

# Air Fans Duct Systems -Energy Auditing Guidelines

## 1. Introduction

Processes in buildings, industrial and commercial systems may require transfer of fresh air and fluidized materials. This material transfer can be through either induction of the air into or extraction from the system. This is achieved using fan-duct systems. These systems should be designed and operated in a way that it delivers materials as per process requirements while using energy efficiently.

Energy managers and auditors should understand the working principles of these systems. This will help them to suggest interventions to ensure that they are operated efficiently. This section of the guidebook focuses on auditing energy usage in fan duct systems where electrical motors are used as prime movers. It provides a step-by-step guide of auditing these systems. To effectively audit the system, it is important to understand the components of the system.

## 2. Components of fan- duct systems

Figure 1 illustrates the components of a fan-duct system:

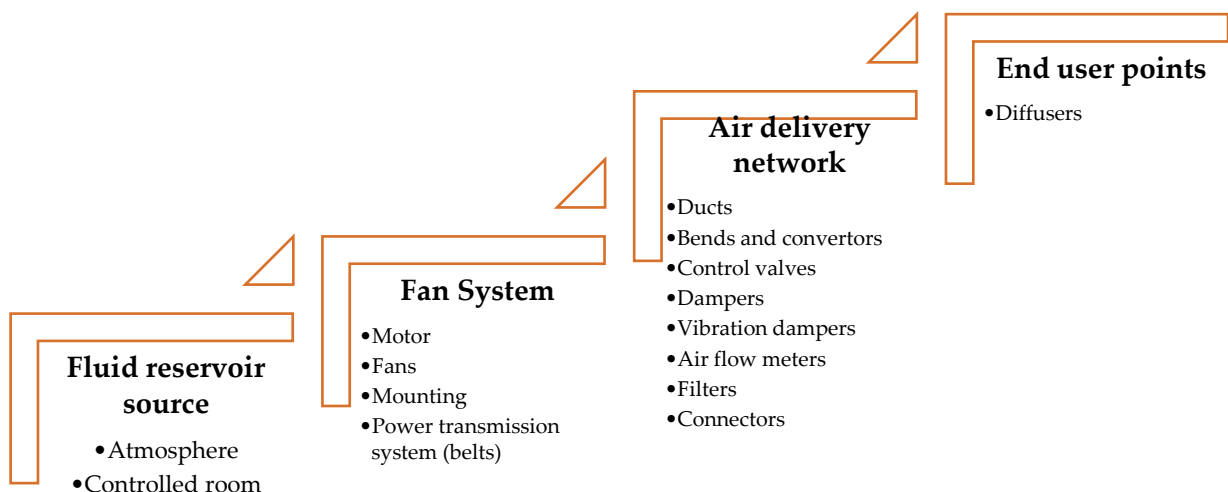


*Figure 1:Parts of a fan-duct system*

Components in Figure 1 can be assembled into different system configurations such as the one shown Figure 2.

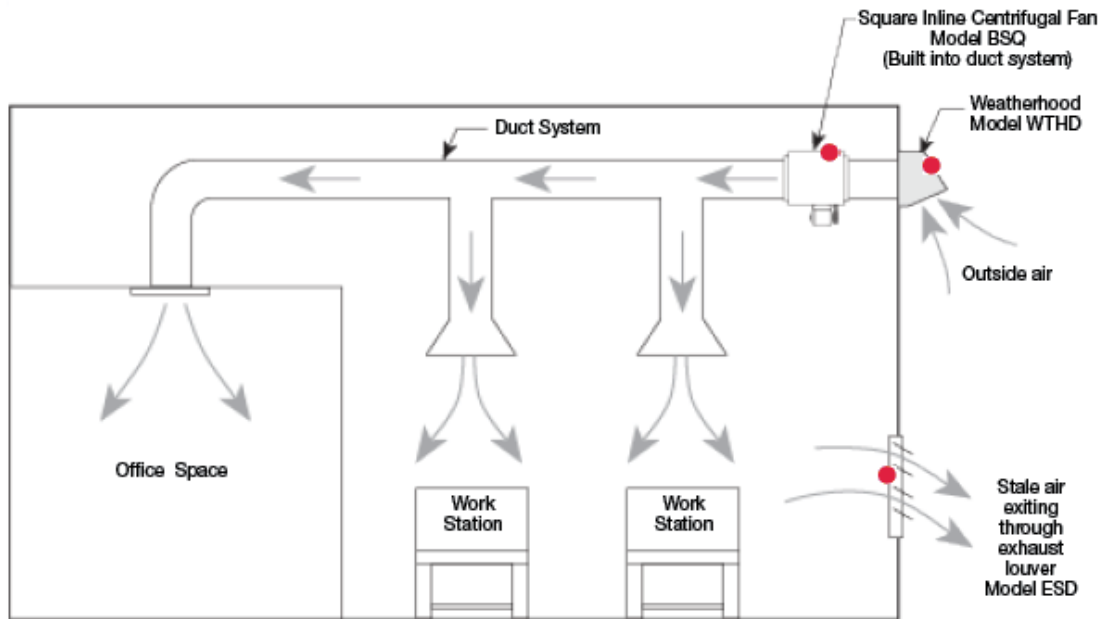


Figure 2: Assembled Fan duct system

In carrying out an energy audit, the energy auditor should consider all the components, processes and configurations described therein. The approach used for auditing the system depends on their configuration and end use. There are three main air delivery system configurations in buildings and industrial system: open, semi-closed and fully closed.

In an open system, the air or fluidised material is terminally delivered or extracted to or from the point of use without any circulation. In a semi-closed system air is circulated several times within the point of use before it is extracted out, and some fresh air is supplied from an external source. A fully closed system on the other hand, the fan-duct system circulates air within a closed space with minimal or no external supply.

The configuration notwithstanding, the air flow requirement at the point of use can either be constant or variable. Once the auditor has established the configuration, they should sequentially audit the energy use and recommend the energy conservation measures.

### 3. Steps in auditing air fan-duct systems

Auditing the energy use of an air fan duct system has three fundamental steps, as illustrated in Figure 3:

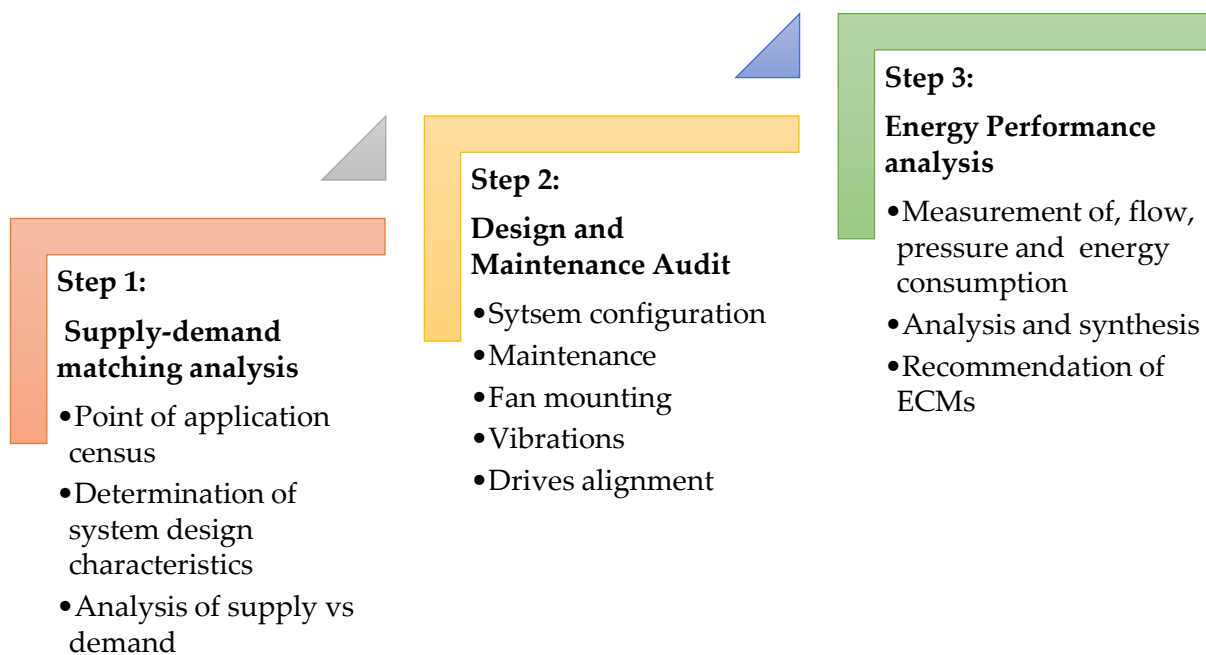


*Figure 3: Steps in auditing fan air duct systems*

The processes illustrated in Figure 3 are sequential, with the results from the preceding step informing the analysis of the succeeding step.

### **Step 1: Supply-demand matching analysis**

For efficient operation of an air fan duct system, the fan discharge capacity should meet the discharge requirements at the points of use. Situations where the capacity is either oversized or undersized will always lead to inefficient operations due to:

Poor fan loading factor

The efficiency of a motor has been empirically established to increase with the loading factor up to a certain limit. The recommended factors vary with the motor capacity and can be determined from the motor load efficiency curves.

Friction head losses

In cases where the ventilation air demand is less than the designed supply capacity, the operator will be forced to throttle the system, leading to an increase in the velocity in the ducting. This leads to an increase in friction losses, as explained by the Darcy–Weisbach relationship.

Demand-supply matching analysis is conducted in two steps:

*i. Determination of the facility air requirements*

The energy auditor should measure air demand for a given application and period. This demand should then be compared with the fan-duct system's capacity. The air demand can be established from design documents. In their absence, the demand can be computed based on the standards. For instance, the air demand in a conference hall can be determined using the number of rooms in use, number of people, air quality requirements and ambient conditions.

*ii. Determination of the existing fan-duct system supply capacity*

To determine the existing supply capacity, the auditor should establish fan-duct system specifications. The specifications include: the design flow rate; design operating pressure; fan efficiency; fan speed; motor power rating; and motor efficiency. These specifications can be obtained from the nameplate and the data sheet of the fan. To get the actual supply flow parameters, measurements should be carried out. The supply discharge should match the end use requirements. A tolerance of 5% deviation is acceptable. Additionally, the supply discharge should be at least 75% of the rated fan capacity which can be read off from the nameplate or design document. Figure 4 shows an example of a fan's specifications from a catalogue.

| QPRB                |      |       |       |       |       |         |        |            |           |                   |                  |                         |
|---------------------|------|-------|-------|-------|-------|---------|--------|------------|-----------|-------------------|------------------|-------------------------|
| Performances        |      |       |       |       |       |         |        |            |           |                   |                  |                         |
| Description         | Code | Poles | Motor | P mec | I nom | I start | IP/Cl. | Efficiency | FMEG<br>N | Q max             | PD <sup>2</sup>  | Lp                      |
|                     |      |       | size  | kW    | A     | A       |        | %          |           | m <sup>3</sup> /h | kgm <sup>2</sup> | dB(A) @1.5m<br>Breakout |
| QPRB900R/4 (esec.4) | -    | 4     | 180   | 18,5  | -     | -       | -      | -          | -         | 18000             | 34               | 73                      |
| QPRB900R/4 (esec.4) | -    | 4     | 180   | 22    | -     | -       | -      | -          | -         | 25200             | 34               | 73                      |
| QPRB900/4 (esec.4)  | -    | 4     | 200   | 30    | -     | -       | -      | -          | -         | 32400             | 37               | 74                      |

Figure 4: Sample of a fan specification

### Example 1

Let us take a case of a food processing facility which requires dust extraction using air at the rate of 19,500 m<sup>3</sup>/hr. The facility is fitted with a supply fan with the following specifications:

| Parameter        | Value                           |
|------------------|---------------------------------|
| Rated discharge: | 32,400m <sup>3</sup> /hr        |
| Pressure:        | 3334.3Pa (34kg/m <sup>2</sup> ) |
| Motor Rating:    | 30 kW                           |

Comparing the demand (19,500 m<sup>3</sup>/hr) to the rated supply (32,400m<sup>3</sup>/hr), the demand is 60% of the rated fan capacity. Assuming the pressure drop along the line is 3334.3Pa, the fluid power at this point is calculate as;

$$P_f(kW) = \frac{Q \times \Delta p}{1000 \times 3600}$$

$$P_f(kW) = \frac{19500 \times 3334.3}{1000 \times 3600} = 18.06kW$$

The loading factor therefore:

$$Loading\ Factor = \frac{18.06}{30} = 60.2 \%$$

The loading factor is below the optimal loading factor of 75%, which would have translated to a motor rating of 22 kW.

*(Note: The calculation is based on assumptions that the pressure drop used is equal to the rated pressure which in practical case should be lower.)*

In this scenario, the auditor should investigate the reason for low loading. This can be due to poor operation practises or oversizing of the fan. One of the poor operation practises could be running the plant below its optimal capacity. For oversizing, it could be an original design problem or a retrofitting the original fan with a bigger one. If the load and supply is within the acceptable limits, the auditor should still go ahead to undertake the process audit of the air fan motor system. This include the design, maintenance and other operation issues.

### Step 2: Design and Maintenance Audit

In addition to air demand matching or loading, the energy performance of air fan-duct systems is also a function of design and operating conditions. The design involves system sizing and configuration while operating conditions are informed mainly by

air requirements, maintenance, ambient conditions and settings of the system. An energy auditor should be well versed with the design and operating principles of the air fan duct system being audited.

Figure 5 illustrates the steps of auditing the air fan duct system design, maintenance and operations.



Figure 5: Steps of auditing the system design, maintenance and operations

The following are the design, maintenance and operations considerations for some of the major components.

#### Air inlet System

The air inlet system should be aligned in such a way that it directs air in a manner to maximise fan performance. This means it has to achieve the correct balance of airflow and velocity to minimise noise and pressure losses. The guide vanes should be in the same inclination with the impellor blades. (draw an illustration) In some cases, the inlet duct geometry can be changed (for example to introduce a bend) and the turning guide vanes are used to direct air into the fan.

The design should also account for potential of exhaust-to-intake recirculation. This is useful in the HVAC system (see the HVAC chapter).

Filters should be cleaned regularly to avoid clogging which might lead to high pressure losses and bacteria

culturing. The pressure drops across the filters should be checked to ensure it is always less than 2Pa.

#### Fans and fan drive

The auditor should check that the fan specifications are compatible with the air requirements and delivery network. This can be done by comparing the system operating point to the fan-duct characteristics curve.

Additionally, the auditor should assess the stability of the fan by evaluating the vibrations. Vibrations can be caused by loose mounting, belts and couplings, worn bearings and impellor imbalance.

It is best practise to ensure maintenance of the impellers by balancing them. The impellor maintenance cycle is dependent on the running hours and the working environment as specified in the manufacturer's manual.

Vibrations, flowrate and pressure are measured by use of a vibrometer, flow meter and pressure gauge respectively. *(Energy losses due to vibrations is discussed in the Liquid pumping systems' section of this guidebook).*

Further, the energy auditor should check the belt drives (belts, pulleys and motors) for wear, loose mounting and tension. Loose and worn-out belts lead to poor power transfer from the motor to the fan. *(belts power transfer is discussed in the analysis section).*

#### Delivery Network

The fan-duct system delivery network consists mainly of air-ducts, dampers, filters, flex connectors and air diffusers. During an energy audit, the auditor should check the air flow in the ducts. This to ensure air is moving at the recommended speed and allowable pressure drops. Pressure drops in all sections and branches of the duct should be balanced to ensure smooth air supply and minimise energy losses. Unbalanced pressure drops can lead to oversizing of the fan.

*(Pressure balance analysis will be demonstrated using an example in the analysis section)*

**NOTE:** Air speeds for different air requirements and applications can be obtained from ASHRAE Standards and ASHRAE Handbook on ventilation and air transfer.

*The information offered by the Standards is for illustrative purposes and is not a substitute for professional engineering advice. The information from the standard should be collaborated with other authoritative sources for up-to-date guidance, especially when dealing with hazardous or combustible materials.*

#### End use

The auditor should establish whether the end use condition is right and compatible with the fan duct system. Some of the end uses of air fan duct systems are to supply air to:

- i. Manufacturing sites
- ii. Operation theatre
- iii. Warehouse
- iv. Conference hall
- v. Dust extraction

#### Accessories

The auditor should assess whether the fan duct system accessories such as air flowmeters, pressure gauges, temperatures and humidity meters are in good working conditions.

It is worth noting that a poorly designed or maintained air fan-duct system not only leads to energy losses and poor service delivery but is also an operational hazard. A whole system audit is essential for optimal realization of energy savings. This implies that the analysis of energy performance should go beyond the fan output. The air delivery networks design and maintenance contribute to the overall energy performance of the system.

### **Step 3: Energy Performance Analysis**

After carrying out the air supply-demand load matching and the design and maintenance assessment, the auditor should undertake primary data collection. Measurement and data collection should be done within the operation cycle of the facility. The information obtained will be used in energy performance analysis. The analysis will inform the energy conservation measures (ECMs) that can be implemented by the facility. This section covers energy performance analysis.

The energy performance of the fan-duct system can be computed using equation 1 to 5. The hourly air average flow rate and power demand are calculated using equations 1 to 5. These will assist in calculating energy savings.

Hourly power demand  $P_h$  is determined using equation 1.

$$P_h = \Delta H \times V_h \quad (1)$$

$$V_h = \frac{Q_h}{\rho C_{air} \Delta T_{dsn}} \quad (2)$$

$$Q_h = m_{dsn} C_{air} \Delta T_h \quad (3)$$

$$m_{dsn} = \frac{Q_{dsn}}{C_{air} \Delta T_{dsn}} \quad (4)$$

$$E_T = \sum_{i=1}^N p_i \times t \quad (5)$$

Where:

|           |                                  |
|-----------|----------------------------------|
| $Q_{dsn}$ | System design cooling load       |
| $m_{dsn}$ | System design air mass flow rate |
| $C_{air}$ | Specific heat capacity of air    |

|                  |                                                                                                                 |
|------------------|-----------------------------------------------------------------------------------------------------------------|
| $\Delta T_{dsn}$ | System design temperature difference between the maximum assumed ambient temperature and target set temperature |
| $Q_h$            | Calculated hourly cooling load.                                                                                 |
| $\Delta T_h$     | Temperature difference between the average hourly measured temperature and set target room temperature          |
| $V_h$            | Average hourly air volumetric flow rate                                                                         |
| $\rho$           | Air density                                                                                                     |
| $P_h$            | Average hourly power demand                                                                                     |
| $\Delta H$       | Pressure drops across the duct system                                                                           |
| $E_T$            | Total energy consumed over the operation period                                                                 |
| $p_i$            | Average periodic hourly power demand ( <i>10 minutes, hourly etc</i> )                                          |
| $t$              | Time along which power is averaged                                                                              |
| $i$              | Counter of averaging periods                                                                                    |
| $N$              | Total number of average periods in given operation cycle                                                        |

## Air Duct Energy Performance

### Example 1

Consider a chocolate packaging facility hosting 100 persons. The facility's machines and workers generate about 1110.0 kJ/s of heat. Its air conditioning system has a ventilation fan for cooling and supply of fresh air. The temperature of the packing room is supposed to be maintained at 15°C. The fan was designed to extract heat from the space by assuming an ambient temperature of 30°C.

During an energy audit the following information was collected:

- a) Fan Motor power = 30 kW
- b) Motor speed =1500 RPM
- c) Fan design flow rate = 70 m<sup>3</sup>/s
- d) Maximum pressure = 220 Pa (N/m<sup>2</sup>)
- e) Working hours 24 hours per day and 300 days per year.

Measurements were carried out and information presented in table 1

*Table 1: Measurements carried out during an Energy audit*

| No. | Date and time  | Power Demand [kW] | Ambient Temperature [°C] | Set Temperature [°C] | Measured air flow rate m <sup>3</sup> /s |
|-----|----------------|-------------------|--------------------------|----------------------|------------------------------------------|
| 1   | 01:59:00       | 27.60             | 19.56                    | 15.00                | 60.16                                    |
| 2   | 05:59:00       | 27.60             | 18.87                    | 15.00                | 60.16                                    |
| 3   | 09:59:00       | 27.60             | 22.16                    | 15.00                | 60.16                                    |
| 4   | 11:59:00       | 27.23             | 24.95                    | 15.00                | 60.16                                    |
| 5   | 12:59:00       | 27.54             | 24.85                    | 15.00                | 60.16                                    |
| 6   | 21:59:00       | 27.73             | 21.46                    | 15.00                | 60.16                                    |
| 7   | 00:59:00       | 27.98             | 19.96                    | 15.00                | 60.16                                    |
| 8   | 02:59:00       | 27.35             | 19.33                    | 15.00                | 60.16                                    |
| 9   | 03:59:00       | 27.29             | 19.11                    | 15.00                | 60.16                                    |
| 10  | 04:59:00       | 27.73             | 19.08                    | 15.00                | 60.16                                    |
| 11  | 06:59:00       | 27.29             | 19.15                    | 15.00                | 60.16                                    |
| 12  | 07:59:00       | 27.66             | 20.06                    | 15.00                | 60.16                                    |
| 13  | 08:59:00       | 27.54             | 20.86                    | 15.00                | 60.16                                    |
| 14  | 10:59:00       | 27.60             | 23.96                    | 15.00                | 60.16                                    |
| 15  | 12:59:00       | 27.54             | 25.12                    | 15.00                | 60.16                                    |
| 16  | 13:59:00       | 27.23             | 25.63                    | 15.00                | 60.16                                    |
| 17  | 14:59:00       | 27.54             | 25.20                    | 15.00                | 60.16                                    |
| 18  | 15:59:00       | 27.73             | 24.81                    | 15.00                | 60.16                                    |
| 19  | 16:59:00       | 27.98             | 24.22                    | 15.00                | 60.16                                    |
| 20  | 17:59:00       | 27.60             | 22.63                    | 15.00                | 60.16                                    |
| 21  | 18:59:00       | 27.23             | 22.81                    | 15.00                | 60.16                                    |
| 22  | 19:59:00       | 27.54             | 22.37                    | 15.00                | 60.16                                    |
| 23  | 20:59:00       | 27.73             | 21.83                    | 15.00                | 60.16                                    |
| 24  | 22:59:00       | 27.98             | 21.11                    | 15.00                | 60.16                                    |
|     | <b>Average</b> | <b>27.57</b>      | <b>21.99</b>             | <b>15.00</b>         | <b>60.16</b>                             |

## Analysis

Using data in table 1, a graph of ambient temperature and power demand Vs time is plotted as shown in Figure 1

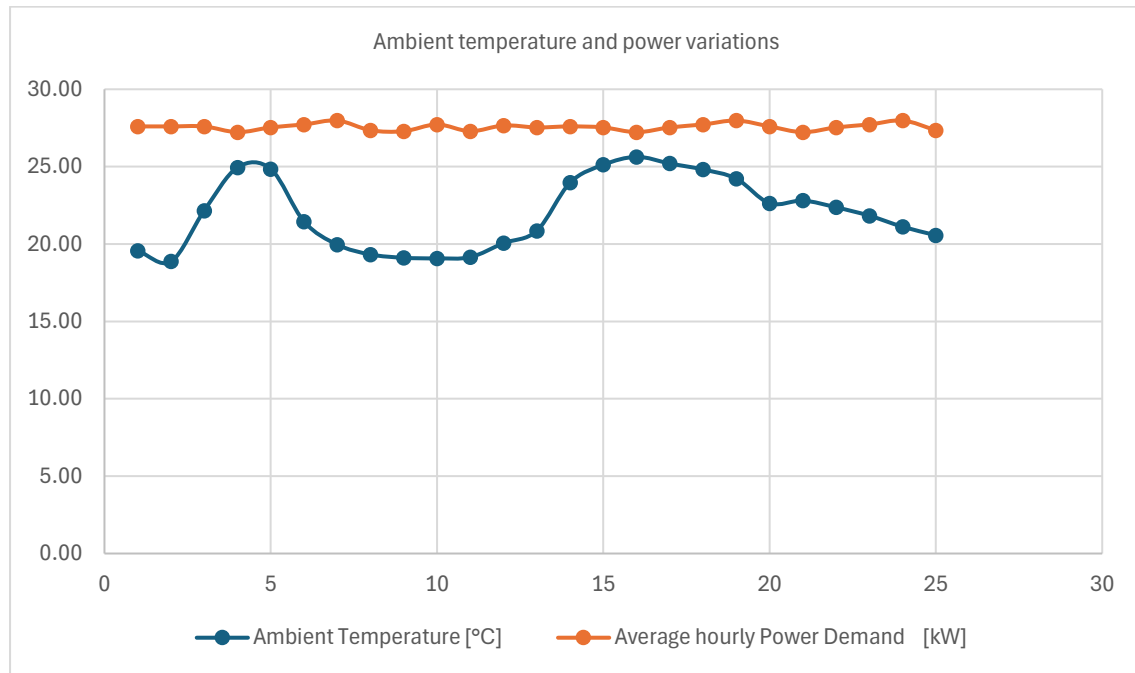


Figure 6: A trend of ambient temperature and Power demand Vs Time

From table 1 and using equation 5, total measured energy consumption in 24 hours for is 661.81 kWh. Additionally, from table 1 and figure 1, it can be seen that the fan has almost constant power demand and runs at almost constant speed and flow rate. There is need for a variable frequency drive to vary the speed of the fan. The change in air demand is as a result of varying temperatures.

Using the collected data in table 1,  $Q_h$  is calculated using air mass flow rate required to achieve design condition (cooling load of 1110.0 kJ/s, ambient temperature of 30°C and set room temperature of 15°C.)

The total energy consumed over an operation cycle is the product of the average hourly power demand measured and time, as shown in equation 5.

Analysis of the measurements was carried and presented in table 2.

Table 2

|                   | Date & Time | Hourly Temperature Change | Expected Hourly cooling Load (Qh) | Expected hourly mass flow kg/m3 | Expected hourly air flow rate m3/s | Pressure Pa | Hourly Power put air in kW | Expected Hour motor power demand (kW) |
|-------------------|-------------|---------------------------|-----------------------------------|---------------------------------|------------------------------------|-------------|----------------------------|---------------------------------------|
| Design Conditions |             | 15.00                     | 1,111.00                          | 73.70                           | 60.16                              | 200.00      | 12.03                      | 20.57                                 |

Table 3

|   | Date & Time | Hourly Temperature Change | Expected Hourly cooling Load (Qh) | Expected hourly mass flow kg/m3 | Expected hourly air flow rate m3/s | Pressure Pa | Hourly Power put air in kW | Expected Hour motor power demand (kW) |
|---|-------------|---------------------------|-----------------------------------|---------------------------------|------------------------------------|-------------|----------------------------|---------------------------------------|
| 1 | 01:59:00    | 4.56                      | 337.87                            | 22.41                           | 18.30                              | 200.00      | 3.66                       | 6.26                                  |
| 2 | 05:59:00    | 3.87                      | 286.85                            | 19.03                           | 15.53                              | 200.00      | 3.11                       | 5.31                                  |
| 3 | 09:59:00    | 7.16                      | 530.28                            | 35.18                           | 28.72                              | 200.00      | 5.74                       | 9.82                                  |
| 4 | 11:59:00    | 9.95                      | 736.74                            | 48.87                           | 39.90                              | 200.00      | 7.98                       | 13.64                                 |
| 5 | 12:59:00    | 9.85                      | 729.38                            | 48.38                           | 39.50                              | 200.00      | 7.90                       | 13.50                                 |
| 6 | 21:59:00    | 6.46                      | 478.16                            | 31.72                           | 25.89                              | 200.00      | 5.18                       | 8.85                                  |
| 7 | 00:59:00    | 4.96                      | 367.41                            | 24.37                           | 19.90                              | 200.00      | 3.98                       | 6.80                                  |
| 8 | 02:59:00    | 4.33                      | 320.43                            | 21.26                           | 17.35                              | 200.00      | 3.47                       | 5.93                                  |
| 9 | 03:59:00    | 4.11                      | 304.62                            | 20.21                           | 16.50                              | 200.00      | 3.30                       | 5.64                                  |

|              | Date & Time | Hourly Temperature Change | Expected Hourly cooling Load (Qh) | Expected hourly mass flow kg/m3 | Expected hourly air flow rate m3/s | Pressure Pa | Hourly Power put air in kW | Expected Hour motor power demand (kW) |
|--------------|-------------|---------------------------|-----------------------------------|---------------------------------|------------------------------------|-------------|----------------------------|---------------------------------------|
| 10           | 04:59:00    | 4.08                      | 301.83                            | 20.02                           | 16.34                              | 200.00      | 3.27                       | 5.59                                  |
| 11           | 06:59:00    | 4.15                      | 307.51                            | 20.40                           | 16.65                              | 200.00      | 3.33                       | 5.69                                  |
| 12           | 07:59:00    | 5.06                      | 374.50                            | 24.84                           | 20.28                              | 200.00      | 4.06                       | 6.93                                  |
| 13           | 08:59:00    | 5.86                      | 433.72                            | 28.77                           | 23.49                              | 200.00      | 4.70                       | 8.03                                  |
| 14           | 10:59:00    | 8.96                      | 663.79                            | 44.03                           | 35.95                              | 200.00      | 7.19                       | 12.29                                 |
| 15           | 12:59:00    | 10.12                     | 749.55                            | 49.72                           | 40.59                              | 200.00      | 8.12                       | 13.88                                 |
| 16           | 13:59:00    | 10.63                     | 787.54                            | 52.24                           | 42.65                              | 200.00      | 8.53                       | 14.58                                 |
| 17           | 14:59:00    | 10.20                     | 755.78                            | 50.13                           | 40.93                              | 200.00      | 8.19                       | 13.99                                 |
| 18           | 15:59:00    | 9.81                      | 726.86                            | 48.22                           | 39.36                              | 200.00      | 7.87                       | 13.46                                 |
| 19           | 16:59:00    | 9.22                      | 682.96                            | 45.30                           | 36.98                              | 200.00      | 7.40                       | 12.64                                 |
| 20           | 17:59:00    | 7.63                      | 565.07                            | 37.48                           | 30.60                              | 200.00      | 6.12                       | 10.46                                 |
| 21           | 18:59:00    | 7.81                      | 578.21                            | 38.36                           | 31.31                              | 200.00      | 6.26                       | 10.70                                 |
| 22           | 19:59:00    | 7.37                      | 545.98                            | 36.22                           | 29.57                              | 200.00      | 5.91                       | 10.11                                 |
| 23           | 20:59:00    | 6.83                      | 505.85                            | 33.56                           | 27.39                              | 200.00      | 5.48                       | 9.36                                  |
| 24           | 22:59:00    | 6.11                      | 452.88                            | 30.04                           | 24.52                              | 200.00      | 4.90                       | 8.38                                  |
| <b>Total</b> |             |                           |                                   |                                 |                                    |             |                            | <b>231.86</b>                         |

|  | Date & Time | Hourly Temperature Change | Expected Hourly cooling Load (Qh) | Expected hourly mass flow kg/m <sup>3</sup> | Expected hourly air flow rate m <sup>3</sup> /s | Pressure Pa | Hourly Power put air in kW | Expected Hour motor power demand (kW) |
|--|-------------|---------------------------|-----------------------------------|---------------------------------------------|-------------------------------------------------|-------------|----------------------------|---------------------------------------|
|  |             |                           |                                   |                                             |                                                 |             |                            |                                       |

From the tables 1 and 3, the expected energy consumption in 24 hours, if the fan had a VFD, is 231.86 kWh. The potential energy savings for this specific day is the difference between the energy measured (661.81 kWh) and expected consumption (231.86 kWh) which is 429.96 kWh.

Annual energy savings can be approximated by assuming that all the days of the year will have similar savings. More accurate energy savings can be projected by considering the average daily temperatures for the previous years.

Depending on the design of the air fan duct system, there can be other energy efficiency and conservation measures. For example, the use of free cooling, controlling parameters of HVAC system and monitoring the recirculation of the conditioned air.

## Example 2

During an energy audit of a pneumatic (material lifting) feeding system, that runs for 24 hours a day, the following data was obtained:

| S/N | Item                 | Quantity/Measure        |
|-----|----------------------|-------------------------|
| 1   | Material density     | 450 kg/m <sup>3</sup>   |
| 2   | Duct diameter        | 300 mm                  |
| 3   | Duct length          | 25 m                    |
| 4   | Air speed            | 25m/s                   |
| 5   | Air flow rate        | 63.10 m <sup>3</sup> /h |
| 6   | Motor rating         | 45 kW                   |
| 7   | Average power demand | 41.6 kW                 |

| S/N | Item                                      | Quantity/Measure             |
|-----|-------------------------------------------|------------------------------|
| 8   | Fan design efficiency                     | 60%                          |
| 9   | Measured dust throughput                  | 67,120 kg/h                  |
| 10  | Recommended maximum air to material ratio | 1:15                         |
| 11  | Dust classification                       | Fine dry dust                |
| 12  | Air density at this condition             | 1.204 kg/m <sup>3</sup>      |
| 13  | Dynamic viscosity of air                  | 1.81 × 10 <sup>-5</sup> Pa.s |
| 14  | Pipe, the absolute roughness              | 0.045 mm                     |

The information was used to establish the performance of the system.

i. *Establishing the pressure drop along the pipe.*

This is calculated using the Darcy-Weisbach equation, (equation 6).

$$\Delta H = f \frac{L}{D} \frac{\rho v^2}{2} \quad (6)$$

Where:

$\Delta H$  Pressure drop along the pipe

$f$  Darcy friction factor

$L$  Length of the duct

$D$  Hydraulic diameter of the duct

$\rho$  Density of air

$v$  Air velocity

Friction factor for turbulent flow is approximated by Haaland approximation equation, (equation 7).

$$\frac{1}{\sqrt{f}} \approx -2.0 \log_{10} \left[ \left( \frac{\epsilon/D}{3.7} \right)^{1.11} + \frac{6.9}{Re} \right] \quad (7)$$

Where:

$\epsilon$  Absolute roughness

$Re$  Reynolds number

*It should be noted that pneumatic air transport system operates in turbulent zone, that is Reynolds number above 3000.) For commercial steel pipe, the absolute roughness typically ranges from 0.045 mm to 0.09 mm*

Reynolds number is calculated using equation 8.

$$Re = \frac{\rho v D}{\mu} \quad (8)$$

Where  $\mu$  is dynamic viscosity of air or fluid viscosity.

The results of the energy audit were analysed and results presented in table 4.

*Table 4: Results of the analysis of energy audit*

| SN. | Parameter                                                  | Value                   |
|-----|------------------------------------------------------------|-------------------------|
| 1   | Reynolds Number                                            | 498,757                 |
| 2   | Air flow rate                                              | 1.767 m <sup>3</sup> /s |
| 3   | Expected amount of dust mass of dust collection per hour   | 117,819.05 kg/h         |
| 4   | Friction factor                                            | 0.016                   |
| 5   | Pressure drop assuming only air only is transported        | 871.646 Pa              |
| 6   | Pressure drop for air-dust mixture transported in the duct | 13,407.71 Pa            |
| 7   | Expected fluid power for air-dust mixture                  | 23.7 kW                 |

The reason for higher pressure drop of the air-dust mixture, is the average density of air-dust mixture at the ratio of 1:15 is 18.52 kg/m<sup>3</sup>.

## Observations

From the analysis it is observed that:

- a. The dust extraction system operating at about 56.97% of the design requirements. (*the ideal should be at least 75%*)
- b. The system fan operation efficiency is 52.65% (*the ideal should be between 60 - 65%*)

From power and energy measurements, it is observed that the system is consuming an average of 41.6 kW while delivering 23.7 kW.

The system can be improved by redesigning it to reduce energy losses due to pressure losses. This can be done by reducing air speed in the duct from 25m/s to 20 m/s, then increasing the diameter of the duct from 300mm to 350 mm (recall the relationship between the velocity and diameter in the Darcy-Weisbach equation). Recalculating using these new parameters, the following will be observed:

- a. Pressure drop change from 13,407.71Pa to 9,193.85 Pa
- b. Fluid power changes from 23.7 kW to 16.3kW
- c. Reduction in the motor fan rating from 45 kW to 37 kW; assuming fan fluid efficiency of 60% and mechanical efficiency of 90%.

## Example 3

During an energy audit on a belt drive for an air fan, the following data was collected and presented in Table 5.

| S/N | Item                                                                     | Quantity/Measure        |
|-----|--------------------------------------------------------------------------|-------------------------|
| 1   | Rated motor power                                                        | 37 kW                   |
| 2.  | Rated motor speed                                                        | 1,487 RPM               |
| 3   | Measured motor speed                                                     | 1,475 RPM               |
| 4   | Rated fan flow                                                           | 7,760 m <sup>3</sup> /h |
| 5   | Rated fan pressure                                                       | 10,970.0 Pa             |
| 6   | Design fan efficiency                                                    | 65%                     |
| 7   | Design belt drive efficiency                                             | 97%                     |
| 8   | Motor pulley size (diameter)                                             | 250 mm                  |
| 9   | Fan pulley size (diameter)                                               | 350 mm                  |
| 10  | Belt type                                                                | 8VF2360                 |
| 11  | Design coefficient of friction<br>between belts and cast-iron<br>pulleys | 0.23                    |
| 12  | Duct diameter                                                            | 350 mm                  |
| 13  | Dust density                                                             | 450 kg/m <sup>3</sup>   |
| 14  | Measured pulley speed                                                    | 878.5 RPM               |
| 15  | Measured air flow rate                                                   | 6,372 m <sup>3</sup> /h |
| 16  | Measure pulley centre distance                                           | 726 mm                  |
| 17  | Duct diameter                                                            | 350 mm                  |

*Calculations of expected power transmitted by the belt system*

1. Expected fan pulley speed is calculated using equation 10

$$N_f = \frac{N_m \times d_m}{d_f} \quad (10)$$

$$N_f = \frac{350 \times 1475}{250} = 1053.57 \text{ RPM}$$

Where:

|       |                          |
|-------|--------------------------|
| $d_m$ | Motor pulley diameter    |
| $d_f$ | Fan pulley diameter      |
| $N_m$ | Motor pulley speed (RPM) |
| $N_f$ | Fan pulley speed (RPM)   |

The value for expected fan pulley speed, (1053.57 RPM) is more than the measured value, (878.5 RPM). This means that the belt drive cannot transfer the expected power. The lower speed of the fan pulley can as a result of worn-out belt or fan pulley. The Power (Kw) required to drive air mixture at 6,372m<sup>3</sup>/h and pressure drop of 10,970 Pa is calculated by equation 11.

$$Power_{air} = \frac{\Delta P_{air} \times Q_{air}}{1000 \times 3600} \quad (11)$$

$$\frac{10,970 \times 6,372}{1000 \times 3600} = 19.42 \text{ kW}$$

2. Expected power transfer (EPT) to the fan is calculated using equation 12.

$$EPT = MRP \times \eta_{blt} \times \eta_{fp} \quad (12)$$

$$EPT = 37 \times 0.97 \times 0.65 = 23.33 \text{ kW}$$

Where:

|               |                          |
|---------------|--------------------------|
| MRP           | Motor Rated power        |
| $\eta_{belt}$ | Belt transfer efficiency |
| $\eta_{fp}$   | Fan efficiency           |

Expected power (kW) to drive air as per design conditions is calculated using equation 13.

$$Power_{air} = \frac{\Delta P_{air} \times Q_{air}}{1000 \times 3600} \quad (13)$$

$$\frac{10,970 \times 7,760}{1000 \times 3600} = 23.64 \text{ kW}$$

Comparing this calculated value and the expected power transfer of 23.33 kW, we can deduce that the load and the supply power is matched.

3. Expected power transfer from motor to the fan pulley can be calculated using equation 14.

$$EPT = MRP \times \eta_{belt} \quad (14)$$

$$EPT = 37 \times 0.97 = 35.89 \text{ kW}$$

Power transfer from motor pulley to fan pulley ( $P_{m-p}$ ) is given by equation 15.

$$P_{m-p} = (T_1 - T_2) \times v_{belt} \quad (15)$$

Where:

|            |                                   |
|------------|-----------------------------------|
| $T_1$      | belt tension on the tension side  |
| $T_2$      | belt tension on compression side. |
| $v_{belt}$ | Belt velocity                     |

The relationship between  $T_1$  and  $T_2$  is given by equation 16.

$$2.3 \times \log_{10} \left( \frac{T_1}{T_2} \right) = \mu \theta \quad (16)$$

Where:

- $\mu$  coefficient of friction between belts and pulleys
- $\theta$  the contact angle of the belt on the pulley

The contact angle is given by equation 17.

$$\theta = \pi - 2\arcsin\left\{\frac{r_{motor} - r_{fan}}{Cd}\right\} \quad (17)$$

Where:

$r_{motor}$  Radius of motor pulley

$r_{fan}$  Radius of fan pulley

$Cd$  Centre to centre distance between the pulleys

Using values in table 5.

$$\theta = \pi - 2\arcsin\left\{\frac{175 - 125}{726}\right\} = 3.0036 \text{ rads } (\approx 172.094^\circ)$$

Tensions  $T_1$  and  $T_2$  are calculated using equations 15, 16 and 17

Belt velocity  $V_{belt}$  is calculated using equation 17.

$$V_{belt} = \frac{\pi d_m N_m}{60} \quad (17)$$

$$V_{belt} = \frac{\pi \times 0.25 \times 1475}{60} = 19.31 \text{ m/s}$$

$$35890 = (T_1 - T_2)19.31$$

Therefore  $(T_1 - T_2) = 1858.62 \text{ N}$

$$2.3 \times \log_{10}\left(\frac{T_1}{T_2}\right) = 0.23 \times 3.0036$$

$$\left(\frac{T_1}{T_2}\right) = 1.9909$$

Then  $T_1 = 3734.58\text{N}; T_2 = 1875.58 \text{ N}$

Length of belt of the drive as of the time energy audit is calculated using equation 18.

$$L_{bt} = \pi(r_{motor} + r_{fan}) + 2Cd + \frac{(r_{motor} - r_{fan})}{Cd} \quad (18)$$

Then

$$L_{belt} = 2397.92 \text{ mm}$$

The calculated belt length is higher than the specified drive belt length 2360 mm (8VF2360) by 37.92mm. This implies that the belt expanded. This results in reduction in power transmission capacity of the belt leading to losses. This phenomenon is called permanent belt creep.

The loss of power transmission capacity can be calculated by equation 19.

$$Power_{loss} = \frac{\Delta L \times P_{input}}{L_{belt}} \quad (19)$$

$$= \frac{37.92 \times 35.89}{2360} = 0.577kW$$

This loss is equivalent to 1.6% of the transmitted power.

The energy loss due to decrease in the coefficient of friction can be calculated equation 15 and 20. The belt velocity (v) is calculated using equation 20.

$$v = \frac{\pi DN}{60} \quad (20)$$

Velocity based on measured 878.5 RPM

Velocity based on expected design speed 1053.57 RPM

Power transferred can be calculated using equation 15.

Velocity based on 878.5 RPM at 350mm diameter is 16.08m/s

Velocity based on 1053.57 RPM at 350mm diameter is 19.3m/s

Change in power assuming no change in tension.

$$\Delta P = (T_1 - T_2)(19.3 - 16.08) = 3.22 \text{ kW}$$

This loss is equivalent to 8.97% of the transmitted power.

The resultant total power transmission loss is the summation of the losses due to change in belt length (0.577kW) and friction (3.22 kW) which is 3.897 kW.

#### Example 4

During an energy audit of a fan system supplying air to appoint of use via a 4-way duct system, the following data was collected: fan capacity is 9 m<sup>3</sup>/s; pressure 278Pa; motor rating of 5.0 kW; motor efficiency of 92%; and operating 12 hours per day.

The main duct from the air handling unit is 20m long with a diameter of 1.287m. Table 4 shows the results of air flow measurements, duct resistance and pressure drop calculations.

Table 4: Results of air flow measurements, duct resistance and pressure drops

| Branch | Starting point from main duct (m)                                                                    | Length measure from main duct (m) | Diameter (m) | Air demand m <sup>3</sup> /s | Resistance (Pa s <sup>2</sup> /m <sup>5</sup> ) | Pressure drop (Pa) |
|--------|------------------------------------------------------------------------------------------------------|-----------------------------------|--------------|------------------------------|-------------------------------------------------|--------------------|
| A      | L <sub>a</sub> =20, D=0.521m                                                                         | 5                                 | 0.521        | 1.8                          | 13.81                                           | 77.90              |
| B      | L <sub>b</sub> =28<br>Section 1 is 20m, D=1.287m, Section B, L=8m D= 1.129                           | 2                                 | 0.534        | 2.4                          | 5.69                                            | 77.93              |
| C      | L <sub>c</sub> =31<br>Section 1 is 20m, D=1.287m, Section B, L=8m D= 1.129, Section C, 3m, D= 0.874m | 3                                 | 0.575        | 2.0                          | 6.47                                            | 78.12              |
| D      | L <sub>d</sub> =31<br>Section 1 is 20m, D=1.287m, Section B, L=8m D= 1.129, Section C, 3m, D= 0.874m | 5                                 | 0.583        | 1.6                          | 9.16                                            | 78.03              |

From table 4, it is observed that the highest pressure drop is 78.12 Pa along branch C and the lowest is 77.90Pa along branch A. This is a difference of 0.21Pa, which is 0.2%.

This is an indication of a good balanced air duct system (*pressure difference should be below 1%*).

In this case you need to establish pressure balance. Pressure balance is established by calculating pressure drops along each of the duct ways. Pressure drop in each of the duct ways is determined using equations 22 and 23.

$$\Delta P = RQ^2 \quad (22)$$

$$R = \frac{8\rho f_d L}{\pi^2 D^5} \quad (23)$$

Example: Resistance and pressure drop along the main section of the duct is

$$R = \frac{8 \times 1.24 \times 0.101 \times 20}{\pi^2 \times 1.287^5} = 0.5755 \text{ Pa} \cdot \text{s}^2/\text{m}^6$$

$$\Delta P = 0.5755 \times 7.8^2 = 35.02 \text{ Pa}$$

Total resistance along duct balances is calculated by summing up resistances of along each section.

Consider an energy audit of a system whose parameters and analysis are presented in Table 5. (draw the illustration)

Table 5: System parameters of an air duct system

| Branch | Starting point from main duct (m) | Length measure from main duct (m) | Diameter (m) | Target Air demand m <sup>3</sup> /s | Resistance (Pa s <sup>2</sup> /m <sup>5</sup> ) | Pressure drop (Pa) in balanced system | Measured Air flow | In Unbalanced system Pressure drop (Pa) |
|--------|-----------------------------------|-----------------------------------|--------------|-------------------------------------|-------------------------------------------------|---------------------------------------|-------------------|-----------------------------------------|
| A      | L <sub>a</sub> =20, D=0.521m      | 5                                 | 0.521        | 1.8                                 | 13.81                                           | 77.90                                 | 2.3               | 105.036                                 |

|   |                                                                                                                                         |   |       |     |      |       |     |       |
|---|-----------------------------------------------------------------------------------------------------------------------------------------|---|-------|-----|------|-------|-----|-------|
| B | L <sub>b</sub> =28<br>Section 1 is 20m,<br>D=1.287m, Section 2, L=8m<br>D= 1.129                                                        | 2 | 0.534 | 2.4 | 5.69 | 77.93 | 2.6 | 82.61 |
| C | L <sub>c</sub> =31<br>Section 1 is 20m,<br>D=1.287m, Section 2, L=8m<br>D= 1.129, Section C, 3m, D=<br>0.874m                           | 3 | 0.575 | 2.0 | 6.47 | 78.12 | 1.7 | 72.73 |
| D | L <sub>d</sub> =31<br><b>Section 1:</b> L=20m,<br>D=1.287m, <b>Section 2:</b> L=8m<br>D= 1.129,<br><b>Section 3:</b> L=3m, D=<br>0.874m | 5 | 0.583 | 1.6 | 9.16 | 78.03 | 1.3 | 71.47 |

From table 5, it is observed that in duct A the pressure drop is 105.036 Pa. This is 27 Pa (34%) above a balanced system illustrated in Table 4. This indicates that the motor is doing extra work to drive unwanted air through duct A. The associated daily energy loss due to this imbalance is calculated using equation 24.

$$E_{loss} = \Delta P \times \Delta Q \times time \quad (24)$$

$$E_{loss} = 27 \times 1.8 \times 12 = 583.2 \text{ Wh}$$

$$= 0.583 \text{ kWh}$$

To convert this mechanical loss to electrical energy loss, it is divided by the motor efficiency.

$$\frac{0.583 \text{ kWh}}{0.92} = 0.6336 \text{ kWh}$$

Let us make a number of observations about this calculated loss:

1. We can compare the loss to the total energy consumption of the motor using the following computation.

Motor energy consumption

$$\frac{\text{motor rating} \times \text{time}}{\text{efficiency}} = \frac{5 \times 12}{0.92} = 65.22kWh$$

2. The percentage electrical energy loss is:

$$\frac{0.6336}{65.22} \times 100 = 0.97\%$$

This percentage loss may appear small compared to the motor consumption. However, for bigger systems (for instance 3.5 MW systems) the energy cost associated with the loss can be significantly higher. Moreover, such unresolved issues might compromise the structural integrity of the system.