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Aircraft Hydraulic Systems - fundamentals

Aircraft hydraulic systems are essential non-propulsive power systems. Hydraulic power systems are used to power major functional aircraft systems, such as, Flight controls (primary and secondary), friction braking, nose gear steering, thrust-reversers, operating heavy cargo doors, etc.

Major parts of functioning hydraulic systems are energy conversion (pumps) – energy transmission (pipes and tubes) – and again energy conversion (actuators). Hydraulic system is not a primary source of power/energy as it receives power from a prime mover (e.g., turbine engines) directly (engine-driven pumps) or indirectly through other non-propulsive power systems, such as, electrics and occasionally pneumatics to power hydraulic pumps.

A design of functioning hydraulic systems is complex and must ensure adequate control and operability under most severe circumstances in operations. Several independent hydraulic systems operate in parallel powering various users and providing for required redundancy.

Part of Fluid Mechanics/Dynamics/Physics which deals with the flow of liquids is called hydraulics. Hydraulics consists of Hydrostatics (stagnant liquids) and Hydrodynamics (liquids in motion).

Hydraulic fluids

Hydraulic fluid must have adequate characteristics to sustain high pressures and temperatures while having low viscosity and physical-chemical stability. It should also be non-toxic and non-flammable. Hydraulic fluid is practically incompressible. Physically, there is no such material that is "incompressible" and even solids will deform under the action of forces and moments. Rather we say that hydraulic fluids are stiff and have rather large bulk modulus. Bulk modulus (or volume modulus of elasticity) is defined as:

$$\beta = -v \cdot \left(\frac{\partial p}{\partial v} \right) \approx -v \frac{\Delta p}{\Delta v} \quad [\text{psi,bar}]$$

A typical value of bulk modulus is for water and is 330,000 psi (about 22,760 bar) at 68°F (20°C) and 15 psi pressure (SL atmospheric pressure). Bulk modulus increases with increasing pressure, but decreases with higher temperature (more compressible). A typical value of bulk modulus for hydraulic oils is about 250,000 psi (1.7241 GPa or 1,724.1 MPa or 17,241 bar). For reference, a bulk modulus of mild steel is 26,000,000 psi (1,793,103 bar or 179.31 GPa). Water cannot be used as a hydraulic fluid in modern aircraft as the temperatures are too high and water does not possess good lubrication properties. Plus water can freeze at low temperatures. Hence, most hydraulic fluids are or synthetic- or mineral-based. Some basic properties of liquids will be highlighted below.

Example Q: A 10 in^3 sample of hydraulic oil in a cylinder is pressurized from 100 to 2000 psi. If the bulk modulus for that hydraulic fluid is 250,000 psi (1,740 Mpa), find the change of the oil volume.

A: Pressure difference is 1,900 psi (2,000-100) and the volume is given. We need to find change of volume from the above equation on bulk modulus. Hence,

$$\Delta v = -v\frac{\Delta p}{\beta} = -10\frac{1,900}{250,000} = -0.076 \quad \left[\text{in}^3\right]$$

$$\frac{\Delta v}{v}\left[\%\right] = -\frac{\Delta p}{\beta}\times 100 = -\frac{1,900}{250,000}\times 100 = -0.76\%$$

Negative sign in the above problem comes from the fact that the original volume of the fluid decreased (condensed) due to applied compression pressure.

Specific mass or mass density of hydraulic fluid is defined as:

$$\rho = \frac{M}{V} \quad \left[\frac{\text{kg}}{\text{m}^3}, \frac{\text{slug}}{\text{ft}^3}\right]$$

Mass density is practically constant for liquids, which is the result of practical incompressibility. On the other hand, the specific weight is defined as:

$$\gamma = \frac{W}{V} = \frac{Mg}{V} = \frac{M}{V}g = \rho g \quad \left[\frac{\text{N}}{\text{m}^3}, \frac{\text{lb}}{\text{ft}^3}\right]$$

The specific gravity (SG) is often used in practical hydraulics and is defines as the ratio:

$$SG = \frac{\gamma_{oil}}{\gamma_{water}} = \frac{\rho_{oil}}{\rho_{water}} \quad [-]$$

Many hydraulic fluids like other oils are lighter than water and have thus SG < 1. Typical value of specific weight for many hydraulic liquids is 56 lb/ft^3, while for pure water it is 62.4 lb/ft^3. Hence the SG for such hydraulic liquid is 0.897 or rounded to 0.9 (90% of water). Hence, many (mineral-based) oils are in fact lighter than water, but that is not always the case (synthetic oils). On the other hand, Mercury (Hg) is a metal, which is liquid at room temperatures and is much heavier than water.

In hydrodynamic problems, we deal with the flow or dynamics of moving hydraulic liquids. Any real fluid will possess the fundamental property of viscosity. Viscosity is the result of the momentum exchange on the molecular/atomic level and macroscopically it represents resistance to flow and dissipation of motion energy. We can define dynamic or absolute viscosity as:

$$\mu = \frac{\tau}{\left(\frac{\partial v}{\partial y}\right)} \approx \frac{F/A}{v/y} = \frac{\text{Shear stress in fluid}}{\text{Slope of velocity profile}} \quad [\text{Pa}\times\text{s}]$$

The other units for dynamic viscosity are lb·s/ft^2 in imperial system and in cgs-system it is dyn·s/cm^2 or 1 Poise (P). More common unit is centi-Poise or cP. Since, 1 N is 10^5 dyn, we have1 Pa·s equal to 10 P or 10^3 cP. On the other hand, kinematic viscosity is defined as:

$$\nu = \frac{\mu}{\rho} \quad \left[\frac{\text{m}^2}{\text{s}}\right]$$

Other units of kinematic viscosity are ft^2/s in Imperial system and 1 cm^2/s or 1 Stokes (1 S) in cgs-system. It is more common to use the unit of one cS which is 10^{-2} St and 1 m^2/s is equal to 10^6 cS or 10^4 S. Hence, 1 cS= 10^{-6} m^2/s.

Dynamic viscosity of water and many oils decreases (quite steeply) with increasing temperature, but interestingly increases mildly with increasing temperature for air. Similarly, the kinematic viscosity of many oils decreases steeply with increasing temperature, while for the air it increases with increasing temperatures. However, kinematic viscosity of air (and many gases) decreases rapidly with decreasing atmospheric pressure as the molecular transport is hindered due to larger mean free path and larger average distances between molecules.

Hydraulic pressure

A pressure in hydraulic system is achieved by squeezing stiff hydraulic fluid. Since the bulk modulus of hydraulic fluids is so high (many magnitudes higher than for gases), a very small volume change of the (hydraulic fluid - liquid) oil will result in high pressures being generated. Pascal's-Law (Blaise Pascal) states that the fluid pressure will propagate instantly in all direction and to every corner of the hydraulic fluid and it will act isotropically (being the same in all directions at a given point in space). In reality, such "instantaneous" propagation is not possible. More correctly, the pressure disturbances will propagate rapidly about several thousand meters per second (1500 m/s in freshwater or about 4.5 faster than in the air at SL) and hence practically instantaneously for many applications. A hydraulic pressure acting on a circular piston of diameter D within a cylinder of a hydraulic actuator will create a force:

$$\text{F} = p \cdot A = p \cdot \frac{D^2 \pi}{4} \quad [\text{lb,N}]$$

The SI (International System) unit of pressure is one *Pascal*, which is one Newton per meter squared (N/m^2). In British Imperial system, the unit of pressure is a pound per foot squared (lb/ft^2) or more commonly a pound per inch squared (lb/inch^2) or "*psi*". Since Pascal is a small unit it is more common to use hPa (100 Pascal), kPa (thousand Pa), MPa (million Pa) or "*bar*" (1 bar is 100,000 Pa). One bar is about 14.5 psi. It is also common to find an older unit of atmosphere in which case one "*ata*" (atmosphere absolute) is about 1.013 bar or 14.696 (14.7) psi or 2116 lb/ft^2. A typical 3,000 psi hydraulic system pressure equals about 204 ata or 207 bar. It is also common to use “ata” and bar interchangeably although 1 standard “ata” is 1.01325 bar (standard SL ISA pressure). We can say that 1 psi is about 2 inch Hg or about 6,895 Pa (7,000 Pa to simplify).

Example Q: What net force is acting on a balanced double-acting actuator ram if the piston diameter is D=10 cm and the ram/rod diameter is d=5 cm. Pressure on the HP side is 2900 psi (200 bar) and on the LP side or return side is 87 psi (6 bar)?

A: The effective surface area on which the pressure difference acts is:

$$A_{eff} = \frac{D^2 \pi}{4} - \frac{d^2 \pi}{4} = \frac{\pi}{4}\left(D^2 - d^2\right) \quad \left[\mathrm{m}^2\right]$$

Which is 78.54 cm^2 minus 19.63 cm^2 or 58.91 cm^2. The HP pressure converted into bar is 200 bar and the LP pressure is 6 bar and hence the pressure difference is 200-6=194 bar or 2,813 psi. The net force on the ram of the linear actuator is now:

$$\mathrm{F} = \Delta p \cdot A_{eff} = \left(194 \times 10^5\right) \cdot \left(58.91 \times 10^{-4}\right) = 114,285 \text{ N} = 25,711 \text{ lb}$$

In hydrostatic problems, we deal with the pressure distribution in stagnant liquids under the influence of gravitational attraction. Since there is no actual motion, shear stresses do not exist and we only have normal pressures. A pressure in a water column is proportional to depth:

$$p(z) = \rho \cdot g \cdot z = \gamma \cdot z \quad [\text{Pa, psi}]$$

The specific weight of pure water (freshwater) is 62.4 lb/ft^3 or 9,810 N/m^3. Mass density of freshwater is 1,000 kg/m^3. Salt water is somewhat “heavier” due to the presence of dissolved minerals and is typically about 1,030 kg/m^3. The salinity of ocean/sea water can vary a bit based on geographical location (1,010-1,040 kg/m^3). The specific weight of seawater (sw) is hence 10,104.3 N/m^3 or about 64.3 lb/ft^3. For example, in a freshwater (fw) lake dam, the hydrostatic pressure at the depth of 100 ft (30 m) is 6,240 lb/ft^2 or 43.33 psi. That is about 0.433 psi/ft of water column. Equivalently, in SI system the hydrostatic pressure at 30 m is 2.943 bar (294,300 Pa) or about 9,810 Pa/m. The absolute pressure at that depth is the hydrostatic pressure plus the atmospheric pressure at the water surface, which in the case of SL freshwater lake would be 14.696 psi, 29,92 inch Hg, 1 ata, or 1.01325 bar.

Continuity equation or mass balance in hydraulic system

In Hydrodynamics, we deal with moving (flowing) liquids. The general mass balance (conservation) equation for compressible fluid flowing through a conduit in integral form is:

$$\dot{m} = \frac{dm}{dt} = \rho \cdot \bar{u} \cdot A_{cross} = \text{const} \quad \left[\frac{\text{kg}}{\text{s}}, \frac{\text{lb}}{\text{s}}, \frac{\text{slug}}{\text{s}}\right]$$

If the fluid is approximately incompressible, such as is practically in hydraulic systems, then we can actually use volume-of-fluid balance:

$$\frac{\dot{m}}{\rho} = \frac{1}{\rho}\frac{dm}{dt} = \frac{dV}{dt} = \dot{V} = \bar{u} \cdot A_{cross} = \text{const} \quad \left[\frac{\text{m}^3}{\text{s}}, \frac{\text{ft}^3}{\text{s}}\right]$$

Clearly, as the cross section of a conduit (fluid guide) decreases, the fluid must speed up to conserve mass-volume. At the same time using the energy/momentum equation, the static pressure will drop in the throat, which is the fundamental principle behind the *Venturi*-effect.

Energy considerations in hydraulic system

The energy equation used in design and operation of a hydraulic system is a familiar **Bernoulli** equation for incompressible fluids. It is given in integral form here. It is also often given in terms of height (head) with the linear dimension, instead of pressure directly:

$$z_1 + \frac{p_1}{\rho g} + \frac{v_1^2}{2g} + H_p - H_m - H_L = z_2 + \frac{p_2}{\rho g} + \frac{v_2^2}{2g} \quad [\text{ft,m}]$$

Here, "z" is elevation head, "p/γ" is pressure head and "$v^2/2g$" is velocity (kinetic) head.

Hence, the pump Head has to provide for all loses (friction and local), hydraulic motors and actuators (or any other users), static head (elevation difference), and pressure difference (reservoirs):

$$H_p = (z_2 - z_1) + \left(\frac{p_2}{\rho g} - \frac{p_1}{\rho g}\right) + \left(\frac{v_2^2}{2g} - \frac{v_1^2}{2g}\right) - H_m - H_L \quad [\text{ft,m}]$$

A pump head H_P expressed in feet can be calculated from (1 foot is about 0.305 m):

$$H_p = \frac{3{,}950 \times HHP(\text{hp})}{Q(\text{gpm}) \times SG} \quad [\text{ft}] \qquad HHP(\text{hp}) = \frac{p(\text{psi}) \times Q(\text{gpm})}{1{,}714}$$

In SI system of units the pump head is:

$$H_p = \frac{P_P(\text{W})}{Q(\text{m}^3/\text{s}) \times \gamma(\text{N/m}^3)} \quad [\text{m}]$$

For a hydraulic motor or actuator, the same equation is used, however; the power will be extracted from the fluid.

A theoretical pump (or equivalently motor/actuator) power is:

$$P_p = p \times Q = H_p \times \gamma \times Q \quad [\text{W,HP,ft-lb/s}]$$

Note that 1 HP is about 0.746 W (W=J/s) or 550 ft-lb/s (33,000 ft-lb/min). A pump capacity (*Q*) is expressed in volume of incompressible fluid being delivered in amount of time (m^3/s, liter, gpm – gallons per minute, ft^3/s, etc.). Pumping and pipeline characteristic are shown in Fig. 1. Pumps can be combined in a series to increase Head or effort or in a parallel to increases flow capacity at the same Head. Series-parallel combination of 4 pumps will increase both. Each pump may also have 2, or more stages, where pressure is increased in discrete fashion after each stage. Pipeline (conduit) Head losses include friction along straight lines and local losses, such as in filters, valves, curvatures, etc.

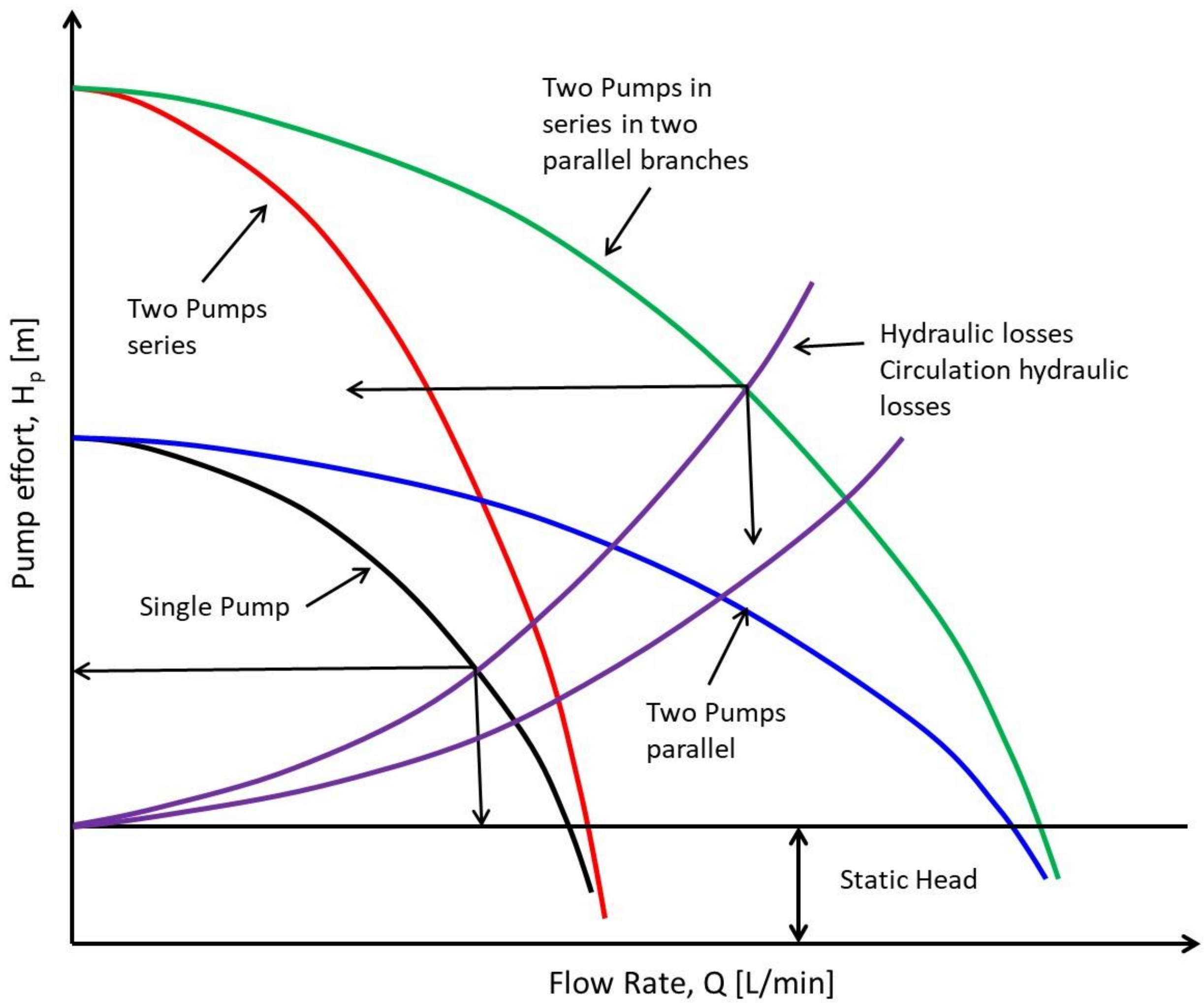

Figure 1: Pumping characteristics using single pump, two pumps in series or parallel, and a series-parallel layout using four pumps (two in series in two parallel branches).

Power considerations in hydraulic system

To see the flow of power from the prime mover to the external load, let us assume that DC electric power is supplied to DC electric motor powering a centrifugal hydraulic pump. That hydraulic pump powers a linear actuator, which then performs work on an external load (e.g., moving elevator in a fully hydraulically powered irreversible flight control system). For various powers, we can write:

$$P_i = V_{DC} \times I_{DC} \quad [\mathrm{W}]$$
$$P_{em} = T_{em} \times \omega_{em} \quad [\mathrm{W}]$$
$$P_{pump} = p \times Q \quad [\mathrm{W}]$$
$$P_{act} = F \times v \quad [\mathrm{W}]$$

Each of the power conversions is accompanied by associated efficiencies. Hence, we can write that the overall efficiency of the conversion is:

$$\eta_{tot} = \frac{P_{out}}{P_i} = \eta_{em}\eta_{pump}\eta_{act} \quad [-]$$
$$\eta_{em} = \frac{P_{em}}{P_i} = \frac{T_{em} \times \omega_{em}}{V_{DC} \times I_{DC}} \quad \eta_{pump} = \frac{P_{pump}}{P_{em}} = \frac{p \times Q}{T_{em} \times \omega_{em}} \quad \eta_{act} = \frac{P_{act}}{P_{pump}} = \frac{F \times v}{p \times Q}$$

Example Q: What is total efficiency of the hydraulic system if the DC electric motor is 95% efficient, pump operates with 85% efficiency at given rotor speed and the actuator is 90% efficient?

A: the total efficiency is the multiple of these individual efficiencies, i.e., 0.95x0.85x0.9=0.7268 or about 72.7%. If, for example, 100 kW (134 HP) were delivered by a DC electrical power system to the electromotor powering the centrifugal pump, then the linear actuator will deliver about 73 kW (97 HP) to perform useful function.

Energy loses in hydraulic system

As the hydraulic fluid circulates in a closed system (from reservoir back to reservoir), it will experience losses of the useful energy/power due to frictional losses. At the end all losses will be converted into heat. A hydraulic fluid may upon return also be considerably warmer than when it was first drawn fresh from the reservoir. Hence, there will be direct and indirect heat losses. Usually in aircraft hydraulic systems many heat exchangers exist that would recuperate some of the heat (e.g., oil-fuel heater).

A hydraulic fluid flowing through the tubes, pipes, fittings, valves, pumps, motors, actuators, and filters may be laminar or turbulent. Laminar flow only exist at low Reynolds numbers (for circular tubes that implies $Re < 2{,}000$). Turbulent flow exist for all other flow conditions. The problem with turbulent flow is that it creates much higher friction than laminar. That can be seen from the *Moody* diagram shown in Fig. 2 here.

A famous *Darcy-Weisbach* equation is used to calculate frictional losses through straight circular pipes/tubes of length "*L*" and Diameter "*D*" with fluid's average speed being "*v*". The Moody friction coefficient is "*f*" and it depends on the nature of the flow (laminar, turbulent) and pipe's inner surface roughness:

$$\frac{\Delta p_L}{\gamma_{oil}} = H_L = f \cdot \left(\frac{L}{D}\right) \cdot \frac{v^2}{2g} \quad [\text{ft,m}]$$

Reynolds number is defined as:

$$\text{Re} = \frac{\rho \cdot u \cdot D_H}{\mu_{oil}} = \frac{u \cdot D_H}{\nu_{oil}} \quad [\text{-}]$$

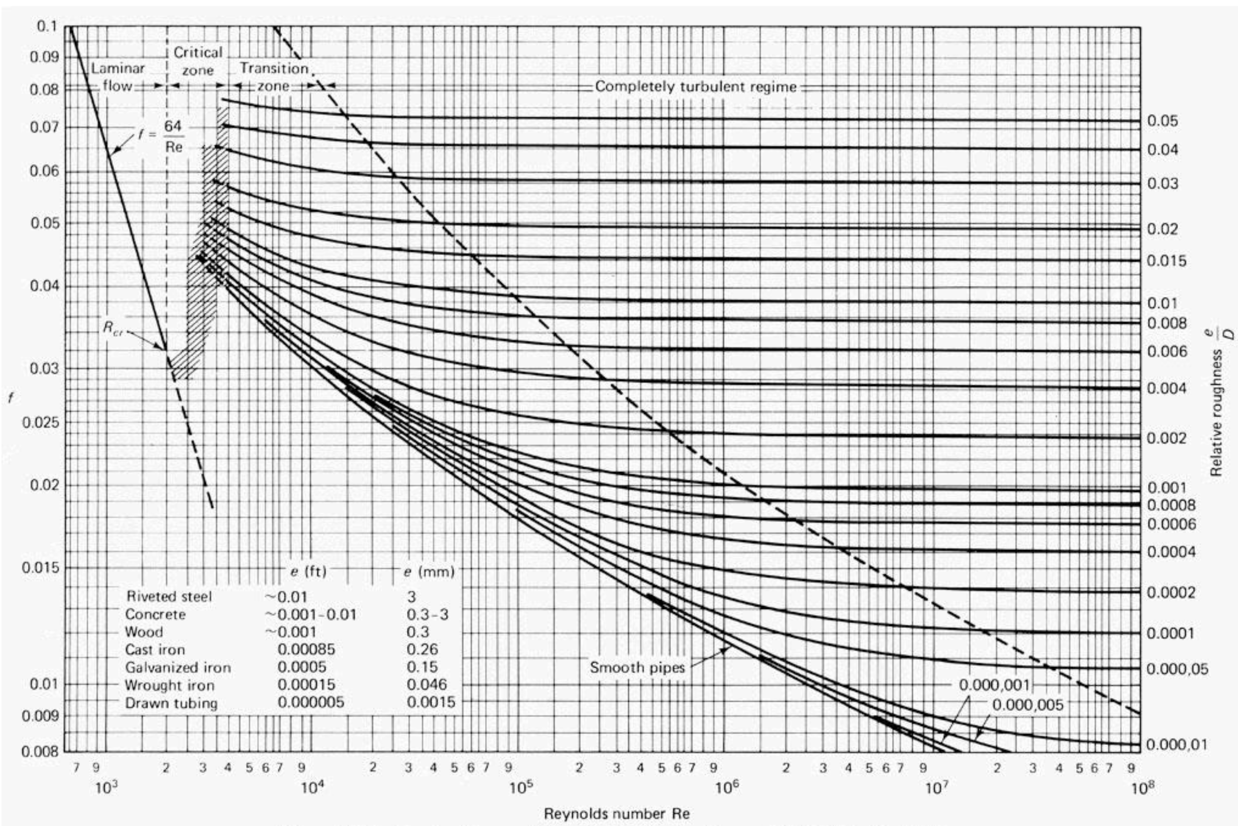

Figure 7.13 Moody diagram. (From L. F. Moody, *Trans. ASME*, Vol. 66, 1944.)

Figure 2: Friction factor as a function of Reynolds number and surface roughness (Moody diagram).

In the case of laminar flow (Re < 2,000), the friction factor is:

$$f = \frac{64}{\text{Re}} \quad [\text{-}]$$

In the case of turbulent flow (Re => 2000), for not neither smooth flow (no surface roughness) nor fully "rough flow" the friction factor is calculated from the implicit *Colebrook* equation:

$$\frac{1}{\sqrt{f}} = -2\log_{10}\left(\frac{e/D}{3.7} + \frac{2.51}{\text{Re}\sqrt{f}}\right) \quad [\text{-}]$$

Here, the absolute surface roughness is "e" and the relative surface roughness is "e/D" and essentially varies between 0.000985 and 0.0333 (from Nikuradse's experiments). For very smooth pipes/tubes, the Moody's friction factor can be computed from the Blasius' equation:

$$f = \frac{0.316}{\text{Re}^{0.25}} \quad [\text{-}]$$

For very rough inner pipe surfaces, we can use *von-Kármán* equation:

$$\frac{1}{\sqrt{f}} = 2\log_{10}\left(\frac{1}{e/D}\right) + 1.14 \quad [\text{-}]$$

In the case of head (energy) losses through fittings (elbows, bends, etc.) and valves, we can write *Darcy-Weisbach* equation in the following form:

$$\frac{\Delta p_L}{\gamma_{oil}} = H_L = K \cdot \frac{v^2}{2g} = f \cdot \left(\frac{L}{D}\right)_{eq} \cdot \frac{v^2}{2g} \quad [\text{ft,m}]$$

Hence, the K-factor can be expressed in terms of "*equivalent pipe length*":

$$K = f \cdot \left(\frac{L}{D}\right)_{eq} \quad [\text{-}] \quad \Rightarrow \quad \left(\frac{L}{D}\right)_{eq} = \frac{K}{f}$$

For example, globe valve fully open has K-factor equal to 10 (1/2 open would be $K=12.5$). For typical materials that would be about equivalent (L/D) of 350. In another example, a 45^{o}-elbow has $K=0.42$ and equivalent (L/D) of 15.

Example Q: What are total frictional losses of a complex hydraulic piping with many elbows, bends, valves, etc., and with the equivalent pipe length of 300 m (984 ft) with the inner diameter of 1 cm (about 2/5 inch)? Drawn tubes were used with the absolute roughness of 0.0015 mm (1.5 micrometer), and the average speed is 0.75 m/s (2,5 ft/s). Skydrol LD-4 hydraulic fluid was used with the viscosity of 3.93 cS at 99^{o}C (1 S=10^{-4} m^2/s) and density of 1.006 g/cm^3 (1,006 kg/m^3) at 25^{o}C.

A: The Reynolds number is

$$\text{Re} = \frac{u \cdot D_H}{\nu_{oil}} = \frac{0.75 \times 10^{-2}}{3.93 \times 10^{-6}} = 1{,}908.4 < 2{,}000\ (\text{laminar}) \quad [\text{-}]$$

The friction factor for laminar flow is now (see also Moody diagram):

$$f = \frac{64}{\mathrm{Re}} = \frac{64}{1,908} = 0.0335 \quad [\text{-}]$$

According to *Darcy-Weisbach* equation, we have:

$$\frac{\Delta p_L}{\gamma_{oil}} = H_L = f \cdot \left(\frac{L}{D}\right)_{eq} \cdot \frac{v^2}{2g} = 0.0335 \cdot \left(\frac{300}{10^{-2}}\right)_{eq} \cdot \frac{0.75^2}{2 \cdot 9.81} = 28.85 \quad [\mathrm{m}]$$

$$\Delta p_L = H_L \cdot \gamma_{oil} = 28.85 \times 1,006 \times 9.81 = 284,717 \text{ Pa} = 2.85 \text{ bar} = 41.28 \text{ psi}$$

Important note: For more details on fluid mechanics hydraulics and aircraft hydraulic systems fundamentals consult:

1. Daugherty, R. L., Franzini, J. B., and Finnemore, E. J. (1985). *Fluid Mechanics: with Engineering Applications* (8th Ed.). New York, NY: McGraw-Hill.

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4. Moir, I. & Seabridge A. (2008). *Aircraft Systems* (3rd ed.). Chichester, West Sussex, UK: John Wiley.

THE END of Hydraulics fundamentals Tutorial
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