Chapter 1
Basic Equations for Flowing Streams

1.1 Total Energy Balance

Consider the energy interactions as a stream of material passes in steady flow between points 1 and 2 of a piping system, as shown in Fig. 1.1. From the first law of thermodynamics, we have for each unit mass of flowing fluid:

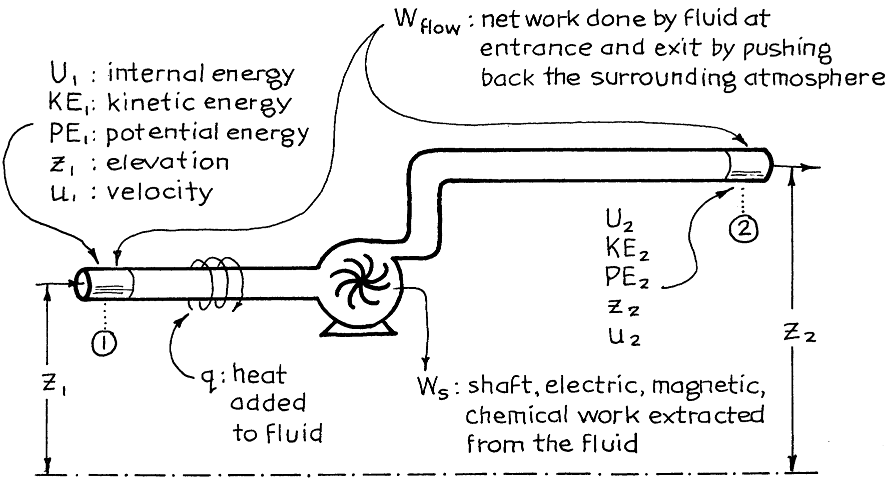


Fig. 1.1 Energy aspects of a single-stream piping system

O. Levenspiel, *Engineering Flow and Heat Exchange*,
DOI 10.1007/978-1-4899-7454-9_1

$$\Delta U + \Delta(gz) + \Delta\left(\frac{u^2}{2}\right) + \Delta\left(\frac{p}{\rho}\right) = q - W_s \qquad \left[\frac{\text{J}}{\text{kg}}\right] \tag{1.1}$$

where: ΔU = internal energy; $\Delta(gz)$ = Potential energy, PE; $\Delta\left(\frac{u^2}{2}\right)$ = Kinetic energy, KE; $\Delta\left(\frac{p}{\rho}\right)$ = Flow work gained by fluid; q = Heat added to fluid from surroundings; W_s = Work received by surroundings from fluid

Consider the internal energy term in the above expression. From the second law of thermodynamics,

$$\Delta U = \int T\,dS - \int p\,d\left(\frac{1}{\rho}\right) + \text{magnetic, electrical, chemical work, etc.} \tag{1.2}$$

The $\int T\ dS$ term accounts for both heat and frictional effects. Thus, in the ideal situation where there is no degradation of mechanical energy (no frictional loss, turbulence, etc.):

$$\int T\,dS = q = \text{heat added to flowing fluid from surroundings}$$

On the other hand, in situations where there is degradation (frictional losses),

$$\int T\,dS = q + \Sigma F \tag{1.3}$$

where: $\int T\,dS$ = Total heat added to fluid; q = Heat from surroundings; ΣF = Heat generated within the fluid by friction

Noting that $\Delta H = \Delta U + \Delta(p/\rho)$, we can rewrite equation (1.1) as

$$\boxed{\Delta H + \Delta(gz) + \Delta\left(\frac{u^2}{2}\right) = q - W_s \qquad \left[\frac{\text{J}}{\text{kg}}\right]} \tag{1.4}$$

This is the first law of thermodynamics in its usual and useful form for steady-flow single-stream systems.

[AUTHOR'S NOTE: g_c is a conversion factor, to be used with American engineering units. In SI units, g_c is unity and drops from all equations. Since this book uses SI units throughout, g_c is dropped in the text and problems.]

1.2 Mechanical Energy Balance

For each kilogram of real flowing fluid, with its unavoidable frictional effects, with no unusual work effects (magnetic, electrical, surface, or chemical), and with constant value of g, equations (1.1) and (1.3) combined give the so-called mechanical energy balance.

ME gained by fluid — Along flow path — Work received by surroundings — ME lost by fluid

$$g\Delta z + \Delta\left(\frac{u^2}{2g}\right) + \int \frac{dp}{\rho} + W_s + \Sigma F = 0 \quad \left[\frac{\mathrm{J}}{\mathrm{kg}} = \frac{m^2}{s^2}\right] \tag{1.5a}$$

For incompressible fluids this term becomes ($\Delta p / \rho$)

Friction loss, or mechanical energy transformed into internal energy, and used to head or vaporize the fluid or ME lost by fluid.

Multiplying by $1/g$ gives, in alternative form,

$$\Delta z + \Delta\left(\frac{u^2}{2g}\right) + \frac{1}{g}\int \frac{dp}{\rho} + \frac{1}{g}W_s + \frac{1}{g}\Sigma F = 0 \quad \left[\begin{matrix}\text{m of}\\ \text{fluid}\end{matrix}\right] \tag{1.5b}$$

called shaft work — Lost head = h_L

In differential form these equations are

$$gdz + u\,du + \frac{dp}{\rho} + dW_s + d(\Sigma F) = 0 \quad \left[\frac{\mathrm{J}}{\mathrm{kg}}\right] \tag{1.6a}$$

and

$$dz + \frac{u\,du}{g} + \frac{1dp}{g\,\rho} + \frac{1}{g}dW_s + d(h_L) = 0 \quad [\mathrm{m}] \tag{1.6b}$$

These equations, in fact, represent not a balance, but a loss of mechanical energy (the transformation into internal energy because of friction) as the fluid flows down the piping system. In the special case where the fluid does no work on the surroundings (W = 0) and where the frictional effects are so minor that they can be completely ignored (ΣF = 0), the mechanical energy balance reduces to

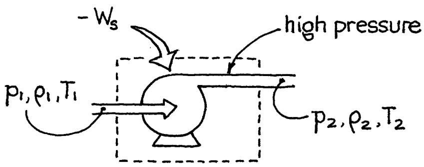
$$g\Delta z + \Delta\frac{u^2}{2} + \int \frac{dp}{\rho} = 0 \tag{1.7}$$

which is called the Bernoulli equation.

The mechanical energy balance, equations (1.5a), (1.5b), (1.6a), (1.6b), and (1.7), is the starting point for finding work effects in flowing fluids—pressure drop, pumping power, limiting velocities, and so on. We apply these expressions to all types of fluids and mixtures.

1.3 Pumping Energy and Power: Ideal Case

Pumps, compressors, and blowers are the means for making fluids flow in pipes. The shaft work needed by the fluid is found by writing the mechanical energy



balance about the device. In the ideal case where the kinetic and potential energy changes and frictional losses are negligible, equation (1.5a and b) reduces to

$$-W_{s,\text{ideal}} = \int_{p_1}^{p_2} \frac{dp}{\rho} \quad \left[\frac{\text{J}}{\text{kg}}\right] \tag{1.8}$$

received by fluid

For *liquids* and *slurries*, ρ and $T \cong$ const, so the shaft work from the surroundings to the fluid is

$$-W_{s,\text{ideal}} = \frac{p_2 - p_1}{\rho} = \frac{\Delta p}{\rho} \quad \left[\frac{\text{J}}{\text{kg}}\right] \tag{1.9}$$

Thus the work delivered by the fluid

$$+\dot{W}_{s,\text{ideal}} = \dot{m}W_{s,\text{ideal}} = (\rho u A) - W_{s,\text{ideal}} \qquad \left[\frac{\text{J}}{\text{s}} = \text{W}\right] \tag{1.10}$$

Assuming ideal gas behavior and adiabatic reversible compression or expansion, the work received by each unit of flowing gas is

$$\begin{aligned} -W_{s,\text{ideal}} &= \frac{k}{k-1}\frac{RT_1}{(mw)}\left[\left(\frac{p_2}{p_1}\right)^{(k-1)/k} - 1\right] = C_p(T_2 - T_1) \\ &= \frac{k}{k-1}\frac{RT_2}{(mw)}\left[1 - \left(\frac{p_1}{p_2}\right)^{(k-1)/k}\right] \qquad \left[\frac{\text{J}}{\text{kg}}\right] \end{aligned} \tag{1.11}$$

The power produced by the flowing gas is then

$$\dot{m}W_{s,\text{ideal}} = (mw)\dot{n}W_{s,\text{ideal}} \quad [\text{W}] \tag{1.12}$$

where

$$k = \frac{C_p}{C_v}, \quad \frac{RT_i}{(mw)} = \frac{p_i}{\rho_i}, \quad \dot{n}RT_i = p_i v_i, \quad \text{and} \quad \frac{T_2}{T_1} = \left(\frac{p_2}{p_1}\right)^{(k-1)/k} \tag{1.13}$$

1.4 Pumping Energy and Power: Real Case Compression

For *gases* compare *ideal adiabatic compression* with the real situation with its frictional effects and heat interchange with the surroundings, both cases designed to take fluid from a low pressure p_1 to a higher pressure p_2. The *p*-*T* diagram of Fig. 1.2 shows the path taken by the fluid in these cases.

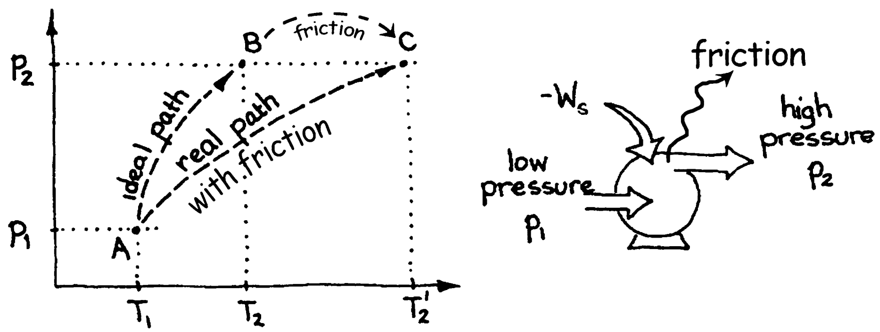


Fig. 1.2 In a real adiabatic compression (with friction), the fluid leaves hotter than in an ideal compression

For real compression some of the incoming shaft work is needed to overcome friction and ends up heating the gas. Thus, the actual incoming shaft work is greater than the ideal needed and related to it by

$$W_{s,\mathrm{actual}} = \frac{W_{s,\mathrm{ideal}}}{\eta}, \quad W_s < 0 \tag{1.14}$$

where η is the compressor efficiency, typically

$\eta = 0.55–0.75$ for a turbo blower
$\eta = 0.60–0.80$ for a Roots blower
$\eta = 0.80–0.90$ for an axial blower or a two-stage reciprocating compressor

The temperature rise in ideal and real compression (see Fig. 1.2) is related to the compressor efficiency by

$$\eta = \frac{T_2 - T_1}{T_2' - T_1 - (q/C_p)} \tag{1.15}$$

where q(J/kg) is the heat going from surroundings to the compressor and then to the fluid, per kg of fluid being compressed.

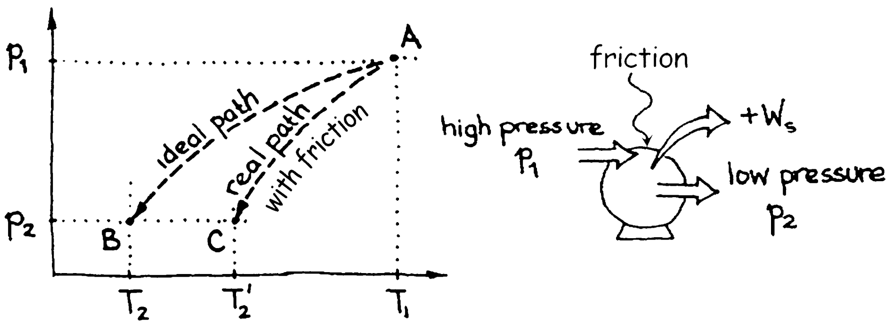


Fig. 1.3 In a real power producer (with friction), the fluid leaves hotter than in an ideal power producer

1.4.1 Expansion

Next consider the *reverse operation* in which flowing gas expands from a high pressure p_1 to a lower pressure p_2 *to produce work*. The turbine is an example of such a device.

In the real situation with its frictional losses, less work is produced than would be generated ideally. Figure 1.3 shows the *p*-*T* paths taken by the gas in the real and the ideal cases. The efficiency of the turbine relates these work terms, as follows:

$$W_{s,\text{actual}} = \eta W_{s,\text{ideal}} \tag{1.16}$$

and the outlet temperature of the fluid in the two cases is (see Fig. 1.3)

$$\eta = \frac{T_2' - T_1 - \left(q/C_p\right)}{T_2 - T_1} \tag{1.17}$$

where q again represents the heat added to each kilogram of flowing gas.

For *liquids* the relationship between actual and ideal work is given by equations (1.14) and (1.16), the same as for gases. However, since the work needed to compress a liquid is very much smaller than for the same mass of gas (by 2 or 3 orders of magnitude), the temperature change is usually quite small and often can be safely neglected when compared with the other energy terms involved. Thus, more usefully, the efficiency of operations between p_1 and p_2 is best gotten from equation (1.9), or

$$\eta_{\text{compression}} = \frac{-W_{s,\text{ideal}}}{-W_{s,\text{actual}}} = \frac{p_2 - p_1}{\rho(-W_{s,\text{actual}})} \tag{1.18}$$

and

$$\eta_{\text{expansion}} = \frac{W_{s,\text{actual}}}{W_{s,\text{ideal}}} = \frac{\rho(W_{s,\text{actual}})}{p_1 - p_2} \tag{1.19}$$

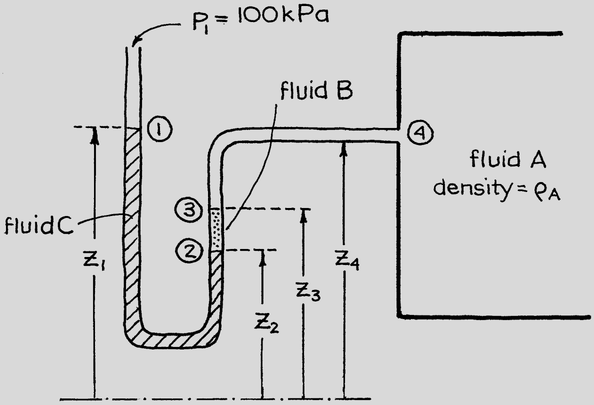
As may be seen in Figs. 1.2 and 1.3, for real compression or expansion, a portion of the mechanical energy is lost by friction to heat the flowing fluid. This is the unavoidable tax imposed by the second law of thermodynamics on all real processes.

Example 1.1. Hydrostatics and Manometers

Find the pressure p_4 in the tank from the manometer reading shown below, knowing all heights z_1, z_2, z_3, z_4, all densities ρ_A, ρ_B, ρ_C, and the surrounding pressure p_1.

(continued)

(continued)



Solution

To find the pressure at point 4, apply the mechanical energy balance from a point of known pressure, point 1, around the system to point 4. Thus, from point 1 to point 2, we have

$$g\Delta z + \cancelto{=0}{\frac{\Delta u^2}{2}} + \int \frac{dp}{\rho} + \cancelto{=0}{W_s} + \cancelto{=0}{\sum F} = 0$$

and for fluids of constant density (liquids), this reduces to

$$p_2 - p_1 = \rho_C g(z_1 - z_2) \quad \left[\frac{kg}{m^3} \cdot \frac{m}{s^2} \cdot m = Pa\right]$$

Repeating this procedure gives

$$p_3 - p_2 = \rho_B g(z_2 - z_3)$$
$$p_4 - p_3 = \rho_A g(z_3 - z_4)$$

Adding the above expression and noting that $p_1 = 100$ kPa gives the desired expression

(continued)

(continued)

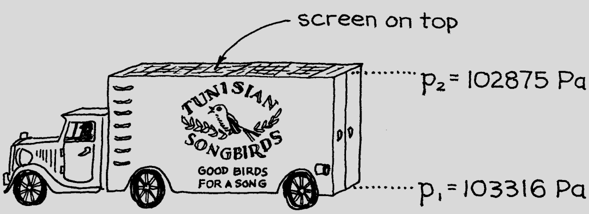
$$p_4 = 100 + G[\rho_C(z_1 - z_2) + \rho_B(z_2 - z_3) + \rho_A(z_3 - z_4)], \qquad [\text{kPa}]$$

The same strategy of working around the system holds for other geometries and for piping loops.

Example 1.2. Counting Canaries Italian Style

Italians love birds, many homes have these happy songsters in little cages, and to supply them is a big business. Tunisian Songbirds, Inc., is a major supplier of canaries for Southern Italy, and every Wednesday a large truck carrying these chirpy feathered creatures is loaded aboard the midweek Tunis to Naples ferry. The truck's bird container is 2.4 m wide, 3.0 m high, solid on the sides and bottom, open at the top except for a restraining screen, and has a total open volume available for birds of 36 m^3. On arrival at Naples a tax of 20 lira/bird is to be charged by the customs agent, but how to determine the amount to be assessed? Since counting these thousands of birds one by one would be impractical, the Italians use the following ingenious method.

The customs agent sets up his pressure gauges and then loudly bangs the side of the van with a hammer. This scares the birds off their perches up into the air. Then he carefully records the pressure both at the bottom and at the top of the inside of the van.



If the pressure at the bottom is 103,316 Pa, the pressure at the top is 102,875 Pa, and the temperature is 25 °C, how much tax should the customs agent levy?

Additional data: Juvenile canaries have a mass of 15 g and a density estimated to be 500 kg/m^3.

Solution

With birds flying in all directions, consider the interior of the van to be a "fluid" or "slurry" or a "suspension" of mean density $\overline{\rho}$; then the mechanical energy balance of equation (1.5) reduces to

$$p_1 - p_2 = \overline{\rho} g(z_2 - z_1) \tag{i}$$

where

$$\overline{\rho} = \frac{\text{total mass}}{\text{total volume}} = \frac{m_{\text{birds}} + m_{\text{air}}}{V_{\text{total}}} = \frac{\rho_b V_b + \rho_a V_a}{V_t}$$
$$= \rho_b \left(\frac{V_b}{V_t}\right) + \rho_a \overbrace{\left(\frac{V_a}{V_t}\right)}^{=0}$$

In their calculations the customs agents ignore the second term in the above expression because the density of air is so small compared to the density of the birds. Thus, on replacing all known values into equation (i) gives

$$103{,}316 - 102{,}875 = [(500)(V_b/V_t)](9.8)(3 - 0)$$

from which the volume fraction of birds in the van is found to be

$$\frac{V_b}{V_t} = 0.03$$

The number of birds being transported is then

$$N = \left(0.03 \frac{\text{m}^3 \ \text{birds}}{\text{m}^3 \ \text{van}}\right)(36\,\text{m}^3\,\text{van})\left(500 \frac{\text{kg}}{\text{m}^3\,\text{bird}}\right)\left(\frac{1 \ \text{bird}}{0.015 \ \text{kg}}\right)$$
$$= 36{,}000 \ \text{birds}$$

therefore

$$\text{Tax} = \left(20 \frac{\text{L}}{\text{bird}}\right)(36{,}000 \ \text{birds}) = 720{,}000\,\text{L}$$

Example 1.3. Compressor Efficiency
An adiabatic compressor takes in 1 atm, 300 K air and produces a product stream of 3 atm, 450 K air. What is its efficiency? Take $k = C_p/C_v = 1.4$.

Solution
The efficiency of the real adiabatic compressor is given by equation (1.15), or

$$\eta = (T_2 - T_1)/\left(T_2' - T_1\right) = (T_2 - 300)/(450 - 300) \qquad \text{(i)}$$

For ideal compression, the exit temperature is given by equation (1.13), or

$$T_2/T_1 = (p_2/p_1)^{(k-1)k} = (3/1)^{0.4/1.4} = 1.36$$

and with $T_1 = 300$ K we find

$$T_2 = 1.36(300) = 408 \text{ K} \qquad \text{(ii)}$$

Combining equations (i) and (ii) gives the compressor efficiency to be

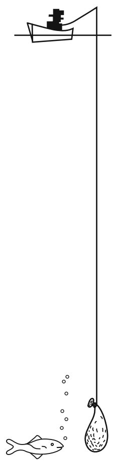
$$\eta = (408 - 300)/(450 - 300) = 0.72, \quad \text{or} \quad 72\%$$

Problems on Energy Balances

1.1. Thermodynamics states that at high enough pressure diamond is the stable form for carbon. General Electric Co. and others have used this information to make diamonds commercially by implosion and various other high-pressure techniques, all complex and requiring sophisticated technology.

Let us try something different. Take a canvas sack of lead pencils, charcoal briquettes, or coal out in a rowboat to one of the deepest parts of the ocean, the Puerto Rico trench; put some iron pipe in the sack, lower it to the ocean bottom 10 km below, wait a day, and then haul it up. Lo and behold!—a sack full of diamonds, we hope. It may work if the pressure on the ocean bottom is above the critical, or transition, pressure. Find the pressure on the ocean bottom.

Data: Down to 10 km, seawater has an average density of 1,036 kg/m^3.



1.2. *Streamline trains*. Forest Grove, Oregon, has a museum—a railroad museum—and with your admission ticket you get a free ride around their private track on either an old 1810 puffer or a streamliner of the 1950 era which was designed to speed at 160 km/h.

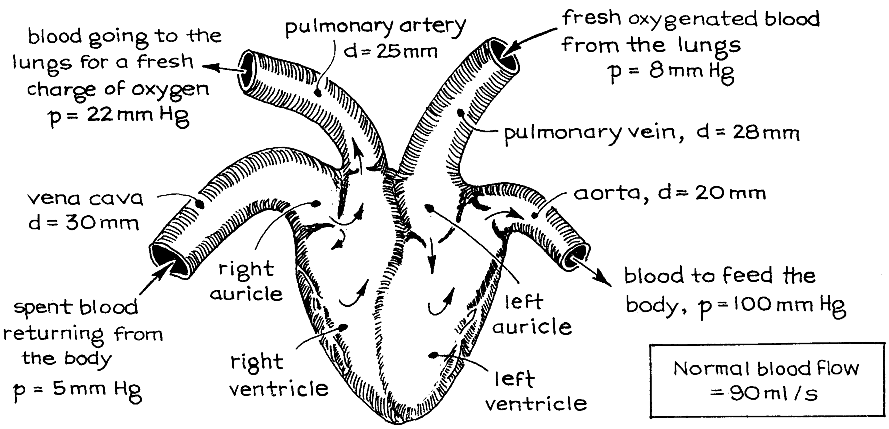
To measure the speed of the streamliner, we attach a pressure measuring device at the very front of the engine, at the stagnation point for the flowing air. We then measure the pressure when the train is moving and when it is standing still. We find:

(i) On a nice sunny 25 °C day, we get a pressure reading of $p = 102{,}750$ Pa when the streamliner is not moving.
(ii) When the streamliner is traveling at its museum top speed along the straightaway, we find $p = 102{,}760$ Pa.

How fast is the train barreling along?

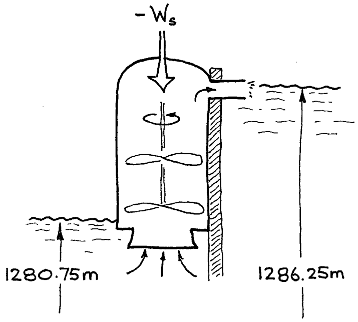
1.3. *Artificial hearts*. The human heart is a wondrous pump, but only a pump. It has no feelings, no emotions, and its big drawback is that it only lasts one lifetime. Since it is so important to life, how about replacing it with a compact, super reliable mechanical heart which will last two lifetimes. Wouldn't that be great? The sketch below gives some pertinent details of the average relaxed human heart. From this information calculate the power requirement of an ideal replacement heart to do the job of the real thing.

Comment. Of course, the final unit should be somewhat more powerful, may be by a factor of 5, to account for pumping inefficiencies and to take care of stressful situations, such as running away from hungry lions. Also assume that blood has the properties of water.

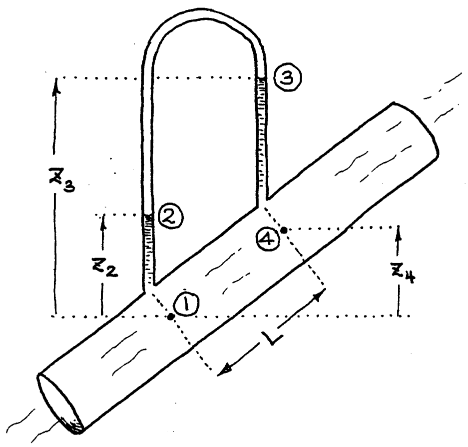


1.4. *The Great Salt Lake flood.* The water level of the Great Salt Lake in Utah has been rising steadily in recent years. In fact, it has already passed its historic high of 1283.70 m above mean sea level set in June 1873.[1] This rise has flooded many of man's works, and if it continues it will damage many more including the road bed of the main railroad line from San Francisco to the East Coast as well as long stretches of interstate highway I-80.

One idea for countering this alarming rise is to pump water out of the lake up over a dam into channels that lead to two very large evaporation ponds. Determine the annual energy cost of pumping an average of 85 m^3/s of water year round if electricity costs \$0.0385/kW · h. The six giant 85 % efficient turbines are designed to raise water from an elevation of 1,280.75–1,286.25 m above mean sea level, the lake water has a density of 1,050 kg/m^3, and the exhaust pipe is 3 m i.d.

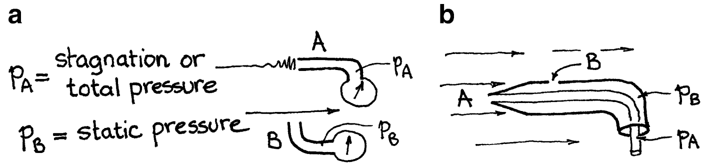


1.5. For the manometer shown on the next page, develop the expression for the pressure difference $p_1 - p_4$ as a function of the pertinent variables. In the sketch on the next page, is the fluid flowing up or down the pipe?



[1] See the *Ogden Standard Examiner*, 15 May 1986.

1.6. *Pitot tubes* are simple reliable devices for measuring the velocity of flowing fluids. They are used in the laboratory, and, if you look carefully, you will see them on all airplanes. Sketch (a) shows how the pitot tube works. Fluid flows past probe B but is brought to a stop at probe A, and according to Bernoulli's equation the difference in velocity is translated into a difference in pressure. Thus probe A, which accounts for the kinetic energy of the fluid, reads a higher pressure than does probe B. Real pitot tubes compactly combine these two probes into two concentric tubes as shown in sketch (b).



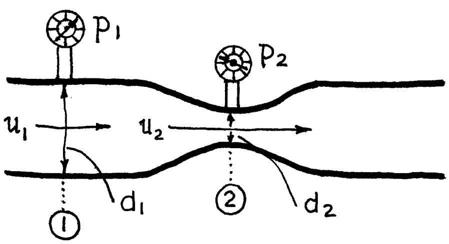
(a) Develop the general expression for flow velocity in terms of the pressures p_A and p_B.

(b) Titan, Saturn's moon, is the largest satellite in our solar system. It is roughly half the diameter of the Earth, its atmosphere consists mainly of methane, and it is probably the easiest object to explore in the outer solar system. As the Voyager 2 spacecraft slowly settles toward the surface of Titan through an atmosphere at -130 °C and 8.4 kPa, its pitot tube reads a pressure difference of 140 Pa. Find the speed of the spacecraft.

1.7. A *venturi meter* is a device for measuring the flow rate of fluid in a pipe. It consists of a smooth contraction and expansion of the flow channel, as shown below ($p_1 \gg p_2$). Pressure measurements at the throat and upstream then give the flow rate of fluid. For liquid flowing through an ideal venturi, show that the approach velocity u_1 is given by the following equation:

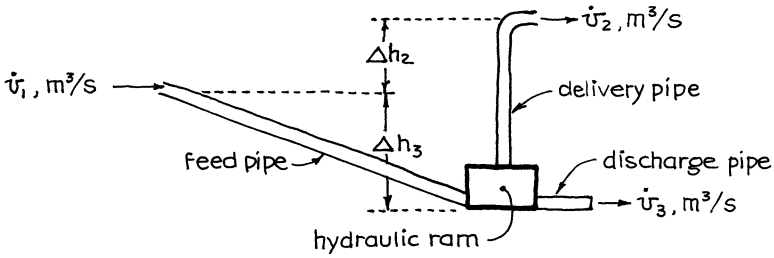
$$u_1 = \frac{1}{(\alpha^4 - 1)^{1/2}} \cdot \left(\frac{2(p_1 - p_2)}{\rho} \right)^{1/2} \quad \text{where} \quad \alpha = \frac{d_1}{d_2}$$

Note: For a well-designed venturi, where $d_2 < d_1/4$, this expression is off by 1–2 % at most, because of frictional effects. Thus, in the real venturi meter, the "1" in the numerator of the above expression should be replaced by 0.98–0.99.



1.8. A *hydraulic ram* uses the kinetic energy of flowing fluid to raise part of that fluid to a higher derivation. The principle of operation is as follows:

When water flowing down a supply tube is abruptly stopped, the pressure at the bottom of the pipe surges, and this allows some of the water to be raised above the feed level. With proper valving this pulsing action repeats 15–200 times/min, with pumping efficiencies as high as 90 %. This type of pump requires no motor and is convenient to use in faraway places.

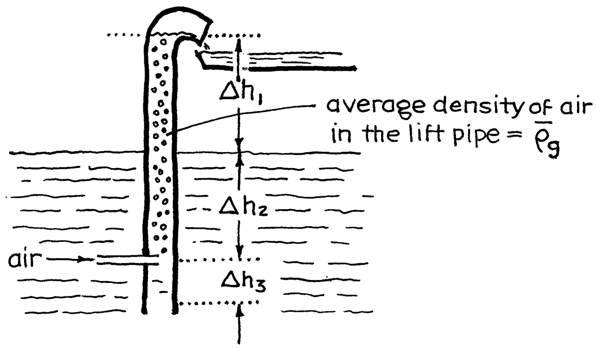


(a) Develop an expression relating the fraction of feed which can be delivered to the higher elevation to the pertinent variables shown above.

(b) A stream flows past my home, and I want to use it for my domestic water supply. I do not want to buy electricity to pump the water up to my house, so I've decided to use a hydraulic ram. If the fall of the stream is 3 m, the usable flow rate in the feed pipe is 2 lit/s, and the height from the ram to my storage tank is 8 m, what delivery rate can I expect at 50 % efficiency if the efficiency is defined as actual delivery rate divided by the theoretical?

1.9. The *air lift pump*[2] works by pumping small air bubbles into the bottom of a vertical pipe immersed in the fluid to be raised, as shown below. Ideally, the bubbles are so small that the relative velocity between air and water is negligible. Actual air lift pumps can achieve pumping efficiencies of 75 % or more. For a 60 % water and 40 % air mixture in the lift pipe, how high can an ideal air lift pump raise the water?

[2] For practical applications see F. A. Zenz, Chem. Eng. Prog. **89** 51 (August 1993).



1.10. A pilot-scale fluidized bed combustor needs a continuous supply of 4 m^3/s of 120 kPa air. The room temperature is 293 K.

(a) What size of compressor operating at 74 % efficiency will do the job?
(b) What will be the temperature of the air leaving the compressor if no heat is lost to the surroundings?

1.11. I want to get into the *Guinness Book of Records* by constructing the world's highest fountain. For this I will pump water out of a 2-cm-i.d. pipe pointing straight up. Find the compressor power needed for the stream of water to rise 100 m. Now people tell me that I have to consider frictional effects, but I've got an ace up my sleeve. The most honest-looking fellow at the race track sold me a very, very special powder. One pinch into the water supply tank and friction in the pipe and in the air magically disappears. So please don't worry about friction, just make your calculations assuming that frictional effects can be ignored.

1.12. Consider a very high column of gas, isothermal, and with an average compressibility factor of $\overline{Z}$.

(a) Show that the pressure change between the top (point 2) and the bottom (point 1) of this column is given by

$$p_2 = p_1 e^{-g(mw)(z_2 - z_1)/\overline{Z}RT}$$

(b) A capped natural gas well has a pressure of 15 bar at ground level. Assuming this natural gas to be pure methane, calculate the pressure of gas 5,000 m underground if the temperature is 300 K and $\overline{Z} = 0.95$ throughout.

1.13. What is the air pressure on top of Mt. Hood (~3,430 m) assuming that the temperature all about the mountain is 7 °C? Assume 1 atm at sea level.

1.14. Should we look for an adiabatic gas compressor or an isothermal? Which needs less power? To find out, please compare the power needed to compress a stream of room temperature air from 1 bar to 10 bar in these two ways.

1.15. An adiabatic 82 % efficient power turbine takes in hot 3 atm air and produces 1,000 kW of work and an exhaust air stream at 300 K and 1 atm. What is the temperature of the hot incoming air?

1.16. This chapter notes that much less work is needed to compress liquid than gas; consequently, the associated temperature rise for the liquid is much smaller than for the gas and often can safely be neglected. Let us check this statement by comparing the ideal work and temperature rise associated with the compression from 1 to 2 atm of 1 kg of flowing streams of air and of water entering at 20 °C. Note that per unit mass $\Delta H = C_p \Delta T$, where C_p is given for both air and water in the appendix.

1.17. Lots of artificial heart pumps are actually left ventricular assist devices. To help design such devices, calculate the fraction of the total work that is done by the left side of the heart. See Problem 1.3 for additional details or contact Professor Carlos A. Ramirez at University of Puerto Rico.

1.18. An adiabatic 82 % efficient power turbine takes in hot 3 atm air and produces 1,000 kw of work and an exhaust air stream at 300 k and 1 atm. What is the temperature of the hot incoming air?

1.19. Air at 3.3 atm and 7.62 mol/min enters and flows through some experimental equipment for which the frictional loss is $\Sigma F = 10^5$ J/kg of flowing air. The whole setup is immersed in boiling water and thus can be taken to be at 100 °C.

What is the pressure of the air leaving the equipment? Ignore any possible kinetic energy contribution.

1.20. A combustion gas (0.1 m^3/s, 208 °C, 1 bar, mw = 0.030 kg/mol, Cp = 36 J/mol • K) from a reactor enters a compressor and leaves at 408 °C and 5 bar. The whole unit is hot, and its heat loss to the surroundings is 9 kw. What is the power consumption of the compressor, and what is its efficiency?

1.21. Here are two ways of getting a stream of air (1 mol/s) from 20 °C 1 atm to 200 °C and 10 atm:

(1) Compress adiabatically then heat at constant pressure.
(2) Heat first, then compress adiabatically. For each of these two ways, determine the heating requirement and the compressor requirement for the adiabatic 100 % efficient compressor. Take $C_{p,\ air} = 29$ J/mol K.

Which arrangement would you choose?

1.22. For a high-temperature catalyst test cell, 1 mol/s of air at 300 K and 1 atm is first compressed in a well-insulated 50 % efficient compressor, then heated to 900 k in a heat exchanger for which the pressure drop is negligible. This air then flows through the isothermal 900 K test cell for which the frictional loss is estimated to be F = 179,500 J/kg of flowing air and finally exits at 1 atm. Find the duty of the heat exchanger, and assume $\overline{C}_{p,\text{air}} = 30$ J/mol K.

1.23. A reactor in our chemical plant is presently being fed a stream of hot high-pressure air (0.07 m3/s, 5 bar, 200 °C). We produce this stream by feeding room temperature air (20 °C, 1 bar) to a 60-kw adiabatic compressor and then passing the high pressure stream (5 bar) through a heat exchanger having negligible pressure drop to get the desired temperature.

What is the efficiency of the compressor?
What is the duty of the heat exchanger?

1.24. This chapter notes that much less work is needed to compress liquid in gas; consequently the associated temperature rise for the liquid is much smaller than for the gas and often can safely be neglected. Let us change this statement by comparing the ideal work and temperature rise associated with the compression from 1 to 2 atm of 1 kg of flowing stream of air and water entering at 20 °C.

1.25. From CEN I read about Joseph Gay-Lussac's ballooning ventures long ago, and it reminded me of the Great American Lead Balloon Contest of 1977 held by the staff of the Arthur D. Little Co. of Boston. The winning balloon was close to spherical, about 2 m in circumference, fabricated with a 1-mil lead foil skin, and filled with helium.

In Sept. 2021 Alma Ata in Russia (the world's largest center of lead processing as we all well know) is planning to hold a contest to see who could build the world's smallest spherical lead balloon that could float on air in their giant stadium. The winning prize is 3 million rubles, roughly equivalent to 200,000 euros.

NASA of the USA, the Russian Space agency, and other organizations are planning to compete, so I'm thinking, why not me too, with my grad students.

I wonder what would be the diameter of the smallest perfectly spherical hydrogen-filled balloon with a 0.4-mm-thick lead skin which would just float in air on a quiet 20 °C day at sea level and how does it compare with what was reported in CEN, pg 47, July 19, 2004.