

Engineering Design Example

Compressed-Air System for a Manufacturing Plant

[From L.C. Burmeister, *Elements of Thermal-Fluid System Design*, Prentice Hall, 1998]

A C/A system is to be designed and installed to operate C/A tools:

Tool	Location	Number	Free air/tool @ 90 psig. cfm	Total free air, cfm	Load factor
Blowgun, chuck, vise	Machine shop	10	10	100	0.5
Grinder	Cleaning room	10	50	500	
Chipper	Cleaning room	10	40	400	
Hoist	Cleaning room	2	30	60	
				960	0.5
Screwdriver	Assembly room	20	10	200	
Nutsetter	Assembly room	2	20	40	
				240	0.5
Woodborer	Shipping room	1	40	40	
Screwdriver	Shipping room	1	10	10	
Hoist	Shipping room	1	30	30	
				80	0.5
				1,380	

Compressor and piping layout

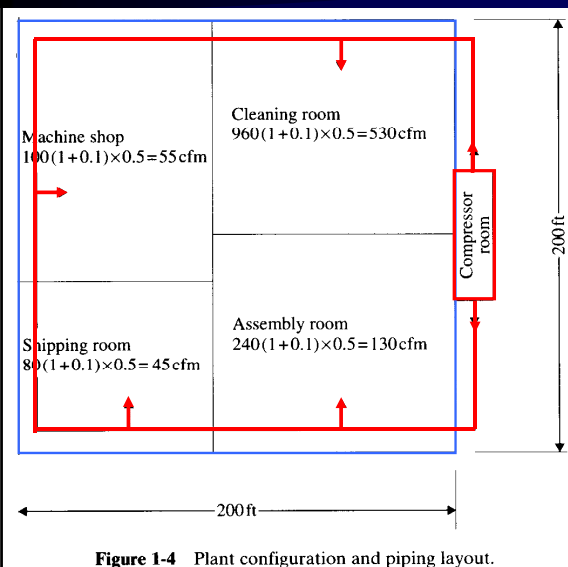


Figure 1-4 Plant configuration and piping layout.

Air supply circumferentially from two sides (reliability), based on locations and tools.

Possible design steps:

- Estimate the load [cfm] based on current and future demand.
- Size the compressor(s).
- Size the pipes so that $\Delta p < 10$ psi.
- Size air receiver/reservoir to "damp" peak-demands and dynamics of the system on compressor .



System "load": Compressed air rate

- Peak load is 1380 cfm, from the table.
- Average load (factor 0.5) is 50% of the peak load.
- Allowance for leakage 10% and 5% per year increase for 5 years is 25%, totaling $1380 \times 1.35 = 1900$ cfm.
- Centrifugal or reciprocating compressor may be chosen (later). From handbooks:

$$W = \dot{m} c_p (T_2 - T_1) = \rho \dot{V} c_p T_1 \left(\left(\frac{P_2}{P_1} \right)^{(k-1)/k} - 1 \right) =$$

$$= \left(0.075 \frac{\text{lb}_m}{\text{ft}^3} \right) \left(1900 \frac{\text{ft}^3}{\text{min}} \right) \left(0.24 \frac{\text{Btu}}{\text{lb}_m} \right) (530 \text{ R}) \left(\frac{114 \text{ psi}}{14 \text{ psi}} \right)^{(1.4-1)/1.4} - 1 \left(60 \frac{\text{min}}{\text{h}} \right) \left(3413 \frac{\text{Btu}}{\text{kWh}} \right) = 260 \text{ kW}$$

Tools 90 psi + 10 psi friction + 14 psi atmospheric

For typical compressor efficiency $\eta = 0.7$:

$$W_{\text{actual}} = \frac{W}{\eta} = \frac{260 \text{ kW}}{0.7} = 374 \text{ kW} = 500 \text{ HP}$$

Dynamics of air consumption in time

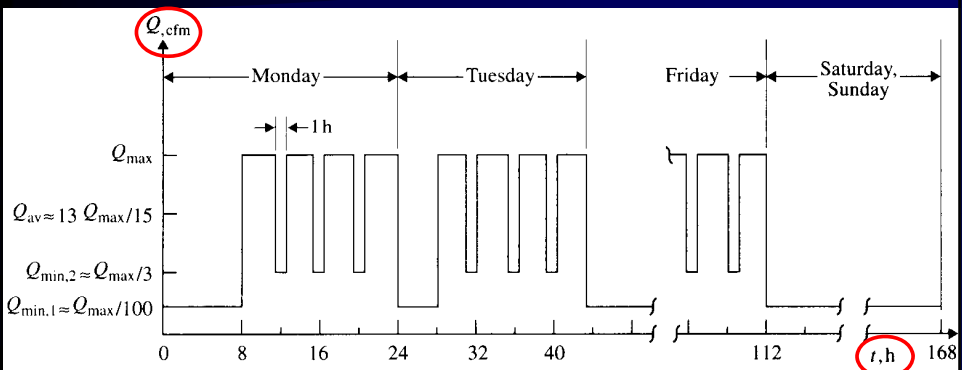


Figure 1-3 Estimated free-air consumption versus time.

The above load dynamics and load factors (0.5) suggest that the determined 500 HP compressor power is overestimated

System “load” and Compressor resizing

- Take into account 50% load factor.
- Allowance for 25% plant expansion for 5 years may be replaced with addition of second compressor if and when needed, so:

$$W_{actual,NEW} = \frac{0.5 \times 1.1}{1.1 + 0.25} W_{actual} = \frac{0.5 \times 1.1}{1.1 + 0.25} 374 \text{ kW} = 150 \text{ kW} = 201 \text{ HP}$$

Also,

$$\dot{V}_{NEW} = \frac{0.5 \times 1.1}{1.1 + 0.25} \dot{V} = \frac{0.5 \times 1.1}{1.1 + 0.25} 1900 \text{ cfm} = 770 \text{ cfm}$$

Prorated by

Piping sizing

- Pipe diameter (D) is determined to handle cleaning room (530 cfm) and machine shop (55 cfm) pipe run with half allowable pressure drop (10 psi), i.e.:

$$\Delta p = f \frac{L}{D} \frac{\rho V}{2 g_c} = \frac{8}{\pi^2} f \frac{L}{D^5} \rho \frac{Q^2}{g_c}$$

$$\frac{10 \text{ lb}_f}{2 \text{ in}^2} = \frac{8}{\pi^2} 0.025 \frac{100 \text{ ft}}{D^5} \left(0.075 \frac{\text{lb}_m}{\text{ft}^3} \right) \frac{\left(530 \frac{\text{ft}^3}{\text{min}} + 55 \frac{\text{ft}^3}{\text{min}} \right)^2}{\left(32.2 \frac{\text{lb}_m \text{ ft}}{\text{lb}_f \text{ s}^2} \right)} \left(12 \frac{\text{in}}{\text{ft}} \right) \left(60 \frac{\text{s}}{\text{min}} \right)$$

$D = 4.13 \text{ in} \approx 4 \text{ in}$ satisfy the above equation.

Layout

- Similarly, for piping run from cleaning room to machine shop (55 cfm) and $\Delta p/2 = 5$ psi, $D = 1.6 \approx 2$ in.

Piping sizing (*continue*)

- Remaining two piping runs' diameters are 2 and 2.5 in.
- However, to allow for future expansions, simplify installation and maintenance processes, we may select the 4 in pipe diameter for all pipe runs.
- Or we may stick with the calculated sizes ...

Layout

Air receiver sizing

Conservation of mass:

$$\frac{dm}{dt} = -\rho_0(Q_{in} - Q_{out}), \text{ also: } \rho = \frac{p}{RT} \text{ and } m = \rho \forall = \forall p / RT$$

$$\frac{d\left(\frac{\forall p}{RT}\right)}{dt} = \left(\frac{p_0}{RT}\right)(Q_{in} - Q_{out}) \Rightarrow \frac{dp}{dt} = \frac{-p_0}{\forall}(Q_{in} - Q_{out}) = \text{constant}$$

$$\forall = \frac{t p_0 (Q_{in} - Q_{out})}{(p_1 - p_2)} \quad \leftarrow$$

Assume that for $t = 2 \text{ min}$: $(Q_{out} - Q_{in}) = 76 \text{ cfm}$ (10% of $Q_{nominal}$) and $(p_1 - p_2) = 10 \text{ psi}$

Then, $\forall = (2 \text{ min})(14 \text{ psi})(76 \text{ cfm}) / (10 \text{ psi}) = 213 \text{ ft}^3$, NOTE: $(Q_{out} - Q_{in}) = Q_{out}$ if $Q_{in} = 0$

The volume \forall_{pipe} of the piping is:

$$\forall_{\text{pipe}} = L\left(\frac{\pi}{4}\right)(D^2) = (400 \text{ ft})\left(\frac{\pi}{4}\right)(4^2 + 2^2) \text{ in}^2 \left(\frac{\text{ft}^2}{144 \text{ in}^2}\right) = 44 \text{ ft}^3 \quad \leftarrow$$

Thus, the volume of the receiver tank(s) is(are):

$$\forall_{\text{tank}} = \forall - \forall_{\text{pipe}} = 213 \text{ ft}^3 - 44 \text{ ft}^3 = 169 \text{ ft}^3 \quad \leftarrow$$

Layout

Final comments...

- The major parameters (compressor, piping, receiver tank) have been sized.
- Many other details remained to be resolved, see the previous slide Figure.
- Installation and operational cost, as well as maintenance, safety, reliability, etc., may be determining factors in designing or selecting different components ...