HEATING AND POURING
To perform a casting operation, the metal must be heated to a temperature somewhat above its melting point and then poured into the mold cavity to solidify. In this section, we consider several aspects of these two steps in casting.

Heating furnaces of various kinds are used to heat the metal to a molten temperature sufficient for casting. The heat energy required is the sum of
(1) the heat to raise the temperature to the melting point,
(2) the heat of fusion to convert it from solid to liquid,
(3) the heat to raise the molten metal to the desired temperature for pouring.
This can be expressed:
\[
H = \rho V \{ C_s [T_m - T_o] + H_f + C_l (T_p - T_m) \}
\]

Where
\( H \) = total heat required to raise the temperature of the metal to the pouring temperature, J
\( \rho \) = Density g/cm\(^3\)
\( V \) = Volume of metal Heated cm\(^3\)
\( H_f \) = Heat of Fusion J/g
\( C_s \) = weight specific heat for the solid metal, J/g\(^\circ\)C
\( C_l \) = weight specific heat of the liquid metal, J/g\(^\circ\)C
\( T_p \) = Pouring Temperature \(^\circ\)C
\( T_m \) = Melting Temperature of metal \(^\circ\)C
\( T_o \) = starting temperature-usually ambient\(^\circ\)C

The above equation is of conceptual value, but its computational value is limited, notwithstanding our example calculation.
Use of Eq. (1) is complicated by the following factors:
(1) Specific heat and other thermal properties of a solid metal vary with temperature, especially if the metal undergoes a change of phase during heating.
(2) A metal’s specific heat may be different in the solid and liquid states.
(3) Most casting metals are alloys, and most alloys melt over a temperature range between a solidus and liquidus rather than at a single melting point; thus, the heat of fusion cannot be applied so simply as indicated above.

(4) The property values required in the equation for a particular alloy are not readily available in most cases.

(5) There are significant heat losses to the environment during heating.

**EX1** One cubic meter of a certain eutectic alloy is heated in a crucible from room temperature to 100°C above its melting point for casting. The alloy’s density = 7.5 g/cm³, melting point = 800°C, specific heat=0.33 J/g°C in the solid state and 0.29 J/g°C in the liquid state; and heat of fusion= 160 J/g. How much heat energy must be added to accomplish the heating, assuming no losses?

**Sol:**

\[ H = \{7.5(10^6)\}(0.33)(800-25)+ 160+(0.29(100)) \]

\[ = 3335(10^6) \text{ J} \]
POURING THE MOLTEN METAL

After heating, the metal is ready for pouring. Introduction of molten metal into the mold, including its flow through the gating system and into the cavity, is a critical step in the casting process. For this step to be successful, the metal must flow into all regions of the mold before solidifying. Factors affecting the pouring operation include pouring temperature, pouring rate, and turbulence. The pouring temperature is the temperature of the molten metal as it is introduced into the mold. What is important here is the difference between the temperature at pouring and the temperature at which freezing begins (the melting point for a pure metal or the liquidus temperature for an alloy). This temperature difference is sometimes referred to as the superheat. This term is also used for the amount of heat that must be removed from the molten metal between pouring and when solidification commences. Pouring rate refers to the volumetric rate at which the molten metal is poured into the mold. If the rate is too slow, the metal will chill and freeze before filling the cavity. If the pouring rate is excessive, turbulence can become a serious problem. Turbulence in fluid flow is characterized by erratic variations in the magnitude and direction of the velocity throughout the fluid. The flow is agitated and irregular rather than smooth and streamlined, as in laminar flow. Turbulent flow should be avoided during pouring for several reasons. It tends to accelerate the formation of metal oxides that can become entrapped during solidification, thus degrading the quality of the casting. Turbulence also aggravates mold erosion, the gradual wearing away of the mold surfaces due to impact of the flowing molten metal. The densities of most molten metals are much higher than water and other fluids we normally deal with. These molten metals are also much more chemically reactive than at room temperature. Consequently, the wear caused by the flow of these metals in the mold is significant, especially under turbulent conditions. Erosion is especially serious when it
occurs in the main cavity because the geometry of the cast part is affected.

**ENGINEERING ANALYSIS OF POURING**

There are several relationships that govern the flow of liquid metal through the gating system and into the mold. An important relationship is *Bernoulli’s theorem*, which states that the sum of the energies (head, pressure, kinetic, and friction) at any two points in a flowing liquid are equal. This can be written in the following form:

\[
\begin{align*}
    h_1 + \frac{p_1}{\rho} &= \frac{v_1^2}{2g} + F_1 = \frac{p_2}{\rho} + \frac{v_2^2}{2g} + F_2
\end{align*}
\]

Bernoulli’s equation can be simplified in several ways. If we ignore friction losses (to be sure, friction will affect the liquid flow through a sand mold), and assume that the system remains at atmospheric pressure throughout, then the equation can be reduced to

\[
\begin{align*}
    h_1 + \frac{v_1^2}{2g} &= h_2 + \frac{v_2^2}{2g}
\end{align*}
\]

This can be used to determine the velocity of the molten metal at the base of the sprue. Let us define point 1 at the top of the sprue and point 2 at its base. If point 2 is used as the reference plane, then the head at that point is zero \((h_2 = 0)\) and \(h_1\) is the height (length) of the sprue. When the metal is poured into the pouring cup and overflows down the sprue, its initial velocity at the top is zero \((v_1 = 0)\). Hence, Eq. (3) further simplifies to

\[
\begin{align*}
    h_1 &= \frac{v_2^2}{2g}
\end{align*}
\]

which can be solved for the flow velocity.
\[ v = \sqrt{2gh} \]

where \( v \) = the velocity of the liquid metal at the base of the sprue, cm/s; \( g \) = 981 cm/s/s and \( h \) = the height of the sprue, cm

Another relationship of importance during pouring is the continuity law, which states that the volume rate of flow remains constant throughout the liquid. The volume flow rate is equal to the velocity multiplied by the cross-sectional area of the flowing liquid. The continuity law can be expressed:

\[ Q = v_1A_1 = v_2A_2 \]

where \( Q \) = volumetric flow rate, cm\(^3\)/s (in\(^3\)/sec); \( v \) = velocity as before; \( A \) = cross-sectional area of the liquid, cm\(^2\) and the subscripts refer to any two points in the flow system. Thus, an increase in area results in a decrease in velocity, and vice versa. Equations indicate that the sprue should be tapered. As the metal accelerates during its descent into the sprue opening, the cross-sectional area of the channel must be reduced; otherwise, as the velocity of the flowing metal increases toward the base of the sprue, air can be aspirated into the liquid and conducted into the mold cavity. To prevent this condition, the sprue is designed with a taper, so that the volume flow rate \( vA \) is the same at the top and bottom of the sprue.
Schematic showing the advantages of a tapered sprue over a straight-sided sprue. (a) Natural flow of a free-falling liquid. (b) Air aspiration induced by liquid flow in a straight-sided sprue. (c) Liquid flow in a tapered sprue.

Assuming that the runner from the sprue base to the mold cavity is horizontal (and therefore the head h is the same as at the sprue base), then the volume rate of flow through the gate and into the mold cavity remains equal to \( v_A \) at the base. Accordingly, we can estimate the time required to fill a mold cavity of volume \( V \) as

\[
MFT = \frac{V}{Q}
\]

Where \( TMF \) = mold filling time, s (sec); \( V \) = volume of mold cavity, cm\(^3\) and \( Q \) = volume flow rate, as before. The mold filling time computed by Eq. (6) must be considered a minimum time. This is because the analysis ignores friction losses and possible constriction of flow in the gating system; thus, the mold filling time will be longer than what is given by Eq. (6).

**EX2** A mold sprue is 20 cm long, and the cross-sectional area at its base is 2.5 cm\(^2\). The sprue feeds a horizontal runner leading into a mold cavity whose volume is 1560 cm\(^3\). Determine:

(a) velocity of the molten metal at the base of the sprue,
(b) volume rate of flow,
(c) time to fill the mold.

(a) The velocity of the flowing metal at the base of the sprue is given by Eq. (4):

\[
V = \sqrt{2(981)(20)} = 198.1 \text{ cm/s}
\]

(b) The volumetric flow rate is

\[
Q = (2.5 \text{ cm}^2)(198.1 \text{ cm/s}) = 495 \text{ cm}^2/\text{s}
\]

(c) Time required to fill a mold cavity of 100 in\(^3\) at this flow rate is

\[
TMF = \frac{1560}{495} = 3.2 \text{ s}
\]
FLUIDITY
The molten metal flow characteristics are often described by the term fluidity, a measure of the capability of a metal to flow into and fill the mold before freezing. Fluidity is the inverse of viscosity as viscosity increases, fluidity decreases. Standard testing methods are available to assess fluidity, including the spiral mold test shown in Figure in which fluidity is indicated by the length of the solidified metal in the spiral channel. A longer cast spiral means greater fluidity of the molten metal.

Factors affecting fluidity include
1. pouring temperature relative to melting point,
2. metal composition
3. viscosity of the liquid metal
4. heat transfer to the surroundings.

A higher pouring temperature relative to the freezing point of the metal increases the time it remains in the liquid state, allowing it to flow further before freezing. This tends to aggravate certain casting problems such as oxide formation, gas porosity, and penetration of liquid metal into the interstitial spaces between the grains of sand forming the mold. This last problem causes the surface of the casting to contain imbedded sand particles, thus making it rougher and more abrasive than normal. Composition also affects fluidity, particularly with respect to the metal’s solidification mechanism. The best fluidity is obtained by metals that freeze at a constant temperature (e.g., pure metals and eutectic alloys). When solidification occurs over a temperature range (most alloys are in this category), the partially solidified portion interferes with the flow of the liquid portion, thereby reducing fluidity. In addition to the freezing mechanism, metal composition also determines heat of fusion—the amount of heat required to solidify the metal from the liquid state.
A higher heat of fusion tends to increase the measured fluidity in casting.
Problems in Heating and Pouring

10.1 A disk 40 cm in diameter and 5 cm thick is to be cast of pure aluminum in an open-mold casting operation. The melting temperature of aluminum = 660°C, and the pouring temperature will be 800°C. Assume that the amount of aluminum heated will be 5% more than what is needed to fill the mold cavity. Compute the amount of heat that must be added to the metal to heat it to the pouring temperature, starting from a room temperature of 25°C. The heat of fusion of aluminum = 389.3 J/g. Other properties can be obtained from Tables 4.1 and 4.2 in the text. Assume the specific heat has the same value for solid and molten aluminum.

10.2. A sufficient amount of pure copper is to be heated for casting a large plate in an open mold. The plate has dimensions: length = 20 in, width = 10 in, and thickness 3 in. Compute the amount of heat that must be added to the metal to heat it to a temperature of 2150°F for pouring. Assume that the amount of metal heated will be 10% more than what is needed to fill the mold cavity. Properties of the metal are: density = 0.324 lbm/in³, melting point = 1981°F, specific heat of the metal = 0.093 Btu/lbm °F in the solid state and 0.090 Btu/lbm °F in the liquid state, and heat of fusion = 80 Btu/lbm.

10.3. The down sprue leading into the runner of a certain mold has a length = 175 mm. The cross-sectional area at the base of the sprue is 400 mm². The mold cavity has a volume ¼ 0.001 m³. Determine (a) the velocity of the molten metal flowing through the base of the downsprue, (b) the volume rate of flow, and (c) the time required to fill the mold cavity.

10.4. A mold has a down sprue of length = 6.0 in. The
cross-sectional area at the bottom of the sprue is 0.5 in$^2$. The sprue leads into a horizontal runner which feeds the mold cavity, whose volume=75 in$^3$. Determine (a) the velocity of the molten metal flowing through the base of the down sprue, (b) the volume rate of flow, and (c) the time required to fill the mold cavity.

10.5. The flow rate of liquid metal into the downsprue of a mold = 1 L/s. The cross-sectional area at the top of the sprue =800 mm$^2$, and its length =175 mm.
What area should be used at the base of the sprue to avoid aspiration of the molten metal?

10.6. The volume rate of flow of molten metal into the Down sprue from the pouring cup is 50 in$^3$/sec. At the top where the pouring cup leads into the downsprue, the cross-sectional area=1.0 in$^2$.Determine what the area should be at the bottom of the sprue if its length =8.0 in. It is desired to maintain a constant flow rate, top and bottom, in order to avoid aspiration of the liquid metal.

10.7. Molten metal can be poured into the pouring cup of a sand mold at a steady rate of 1000 cm$^3$/s. The molten metal overflows the pouring cup and flows into the downsprue. The cross-section of the sprue is round, with a diameter at the top=3.4 cm. If the sprue is 25cm long, determine the proper diameter at its base so as to maintain the same volume flow rate.

10.8. During pouring into a sand mold, the molten metal can be poured into the downsprue at a constant flow rate during the time it takes to fill the mold. At the end of pouring the sprue is filled and there is negligible metal in the pouring cup. The downsprue is 6.0 in long. Its cross-sectional area at the top=$\frac{3}{4}$0.8 in$^2$ and at the base=0.6 in$^2$.The cross-sectional area of the runner leading from the sprue also = 0.6 in$^2$, and it is 8.0 in long before leading into the mold cavity, whose volume=65 in$^3$. The volume of the riser located along the runner near the mold cavity= 25 in$^3$. It takes a total of 3.0 sec to fill the entire mold.
(including cavity, riser, runner, and sprue. This is more than the theoretical time required, indicating a loss of velocity due to friction in the sprue and runner.
Find (a) the theoretical down sprue velocity and flow rate at the base of the Mold
(b) the total volume of the mold;
(c) the actual velocity and flow rate at the base of the sprue;
(d) the loss of head in the gating system due to friction.