Applied Fluid Mechanics

Chapter 1

The Nature of Fluids and The Study of Fluid Mechanics

Amjad El-Qanni, PhD

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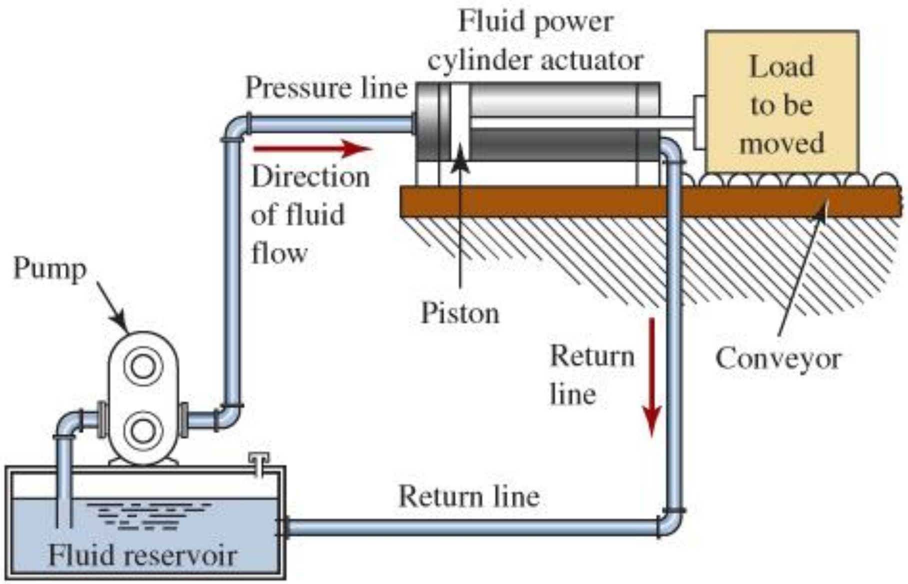
We'll study the behaviour of fluids, both gases and liquids, particularly with regard to piped and pumped systems.

So many pictures could work as the introduction, though, because this course includes water flow in rivers, boats floating on the ocean, and the way that airplanes can fly. The fundamentals of Fluid Mechanics have many, many applications.

Typical piping system for fluid power



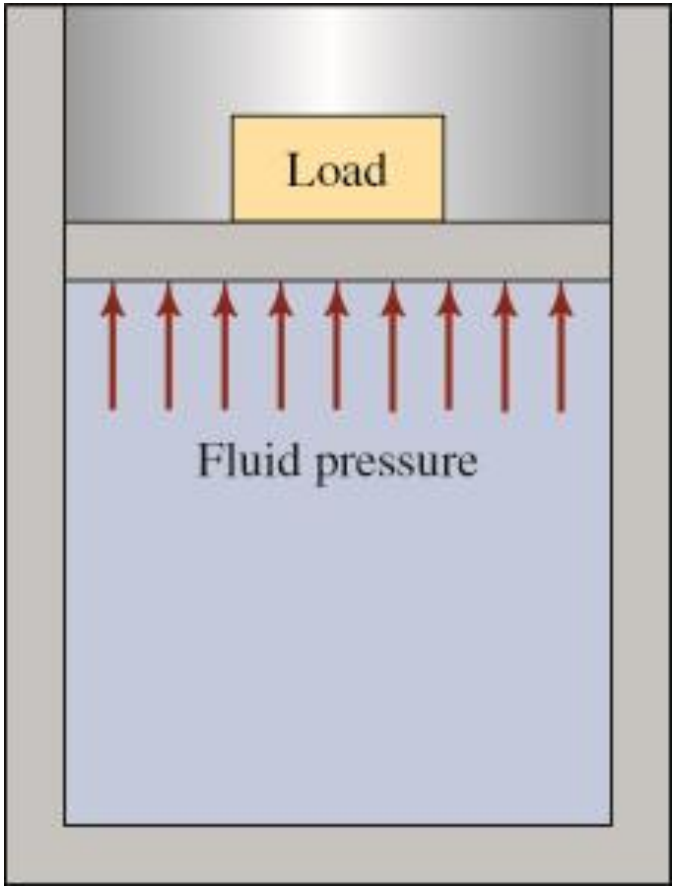
Trace out this system and see how rotating the shaft of a pump, with something like an electric motor, can translate into using fluid to push a heavy load in a straight line for a given distance.

Major Classification of Fluids

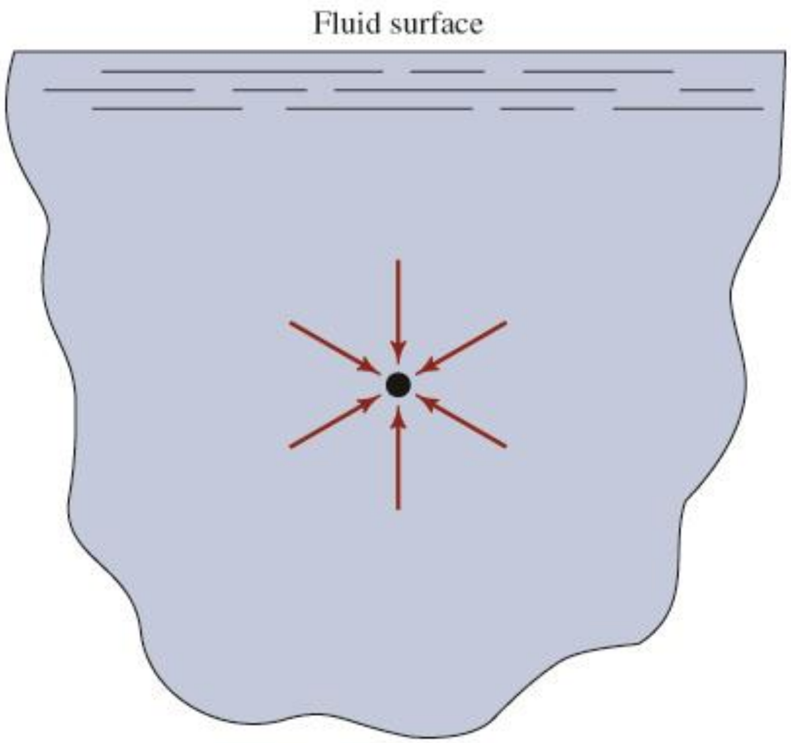
- Gases are compressible, meaning that their volume significantly reduces when pressure is increased.
- Liquids are incompressible, because even with a significant increase in pressure, their volume does not change very much at all.
- Gases are typically much less dense than liquids.
- Both gases and liquids are fluids.

Pressure

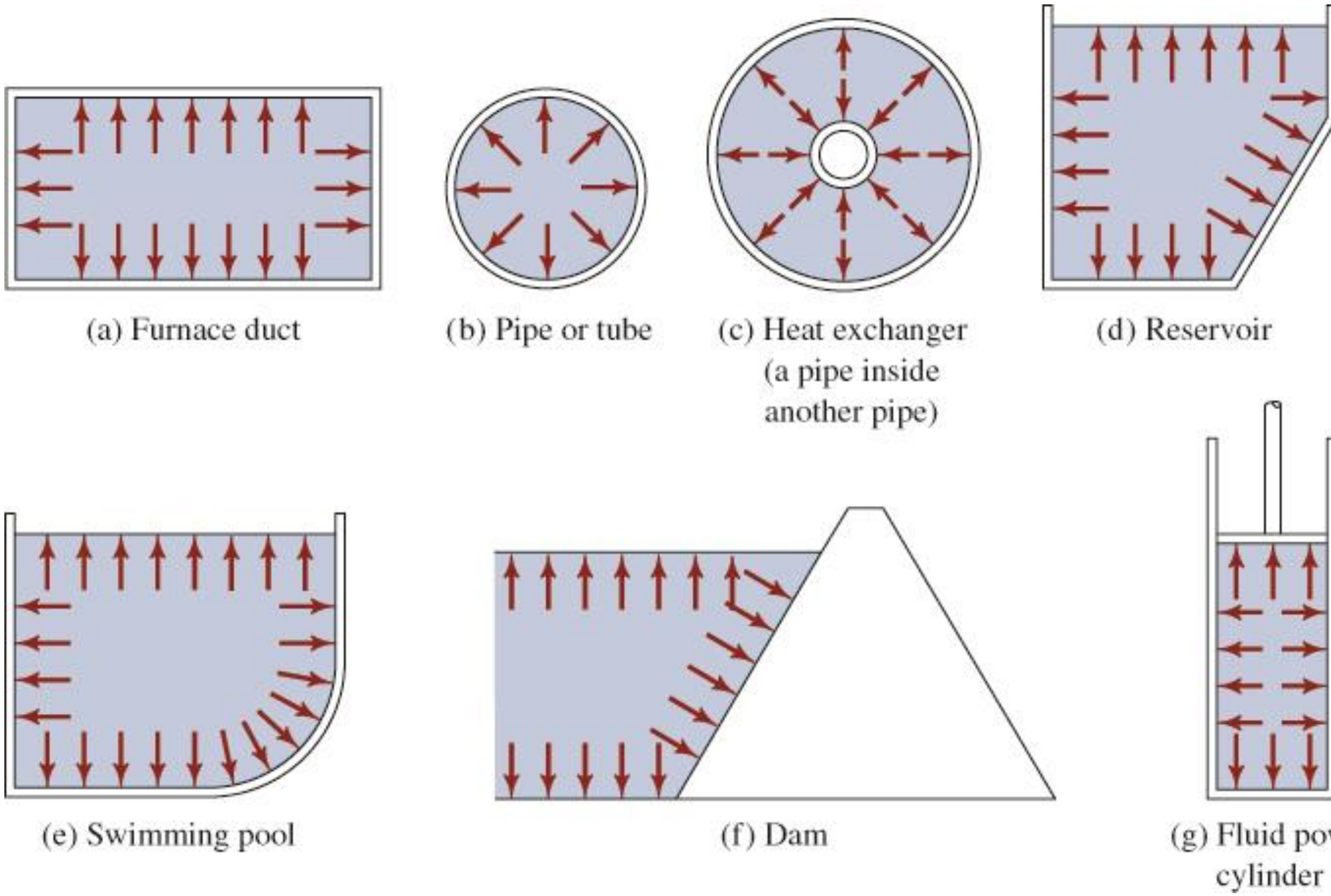
- Pressure is a force exerted on a unit area, and, as such, will always include a unit of force divided by a unit of area such as pounds/square inch, Newtons/meters squared, or something similar.



Pressure in a fluid acts uniformly in all directions on a small volume of fluid



Fluid pressure acts perpendicular to boundaries



Critical concepts from background coursework:

- SI unit system - meter, second, kilogram, newton
- U.S. Customary unit system - foot, second, slug, pound
- Weight and Mass
  – Remember that weight is a force, reported in newtons or pounds. Mass is an inertia, reported in kilograms or slugs.
- Temperature
  – If measured relative to absolute zero, then reported in Kelvin or Rankine. Commonly reported, though, in Celsius or Fahrenheit.

Summary of Units

Quantity	Basic Definition	Standard SI Units	Other Metric Units Often Used	Standard U.S. Units	Other U.S. Units Often Used
Length (L)	—	meter (m)	millimeter (mm); kilometer (km)	foot (ft)	inch (in); mile (mi)
Time	—	second (s)	hour (h); minute (min)	second (s)	hour (h); minute (min)
Mass (m)	Quantity of a substance	kilogram (kg)	$N \cdot s^2/m$	slug	$lb \cdot s^2/ft$
Force (F) or weight (w)	Push or pull on an object	newton (N)	$kg \cdot m/s^2$	pound (lb)	kip (1000 lb)
Pressure (p)	Force/area	N/m^2 or pascal (Pa)	kilopascals (kPa); bar	lb/ft^2 or psf	lb/in^2 or psi; kip/in^2 or ksi
Energy	Force times distance	$N \cdot m$ or Joule (J)	$kg \cdot m^2/s^2$	$lb \cdot ft$	$lb \cdot in$
Power (P)	Energy/time	watt (W) or $N \cdot m/s$ or J/s	kilowatt (kW)	$lb \cdot ft/s$	horsepower (hp)
Volume (V)	L^3	m^3	liter (L)	ft^3	gallon (gal)
Area (A)	L^2	m^2	mm^2	ft^2	in^2
Volume flow rate (Q)	V/time	m^3/s	L/s; L/min; m^3/h	ft^3/s or cfs	gal/min (gpm); ft^3/min (cfm)
Weight flow rate (W)	w/time	N/s	kN/s; kN/min	lb/s	lb/min; lb/h
Mass flow rate (M)	m/time	kg/s	kg/h	slugs/s	slugs/min; slugs/h
Specific weight (γ)	w/V	N/m^3 or $kg/m^2 \cdot s^2$		lb/ft^3	
Density (ρ)	m/V	kg/m^3 or $N \cdot s^2/m^4$		$slugs/ft^3$	

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TABLE K.1 Conversion factors

Mass Standard SI unit: kilogram (kg). Equivalent unit: $N \cdot s^2/m$.

$\frac{14.59\ kg}{slug}$ $\frac{32.174\ lb_m}{slug}$ $\frac{2.205\ lb_m}{kg}$ $\frac{453.6\ grams}{lb_m}$ $\frac{2000\ lb_m}{ton_m}$ $\frac{1000\ kg}{metric\ ton_m}$

Force Standard SI unit: Newton (N). Equivalent unit: $kg \cdot m/s^2$.

$\frac{4.448\ N}{lb_f}$ $\frac{10^5\ dynes}{N}$ $\frac{4.448 \times 10^5\ dynes}{lb_f}$ $\frac{224.8\ lb_f}{kN}$

Length

$\frac{3.281\ ft}{m}$ $\frac{39.37\ in}{m}$ $\frac{12\ in}{ft}$ $\frac{1.609\ km}{mi}$ $\frac{5280\ ft}{mi}$ $\frac{6076\ ft}{nautical\ mile}$

Area

$\frac{144\ in^2}{ft^2}$ $\frac{10.76\ ft^2}{m^2}$ $\frac{645.2\ mm^2}{in^2}$ $\frac{10^6\ mm^2}{m^2}$ $\frac{43\ 560\ ft^2}{acre}$ $\frac{10^4\ m^2}{hectare}$

Volume

$\frac{1728\ in^3}{ft^3}$ $\frac{231\ in^3}{gal}$ $\frac{7.48\ gal}{ft^3}$ $\frac{264.2\ gal}{m^3}$ $\frac{3.785\ L}{gal}$ $\frac{35.31\ ft^3}{m^3}$

$\frac{28.32\ L}{ft^3}$ $\frac{1000\ L}{m^3}$ $\frac{61.02\ in^3}{L}$ $\frac{1000\ cm^3}{L}$ $\frac{1.201\ U.S.\ gal}{Imperial\ gallon}$

Volume Flow Rate

$\frac{449\ gal/min}{ft^3/s}$ $\frac{35.31\ ft^3/s}{m^3/s}$ $\frac{15\ 850\ gal/min}{m^3/s}$ $\frac{3.785\ L/min}{gal/min}$

$\frac{60\ 000\ L/min}{m^3/s}$ $\frac{2119\ ft^3/min}{m^3/s}$ $\frac{16.67\ L/min}{m^3/h}$ $\frac{101.9\ m^3/h}{ft^3/s}$

Density **(mass/unit volume)**

$\frac{515.4\ kg/m^3}{slug/ft^3}$ $\frac{1000\ kg/m^3}{gram/cm^3}$ $\frac{32.17\ lb_m/ft^3}{slug/ft^3}$ $\frac{16.018\ kg/m^3}{lb_m/ft^3}$

Specific Weight **(weight/unit volume)**

$\frac{157.1\ N/m^3}{lb_f/ft^3}$ $\frac{1728\ lb/ft^3}{lb/in^3}$

Pressure Standard SI unit: pascal (Pa). Equivalent units: N/m^2 or $kg/m \cdot s^2$.

$\frac{144\ lb/ft^2}{lb/in^2}$ $\frac{47.88\ Pa}{lb/ft^2}$ $\frac{6895\ Pa}{lb/in^2}$ $\frac{1\ Pa}{N/m^2}$ $\frac{100\ kPa}{bar}$ $\frac{14.50\ lb/in^2}{bar}$

$\frac{27.68\ inH_2O}{lb/in^2}$ $\frac{249.1\ Pa}{inH_2O}$ $\frac{2.036\ inHg}{lb/in^2}$ $\frac{3386\ Pa}{inHg}$ $\frac{133.3\ Pa}{mmHg}$ $\frac{51.71\ mmHg}{lb/in^2}$

$\frac{14.696\ lb/in^2}{Std.\ atmosphere}$ $\frac{101.325\ kPa}{Std.\ atmosphere}$ $\frac{29.92\ inHg}{Std.\ atmosphere}$ $\frac{760.1\ mmHg}{Std.\ atmosphere}$

TABLE K.1 Conversion factors (*continued*)

Note: Conversion factors based on the height of a column of liquid (e.g., inH_2O and mmHg) are based on a standard gravitational field ($g = 9.806\,65\ m/s^2$), a density of water equal to 1000 kg/m^3, and a density of mercury equal to 13 595.1 kg/m^3, sometimes called *conventional values* for a temperature at or near 0°C. Actual measurements with such fluids may vary because of differences in local gravity and temperature.

Energy Standard SI unit: joule (J). Equivalent units: N·m or kg·m^2/s^2.

$$\frac{1.356\ \text{J}}{\text{lb-ft}} \quad \frac{1.0\ \text{J}}{\text{N·m}} \quad \frac{8.85\ \text{lb-in}}{\text{J}} \quad \frac{1.055\ \text{kJ}}{\text{Btu}} \quad \frac{3.600\ \text{kJ}}{\text{W·h}} \quad \frac{778.17\ \text{ft-lb}}{\text{Btu}}$$

Power Standard SI unit: watt (W). Equivalent unit: J/s or N·m/s.

$$\frac{745.7\ \text{W}}{\text{hp}} \quad \frac{1.0\ \text{W}}{\text{N·m/s}} \quad \frac{550\ \text{lb-ft/s}}{\text{hp}} \quad \frac{1.356\ \text{W}}{\text{lb-ft/s}} \quad \frac{3.412\ \text{Btu/hr}}{\text{W}} \quad \frac{1.341\ \text{hp}}{\text{kW}}$$

Dynamic Viscosity Standard SI unit: Pa·s or N·s/m^2 (cP = centipoise)

$$\frac{47.88\ \text{Pa·s}}{\text{lb-s/ft}^2} \quad \frac{10\ \text{poise}}{\text{Pa·s}} \quad \frac{1000\ \text{cP}}{\text{Pa·s}} \quad \frac{100\ \text{cP}}{\text{poise}} \quad \frac{1\ \text{cP}}{1\ \text{mPa·s}}$$

Kinematic Viscosity Standard SI unit: m^2/s (cSt = centistoke)

$$\frac{10.764\ \text{ft}^2\text{/s}}{\text{m}^2\text{/s}} \quad \frac{10^4\ \text{stoke}}{\text{m}^2\text{/s}} \quad \frac{10^6\ \text{cSt}}{\text{m}^2\text{/s}} \quad \frac{100\ \text{cSt}}{\text{stoke}} \quad \frac{1\ \text{cSt}}{1\ \text{mm}^2\text{/s}} \quad \frac{10^6\ \text{mm}^2\text{/s}}{\text{m}^2\text{/s}}$$

Refer to Section 2.6.5 for conversions involving Saybolt Universal seconds.

General Approach to Application of Conversion Factors. Arrange the conversion factor from the table in such a manner that when multiplied by the given quantity, the original units cancel out, leaving the desired units.

Example 1 Convert 0.24 m^3/s to the units of gal/min:

$$(0.24\ \text{m}^3\text{/s})\frac{15\,850\ \text{gal/min}}{\text{m}^3\text{/s}} = 3804\ \text{gal/min}$$

Example 2 Convert 150 gal/min to the units of m^3/s:

$$(150\ \text{gal/min})\frac{1\ \text{m}^3\text{/s}}{15\,850\ \text{gal/min}} = 9.46 \times 10^{-3}\ \text{m}^3\text{/s}$$

Temperature Conversions (Refer to Section 1.6)

Given the Fahrenheit temperature T_F in °F, the Celsius temperature T_C in °C is

$$T_C = (T_F - 32)/1.8$$

Given the temperature T_C in °C, the Fahrenheit temperature T_F in °F is

$$T_F = 1.8T_C + 32$$

Given the temperature T_C in °C, the absolute temperature T_K in K (kelvin) is

$$T_K = T_C + 273.15$$

Given the temperature T_F in °F, the absolute temperature T_R in °R (degrees Rankine) is

$$T_R = T_F + 459.67$$

Given the temperature T_F in °F, the absolute temperature T_K in K is

$$T_K = (T_F + 459.67)/1.8 = T_R/1.8$$

Be sure that units are explicit, consistent, and properly cancelled in all calculations.

$$p = \frac{0.20\ \text{N}}{\text{mm}^2} \times \frac{(10^3\,\text{mm})^2}{\text{m}^2} = 0.20 \times 10^6\,\text{N/m}^2 = 0.20\text{MPa}$$

$$t = \frac{1.5\ \cancel{\text{km}} \cdot \cancel{\text{h}}}{80\ \cancel{\text{km}}} \times \frac{3600\ \text{s}}{1\,\cancel{\text{h}}}$$

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Density

Density *is the amount of mass per unit volume of a substance.* Using the Greek letter ρ (rho) for density,

$$\rho = m / V$$

In SI units, then, density is kg/m^3 and

in English Customary Units, $slugs/ft^3$

Specific Weight

Specific Weight *is the amount of weight per unit volume a substance.* Using the Greek letter γ (gamma) for specific weight,

$$\gamma = w/V$$

In SI units, then, specific weight is N/m^3 and in English Customary Units, lb/ft^3

Specific Gravity (sg)

Specific Gravity *is the density of a substance relative to the density of water.* The mathematical definition of specific gravity, then, is

$$\text{sg} = \frac{\gamma_s}{\gamma_w \text{ @ } 4°\text{C}} = \frac{\rho_s}{\rho_w \text{ @ } 4°\text{C}}$$

The value for specific gravity is unitless, and the same value whether in SI units or English Customary Units.

Hydrometers are carefully calibrated and then placed in fluid to accurately measure fluid density

Source*:* YAUHENI MESHCHARAKOU/123RF and Ellirra/123RF

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Example Problem 1.6

Example Problem 1.6

If the reservoir from Example Problem 1.5 has a volume of 0.917 m^3, compute the density, the specific weight, and the specific gravity of the oil.

Solution

Density:

$$\rho_o = \frac{m}{V} = \frac{825 \text{ kg}}{0.917 \text{ m}^3} = 900 \text{ kg/m}^3$$

Specific weight:

$$\gamma_o = \frac{w}{V} = \frac{8.093 \text{ kN}}{0.917 \text{ m}^3} = 8.83 \text{ kN/m}^3$$

Specific gravity:

$$\text{sg}_0 = \frac{\rho_o}{\rho_w @ 4°C} = \frac{900 \text{ kg/m}^3}{1000 \text{ kg/m}^3} = 0.90$$