10.2.2 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:

$$h_1 + \frac{p_1}{\rho} + \frac{v_1^2}{2g} + F_1 = h_2 + \frac{p^2}{\rho} + \frac{v_2^2}{2g} + F_2 \qquad (10.2)$$

where h=head, cm (in),

p = pressure on the liquid, N/cm^2 (lb/ in^2) ,

ρ = density , g/cm^3 (lbm/in^3);

v = flow velocity; cm/s (in/sec);

g = gravitational acceleration constant, 981 cm/s/s (32.2x12= 386 in/sec/sec); and

F= head losses due to friction, cm (in). Subscripts 1 and 2 indicate any two locations in the liquid flow.

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

$$h_1 + \frac{v_1^2}{2g} = h_2 + \frac{v_2^2}{2g} \qquad (10.3)$$

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 (h2 = 0) and h1 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 (v1= 0). Hence, Eq. (10.3) further simplifies to

$$h_1 = \frac{v_2^2}{2g}$$

which can be solved for the flow velocity:

$$v = \sqrt{2gh} \qquad (10.4)$$

where v = the velocity of the liquid metal at the base of the sprue, cm/s (in/sec);
g=981 cm/s/s (386 in/sec/sec); and
h = the height of the sprue, cm (in).

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:

$$Q = v_1 A_1 = v_2 A_2 \qquad (10.5)$$

where Q = volumetric flow rate, cm3/s (in3/sec); v = velocity as before; A = cross sectional area of the liquid, cm^2 (in^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 (10.4) and (10.5) 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. 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 VA at the base. Accordingly, we can estimate the time required to fill a mold cavity of volume V as

$$T_{MF} = \frac{V}{Q} \qquad (10.6)$$

Where T_{MF} = mold filling time, s (sec);
V= volume of mold cavity, cm^3 (in^3); and
Q = volume flow rate, as before. The mold filling time computed by Eq. (10.6) 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. (10.6).

Example 10.2 Pouring Calculations

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, and (c) time to fill the mold.

Solution: (a)The velocity of the flowing metal at the base of the sprue is given by Eq. (10.4):

$$v = \sqrt{2(981)(20)} = 198.1 \text{ cm/s}$$

(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

$$T_{MF} = 1560/495 = 3.2\text{s}$$

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 10.3, 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 pouring temperature relative to melting point, metal composition, viscosity of the liquid metal, and 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.

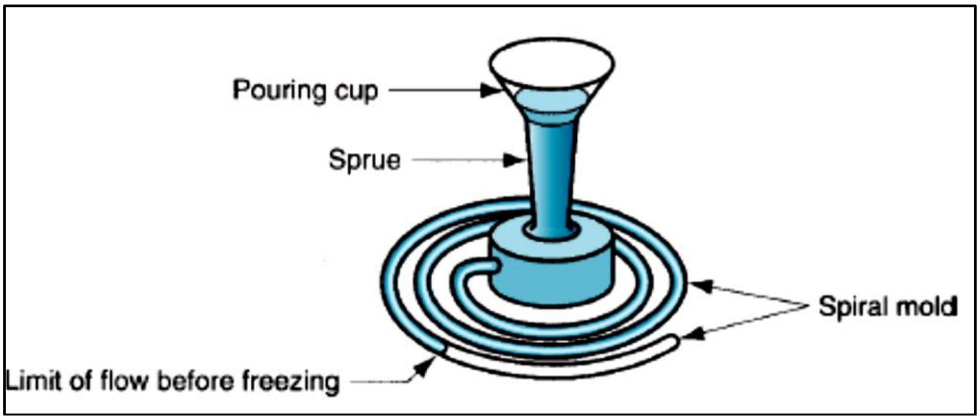


FIGURE 10.3 Spiral mold test for fluidity, in which fluidity is measured as the length of the spiral channel that is filled by the molten metal prior to solidification.

Solidification Time:

Whether the casting is pure metal or alloy, solidification takes time. The total solidification time is the time required for the casting to solidify after pouring. This time is dependent on the size and shape of the casting by an empirical relationship known as Chvorinov's rule, it states that:

$$T_{TS} = C_m \cdot \left(\frac{V}{A}\right)^n$$

Total solidification time (T_{TS}) = time required for casting to solidify after pouring.

Where:

- V **= volume of the casting;**
- A **= surface area of casting;**
- n **= exponent with typical value = 2**
- C_m **= mold constant.**

Mold constant (C_m) depends on:

- **Mold material**
- **Thermal properties of casting metal**
- **Pouring temperature relative to melting point**

Value of (C_m) for a given casting operation can be based on experimental data from previous operations carried out using same mold material, metal, and pouring temperature, even though the shape of the part may be quite different.

What Chvorinov's Rule Tells Us:

- **A casting with a higher volume-to-surface area ratio cools and solidifies more slowly than one with a lower ratio.**
- **To feed molten metal to main cavity, (T_{ST}) for riser must be greater than (T_{ST}) for main casting (molten metal solidifies in riser after the molten metal is solidified in the main casting).**
- **Since mold constants of riser and casting will be equal, design the riser to have a larger volume-to-area ratio so that the main casting solidifies first. This minimizes the effects of *shrinkage*.**

Solidification Shrinkage:

- **Occurs in nearly all metals because the solid phase has a higher density than the liquid phase [see fig. (14 & 15) below].**
- **Thus, solidification causes a reduction in volume per unit weight of metal.**

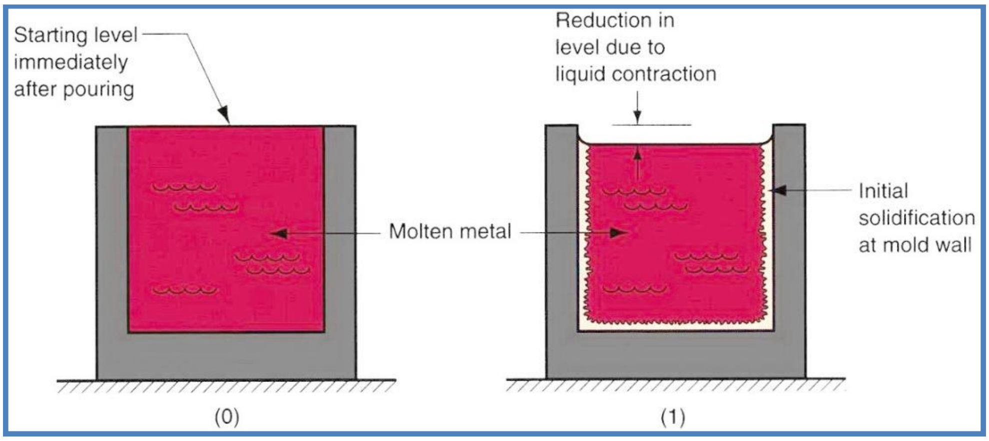


Fig. (14): Shrinkage of a cylindrical casting during solidification and cooling.

(0) Starting level of molten metal immediately after pouring.
(1) Reduction in level caused by liquid contraction during cooling.

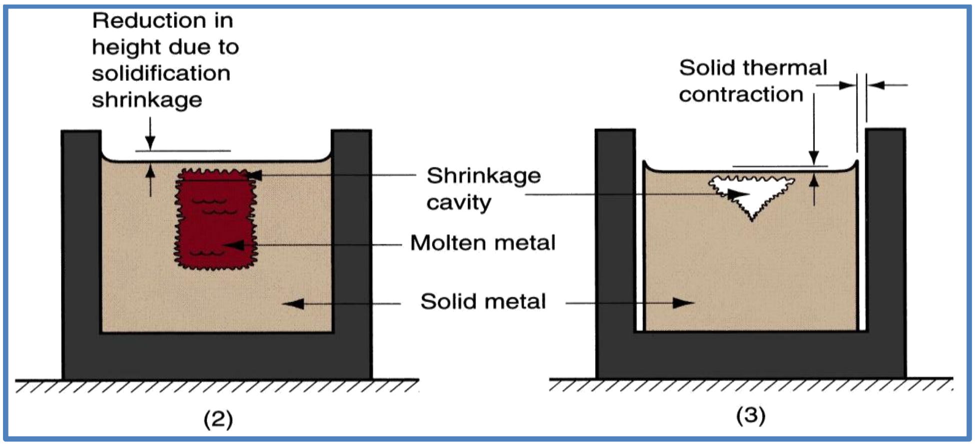


Fig. (15): Shrinkage of a cylindrical casting during solidification and cooling.

(2) reduction in height and formation of <u>shrinkage cavity</u> caused by solidification shrinkage.
(3) further reduction in height and diameter due to thermal contraction during cooling of solid metal (dimensional reductions are exaggerated for clarity).

External & Internal Chills:

When the liquid metal is unable to reach the regions where Solidification is taking place and a feed riser cannot be placed where needed, a porous region can develop due to the shrinkage of solidified metal [see fig. (16) below].

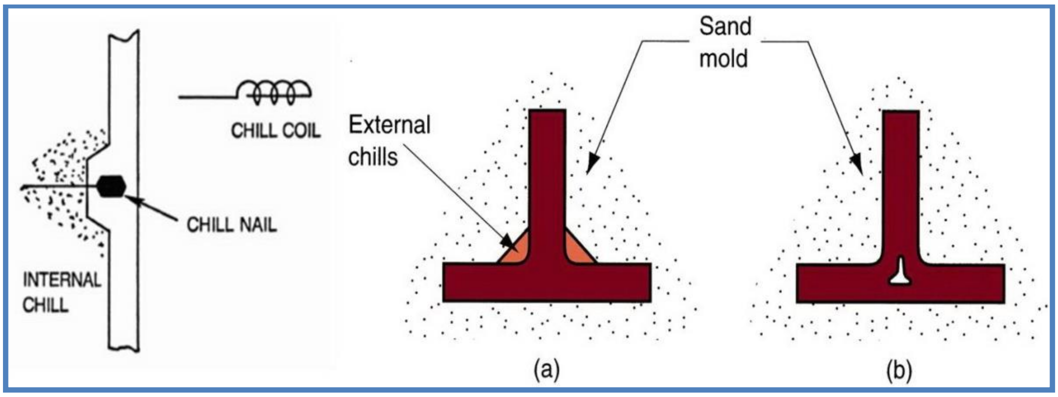


Fig. (16): (a) External & internal chilis to encourage rapid freezing of the molten metal in a thin section of the casting; and (b) the likely result if the external chill were not used.

An external chill made of cast iron molded in the sand will chill the area (where applied) and promote directional solidification and an internal chill is one that (like a chaplet) becomes part of the casting fusing into the area of use.

Porosity due to shrinkage can be reduced by using:

1) **Riser (feeder).**
2) **By using mold materials with high thermal conductivity & by selecting casting alloys with low thermal conductivity & short solidification – temp. – range.**

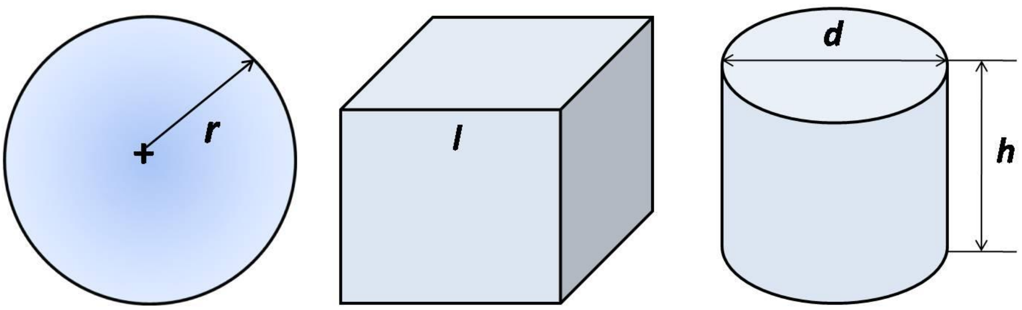
Example (1):

Three pieces of castings having the same volume but with different shapes. One is sphere, one is cube and the other is a cylinder with height that is equal to the diameter ($h = d$). Which of these pieces will solidify the fastest and which one is the lowest?

Solution:

According to the equation of solidification time (Chvorinov rule), the solidification time is inversely proportional to the surface area of the casting:

$$solidification\ time\ (T_{TS}) \propto \left(\frac{Volume}{surface\ area}\right)^2$$



Since the volume (V) is equal for all shapes, we will assume (V = 1), that means:

$$V_{sphere} = V_{cube} = V_{cylinder} = 1$$

Thus, the respective volume and surface area for each of these shapes are:

For the sphere:

$$V_{sphere} = \frac{4\ .\ \pi\ r^3}{3} = 1\ , \quad \Rightarrow \quad \therefore \quad r = \left(\frac{3}{4\ .\ \pi}\right)^{\frac{1}{3}}$$

$$A_{sphere} = 4\ .\pi\ .\ r^2 = 4\ .\pi \left(\frac{3}{4\ .\ \pi}\right)^{\frac{2}{3}} = 4.84$$

$$T_{TS} = C_m \cdot \left(\frac{V}{A}\right)^2 = C_m \cdot \left(\frac{1}{4.84}\right)^2 = 0.043\ C_m$$

For the Cube:

$$V_{cube} = l^3 = 1\ , \quad \Rightarrow \quad \therefore \quad l = 1$$

$$A_{cube} = 6\ .\ l^2 = 6$$

$$T_{TS} = C_m \cdot \left(\frac{V}{A}\right)^2 = C_m \cdot \left(\frac{1}{6}\right)^2 = 0.028\ C_m$$

For the Cylinder:

$$V_{cylinder} = \pi\ .r^2\ .h = \pi\ .r^3\ , \quad \Rightarrow \quad \therefore \quad r = \left(\frac{1}{2\ .\ \pi}\right)^{\frac{1}{3}}$$

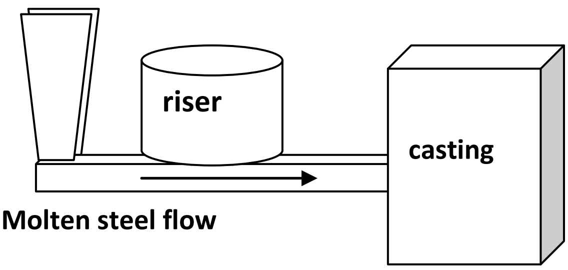
$$A_{cylinder} = 2\,\pi\,.r^2 + 2\,\pi\,.r\,.h = 2\,\pi\,.r^2 + 2\,\pi\,.r.(2\,.\;r) = 6\,\pi.\left(\frac{1}{2\,\pi}\right)^{\frac{2}{3}}$$
$$= 5.54$$

$$T_{TS} = C_m\,.\left(\frac{V}{A}\right)^2 = C_m\,.\left(\frac{1}{5.54}\right)^2 = 0.033\,C_m$$

It is clear from the above results that the cube – shape casting will solidify fastest than the other shapes, and the spherical – shape casting will solidify slowest than the other shapes.

Example (2):

A cylindrical riser must be designed for a sand-casting mold. The casting itself is a steel rectangular plate (cuboid or parallelepiped) with dimensions 7.5 cm x 12.5 cm x 2.0 cm. Previous observation have indicated that the total solidification time (T_{TS}) for this casting = 1.6 min. The cylinder for the riser will have a diameter-to-height ratio = 1 Determine the dimensions of the riser so that its [T_{TS} = 2 min].



Solution:

For the Casting:

1) Find first the volume and Area of the casting (rectangular plate).

$$V_{casting} = 7.5 * 12.5 * 2 = 187.5\ cm^3$$

$$A_{casting} = 2\ [7.5 * 12.5 + 12.5 * 2 + 7.5 * 2] = 267.5\ cm^2$$

2) Use the *Chvorinov's Rule* to find the mold constant (C_m), by using the time of solidification (T_{TS} = 1.6 min).

$$T_{TS} = C_m\left(\frac{V}{A}\right)^n$$

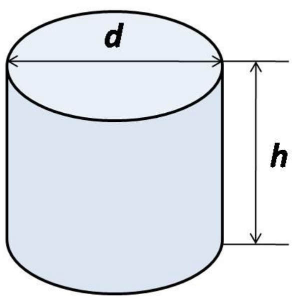
$$1.6 = C_m\left(\frac{187.5}{267.5}\right)^2 \quad\Rightarrow\quad C_m = 3.26\ \frac{min}{cm^2}$$

For the Riser:

1) Find volume and surface area of the riser and also the ratio [V/A]. Write everything in terms of [*d* (diameter of the riser)], and substitute for [*h* = *d*].

2) Use the same mold constant you found above [C_m = 3.26 min].

3) Use the *Chvorinov's Rule* to find the diameter of the riser, by using the time of solidification that you have which is [T_{TS} = 2 min].



$$V_{riser} = \frac{\pi \, . \, d^2 \, . h}{4} = \frac{\pi \, . \, d^3}{4}$$

$$A_{riser} = \pi \, . d \, . h + 2 \, . \frac{\pi \, . \, d^2}{4} = \frac{3 \, \pi \, . \, d^2}{2}$$

$$\frac{V}{A} = \frac{\frac{\pi \, . \, d^3}{4}}{\frac{3 \, \pi \, . \, d^2}{2}} = \frac{d}{6}$$

$$T_{TS} = C_m \left(\frac{V}{A}\right)^n \quad \Longrightarrow \quad 2 = 3.26 * \left(\frac{d}{6}\right)^2 \quad \Longrightarrow \quad d = 4.7 \; cm$$

$$V_{riser} = \frac{\pi \, . \, d^3}{4} = \frac{\pi}{4} \, . \, (4.7)^3 = 81.6 \; cm^3$$

It appears from the above calculation that the volume of the riser is approximately equal to [43.5 %] of the casting volume. This riser volume can be considered as a waste material which can be melting and used again for another casting.