MME 345

Lecture **B:14**

The Design of Gating System

3. Theoretical considerations in gating design

Ref:

[1] ASM Metal Handbook, Vol. 15: Casting, ASM International
[2] Taylor, Flemings, and Wulff. Foundry engineering, Wiley Eastern Limited, 1959.

Topics to discuss....

1. Introduction
2. Laws of fluid dynamics
3. Modes of liquid flow
4. Fluid dynamics in the gating system

1. Introduction

- A major factor in making a good casting is the ability to get the metal from the ladle into the mould cavity with a minimum of turbulence, slag, entrapped sand or other materials which could get swept into the mould from the mould-molten metal system.

- Accomplishing this task consistently requires a basic understanding of fluid flow principles as well as the insight provided by experience.

- In this lecture, quantitative applications of some of the most basic fluid dynamics principles that control gating system design are addressed.

2. Laws of Fluid Dynamics

- Proper design of an optimized gating system will be made easier by the application of several fundamental principles of fluid flow.

- Most modern studies of gating systems have been based upon consideration of two laws of fluid dynamics: **(1) the Law of continuity**, and **(2) the Bernoulli's theorem**.

  these two principles are of interest in gating design
  (1) to calculate metal velocity and flow rates, and
  (2) to obtain an understanding of the fundamentals of metal flow in gating systems

- With a proper application of these fluid principles, the liquid velocity inside the running system can be stream-lined and air and gas entrapment by the liquid can be avoided.

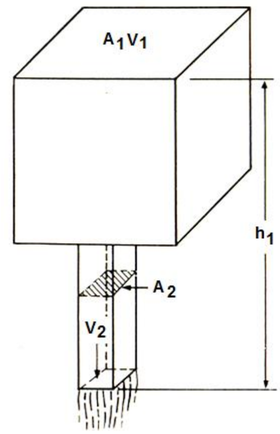
2.1 The Law of continuity

"For a system with impermeable walls and filled with an incompressible fluid, the rate of flow will be the same at all points in the system"

$$Q = A_1V_1 = A_2V_2$$

Q = volume flow rate, m^3/s
A = area of flow passage, m^2
V = linear velocity of flow, m/s

- applies to both steady and non-steady state flows of incompressible fluids in impermeable walled channels
- the permeability of sand moulds can complicate the strict application of this law



❑ If the flow channel narrows down to half its original cross section, the metal velocity must double

2.2 Bernoulli's Theorem

❑ This basic law of hydraulics relates the pressure, velocity, and elevation along a line of flow in a way that can be applied to gating systems

❑ The theorem states that,

"at any point in a full system, the total energy involving the sum of the potential energy, kinetic energy, pressure energy, and frictional energy of a flowing liquid is constant"

$$E = wZ + wPv + \frac{wV^2}{2g} + wF = K$$

w = total weight of the flowing liquid, kg
Z = height of the liquid, m
P = static pressure in liquid, kg/m^2
v = specific volume of liquid, m^3/kg
V = velocity, m/s
F = friction loss per unit weight
K = constant

If the equation is divided by *w*, all the terms reduce to dimensions of length and will represent:

- Potential head = Z
- Pressure head = Pv = P/ρ
- Velocity head = $V^2/2g$
- Frictional loss of head = F

$$Z + Pv + \frac{V^2}{2g} + F = k$$

- The equation allows prediction of the effect of the several variables at different points in the gating system, although several conditions inherent in foundry gating systems complicate and modify its strict application. For example:

  - **The equation is for full systems, and at least at the start of pouring, a gating system is empty. This indicates that a gating system should be designed to establish as quickly as possible the flow conditions of a full system**

  - **The equation assumes an impermeable wall around the flowing metal. In sand foundry practice, the permeability of the mould medium can introduce problems, for example, air aspiration in the flowing liquid**

  - **Additional energy losses due to turbulence and changes in the direction of flow at bend must be accounted for**

  - **Heat loss from the liquid metal is not considered, which will set a limit on the time over which flow can be maintained. Also, solidifying metal on the walls of the gating system components will alter their design while flow continues**

- The potential energy is the maximum at the highest point in the system, that is, the top of the pouring basin

As metal flows from the basin down the sprue, potential energy changes to kinetic energy as the stream increases in velocity because of gravity. As the sprue fills, a pressure head is developed.

Once flow in a filled system is established, the potential and frictional heads become virtually constant, so conditions within the gating system are determined by the interplay of the remaining factors.

The velocity is high where the pressure is low, and vice versa.

$$Z + Pv + \frac{V^2}{2g} + F = k$$

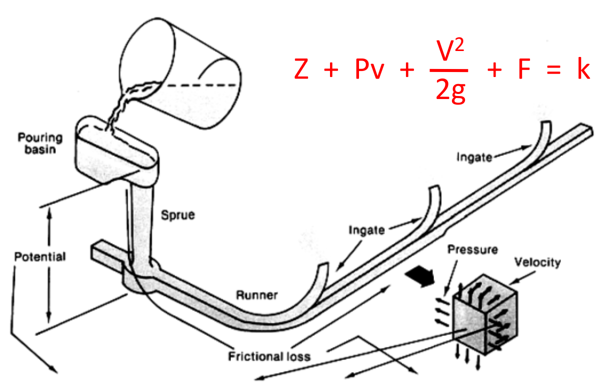


Fig. 2 Schematic illustrating the application of Bernoulli's theorem to a gating system.

- Thus, in gating systems, velocity, **V**, and pressure, **P**, are the critical parameters which are important to control the filling of a mould cavity quickly and cleanly.

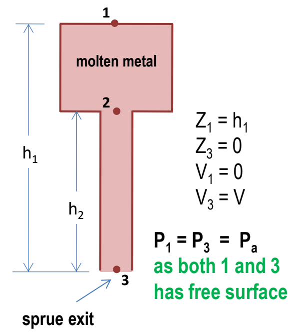
Effect of liquid metal velocity

- Let us measure the velocity of a jet of fluid issuing from an orifice by using Bernoulli's law at points 1 and 3 to balance energies (neglecting frictional losses):

$$Z_1 + P_1 v + \frac{V_1^2}{2g} = Z_3 + P_3 v + \frac{V_3^2}{2g}$$

$$h = V^2 / 2g \quad \text{or,} \quad \mathbf{V^2 = 2gh}$$

This equation is known as the Torricelli's equation.



- Using g = **9.8** m/s², the velocity of liquid at the base of sprue can be determined as

$$V = 4.43\,(h)^{1/2} \text{ m/s}$$

Problem: For a standard pouring basin (h = 50 mm) and a sprue height of 100 mm, what is the liquid metal velocity at the base of the sprue? Answer: 1.72 m/s

Effect of liquid metal pressure

- It is important to keep the actual pressure within a flowing liquid in a sand mold above atmospheric pressure.

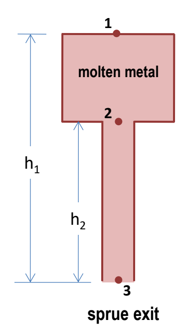
  If the pressure in the molten metal drops below 1 atm, then air can be draw in or "aspirated" into the metal stream, thereby increasing the opportunity for defects within the casting.

- Consider the same simple pouring basin-sprue sketch. Let us assume that the sprue has the same cross sectional area at points 2 and 3.
- From the law of continuity then $\mathbf{V_2 = V_3}$ (since $Q = A_2V_2 = A_3V_3$)
  Writing Bernoulli's Law at points **2** and **3** gives:

$$Z_2 + P_2 v + \frac{V_2^2}{2g} = Z_3 + P_3 v + \frac{V_3^2}{2g}$$

$$P_2 = P_3 - h_2/v = P_3 - h_2\rho$$

$Z_2 = h_2$
$Z_3 = 0$
$\mathbf{P_3 = 1}$ **atm**



- Thus it can be seen that the pressure at point 2 is less than 1 atmosphere.

  gas aspiration will occur at this point in the system

Shape of fallen stream in downsprue

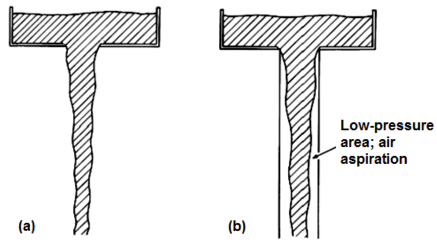
- During free fall through a long parallel channel, the liquid metal gains velocity during descent following the law of continuity ($Q = A_1V_1 = A_2V_2$).

  The result is the tapered shape typical of a free-falling stream shown in the Fig. (a)

Schematic showing the advantages of a tapered sprue over a straight-sided sprue.

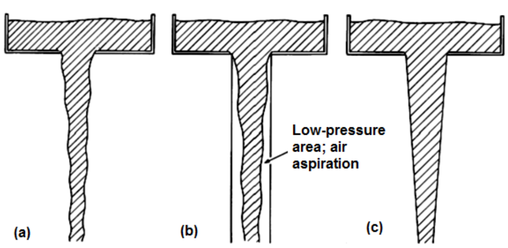
(a) Natural flow of free-falling liquid.

(b) Air aspiration induced by liquid flow in a straight-sided sprue.



- If the same flow is directed down a straight-sided sprue, Fig. (b), the falling stream will create a low-pressure area as it pulls away from the sprue walls and will probably **aspirate air**.

  the flow will tend to be uneven and turbulent, especially when the stream reaches the base of the sprue.



Schematic showing the advantages of a tapered sprue over a straight-sided sprue.

(a) Natural flow of free-falling liquid.

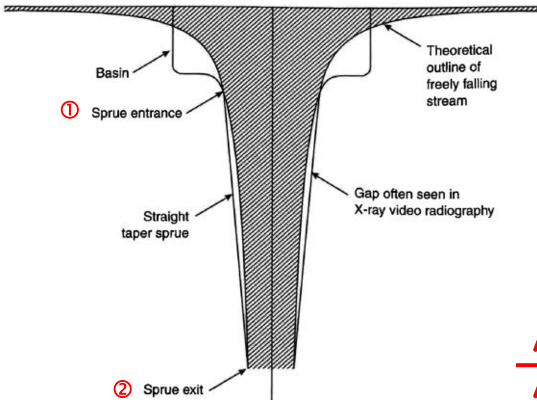
(b) Air aspiration induced by liquid flow in a straight-sided sprue.

(c) Liquid flow in a tapered sprue.

- This is why sprues are progressively tapered, so that **the diminishing cross sectional area compensates the increasing linear velocity** of the metal to provide a constant volume rate of flow.

  The tapered sprue shown in Fig. (c) is designed to conform to the natural form of the flowing stream and therefore reduces turbulence and the possibility of air aspiration.

  It also tends to fill quickly, establishing the pressure head characteristic of the full-flow conditions required by the Bernoulli's equation.



The theoretical hyperbola shape of the falling stream is complicated by the effects of the basin and sprue entrance.

The theoretical dimensions of the sprue needed to meet this requirement are defined by the relations

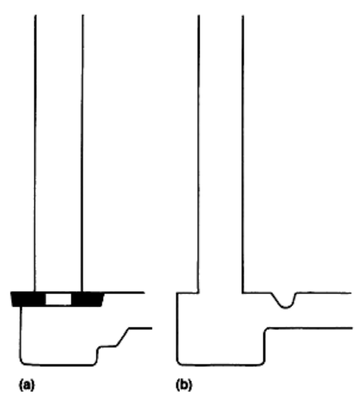
$$Q = A_2V_2 = A_3V_3$$

$$V^2 = 2gh$$

$$\frac{A_1}{A_2} = \frac{V_2}{V_1} = \left(\frac{h_2}{h_1}\right)^{1/2}$$

A denotes the cross-section of the stream, not of the sprue

- Many types of high-production moulding units do not readily accommodate tapered sprues.
- So the gating system designer often try to approximate the effect of a tapered sprue by placing a restriction, or **choke**, at or near the base of the sprue to force the falling stream to back up into the sprue.



Choke mechanisms incorporated into straight-sided sprues to approximate liquid flow in tapered sprues: (a) Choke core. (b) Runner choke.

3. Modes of Liquid Flow

Laminar flow

- particles move smoothly, parallel to the direction of flow
- fluid velocity increases from the surface towards the centre of the channel, where it reaches the maximum
- causes the minimum frictional losses

Turbulent flow

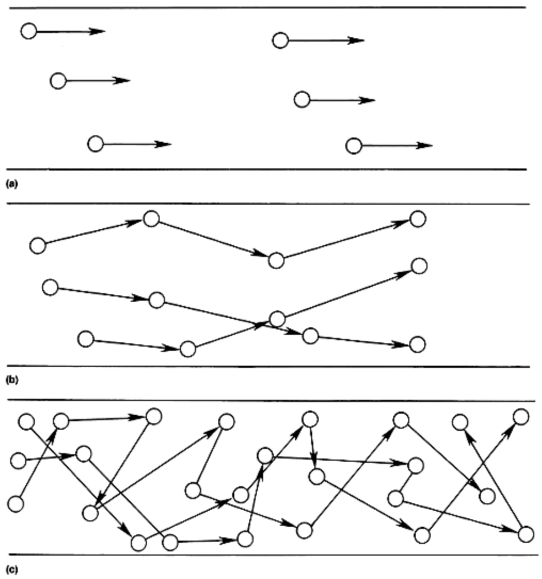
- irregular movement of the liquid particles tumbling in all directions
- turbulence increases with the velocity of the stream
- other factors increasing turbulent flow:
  1. **various local resistances (such as edges and sharp bends)**
  2. **surface area of liquid stream that is exposed to air**
  3. **any suspended second phases (inclusions, slags, gas bubbles, oxide films etc.) entrained in the stream.**

Reynold's number and critical flow velocity

- Reynold's number represents the degree of turbulence
- Re = (inertia force) / (viscous force)

$$Re = \frac{\rho V d}{\mu} = \frac{Vd}{\nu}$$

V = mean velocity of liquid, m/s
d = linear dimension of the channel, m
ρ = density of liquid, kg/m^3
ν = kinematic viscosity of liquid = μ/ρ
μ = dynamic (absolute) viscosity of liquid, N-s/m^2



(a) **Re < 2000**, laminar flow

(b) **2000 ≤ Re <20,000**,

turbulent flow, relatively <u>harmless so long as the surface is not ruptured</u>, thus avoiding air entrainment in the flowing stream

(c) **Re ≥ 20,000**

severe turbulent flow, lead to <u>rupturing of the stream surface</u> with the strong likelihood of air entrainment and dross formation as the flowing metal reacts with gases, and <u>mould erosion</u> with consequent dirt or sand entrapment

Re = 2000 – 5000,

flow starts to change from laminar to turbulent depending on the conditions

Reynold's number, Re, and its relationship to flow characterization

- Two critical flow velocities exist
  - **Lower critical velocity** (below which flow is laminar or viscous)
  - **Upper critical velocity** (above which the flow is turbulent)

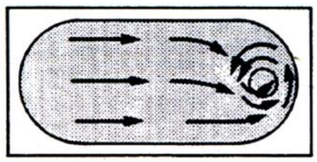
- Typical critical velocity:

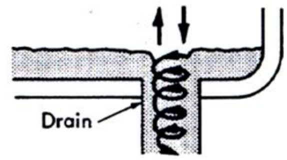
Al bronze and other highly oxide-prone metals	75 mm/s
Al-base and Mg-base alloys	250 mm/s
Cu-base and Fe-base alloys	500 mm/s

- Calculations of Re show that flow of metal in most practical gating systems is turbulent
- So a certain amount of turbulence is inevitable and must therefore be tolerated

In practice the design of gating system does not involve the elimination of metal turbulence, but rather its reduction to a point where it is not harmful.

Vortex

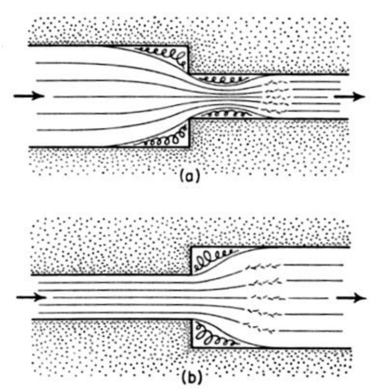




- ❑ causes turbulence that draws air, dross or slag down into the sprue
- ❑ reduces the flow rate and causes disruption as it bursts at the free surface of metal rising in the mould
- ❑ vortex can be minimised by reducing the velocity of metal and by increasing the liquid depth in the pouring cup/basin

Abrupt change in flow channel cross section

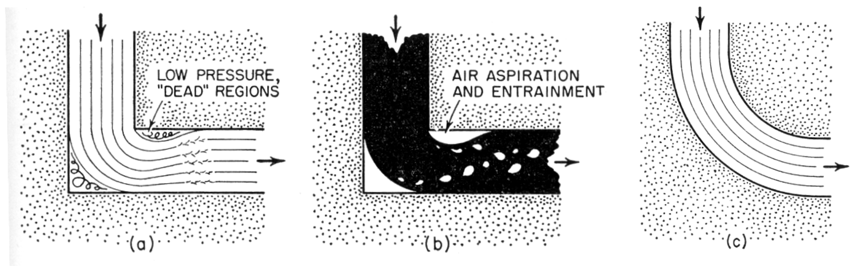
- ❑ Low-pressure zones - with a resulting tendency toward air entrainment (which is also known as **vena contracta** - can be created as the metal stream pulls away from the mould wall
  - **with a sudden reduction in the channel (Fig. a), the law of continuity shows that the stream velocity must increase rapidly. This spurting flow will create a low-pressure zone directly after the constriction**
  - **with a sudden enlargement of the channel (Fig. b), momentum effects will carry the stream forward and create low-pressure zones at the enlargement**



Schematic showing the formation of low-pressure areas due to abrupt changes in the cross section of a flow channel. (a) Sudden reduction of the channel. (b) Sudden enlargement of the channel.

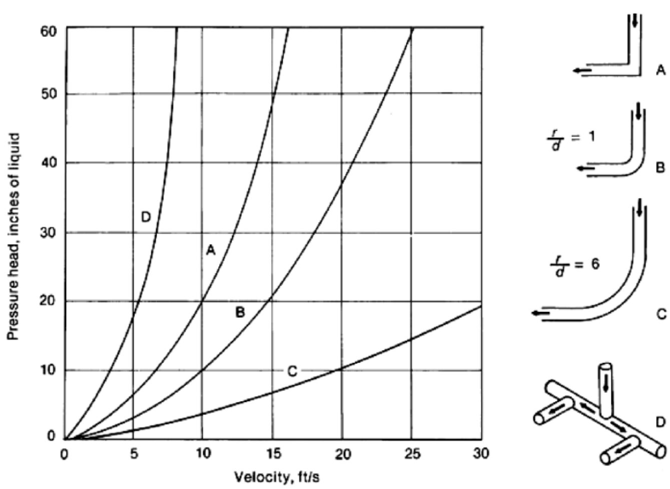
- ❑ The problems shown in the figure can be minimized by making gradual changes in the flow channel cross section; abrupt changes should be avoided

Abrupt change in flow direction



Schematic illustrating fluid flow around right-angle and curved bends in a gating system. (a) Turbulence resulting from a sharp corner. (b) Metal damage resulting from a sharp corner. (c) Streamlined corner that minimizes turbulence and metal damage

- Sudden changes in the direction of flow can produce low pressure zones.
- Problems of air entrainment can be minimized by making the change in direction more gradual.



Abrupt changes in flow direction, in addition to increasing the chances of metal damage, will increase the frictional losses during flow

A system with high frictional losses will require a greater pressure head to maintain a given flow velocity

Effect of pressure head and change in gate design on the velocity of metal flow.
A, 90° bend; B, r/d = 1; C, r/d = 6; D, multiple 90° bends
The variables r and d are the radius of curvature and the diameter of the runner, respectively.

- If the velocity is high, mould gases and air and water from moist atmosphere are aspirated or drawn through the permeable mould into the flowing stream of metal
- The quantity of gas aspirated depends upon
  1. **the partial pressure of gases,**
  2. **permeability of mould, and**
  3. **the gas pressure in the liquid**
- The fate of the mould gas is varied:
  1. **it may react with the metal, forming oxides and dross**
  2. **dissolve in the metal to precipitate later upon freezing**
  3. **remain in the metal as mechanically entrapped bubbles**
- All these possibilities are undesirable
- Can be better tolerated in some metals than in others

4. Fluid Dynamics in the Gating System

- While determining the laws of fluid dynamics, assumptions made are:
  - **the fluid is an incompressible liquid**
  - **the channel is full**
  - **the walls are impermeable**
- The sand moulds used for casting are:
  - **permeable**
  - **liquid metal in the gating system is always accompanied by mould gases and air**
  - **friction at mould wall resulted**
- **So corrections are to be applied**

- Besides, energy is lost due to
  1. **resistance of mould wall to the passage of metal (interface friction)**
  2. **internal friction (viscosity) of liquid metal**
  3. **sudden changes in cross-section**
  4. **sharp changes in direction at bends and junctions**

- So corrections are to be applied using experimentally determined **discharge coefficient**, although such losses are not so high.

Next Class

MME **345**, Lecture **B:15**

The Design of Gating System

4. Design of gating system elements 1