Industrial Ventilation Owning and Operating Costs

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It is of prime importance at the design stage that the designer of an industrial ventilation system makes a reasonable assessment as to the owning and operating costs of an Industrial Ventilation System.

Armed with these findings the designer must consider what improvements can be made by considering a different approach or by using other types of plant. The designer must inform the owner of the plant of any alternatives.

The owning and operating costs of a system are made up of the following items:
- Land acquisition costs
- Design fees
- Total cost of purchasing the plant items
- Method of paying for these, and the rate of interest and payback time
- Installation costs
- Maintenance and renewal costs
- Demolition costs
- Water, and water treatment
- Ancillary services
- Public utility costs
- Waste removal
- Exhaust air and gas cleaning
- The energy costs for plant operation etc.

Each of the above subjects merits a paper in its own rights. Consideration of the actual maintenance costs is a difficult matter as it depends on the type and use of the plant. This paper covers some of the common energy requirements, which can be readily converted into current costs.

Energy Usage

The cost of energy usage in industrial ventilation falls into two categories:
1. Thermal Comfort
2. Shaft energy for appliances involved in ensuring that the correct indoor air conditions are achieved. It must be remembered that badly designed systems having low collection efficiency will require a greater energy usage, to achieve a given target level than will a well-designed system.

Thermal Comfort

The requirements of the occupants to achieve thermal comfort are of prime importance, and may require a considerable energy input especially if cooling is required.

The physical factors involved in thermal comfort are:

- Ambient air temperature
- Mean radiant temperature
- Vapour pressure
- Relative air velocity

The personal factors being:

- Clothing
- Activity
- Process requirements

The correct design conditions for the above four physical factors are required to achieve:

1. Heat addition to the occupied space to replace the heat loss to colder surroundings.
2. Heat and moisture removal from the occupied space by refrigeration.

The above two require heating and cooling plant in order to provide the correct working conditions. The fuels used for the heating application being solid liquid or gaseous, and in some cases direct electricity. In the case of cooling, the energy requirements are provided mainly by electricity, unless absorption refrigeration or a turbine is used. In both, the above full use can be made of heat recovery techniques to conserve energy or the use of renewable sources.

Heating Costs

The yearly energy consumption due to the heating of a building is directly related to:

1. Fabric loss
2. Ventilation loss

The Fabric Loss

The fabric loss is simply determined from:

$\Phi_f = \Sigma A.U\,(\theta_i - \theta_o)$

Φ_f = Heat flow by conduction (kW)

Σ = Summation of

A = Surface area of the enclosing surfaces of the structure (m^2)

U = Thermal transmittance coefficient ($W.m^{-2}.{}^{o}C^{-1}$)

θ_i = Inside air temperature

θ_o = Outside air temperature

Ventilation Loss

The ventilation loss in industrial ventilation systems is due to the vast quantities of air that have to be provided, either heated, cooled and then discharged to outdoors.

The heat loss from a space due to air interchange is determined from either:

1. An Empirical estimation of the rate of air interchange between outdoors and indoors that takes place by wind and thermal forces
2. Controlled ventilation achieved by means of fans

The empirical method given in BS 5925 can be used in the case of a simple building too predict the air interchange rate due to wind and stack effect, for given positions of opening areas.

The symbols used in Table 1 are:
q_{vw} = Air interchange due to wind effects $m^3.s^{-1}$
q_{vs} = Air interchange due to stack effects $m^3.s^{-1}$
q_{vws} = Air interchange due to combined wind and stack effects $m^3.s^{-1}$
A_n = Free area openings of A_1 A_2 A_3 A_4 (m^2)
A_{ew} = Equivalent effective area for wind(m^2)
A_{es} = Equivalent effective area for stack effect (m^2)

Table 1. Equations relating to air interchange due to wind and stack effects.

Conditions.	Typical arrangement.	Governing equations.
Wind only	v_w A_1 A_3 C_{p1} C_{p2} A_2 A_4	$q_{vw} = C_d. A_e\, v.(\Delta C_p)^{0.5}$ $\frac{1}{A_{ew}^{\,2}} = \frac{1}{(A_1+A_2)^2} + \frac{1}{(A_3+A_4)^2}$
Temperature difference only.	A_1 A_3 θ_o θ_i H A_2 A_4	$q_{vs} = C_d\, A_{ew} \left(\frac{2\Delta\theta.gH}{\theta_a}\right)^{0.5}$ $\frac{1}{A_{es}^{\,2}} = \frac{1}{(A_1+A_4)^2} + \frac{1}{(A_3+A_4)^2}$
Combined wind and temperature differences.	v_w A_1 A_3 C_{p1} C_{p2} θ_o H θ_i A_2 A_4	For $q_{vT} = q_{vs}$ $\frac{v_w}{\sqrt{\Delta T}} < 0.26 \sqrt{\frac{A}{A}}\sqrt{\frac{H}{\Delta C\rho}}$ For $q_{vT} = q_{vs}$ $\frac{v_w}{\sqrt{\Delta T}} > 0.26 \sqrt{\frac{A}{A}}\sqrt{\frac{H}{\Delta C\rho}}$

The above methods of ventilation even though attractive, as they do not require expensive fans and the associated maintenance and running costs. They do, however, have serious limitations, as it is impossible to depend on this method for industrial ventilation.

The reason being that the flow rate will vary with the season, giving high air interchange in the winter, possibly when it is least needed. While during the summer months a poor rate of interchange. It will be appreciated that in the case of toxic gases or hot environments, this approach is totally unsuitable and should not be used.

Thermal forces on the other hand in hot process areas may be used to full advantage to save energy by not using fans, provided the air is not contaminated in any way.

In the case of industrial ventilation, the actual volume capacity of the fan would be selected in order to meet the actual design extract and make up air rates.

Air interchange $m^3 h^{-1}$

$$q_v = \frac{c_p . \rho . N}{3600}$$

where
q_v = the air infiltration heat loss factor per unit volume of the space ($W.^{\circ}C^{-1}m^{-3}$)
c_p = the specific heat capacity of the air ($kJ.kg^{-1}\ ^{\circ}C^{-1}$)
ρ = the density of the air $kg.m^{-3}$
N = the number of air changes per hour. (h^{-1})
3600 = the number of seconds in 1 hour.

At temperatures around 20° C with the specific heat capacity of 1.01 $kJ.kg^{-1}$ and density $1.2 kg.m^{-3}$

The above approximates to 0.33N.
As this is for unit volume for a space of volume V the equation becomes
$q_v = 0.33N.V.$
hence the overall rate of heat loss by air interchange is:
$\Phi_v = q_m \times c_p \times (\theta_i - \theta_o)$
Where:
Φ_v = heat loss (kW)
θ_i = inside air temperature
θ_o = outside air temperature

In the case where the fan capacity q_v is known, it is simply a case of inserting this value into the above equation.

The ventilation loss in industrial applications in well thermally insulated buildings is normally in excess of the fabric loss. However, in some instances the building may be deliberately poorly insulated in an attempt to keep the building as cool as possible without reverting to high air change rates, or including costly heat recovery systems. A sound economic appraisal must be applied to each case in order to determine the best approach, bearing in mind the CO_2 reduction that is being striven for.

The energy used to heat the building per year is:
System heat loss kW (Fabric and ventilation) x Number of seconds operation in a year.

This is an over simplified model, as no allowance is made for the fact that full boiler output is not required throughout the year as $\Delta\theta$ the outside design temperature varies throughout the year, and is not constantly at the worst possible temperature.The degree-day concept is used in order to allow for the fact that the system is run less than full load for the year.

A degree-day is a period of 24 hours during which the average outside air temperature is one degree below a base temperature. For general use, the base temperature in the UK is 15.5°C. For example, if over a 24-hour period the average temperature is 4°C below 15.5° C then four degree days is recorded. Assuming that degree days are given from September to May and that the lowest external design temperature is (- 5° C), then the maximum number of degree days is 273 days x (15.5 – (-5))=5596.5 degree days. If 5596.5-degree days existed, this would mean that for the full heating season the outside temperature was constant at – 5 °C for the whole of the time, which would not be the case.

The actual number of degree-days recorded for a given locality indicates the true conditions. A weather factor has to be determined in order to relate the Actual Degree Days to the Maximum Degree Days.

$$Weather\ \ Factor = \frac{ACTUAL\ \ Degree\ \ Days}{MAXIMUM\ \ Degree\ \ Days}$$

The simplified model used above then becomes:
Energy used per year = System output (W) x Weather Factor x Time used per year (seconds)
For the North West of the UK the twenty-year mean degree-days are 2348
Hence Weather factor:

$$WF = \frac{Actual \quad = 2348}{Maximum \quad = 5596\ .5} = 0.42$$

After determining the weather factor further corrections have to be made for the actual time used per year. If heating is required for 24 hours per day and 7 days a week the actual degree days can be used with a weather factor applied. If this is not the case and the following is the operating time, the correction to be made is:
39 weeks x 5 days x 12 hours per day x 3600 seconds per hour.

This would be the case if the boiler supplying the heat were 100% efficient. A reasonable assessment of seasonal efficiency η for a boiler would be 70%
Hence energy used per year is

$$\frac{Rate\ of\ heat\ Loss}{\eta} \text{ x WF x Weeks x days x hours x seconds / hour}$$

The above method of estimation is not very accurate and the following modified model should be used:

1. Required base temperature (°C)

$$= \text{Inside temperature } (^{o}C) - \frac{Average\ Heat\ Gain\ (kW)}{Building\ Heat\ \text{Re}quirement\ (kW.^{o}C^{-1})}$$

2. Equivalent hours of Full load plant operation Eq =

$$Eq = \frac{24\ x\ Degree\ days\ inHeating\ season}{Design\ temperature\ difference\ \ (^{o}C)}$$

$$3.\ \text{Energy Consumption} = \frac{Equivalent\ hours\ x\ \max imum\ heating\ plant\ output\ x\ 3600}{Heating\ plant\ \eta}$$

Note the above equation assumes the system to be in operation for 24 hours per day.

Considering each equation in turn

1. The base temperature taken is 15.5°C; this is the temperature when it is assumed that no heating is required. If the heat gains are known, a more accurate figure could be obtained.

Let "d" be the ratio of degree-days, the values for d are obtained from Table 2 below

Ratio d = $\frac{D_d}{D_{15.5}}$	
Base Temperature °C	$\frac{D_d}{D_{15.5}}$
10	0.33
12	0.57
14	0.82
15	0.94
15.5	1.0
16	1.06
17	1.18
18	1.30

2. The above equation takes into account the average temperature difference throughout the heating season and the length of the heating season (both included in the degree-days) and also in the design temperature difference.
3. This last equation includes all the factors apart from the intermittent operation of the plant and the thermal capacity characteristics of the structure.

Corrections to the temperatures also have to be made for the type and use of the building as well as the operating hours. The use of the above will provide a reasonable estimate of energy usage for a building. Any drastic weekly or monthly variations (apart from severe weather) from these figures indicate control problems.

Shaft Energy for Industrial Ventilation Appliances

This covers all the electrical energy requirements for input and extract fans, pumps automatic filters control devices, cyclones, scrubbers etc. All this energy is required to overcome system resistance of ductwork, enclosures, filters etc. Extra to this energy requirement is that required by the specific plant process, and careful plant design can keep this energy usage at a minimum. The greatest space heating energy requirements normally are due to air replacement. In this case an overall review of fan power and its association with system resistance is necessary.

Mechanical Energy Required for Air Movement

The energy usage depends on two factors, and it will be useful to consider the origins of these.

1) Fan Power, This is the energy consumed by the fan and is called the shaft power.

2) Air Power. Consider Figure 1. which shows a ductwork run with air being forced along it by means of a fan

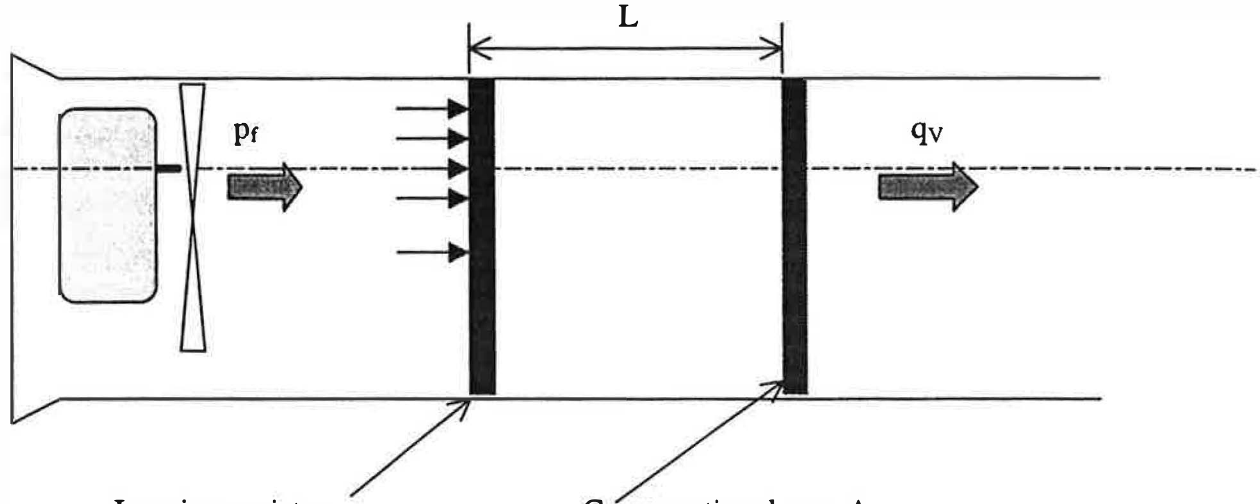

Figure 1. Pressure relationship.

Total pressure exerted by the fan = p_{ft}

Hence force on piston = p_{ft} x A

Work done = Force x Distance moved

= p_{ft} x A x L

$$\text{Power} = \frac{\textit{Work done}}{\textit{Unit time}} = \frac{p_{ft_t} x\ A\ x\ L}{t}$$

Where t is the time in seconds for a gas to move the distance L.

$$\text{But } \frac{A\ x\ L}{t} = \frac{\textit{Volume}}{\textit{time}} = \textit{Flow rate of air}$$

Hence P = p_{ft} x q_V (W)

In certain instances a compressibility coefficient has to be introduced giving:

P = p_{ft} x q_V x K_p

In many instances the pressure is measured in mm of water hence;

P = 9.81 x q_V x p_w x K_p (W)

Where

Efficiency as the air power is the energy transferred in the air per unit time and the shaft power is the energy input to the fan, then:

$$\eta = \frac{Air\ power}{Shaft\ power} x100$$

The above considerations on power requirements have to be related to the system in which the fan is used.

The purpose of a fan is to achieve the following.

1. Convey the air in the correct quantity from the fan inlet overcoming filter and duct work resistance and discharged into to the area to be conditioned. And conversely, in an extract system from the collection point through filters, overcoming the resistance of these and ductwork and discharged to outdoors.
2. Once the air enters the space it must be capable of creating the correct ambient air velocity for comfort or particulate capture.

Excessive Air Change Rate

In many cases of industrial ventilation, particularly with dilution systems over airing takes place. It this is occurring considerable energy savings can be achieved by considering the fan laws.
The power required by a fan is proportional to the velocity flow cubed.

$$P \propto (q_V)^3$$

Thus if q_V is reduced by 25% the new power requirements are $0.75^3 = 0.4218$, and the power requirements are reduced by approximately 58%. From this fact it will be appreciated that it is important to design a system with the absolute minimum possible pressure drop.

Matching the Fan to the System

Figure 2 shows the characteristic curves for a fan running at two speeds N_1 and N_2. Intercepting the fan curves are two characteristic curves for two different ductwork systems. These curves are parabolic in nature, and the pressure drop is approximately proportional to the velocity squared for duct flow.

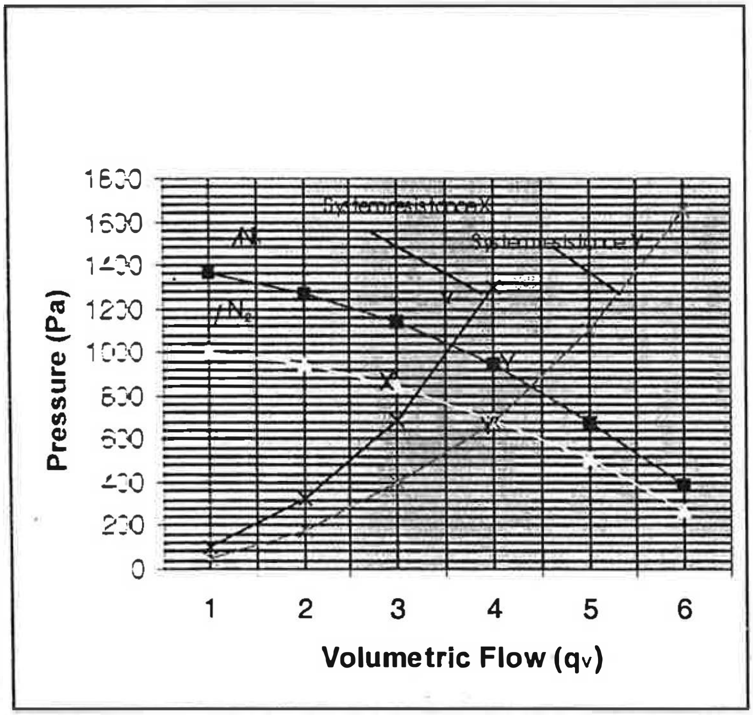

Figure 2 Fan and system curves

The point of operation on the curve is fixed and predictable. Plotting the fan performance curve at a given speed N_1 with the system curve a unique point of intersection at X is determined.

By changing the system resistance to Y another system curve is determined. If the fan speed is reduced to N_2

another set of points for curve X and Y are determined. Understanding this point will allow the designer to fully appreciate the energy saving potentials that can be achieved by consideration of these simple curves.

Conclusions

From the above, it is seen that by considering the degree-days over set period of weeks or months, it is possible to note any change from the normal expectations. Should this change not relate to the prevailing weather conditions, the system should be examined for failure in controls or loading bay doors being left open.

Energy savings can be made to some extent by the use of natural ventilation, the uncontrollable nature and the disadvantages of this method in the industrial environment should be fully understood.

It is essential that full use be made of the fan and system characteristic curves in achieving the lowest possible running cost at the highest operating collection, or distribution efficiency.