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Understanding the Basic Fan Laws

Geoff Edwards, the technical product engineer at Axair Fans UK Limited, explains the three basic fan laws when applied to warehouse ventilation studies.

The Fan Laws are a group of useful equations for determining the effects of a change in the speed, the diameter of the fan and the density of air in the system. They are most useful for determining the impact of extrapolating from a known **fan** performance to a desired performance. So, in short, the basic fan laws are used to express the relationship between fan performance and power.

To start we will consider only the effect of a change in the speed of the fan on the flow rate, pressure and power consumption. We will assume that the fan size and air density are to remain constant.

The first three derivations of the Fan Laws are predicated on a couple of assumptions:

- That there is not an extreme difference in the change of rotational speed of the impeller in question and as such creating significant differences in the density of the air. However, it is unlikely that this would be a problem, you will not be looking at situations beyond the design speed of the impeller. Ignoring special applications, the upper limit for the RPM will be approximately 3600 (60hz supply frequency)

- That there is no change in the diameter of the fan

The First Fan laws: Volume of Air

The first law of fans is a useful tool when working out the volumetric flow rate supplied by a fan under speed control or conversely working out what the RPM would be to deliver a required volume of air and hence what frequency to set a variable speed drive (VSD) to.

Volumetric flow rate (V, m³/hr) varies directly proportional to the ratio of the rotational speed (RPM) of the impeller.

Eq 1.

$$V_2 = \left(\frac{U_2}{U_1}\right) x\, V_1$$

Where:

: Volume 1, m³/hr – Original volume of air

: Volume 2, m³/hr – New Volume of air

: RPM 1 u/min – Original Speed

: RPM 2, u/min – New Speed

Volume of Air Example – Industrial Warehouse, Process Machinery.

A Factory of 37500m^3 space currently requires five air changes an hour to remove waste heat generated by industrial process machinery. Later additional machines are added to the factory and the required number of air changes per hour increases to 6.1 to maintain the desired maximum air temperature within the factory. The original air flow rate, V_1 is 187500 m^3/hr to achieve this. At a pressure loss of 40Pa due to ductwork, louvres and other ancillary items. 20 number 630mm 6 pole short cased external rotor motor fans were used. From the manufacturer's data sheet we know that to deliver this performance, the RPM (U_1) of the fan is

865u/min. V_2, calculated by multiplying the space by the new air change requirements, is simply 37500m^3 x 6.1 which give a new requirement of 228750 m^3/hr. So what is the RPM of the fan required to be to deliver this flow rate increase?

By re-arranging the above formula (Eq. 1) we find that:

$$\mathrm{U}_2 = \left(\frac{V_2}{\mathrm{V}_1}\right) \mathrm{x}\, U_1$$

Substituting in the known parameters gives:

$$\mathrm{U}_2 = \left(\frac{228750}{187500}\right) \mathrm{x}\, 865$$

Therefore:

$$\mathrm{U}_2 = 1055.3\mathrm{u/min}$$

All that then needs to be determined is when under VSD control whether the motor and or impeller is rated to operate at 1055.3u/min. If they are, great, if not either a compromise on the system performance needs to be reached, additional fans added or a reduction in the system pressure needs to be made.

The Second Fan Law: Pressure

This second law describes the relationship between the pressure developed by the fan and its rotational speed. From this equation, we can see just how powerful the effect of increasing the rotational speed of the fan is on pressure development, double the speed and you quadruple the pressure development.

Pressure (P, Pa) varies as the square to the ratio of the rotational speed (RPM, u/min) of the impeller.

Eq. 2

$$p_2 = p_1\left(\frac{U_2}{U_1}\right)^2$$

Where:

p_2: Pressure 2, Pa

p_1: Pressure 1, Pa

U_1: RPM 1, u/min

U_2: RPM 2, u/min

Pressure Example

Continuing with our first situation of the industrial process factory which has added machinery and now requires additional air flow to maintain working conditions what will the pressure development of the fans now be?

This derivation of the first of the Fan Laws is predicated on a couple of assumptions:

By using the above formula (Eq. 2) we find that:

$$p_2 = p_1\left(\frac{U_2}{U_1}\right)^2$$

Substituting in the known parameters gives:

$$p_2 = 40\left(\frac{1055.3}{865}\right)^2$$

Therefore:

$$p_2 = 59.54\text{Pa}$$

The Third Fan Law: Power

The third law provides the required power to deliver the performance change that the system designer is looking for. The cubic nature of this relationship between power and the rotational speed shows how even for small performance gains, large amounts of additional power are needed.

Power (P, kW) varies as the square to the ratio of the rotational speed (RPM, u/min) of the impeller.

$$\mathrm{kW}_2 = \mathrm{kW}_1 \left(\frac{\mathrm{U}_2}{\mathrm{U}_1}\right)^3$$

Where:

P_1: Power, kW_2

P_2: Power, kW_1

U_1: RPM 1, u/min

U_2: RPM 2, u/min

Power Example

If we continue to look at the situation of the expanding factory as we have done with the previous two examples we can see the effect of the additional air flow on the power consumption of the fan. From the original duty point, we know that the power consumption was 2.12kW at 18750m^3/hr @ 40Pa. so what will the total additional power consumption be for all 20 fans?

By using the above formula, (Eq 3.) we find that:

$$\mathrm{kW}_2 = \mathrm{kW}_1 \left(\frac{\mathrm{U}_2}{\mathrm{U}_1}\right)^3$$

By substituting in the known parameters gives:

$$\mathrm{kW}_2 = 2.12 \left(\frac{1055.3}{865}\right)^3$$

Therefore:

$$\mathrm{kW}_2 = 3.85\mathrm{kW/fan}$$

Over 20 fans the total power increase is 34.6kW! So for an airflow increase of a little over 18% the power needed has risen by nearly 45%.

In summary, fan laws are essentially about impellers and what happens to their characteristics when they undergo changes in rotational speed, air density, or are scaled in size. They also help with the understanding of ventilation systems and the relationship between volume air flow rate and system total pressure. Although there are many fan selection softwares available in the marketplace, it is necessary for engineers to have at least a basic understanding of these basic fan laws to aid their overall awareness of how changes within ventilation systems can influence performance.

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