squared.

A second approach would be to use several internal heater cartridges located within the extrusion die itself. One standard sized heater cartridge is 1 cm in diameter and 20 cm in length. Assuming a power density of 60 W/cm² for heating cartridges, the heating power provided by one cartridge is theoretically:

$$P_{\text{Heater}} = \frac{P_{\text{Required}}}{A_{\text{Surface}}} = \frac{8.4 \text{ kW}}{4 \cdot (20 \text{ cm})^2} = 5.3 \text{ W/cm}^2$$

However, a commercially available heater cartridge may have a specified heating power of 1.2 kW. The required number of cartridge heaters would then be:

$$n_{\text{Heaters}} = \frac{P_{\text{Required}}}{P_{\text{Heater}}} = \frac{8.4 \text{ kW}}{1.2 \text{ kW}} = 7$$

Either heating approach is likely feasible from a technical perspective. The decision to use external heating plates or internal cartridge heaters is also dependent on the internal and external geometry of the extrusion die as well as end user preferences.

### 3.2.2 Radiant Heaters

Conductive heaters are used to heat machine components that then heat and contain the polymer. By comparison, radiant heaters are used to directly heat plastic parts, sheet, or film that will remain in a solid or semi-solid state. Compared to conduction heaters, radiant heaters must operate at significantly higher temperatures to provide rates of radiant heat transfer that are similar to conduction heaters [71]. Alternatively, radiant heaters may be operated at lower temperatures with relatively longer heating times.

The design of a ceramic panel heater [72] is shown in Figure 3-9. The heater is essentially consists of a heater sheath wire supported within a protective housing. In this design, the heater sheath wire is fastened to a metal plate which thereby provides more rapid and uniform conductive heat transfer to an outer ceramic layer. For maximum heat transfer and manufacturing productivity, the outer ceramic layer should be selected so that the thermal emissivity maximized radiation at a wavelength compatible with the plastic being heated; heating wavelengths of 2 to 15 μm are typically most effective for plastics [73]. There are many other ceramic panel heater designs that may replace the ceramic layer with a cloth woven of ceramic fiber. Other designs may also locate and support the heating element via groves in a ceramic refractory board. The use of high temperature materials in these ceramic panel heaters enables operating temperatures up to 900 °C.

Ceramic heaters are very common in plastics processing. However, the extensive use of ceramics can provide a heater that is somewhat heavy and not necessarily cleanable. For these reasons, metal panel heaters may be preferred in some processing applications. A metal panel heater design [74] consisting of three radiating bars is shown in Figure 3-10. A nichrome wire is
used to generate heat within each radiating bar. Mica insulating strips provide for electrical insulation of the heating wire from inner and outer stainless steel channels that house the heating assembly. While not shown in the figure, the stainless steel channel may also be coated with a high emissivity coating and backed by thermal insulation to improve heating efficiency. The solid construction of the metal panel heater provides a lighter and more cleanable design than that of ceramic panel heaters, but lower operating temperatures to 600 °C.


A grid of ceramic or metal panel heaters are often used in thermoforming to provide local or "zone" control across the sheet or film being heated. As the number of heaters in the grid increases, the ability to provide local control increases. However, the overall system cost and complexity also increases since each heater requires a corresponding temperature controller and optional thermocouple.

**Example 3-4:** A thermoforming process processes a 1 m × 1 m ABS sheet with a thickness of 3 mm. If the sheet is heated from 20 °C to 120 °C in 30 s, determine the required heating power density.

**Solution:** The density and heat capacity of ABS sheet are respectively 1020 kg/m³ and 2340 J/kg°C. From Eq. 5-8, the minimum required energy to heat the sheet is:

\[
E_{\text{required}} = 1020 \text{ kg/m}^3 \times (0.1 \text{ m} \times 0.1 \text{ m} \times 0.003 \text{ m}) \times 2340 \text{ J/kg°C} \times (120 °C - 20 °C) = 7160 \text{ J}
\]

Given a heating time of 30 s, the required heating power is:

\[
P_{\text{required}} = \frac{E_{\text{required}}}{t_{\text{required}}} = \frac{7160 \text{ J}}{30 \text{ s}} = 240 \text{ W}
\]

The heating power density is:

\[
P_{\text{heating}} = \frac{P_{\text{required}}}{A_{\text{surface}}} = \frac{240 \text{ W}}{(100 \text{ cm})^2} = 0.024 \text{ W/cm}^2
\]

By comparison, the ceramic and metal heaters are commonly rated to provide a heating density of approximately 5 W/cm². The discrepancy between the minimum required heating power density and the typical power density provided by radiant heaters indicates that radiant heating is extremely inefficient. The inefficiencies are due primarily to air currents and heat convection to the surrounding environment, mismatch between area of radiated heat with the target to inadvertently heat nearby equipment, and reflection of radiated heat off the target.

Some plastics manufacturing processes also incorporate quartz tube heaters for sheet or film heating, shrink wrapping, laminating, drying, and other functions. The design of a quartz heater [75] is shown in Figure 3-11. In this design, a nickel/chrome heating wire is wound and enclosed within a transparent quartz tube. A metal mesh can be provided between the heater wire and the ceramic caps to manage vibration and temperature transients, thereby reducing the failure rates of the tube. The heater wire can also be wound with a varying pitch to provide less power at the center of the tube and a more uniform temperature distribution across the length of the tube. All these components consist of high temperature materials, allowing operation of the quartz heater to 930 °C and an emitted wavelength down to 2 μm. Compared to the panel heaters of Figure 3-9 and Figure 3-10, the quartz tube heater has very low mass and very high power density. As such, the response time is on the order of 15 s, which makes this heater suitable for intermittent use in processes with frequent start/stops. By comparison, panel heaters are typically controlled to provide a constant temperature since their response time is on the order of minutes.
3.2.3 Heater Controls

Thermostat heater controls provide either no or full power in response to the monitored temperature. Such “on/off” control is typically provided by electromechanical relays that are cycled on the order of every minute. This intermittent cycling exposes heaters to maximal changes in electrical currents, temperature transients, thermal shock, and increased wire oxidation. This control method not only provides less accurate temperature control but also shorter heater life. Furthermore, such slow control is highly unsuitable for radiant or quartz heaters with a fast response time since the heater temperature can increase to an unsuitably high value before the electromechanical relay is switched off.

Several different types of heater controls have been developed to provide for better power switching and improved control [76]. One simple approach is to replace the electromechanical relay with a mercury displacement relay (MDR). The MDR uses liquid mercury to conduct electricity. Since the MDR requires less electrical power and mechanical movement to make the electrical contact, the cycle time of the MDR can be reduced to 4 s while providing adequate life. For both the electromechanical and mercury displacement relays, the full line power (typically, 120 or 240 or 480 V AC) is provided directly to the heater when the relay is on and zero otherwise. The cyclic nature of an MDR and its corresponding heater temperature is provided in Figure 3-12. In this figure, the ideal power input is 40% for the first 100 s, then increases to 80% for the next 100 s. Since the MDR can not provide a proportional response, the relay cycles the provided power on and off with a minimum time of 4 s.

It should be clear that the use of a slower electromechanical relay with a cycle time of 30 s will provide much worse performance with greater variations in temperature. Indeed, even though the temperature of the system being controlled may vary by only a few degrees, the temperature of the internal nickel/chrome heating elements will be oscillating very significantly – literally hundreds of degrees. Such extreme temperature cycling contributes to the thermal fatigue, oxidation, and premature failure of the heating elements. As such, more rapid heater cycling is preferred to provide less temperature variation and longer heater life. Unfortunately, electromechanical and mercury displacement relays can not provide extremely short cycle times since they have moving components and are subject to wear issues related to cycling. The mercury in MDRs is also considered a hazardous material and is increasingly banned from manufacturing environments.

Figure 3-11: Quartz tube construction

3 Heating and Cooling
For these reasons, solid state relays (SSR) have been developed that incorporate silicon controlled rectifiers (SCR) to control the line voltage to the heater [77]. The SCR is essentially a semiconductor relay that allows the line voltage to pass in a single direction when provided a control signal. The behavior of a single SCR is provided in Figure 3-13. In the figure, the SCR is provided an on/off control signal that can vary rapidly. When the control signal is high, the SCR closes and allows the positive (or forward) line voltage to pass to the heater. When the control signal is low or when the AC line voltage becomes negative, the heater receives no power from the SCR.

Solid state relays typically include two SCRs to admit both the positive and negative line voltage to pass to the heater. Modern SCRs have a switching time on the order of the frequency of the line voltage being controlled. This fast switching time literally means that the AC line voltage may be passed through to the heater on a cycle by cycle basis at a frequency of 60 Hz (or 50 Hz outside North America). Figure 3-14 plots the heater voltage from the SCR and corresponding temperature output. In this example, the ideal power input is 40% for the first 167 ms, so the SCR controller passes two voltage cycles through to the heater and then blocks the next three voltage cycles. The power requirement then increases to 80% for the next 167 ms, so the SCR controller passes a proportionally greater number of voltage cycles to the heater.

By passing the line voltage to the heater on an individual cycle basis, the SCR controller can provide much better control than either the electromechanical or mercury displacement relay. Solid state relays incorporating SCRs have been used for heating control since the 1950s [78]. However, these SSRs have only recently become suitable for high power heating applications such as three phase heaters requiring 480 VAC and 50 amp service (24 kW). While SSRs are extremely efficient, they do dissipate heat and require cooling in high power applications.
Figure 3-13: Voltage provided from a silicon controlled rectifier (SCR)

Figure 3-14: SCR pulsed heater control
For even finer control, some solid state relays incorporating thyristors can be operated in a phase angle control mode. In phase angle mode, the line voltage is not admitted on a cycle by cycle basis. Rather, a portion of each cycle of the line voltage is passed through to the heater based on the fraction of heater power that is requested. Figure 3-15 plots the heater voltage from the SCR and corresponding temperature output using phase angle control. In this example, the ideal power input is 40% for the first 167 ms and 80% for the next 167 ms. The phase angle controller provide a portion of the AC waveform so that the total power (the integral of the line voltage squared) closely matches the required heating power. This thyristor control provides two significant benefits. First, the phase angle control provides the best possible temperature control using an AC line voltage for power. Second, the nearly constant current provided by the phase control to the AC heater reduces thermal shock and increases heater longevity.

A comparison of the described heater controls is provided in Table 3-4; mercury displacement relays have become largely obsolete due to their environmental concerns and reduced performance compared to pulsed solid state relays and phase angle controlled thyristors. Modern temperature controllers can interface with any of these devices. Surprisingly, however, the electromechanical relay continues to predominate compared to the solid state alternatives. Perhaps the reason is that end-users are most familiar with electromechanical relays and do not understand the benefits of the solid state devices. Alternatively, some plastics molding machines may have utilized electromechanical relays and there are cost and/or retrofitting issues associated with upgrading to solid state controls. In any case, it can be expected that solid state relays and thyristors will have increased penetration due to their improved performance and reduced life cycle cost.

Figure 3-15: SCR phase angle heater control
Table 3-4: Specifications of Common Heater Controls

<table>
<thead>
<tr>
<th>Specification</th>
<th>EM relay</th>
<th>MD relay</th>
<th>Pulsed SSR</th>
<th>Phased thyristor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cycle time (ms)</td>
<td>30000</td>
<td>4000</td>
<td>15</td>
<td>n/a</td>
</tr>
<tr>
<td>Control type</td>
<td>on/off</td>
<td>on/off</td>
<td>on/off</td>
<td>proportional</td>
</tr>
<tr>
<td>Typical voltage (VAC)</td>
<td>480</td>
<td>480</td>
<td>240</td>
<td>240</td>
</tr>
<tr>
<td>Typical current (A)</td>
<td>50</td>
<td>50</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>Cost ($)</td>
<td>15</td>
<td>n/a</td>
<td>60</td>
<td>140</td>
</tr>
</tbody>
</table>

3.3 Cooling

Heating is typically provided in plastics manufacturing processes to plasticize or soften the melt so that it may be formed to the desired shape. In most applications, cooling is provided to cure or solidify the melt in its desired shape. Cooling is also required to maintain the temperature of the machine components (sensors, actuators, etc.) at a uniform operating temperature. The next section discusses the most common coolants used in plastics processing. The design and operation of coolant temperature controllers are then discussed with other auxiliary equipment.

3.3.1 Coolants

Cooling is typically performed by conveying coolant through or over the machinery, molds, and other tooling. The amount of cooling that may be provided is governed by the coolant’s material properties, mass flow rates, and other heat transfer characteristics. Fundamentally, the rate of heat transfer provided by the coolant is:

\[ P_{\text{coolant}} = \dot{m} \cdot C_p \cdot \Delta T \]  

where \( \dot{m} \) is the mass flow rate (equal to the density times the volumetric flow rate), \( C_p \) is the heat capacity, and \( \Delta T \) is the temperature change of the coolant. Given that all coolants have a finite heat capacity, Eq. 3-9 indicates that there is a trade-off to be made between the coolant’s flow rate and the coolant’s temperature rise. Improved heat transfer and temperature uniformity requires a lower temperature rise of the coolant with higher coolant flow rates.

For economic and environmental reasons, either water or air is most commonly supplied at controlled temperatures. Cooling oil and ethylene glycol mixtures are also often used for high and low temperature cooling applications, respectively. Some properties of these coolants are provided in Table 3-5. Water has the highest specific heat, yet also the most restricted temperature range. Water is also an excellent solvent and can be corrosive. Ethylene glycol and oil have broader temperature ranges, but
3.3 Cooling

1. have a lower specific heat,
2. are much more viscous than water, and
3. require purposefully designed cooling systems.

Air is also a preferred coolant due to its ready availability and low cost but is not feasible in most applications given its low heat capacity which necessitates very high volumetric flow rates.

**Example 3-5:** A thermoforming process forms a $400 \times 300 \times 3 \text{ mm}$ ABS sheet every 60 s. The sheet is formed at a temperature of 150 °C and ejected at a temperature of 60 °C. Estimate the required flow rate of water allowing a temperature rise of only 2 °C between the mold inlet and outlet.

**Solution:**

It is first necessary to analyze the heat loading from the ABS sheet. The mass of the sheet is the density times the volume, or $1.04 \text{ g/cm}^3 \times 40 \text{ cm} \times 30 \text{ cm} \times 0.3 \text{ cm}$, which equals 374 g. With a specific heat of 2340 J/kg °C, the average heat load from the sheet is:

$$P_{\text{sheet}} = \frac{m_{\text{sheet}} \cdot c_{p,\text{sheet}} \cdot \Delta T_{\text{sheet}}}{t_{\text{cycle}}} = \frac{0.374 \text{ kg} \cdot 2340 \text{ J/kg} \cdot \text{°C} \cdot (150 \text{ °C} - 60 \text{ °C})}{60 \text{ s}} = 1314 \text{ W}$$

From Eq. 3-9, the required mass flow rate of the water is:

$$m = \frac{P_{\text{coolant}}}{c_{p} \cdot \Delta T} = \frac{1314 \text{ W}}{4187 \text{ J/kg} \cdot \text{°C} \cdot 2 \text{ °C}} = 0.157 \text{ kg/s}$$

This mass flow rate corresponds to a volumetric flow rate of 0.16 liters per second or 2.5 gallons per minute, which is within the capabilities of typical mold temperature controllers.

**Example 3-6:** Barrels may be actively air cooled by blowers to reduce their temperature overshoot. Estimate the volumetric rate of air flow required to remove 1000 W allowing an increase in the air temperature of 30 °C.

**Solution:** From Eq. 3-9, the required mass flow rate of the air is:

$$m = \frac{P_{\text{coolant}}}{c_{p} \cdot \Delta T} = \frac{1000 \text{ W}}{1005 \text{ J/kg} \cdot \text{°C} \cdot 30 \text{ °C}} = 0.0332 \text{ kg/s}$$

**Table 3-5: Properties of Common Coolants**

<table>
<thead>
<tr>
<th>Coolant property</th>
<th>Air</th>
<th>Water</th>
<th>Ethylene Glycol</th>
<th>ISO 32 Oil</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower use temperature (°C)</td>
<td>20</td>
<td>1</td>
<td>-56</td>
<td>32</td>
</tr>
<tr>
<td>Upper use temperature (°C)</td>
<td>200</td>
<td>100</td>
<td>134</td>
<td>288</td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>1.22</td>
<td>1000</td>
<td>800</td>
<td>900</td>
</tr>
<tr>
<td>Specific heat (J/kg°C)</td>
<td>1005</td>
<td>4187</td>
<td>2261</td>
<td>1842</td>
</tr>
<tr>
<td>Thermal conductivity (W/m°C)</td>
<td>0.025</td>
<td>0.6</td>
<td>0.18</td>
<td>0.16</td>
</tr>
<tr>
<td>Thermal diffusivity (m²/s)</td>
<td>2.04E–05</td>
<td>1.43E–07</td>
<td>9.95E–08</td>
<td>9.65E–08</td>
</tr>
<tr>
<td>Viscosity (Pa s)</td>
<td>1.8E–05</td>
<td>0.001</td>
<td>4.8</td>
<td>14.1</td>
</tr>
</tbody>
</table>
The volumetric flow rate is:

\[ V = \frac{m}{\rho} = \frac{0.0332 \text{ kg/s}}{1.22 \text{ kg/m}^3} = 0.0272 \text{ m}^3/\text{s} = 57.6 \text{ ft}^3/\text{min} \]

This is a substantial but not excessive rate of air flow that could be supplied with a 120 mm fan operate at 1500 RPM.

### 3.3.2 Coolant Temperature Controllers

The temperature of liquid coolant is typically controlled by a pump connected to one or more heat exchangers. One design [79] is shown in Figure 3-16. This design maintains separate cold and hot coolant reservoirs at controlled temperatures. The hot coolant reservoir uses a heater that is controlled by a regulator in response to a hot side thermocouple; the cold coolant reservoir is maintained by a heat exchanger fed colder fluid as determined by a separate regulator in response to the cold side thermocouple. A single motor turns a shaft with propellers to agitate the fluids in the cold and hot coolant reservoirs. The same shaft drives an impeller to pump coolant at pressure through a heat flow calorimeter and the plastics processing machinery to be cooled. The coolant controller temperature controller compares the observed temperature of the output coolant with the set-point temperature, and thereby intermittently opens the cold and hot coolant control valves. The subsequent addition of the cold and hot fluids is used to change the temperature of the coolant.

The coolant temperature controller of Figure 3-16 and most such commercially available units utilize closed cooling circuits. In other words, the coolant flowing and returning to the plastics manufacturing process is returned and recycled by the coolant temperature controller at the prescribed temperature. The re-circulation of the coolant is beneficial for two reasons.

![Figure 3-16: Coolant temperature controller](image)
First, the closed circuit reduces the amount of coolant consumed by the process and allows different coolants such as water, ethylene glycol mixtures, or oil to be temperature controlled. Second, the closed circuit design reduces issues pertaining to environmental contamination. The only fluid drawn by most coolant temperature controllers is the colder fluid associated with the cold side heat exchanger. However, this colder fluid itself may be on its own closed cooling circuit, and is most often provided by an evaporative cooling tower. Alternatively, the cold fluid may be an internally cooled refrigerant undergoing a compression/expansion cycle with air cooling.

The specifications for some typical cooling systems are provided in Table 3-6. The specifications for the water re-circulator is for a design similar to the coolant temperature controller shown in Figure 3-16. The air cooled chiller refers to a similar design but also includes an air-cooled compressor for supplying cold refrigerant to the heat exchanger in the cold side reservoir. The water re-circulator has the lowest cost and mass while providing an intermediate coolant flow rate at a relatively high supply pressure. The cooling power from the water re-circulator depends on design of the internal heat exchanger as well as the temperatures of the returned coolant and the cold fluid – a cooling power of 5 kW might be typical. Because some temperature gradient is required across the heat exchanger, the water re-circulator can not supply coolant temperatures below the temperature of the cold fluid supply.

The air cooled chiller is more massive and expensive than the water re-circulator due to its inclusion of the refrigeration unit. With only 3.5 kW of cooling power, the specified unit has fairly limited cooling capacity as well as lower coolant flow rate and supply pressure than the water re-circulator. However, the chiller provides at least three key benefits. First, the refrigeration unit within the chiller allows the coolant temperature to decrease below room temperature to 5 °C. Second, the chiller is self contained. It requires no hard plumbing and so can be moved around the plant. Third, it provides a closed cooling circuit without any significant contamination modes. Yet, the chiller requires a large (and often loud) fan for air.

### Table 3-6: Comparison of Cooling Systems

<table>
<thead>
<tr>
<th>Coolant Controller</th>
<th>Water re-circulator</th>
<th>Air cooled chiller</th>
<th>Cooling tower</th>
</tr>
</thead>
<tbody>
<tr>
<td>Purchase cost</td>
<td>$2200</td>
<td>$4000</td>
<td>$9,500</td>
</tr>
<tr>
<td>Power supply</td>
<td>230 VAC 19 A</td>
<td>230 VAC 20 A</td>
<td>230 VAC 10 A</td>
</tr>
<tr>
<td>Flow rate</td>
<td>1.89 l/s 30 GPM</td>
<td>1.26 l/s 20 GPM</td>
<td>6.3 l/s 100 GPM</td>
</tr>
<tr>
<td>Supply pressure</td>
<td>262 kPa 38 psi</td>
<td>171 kPa 25 psi</td>
<td>0, pump required</td>
</tr>
<tr>
<td>Minimum coolant temperature</td>
<td>5 °C above water supply</td>
<td>5 °C</td>
<td>25 °C</td>
</tr>
<tr>
<td>Cooling power</td>
<td>variable 3.5 kW</td>
<td>147 kW 12,000 Btu/hr</td>
<td></td>
</tr>
<tr>
<td>Mass</td>
<td>120 kg</td>
<td>200 kg</td>
<td>450 kg</td>
</tr>
</tbody>
</table>
cooling. Furthermore, the chiller consumes a significant amount of power and generates a significant amount of heat. This heat is often passed into the indoor plant environment, and so additional costs can be incurred for air conditioning.

Given the drawbacks of air cooled chillers, most plastics manufacturing plants use evaporative cooling towers to provide a cold water supply throughout the plant. One design is shown in Figure 3-17 [80]. In this design, the warmed coolant is pumped and misted into a cooling chamber. The upward air flow through the cooling chamber prolongs the downward flow of the water. The water is then cooled not only through heat convection to the air but also due to the evaporation of the water. In this manner, the water may be cooled to below the ambient air temperature with a fraction of the power required by a refrigeration cycle. For comparison, Table 3-6 indicates that a cooling tower can provide many times the cooling power of an air cooled chiller while consuming less power. Coolant flow rates through the cooling tower are also comparatively high, though a pump is required to provide substantial supply pressure.

While efficient, cooling towers have some potential limitations. First, the cooling ability of the cooling tower is related to the temperature of the warmed coolant as well as the temperature and humidity of the surrounding environment. For these reasons, cooling towers can not provide a coolant significantly below the ambient temperature. Second, ambient air contacts the coolant and so offers the potential for two-way contamination. Airborne particulates (dust, pollen, etc.) may contaminate the coolant and jeopardize the operation of the machinery being cooled. At the same time, waterborne contaminants (dissolved metals, chloride, etc.) may be transferred to the circulating air and discharged. For this reason, placement of the cooling tower as well as filtering of the water and air should be considered. Alternative cooling tower designs, referred to as indirect systems, are also available that do not allow the cooling water to come into contact with the air, thereby reducing contamination issues. Unfortunately, these indirect systems require an additional heat exchanger and so are larger, more costly, and less efficient than direct cooling towers.
3.4 Transient Analysis

An understanding about heating and cooling elements is helpful to their specification and operation in plastics manufacturing processes. For the purposes of process control, moreover, it is beneficial to model the dynamic behavior of these elements and their interaction with the machinery and processed materials. Typical analyses may include the heating of a machine barrel or the cooling of a formed plastic. Both of these analyses require the solution of the transient heat conduction equation [81] to obtain the temperature, $T$, as a function of time, $t$, and position, $x$:

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2}$$  \hspace{1cm} (3-10)

where the thermal diffusivity, $\alpha$, is the ratio of the thermal conductivity, $k$, to the product of the density, $\rho$, and the specific heat, $C_p$:

$$\alpha = \frac{k}{\rho C_p}$$  \hspace{1cm} (3-11)

Equation 3-10 is a partial differential solution that is often solved numerically via the finite element or finite difference methods for applications with complex geometries. However, these numerical approaches are not so useful from a controls perspective. Rather, analytical solutions are preferred so to optimize the stability and control of heating and cooling. Two simplified approaches are next presented.

3.4.1 Lumped Thermal Capacitance

One way to simplify the transient heat conduction equation is to assume that the temperature of the solid body varies with time but does not vary substantially as a function of position within the solid body. This model is depicted in Figure 3-18, in which a solid body with volume, $V$, is at a constant initial temperature, $T_i$. At some time, the solid body is exposed to a heating or cooling fluid with a temperature $T_\infty$ and a heat transfer coefficient $h_\infty$. The lumped thermal capacitance analysis will predict the dynamic temperature of the solid body as a function of time.

This approach is valid when the solid body has high internal heat conduction compared to the rate of heat transfer being externally applied. To check the validity of this assumption, the Biot number should be less than one:

$$Bi = \frac{h_\infty}{k} < 1$$  \hspace{1cm} (3-12)

where $k$ is the thermal conductivity of the solid body, and $H$ is the characteristic thickness of the solid body that governs the heating or cooling dynamics.
The heat transfer coefficient \( h_\infty \) is dependent on the geometry of the solid body being heated or cooled as well as the properties and flow rate of the fluid. Specifically, the heat transfer coefficient will differ with laminar and turbulent fluid flow as characterized by the Reynolds number:

\[
\text{Re} = \frac{\rho v x}{\mu}
\]

where \( \rho \) is the density of the surrounding fluid, \( v \) is its linear velocity, \( x \) is the thickness of the boundary layer (often assessed as the tube diameter \( D \) for an internal flow), and \( \mu \) is the fluid viscosity. A high Reynolds number indicates that there is significant fluid inertia compared to the viscous forces and so is likely turbulent. Conversely, a low Reynolds number indicates that the flow is dominated by viscous forces and so predominantly laminar.

For engineering calculations, the heat transfer coefficients may be estimated for internal or external flows according to the formulae provided in Table 3-7, which has been adapted from

\[
\text{Solid Body} \quad V, \rho, \kappa, \varepsilon, \quad T(x,y,z,r=0)-T_i \\
\text{Fluid} \quad h_\infty, T_\infty
\]

**Figure 3-18:** Lumped thermal capacitance model

<table>
<thead>
<tr>
<th>Application</th>
<th>Air</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal laminar flow</td>
<td>( h_\infty = 0.042 \left( \frac{\text{Re}}{L D^2} \right)^{0.33} )</td>
<td>( h_\infty = 2.1 \left( \frac{\text{Re}}{L D^2} \right)^{0.33} )</td>
</tr>
<tr>
<td>Internal turbulent flow</td>
<td>( h_\infty = 0.00053 \frac{\text{Re}^{0.8}}{D} )</td>
<td>( h_\infty = 0.026 \frac{\text{Re}^{0.8}}{D} )</td>
</tr>
<tr>
<td>External laminar flow</td>
<td>( h_\infty = 0.015 \frac{\text{Re}^{0.5}}{L} )</td>
<td>( h_\infty = 0.84 \frac{\text{Re}^{0.5}}{L} )</td>
</tr>
<tr>
<td>External turbulent flow</td>
<td>( h_\infty = 0.00081 \left( \frac{\text{Re}-23,200}{L} \right)^{0.8} )</td>
<td>( h_\infty = 0.041 \left( \frac{\text{Re}-23,200}{L} \right)^{0.8} )</td>
</tr>
</tbody>
</table>
3.4 Transient Analysis

Kreith and Black [82]. In this table, turbulent flow corresponds to Reynolds numbers above 50,000 and the laminar flow equations should be used otherwise. For internal flows, such as cooling lines inside of a mold or die, the variables $D$ and $L$ correspond to the diameter and length of the passageway. For external flows, such as over an extrudate, $L$ corresponds to the length of the solid body undergoing cooling.

Example 3-7: Calculate the heat transfer coefficient and Biot number for an extrudate flowing through a 4 m cooling bath having a water flow velocity of 0.04 m/s. The wall thickness and thermal conductivity of the extrudate are respectively 2 mm and 0.2 W/mK.

Solution: First calculate the Reynolds number to check for laminar or turbulent flow. The exact thickness of the boundary layer is not known. However, a typical water bath is 0.2 m wide. If the extrudate is centered, then a reasonable boundary layer thickness is 0.1 m. The Reynolds number is then:

$$Re = \frac{\rho V x}{\mu} = \frac{1000 \text{ kg/m}^3 \cdot 0.04 \text{ m/s} \cdot 0.1 \text{ m}}{0.001 \text{ Pa s}} = 4000$$

The heat transfer coefficient is:

$$h_\infty = 0.5 \frac{Re^{0.5}}{L} = 0.5 \cdot \frac{4000^{0.5}}{4 \text{ m}} = 13.3 \text{ W/m}^2\text{K}$$

The Biot number for the cooling plastic can then be calculated as:

$$Bi = \frac{h_\infty}{(k/H)} = \frac{13.3 \text{ W/m}^2\text{K}}{(0.2 \text{ W/mK} / 0.002 \text{ m})} = 0.13 < 1$$

This analysis indicates that even while the plastic has a low thermal conductivity, its small wall thickness provides a low internal heating resistance relative to the convective cooling of the water bath.

For applications that have negligible internal resistance, the transient heat conduction Eq. 3-10 simplifies to:

$$\frac{\partial T}{\partial t} = -\frac{h_\infty A}{\rho V c_p} (T - T_\infty) \quad 3-14$$

where $h_\infty$ is the average convective heat transfer coefficient associated with the coolant at temperature $T_\infty$, while $A$, $V$, $\rho$, and $c_p$ are the surface area, volume, density, and specific heat of the solid body. The initial condition is that the solid body has a uniform temperature, $T_i$:

$$T(t = 0) = T_i \quad 3-15$$

The temperature of the solid body may then be solved by integrating Eq. 3-14 and applying the initial condition. The solution is:

$$T(t) = (T_i - T_\infty) \exp \left( -\frac{h_\infty A}{\rho V c_p} t \right) + T_\infty \quad 3-16$$
The total heat transfer, \( Q \), applied to the solid body is:

\[
Q(t) = \rho V c_p (T_i - T_\infty) \left[ 1 - \exp \left( -\frac{h_\infty A}{\rho V c_p} t \right) \right]
\]

Equation 3-16 may be written in the form:

\[
T(t) = (T_i - T_\infty) \exp \left( -\frac{t}{\tau} \right) + T_\infty
\]

where \( \tau \) is the time constant defined for this analysis as:

\[
\tau = \frac{\rho V c_p}{h_\infty A}
\]

The time constant is the amount of time required for the process to change by a factor of \( 1/e \). The time constant is a measure of the rate of decay; higher time constants mean that the system will respond more slowly. Figure 3-19 is a non-dimensional plot of Eq. 3-18 with \( T_i \) set to 100% and \( T_\infty \) set to 0%. Initially, the solid body is at a temperature corresponding to 100%. After a long period of time, the solid body will approach the temperature of the fluid, corresponding to a value of 0%. After one time constant, the temperature has dropped to \( 1/e \) or 36.8% of its initial value; this corresponds to a change of \( (1 - 1/e) \) or 63.2%.

**Figure 3-19:** Dynamic temperature response
Equation 3-19 indicates that the time constant of a system with a lumped thermal capacity increases with the mass, volume, or heat capacity of the solid body but decreases with an increasing heat transfer coefficient or surface area.

Example 3-8: Calculate the exit temperature of an extrudate flowing through a 4 m cooling bath having a water flow velocity of 0.04 m/s. The linear velocity, wall thickness, thermal conductivity, density, and heat capacity of the extrudate are respectively 30 mm/s, 2 mm, 0.2 W/mK, 1000 kg/m$^3$, and 1980 J/kgK. The initial temperature of the extrudate is 200 °C and the temperature of the water bath is 30 °C.

Solution: The previous example estimated a heat transfer coefficient of 13.3 W/m$^2$K. Since plastic extrudates are relatively thin compared to their other dimensions, the volume of the part may be well estimated as the surface area times the wall thickness:

$$V = A \cdot H$$

This approximation allows the substitution of the relationship $V/A = H$ in Eq. 3-19. The time constant of the extrudate may then be evaluated as:

$$\tau = \frac{\rho c_p H}{h_w} = \frac{1000 \text{ kg/m}^3 \cdot 1980 \text{ J/kgK} \cdot 0.002 \text{ m}}{13.3 \text{ W/m}^2 \text{K}} = 298 \text{ s}$$

This result means that it will take 298 s for the temperature of the extrudate to change 68.2% of the difference between the initial extrudate and the coolant temperature.

To calculate the exit temperature of the extrudate, the duration of the cooling time in the water bath is estimated as the length of the water bath divided by the linear velocity of the extrudate:

$$t_{cooling} = \frac{L}{v} = \frac{4 \text{ m}}{0.02 \text{ m/s}} = 200 \text{ s}$$

![Figure 3-20: Extrudate temperature response](image-url)
The temperature of the extrudate will follow Eq. 3-18. Substitution provides the result:

\[
T(t = 200 \text{ s}) = (30 \degree \text{C} - 200 \degree \text{C}) \exp \left( \frac{200 \text{ s}}{298 \text{ s}} \right) + 30 \degree \text{C} = 117 \degree \text{C}
\]

This function is plotted as a function of time in Figure 3-20. Given the length of the water bath and processing conditions, the extrudate has only cooled to a temperature of 117 \degree \text{C}. If this temperature is not sufficiently low, then the extrusion molder may choose to reduce the extrusion velocity, water bath temperature, or extrudate temperature. Alternatively, the length of the water bath may be increased.

### 3.4.2 Finite Thickness Model

Consider a plastic or machine sheet or plate with thickness, \(H\), at an initial temperature \(T_i\). A temperature, \(T_w\), is subsequently applied at the side walls of the sheet as shown in Figure 3-21. The finite thickness analysis will predict the subsequent temperature distribution in the solid. This type of model has many applications including the heating or cooling of cylindrical barrels as well as the cooling of formed plastics.

The heat conduction Eq. 3-10 is a parabolic partial differential equation which is solved by separation of variables [83] leading to a series solution. For a semi-infinite plate with thermal diffusivity, \(\alpha\), and thickness, \(H\), the average temperature in the plate is estimated by the first two terms in the solution as:

\[
\bar{T}(t) = (T_i - T_w) \left[ 0.811 \exp \left( -9.87 \frac{\alpha}{H^2} t \right) + 0.090 \exp \left( -88.8 \frac{\alpha}{H^2} t \right) + \ldots \right] + T_w \quad 3-20
\]

Inspection of Eq. 3-20 indicates that the first term is dominant for two reasons. First, the coefficient 0.811 for the first term is significantly greater than that of the subsequent terms. The maximum value for the average temperature will occur at time 0 where \(\exp(0) = 1\), so the first term provides 81.1% of the solution value at time 0. Second, the coefficient 9.87 within the exponent of the first term is significantly smaller than that of the subsequent terms. As such, the contribution of the higher order terms to the solution will tend to drop off rapidly with time. For example, \(\exp(-0.987) = 0.37\) while \(\exp(-8.88) = 0.00014\).

**Figure 3-21:** Dynamic temperature distribution in a solid with finite thickness
This discussion indicates that the higher order terms are only significant when an accurate solution is needed for times immediately following the application of the heating or cooling at the side walls. For control purposes, the average temperature in the solid may be well estimated as:

$$T(t) = (T_i - T_w) \exp\left(-\frac{t}{\tau}\right) + T_w$$

where $\tau$ is the time constant defined by this analysis as:

$$\tau = \frac{H^2}{9.87 \alpha} = \frac{H^2 \rho c_p}{9.87 k}$$

The time constant indicates that the heating or cooling dynamics are proportional to the square of the wall thickness and inversely proportional to the thermal diffusivity. Consideration of the time constant in Eq. 3-22 for the finite thickness model indicates that the rate of heat transfer slows with increasing part thickness, density, or heat capacity. Furthermore, the dynamics of the finite thickness model also slow with decreasing thermal conductivity since more time is required to transfer heat through the solid due to significant thermal resistance.

**Example 3-9:** An injection molded part is 3 mm thick and molded of polycarbonate with a thermal diffusivity of $1.5 \cdot 10^{-7}$ m$^2$/s and a melt temperature of 290 °C. If the mold wall temperature is maintained at 80 °C, estimate the time required for the plastic to cool to a temperature of 130 °C so the molded part may be ejected.

**Solution:** Substituting the part thickness and material properties into Eq. 3-22 provides:

$$\tau = \frac{H^2}{9.87 \alpha} = \frac{(0.003 \text{ m})^2}{9.87 \cdot 1.9 \cdot 10^{-7} \text{ m}^2/\text{s}} = 4.80 \text{ s}$$

The average temperature of the molded plastic using Eq. 3-21 and a time constant of 4.8 s is plotted as a function of time in Figure 3-22. The analysis indicates that about 8.6 s is required to cool the molded plastic to a suitable ejection temperature. Also plotted is a solution of the heat conduction Eq. 3-20 with nine terms. It is observed that the simplified model of Eq. 3-20 provides a slower dynamic due to the absence of the higher order terms. Still, the simplified model provides a reasonable and conservative solution. Furthermore, the exact solution will over estimate the temperature decay given that

1. the mold wall temperature will increase when contacted by the hot polymer melt,
2. there is a thermal contact resistance between the mold and the molded plastic, and
3. there is a finite thermal resistance between the mold wall and the coolant.

The foregoing analysis may also be applied to a solid having a finite thickness that is only cooled from one side. The left section of Figure 3-23 shows the associated conditions and temperature distribution. This model applies to blow molding and thermoforming where the formed plastic is cooled by a hollow mold. The vast majority of the heat will transfer from the

*** Wo ist Example 3-9 zu Ende??? ***
side of the plastic in contact with the mold while a negligible amount of heat will be transferred by radiation or convection from the other side of the formed part. This model also applies to two shot molding in which a layer of plastic is molded over another layer of plastic having low thermal conductivity.

The temperature dynamics in a finite solid with one sided heat transfer is readily solved once the significance of the negligible heat transfer condition is recognized. Specifically, a zero heat transfer boundary condition requires that:

\[ Q = k \frac{dT}{dx} = 0 \Rightarrow \frac{dT}{dx} = 0 \]  \hspace{1cm} 3-23

**Figure 3-22:** Average temperature during cooling of molded part

**Figure 3-23:** Finite solid with one sided heat transfer
This boundary condition implies that one sided heat transfer can be modeled by Eqs. 3-21 and 3-22 by doubling the thickness of \( H \). The resulting solution satisfies the boundary condition of Eq. 3-23 as depicted by the right section of Figure 3-23. The time constant for one sided heat transfer is:

\[
\tau = \frac{(2\ H)^2}{9.87 \alpha} = \frac{H^2}{2.47 \alpha}
\]

Example 3-10: A blow molding process uses polyethylene with a thermal diffusivity of \( 9.7 \cdot 10^{-8} \text{ m}^2/\text{s} \), a melt temperature of 160 °C, a mold coolant temperature of 30 °C, and an ejection temperature of 90 °C. Determine the cooling time for a part with thickness of 1 mm.

**Solution:** The time for a solid to reach an average target temperature, \( T_{\text{target}} \), may be solved explicitly from Eq. 3-21 as:

\[
t = -r \ln \left( \frac{T_{\text{target}} - T_w}{T_i - T_w} \right)
\]

For a 1 mm thick polyethylene part with one sided heat transfer, the time constant from Eq. 5-24 is estimated as:

\[
\tau = \frac{(2\ H)^2}{9.87 \alpha} = \frac{(0.001\ m)^2}{2.47 \cdot 9.7 \cdot 10^{-8} \text{ m}^2/\text{s}} = 4.17 \text{ s}
\]

The time to cool from 160 °C to an average temperature of 90 °C is then:

\[
t = -r \ln \left( \frac{T_{\text{target}} - T_w}{T_i - T_w} \right) = -4.17 \text{ s} \ln \left( \frac{90^\circ \text{C} - 30^\circ \text{C}}{160^\circ \text{C} - 30^\circ \text{C}} \right) = 3.2 \text{ s}
\]

A similar transient analysis is applicable for cylinders with a diameter, \( D \), at an initial temperature of \( T_i \). When the cylinder’s surface is exposed to an outer wall temperature, \( T_w \), the average temperature of the cylinder is:

\[
\bar{T}(t) = (T_i - T_w) \left[ 0.692 \exp \left( -23.1 \frac{\alpha}{D^2} t \right) + 0.131 \exp \left( -122 \frac{\alpha}{D^2} t \right) + \cdots \right] + T_w
\]

Compared to the temperature of Eq. 3-20 for a sheet, the solution of Eq. 3-26 for a cylinder has some significant differences. First, the 0.692 coefficient in the first term of Eq. 3-26 is less than the 0.811 coefficient in Eq. 3-20. This lower coefficient implies that the higher order terms play a more significant role for the temperature dynamics of the cylinder, which is also verifiable by comparing the coefficients related to the second and higher order terms. Second, the exponents in the first and second terms of Eq. 3-26 are less than the corresponding exponents of Eq. 3-20. The lower exponents means that a cylinder of diameter, \( D \), will cool more quickly than a sheet of thickness, \( H = D \). The reason is that the cylinder has much greater surface area per unit volume and so will conduct more heat given the same surface temperature.

Still, the average temperature in the cylindrical solid may be roughly estimated according to Eq. 3-21 where the time constant, \( \tau \), for a cylinder is defined as:
Example 3-11: An extruder has a steel barrel with a diameter of 250 mm. Given the steel’s thermal diffusivity of $1 \cdot 10^{-5} \text{ m}^2/\text{s}$, determine the time required to raise the barrel temperature from 20 °C to 300 °C assuming a surface temperature of 350 °C applied by the heaters.

Solution: For a 250 mm diameter barrel having a thermal diffusivity of $1 \cdot 10^{-5} \text{ m}^2/\text{s}$, the time constant from Eq. 3-27 is:

$$\tau = \frac{D^2}{23.1 \alpha}$$

From Eq. 3-25, the time to heat the barrel from 20 °C to an average temperature of 300 °C is then:

$$t = -\tau \ln \left( \frac{T_{\text{target}} - T_w}{T_i - T_w} \right) = -271 \text{s} \cdot \ln \left( \frac{300 \degree C - 350 \degree C}{20 \degree C - 350 \degree C} \right) = 511 \text{s}$$

It would take about 8.5 minutes to heat the barrel to an average temperature of 300 °C if a 350 °C surface temperature was applied. It should be noted that the actual heating time for the barrel is dependent on the wattage of the barrel heaters and the applied heating power. The surface temperature of the barrel at the onset of heating could be significantly less than 350 °C, which would extend the heating time. Furthermore, extruder barrels typically contain a screw surrounded by plastic with a relatively low thermal diffusivity. For these reasons, plastics process controllers frequently implement with a soak time after the barrel temperature has reached its target value to ensure that the center of the barrel is at a relatively uniform temperature.

### 3.5 Summary

Heating and cooling are vital elements of most plastics manufacturing processes. Heating is typically applied to plasticate or soften the polymer so that it may readily formed. There are many different forms of heaters. Band heaters, plate heaters, and cartridge heaters are usually constructed of wound resistive wire consisting of a nickel/chrome alloy “nichrome” wrapped around and housed within electrically insulating support members. Nichrome is the material of choice given its operating temperature of 1200 °C, and high electrical resistivity. The power density and maximum operating temperature of heaters is determined by the density of the resistive windings and the properties of the insulating members. Heaters incorporating mica insulation typically provide a power density of about 10 W/cm² and a maximum operating temperature of 480 °C. Higher power densities and operating temperatures are available with different designs and materials, but often with increased cost. Advanced heater designs have been developed to integrate heating sheath elements and thick film heaters more closely with machine components to improve response time and temperature uniformity.

Heaters can be controlled in an “on/off” fashion with conventional electromechanical relays or, more recently, with solid state relays. Electromechanical relays are frequently cycled every 30 s
or so to avoid excessive relay wear and failure. By comparison, solid state relays incorporate silicon controlled rectifiers that can cycle the power with every cycle of the supplied power’s alternating current. As such, solid state relays provide a cycle time of 20 ms. The shorter cycle time of the solid state relay not only provides improved temperature control but also increases the heater lifetime by avoiding excessive heater temperatures. For more continuous heater controls, SCR phase angle or “thyristor” control can provide proportional power to the heater by admitting only a portion of the AC power cycle. While solid state relays and thyristors provide improved control and heater longevity, they are more expensive and have had lower power ratings than conventional electromechanical relays.

Cooling is typically applied to solidify or cure the formed plastic in its desired shape; cooling is also often applied to machine elements to maintain actuators at desired operating temperatures. For economic and environmental reasons, air and water are the most frequently used coolants. Most coolant temperature controllers use closed fluid circuits to minimize contamination of the coolant and the environment. Typically, a heat exchanger is used for transferring heat from the warmed coolant to a supplied cooler fluid. The cooler fluid may be a refrigerant undergoing a compression/expansion cycle with air cooling. Alternatively, the cooler fluid is often chilled water that is more economically provided from a cooling tower incorporating an evaporative cooler.

The temperature dynamics of heating and cooling are predicted by according to the transient heat conduction equation. The lumped thermal capacitance model is used when the solid body being heated or cooled has a small internal heat resistance compared to the rate of heat transfer being externally applied; the heat transfer coefficient is related to the properties of the surrounding fluid and the flow regime as indicated by the Reynolds number. When a solid has a significant internal heat resistance, the solution of the heat conduction equation leads to a series solution. Even so, the temperature dynamics are dominated by the first term of the series solution.

For both the lumped thermal capacitance and the finite thickness analyses, the temperature dynamics are well modeled by a first order model of the form:

\[ T(t) = (T_i - T_m) \exp\left(-\frac{t}{\tau}\right) + T_m \] 3-28

where \( \tau \) is a time constant related to the geometry and material properties of the application. For the lumped capacitance analysis, the time constant increases with the mass, volume, or heat capacity of the solid and decreases with an increasing heat transfer coefficient or surface area. For the finite thickness analysis, the time constant increases with the square of the wall thickness and decreases with the thermal diffusivity of the material. These models are useful in predicting the temperature dynamics of plastics processing machinery, and can also be used to also investigate the stability of the processes and optimize the controller performance.