STANDARD, QUIET AND SUPER QUIET – THE MODELLING OF FLOW AND THE REDUCTION OF TURBULENCES

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ABSTRACT

The understanding of noise and efficiency characteristics of fan motor systems is important for all engineers developing air movement systems whether they are for stand-alone ventilation systems or for air movement solutions incorporated into broader systems.

The volume of air flow and air velocity through static pressure resistances are the main and vital variables controlling system performance in air movement. However if these characteristics are not controlled, then turbulence causes losses and low system performance.

The paper explores the noise characteristics of typical fan types. As the most common fan types, fluid flow characteristics of both axial fans and single inlet centrifugal backward curve fans without housing (plug fans) are detailed and design improvements discussed.

Installation characteristics for improved noise are explored and recommendations for system design improvements are given including performance improvements in condensers and air handling units.

Conclusions for mechanical engineers working on building systems are shown and recommendations and design principles given.

1.0 INTRODUCTION

The movement of air around buildings is vital for human health and wellbeing. This is achieved using both fresh and conditioned air and therefore carries a variation of energy within it. The control of that air and the associated efficiency flow is vital to ensure that the space is ventilated and conditioned correctly.

Inefficient control of air flow results in energy loss which is typically converted to heat and noise. Typically air-conditioning units are temperature controlled at the point of delivery therefore the amount of heat gain due to flow inefficiency is not noticed. Noisy systems on the other hand, are always an issue to the building users and therefore noise and noise control is often a main issue for designers and facility managers.

Noise from air movement units can either radiate from the product or can be carried down a duct within the air stream. Dependent upon the positioning of the mechanical services, either radiated or induct noise values can be of greatest relevance.

Noise or sound travels in the form of a wave and as such has wavelength and frequency characteristics. Measurement of the level or intensity of the sound can be done either from the perspective of sound power or sound pressure. Sound power is most commonly used as sound pressure is dependent upon the surrounds and in particular the distance from the source.

The level or power of the noise is measured in decibels which is a logarithmic unit used to express the ratio between two values of a physical quantity, often power, where one of the values is a reference value. Noise to a human ear is dependent upon both power and frequency, as shown in Figure 1. Note: as decibel is a logarithmic unit, a change in power by a factor of 10 is a 10 dB change in level. A change in sound power by a factor of two (i.e. half the audible noise) is approximately a 3 dB change.

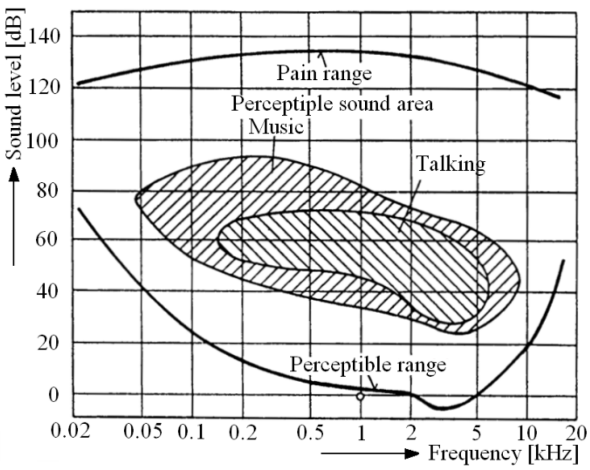


Figure 1: Audible noise characteristics after Ray (1)

The power and frequency of the noise is dependent on the turbulence and power imparted on the air by the fan itself. As shown in Figure 2, the nature of the turbulences can be dramatic with major air disturbances continuing many blade distances from the source itself.

Figure 2: Air turbulences from an aeroplane wing tip; after NASA (2)

The noise spectrum of a fan, as shown typically in Figure 3, is comprised of tones at harmonics of the blade passing frequency, (where the blade passing frequency is equivalent to the number of blades multiplied by the rotation speed) and a continuous broadband noise spectrum which is often the main contribution to the overall sound power level of the fan.

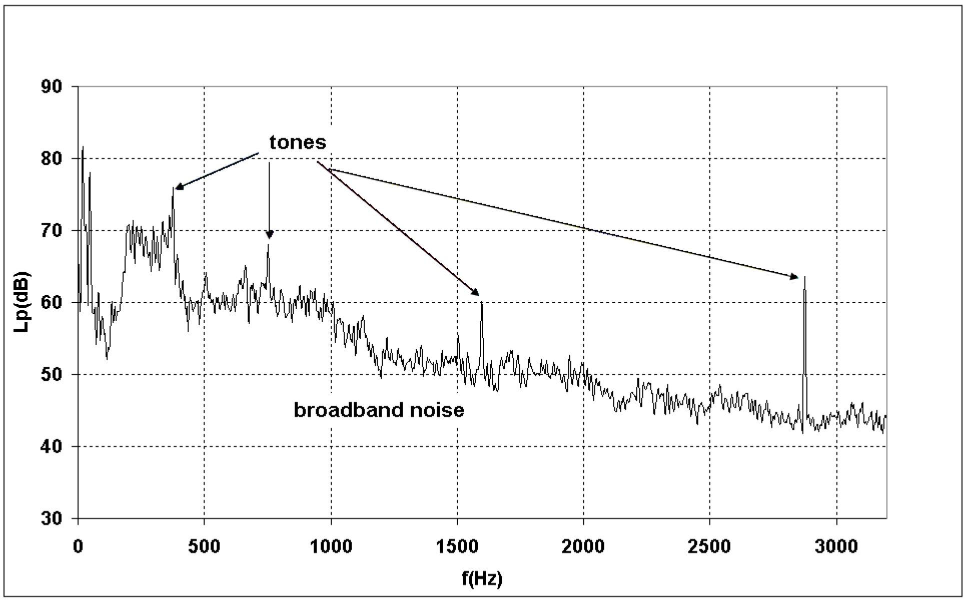


Figure 3: An example of fan acoustic narrowband spectrum; after Denenberg (3)

Tonal noise can occur in axial fans due to circumferential variation of the flow velocity which in turns varies blade load resulting in harmonics tones. In centrifugal fans, interference between rotating blades and exiting pressure side air results in similar tonal pressure waves. Broadband noise is generated by blade tip turbulences as well as other blade surface turbulences and air separations dependent upon blade design. Installation characteristics can affect both tonal and broadband noise and this will be discussed shortly.

2.0 NOISY FANS AND FAN SYSTEMS

If we look at the static efficiency performance of a fan system, Figure 4, we can see that approximately 35% of the drive power is converted to losses associated with the exit of the air from the system. This shows that considerable power can be converted to noise which in turn can increase further especially if impellers are not assembled in the most advantageous way.

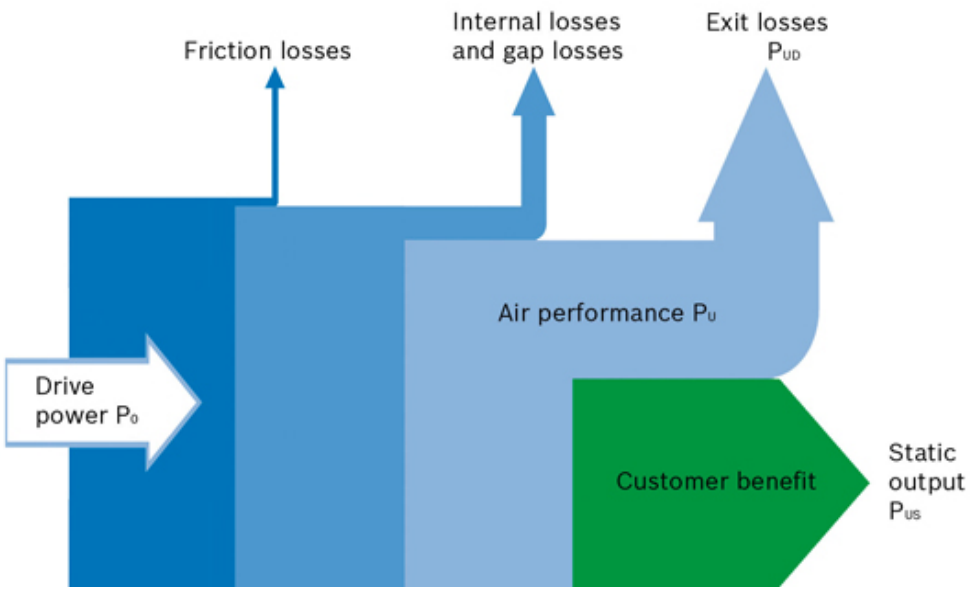


Figure 4: Static losses associated with fans; after ebm-papst GmbH (4)

The noise of a fan can depend on the following parameters:

- Type of fan (axial, centrifugal etc.)
- Geometry of the impeller and stator
- Size and speed of rotation
- Operating point on the fan curve
- Fan installation in the system

As discussed in AIRAH Handbook DA 13 and shown in Figure 5, the broadband noise characteristics of axial and centrifugal fans are different. Typically axial fans have higher frequency noise characteristics whereas centrifugal fans, especially backward curve ones, have broader low frequency noise characteristics. Forward curve centrifugal fans, due to their high number of blades, have similar characteristics to axial fans.

It is important that the selection of a fan is done in its' range of highest efficiency. The most efficient range also coincides with the fans lowest noise generation, as shown in the performance schematics of axial and backward curve fans: Figure 6. If however fans are selected away from their peak efficiency range then dramatic increases in noise can occur. This is especially significant for axial fans if they are used near or above their “stall point”. In this performance region the fan is unstable as delamination of the air away from the axial blades occurs which in turn can cause drastic turbulences both within the air stream and mechanically, within the product. This instability can occur if the installation requirements are not specified correctly or the system resistance of the facility increases with time beyond tolerance, for instance if a filtration system blocks and static pressures increase beyond the specified value.

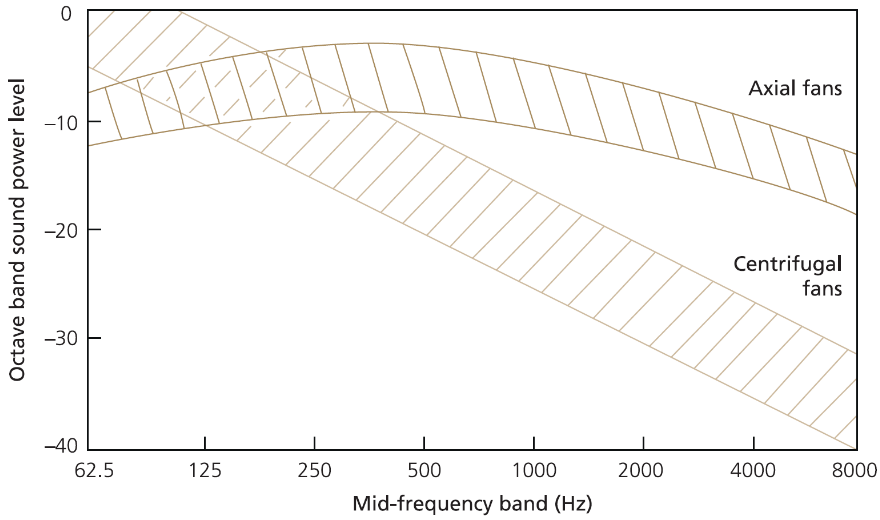
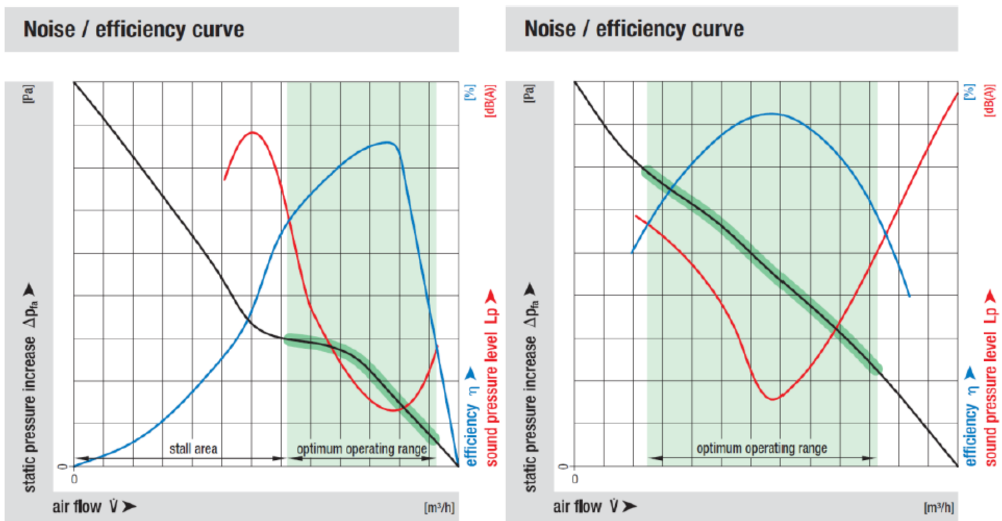


Figure 5: Comparison of typical centrifugal and axial fan noise spectra; after Aherne (5)



Axial Fan   Backward curve centrifugal fan

Figure 6: Noise and efficiency curves for axial fans and backward curve fans; ; after ebm-papst GmbH (4)

2.1. IMPELLER DESIGN

2.1.1 Axial fans

The variety of axial fan blade designs is large. Designs include the use of pressed and bent sheet aluminium blades for use in refrigeration to fibre re-enforced, self-balancing belt driven blades for use in industrial cooling systems.

In order to gain static pressure efficiency, many manufacturers of axial bladed fans adopt the principles of Bernoulli, and design axial blades with aerofoil blade sections, as shown in Figure 7. Figure 7 also shows the flow of air over an axial fan blade which is operating in stall, as discussed previously. Here, both lamellar and turbulent flow can be observed. At these high static pressures air comes away from the blade and the phenomena of vortex shedding can be observed.

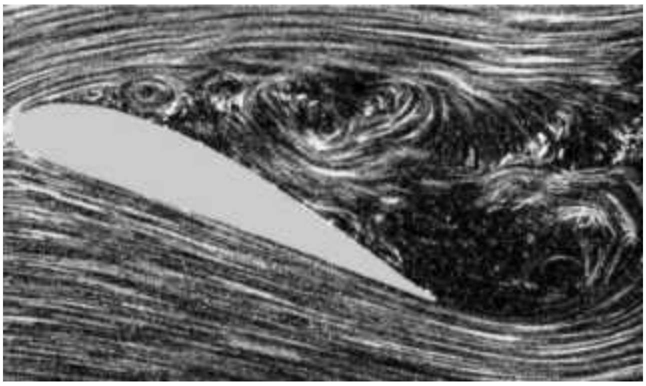


Figure 7: Airflow characteristics of a turbulent axial blade; after NASA (7)

Axial fans are most are most commonly used within a housing. Housings are used to either direct the flow or to increase the efficiency of the fan assembly. The designs vary, the most common being: a plain hole, a full venturi or extended tubes ("short or long case") around the axial impeller.

An example of axial fan placed inside a long tube is shown in Figure 8, which represents an axial impeller in an engine configuration. As shown in the drawing, now that the axial fan is mounted, an interaction between the impeller and the housing occurs and both laminar and turbulent air can result especially due to the interaction of the blade tip and the housing. The purpose of the housing is to control the flow of air and as such creates clear areas of positive and negative pressure. As with all diffusional processes, air flow from positive to negative areas will occur. Reverse flow can occur at the end of the blade or the tip as well as at the motor hub, the latter being dependent upon the assembly design.

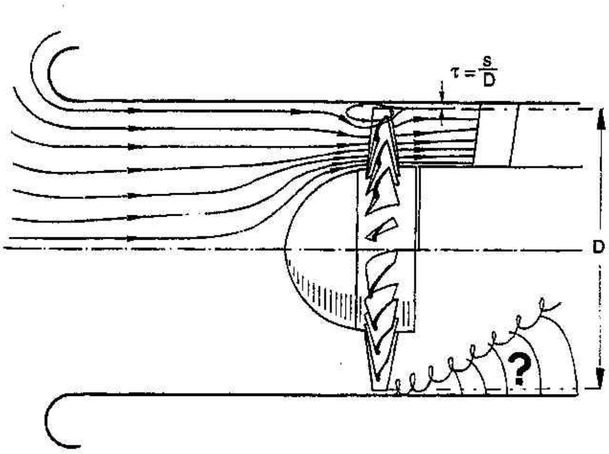


Figure 8: Schematic view of secondary flow driven by the difference between suction and pressure side in the axial blade tip region; after NASA (8)

Turbulent flow at the wing tip and reverse air flows can be improved by changing blade design at the wing tip with the use of "winglets". Winglets are most commonly found in aircraft, as shown in the diagram below, Figure 9.

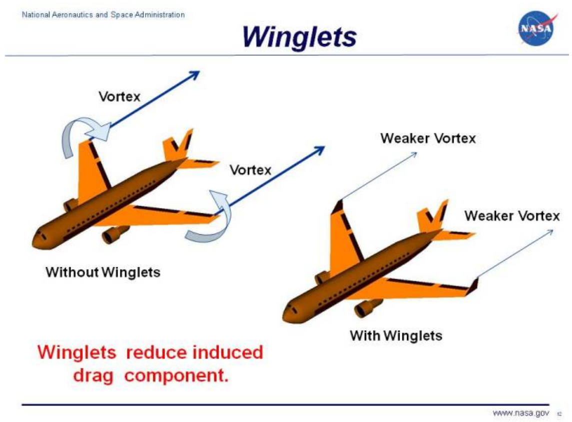


Figure 9: The application of winglets on aircraft after NASA (9)

As shown in Figure 9, air flows around the end of an aircraft blade from the positive pressure to the negative pressure side causing turbulence of vortices. For aircraft, this vortex cases increased drag and therefore increases fuel consumption. In axial fans these vortices cause non-laminar flow which in turn results in increased noise.

The effect of this blade design on axial fans has been investigated by Angelis and Eimer (10), Figure 10. This investigation has shown that winglets reduce noise dramatically, especially at high air volumes.

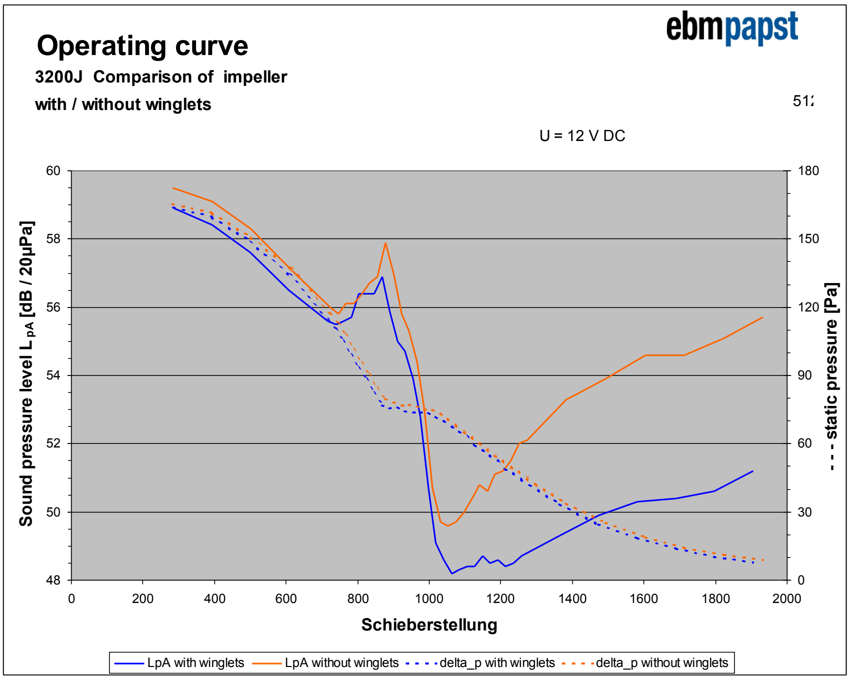


Figure 10: The effect of winglets after Angelis and Eimer (10)
The use of winglets is now typical for most axial fan manufacturers and many designs exist. A typical example is shown below in Figure 11.

Figure 11: Typical winglet at end of axial fan bladel after ebm-papst GmbH (6)

2.1.2 Centrifugal impellers

Centrifugal impellers are of three main types: backward curve, forward curve and radial as shown in Figure 11 after Dwyer (11). Unlike axial fans, centrifugal fans turn air through right angles and as such have more complex flow characteristics. Blade design and the application of the theories of Bernoulli still apply but due to high cost of manufacture, especially in metal based systems, a broader range of plain bladed impellers is commonly used.

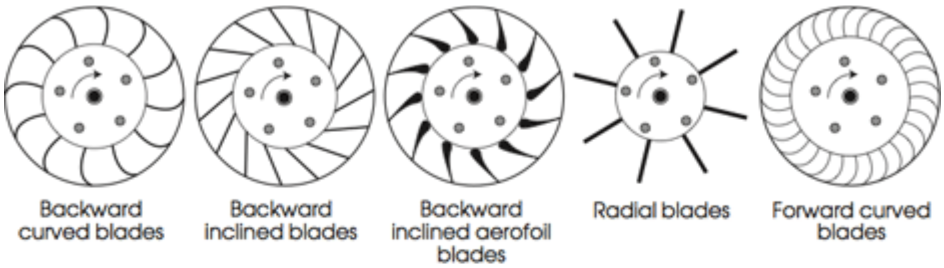


Figure 12: Typical centrifugal fan types after Dwyer (11)

Market shifts and regulatory strategies are moving the centrifugal fan market towards backward curve centrifugal impellers. As with all centrifugal fans, air is drawn into the eye of the impeller and pushed out by the impeller blades at approximately right angles to the incoming air. The numbers of blades are typically low and the impellers can be constructed from a range of metal, plastic and composite materials.

With developments in fluid mechanics and injection moulding technologies, more advanced backward curve impeller designs have been realised. Figure 13, shows the modelling of air flow through a traditional single inlet backward curve impeller and a new composite product.

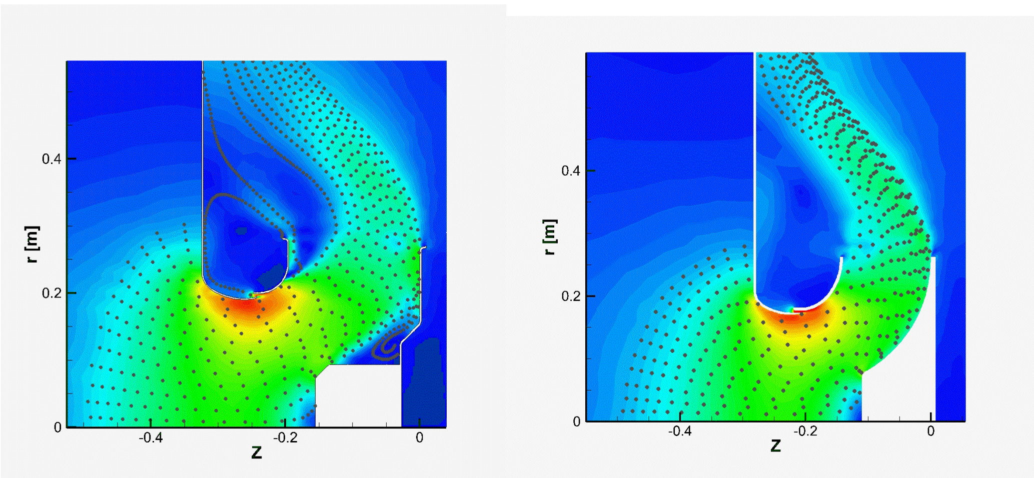


Figure 13: Air flow modelling through traditional single inlet backward curve impeller (left) and new RadiCal impeller (right) after ebm-papst GmbH (12).

By using these technologies, improvements in performance of 5% in efficiency, 4.5dB reduction in peak average noise and 11dB reduction in primary blade passing frequency can be realised. This data is shown below, in Figure 14a, b and c. Although efficiency and overall noise reductions are significant, the reduction in noise at the blade passing frequency is particularly notable. Due to their low number of blades backward curve impellers are known for high low frequency (250Hz) noise characteristics. As seen in Figure 14c, these developments have now almost eradicated the primary blade passing tone at 250Hz and this marks a major landmark in the development of this technology.

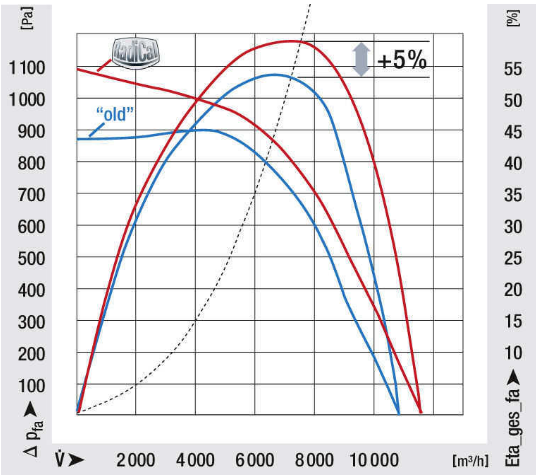


Figure 14a: Efficiency data of traditional and Radical backward curve impellers after ebm-papst GmbH (12)

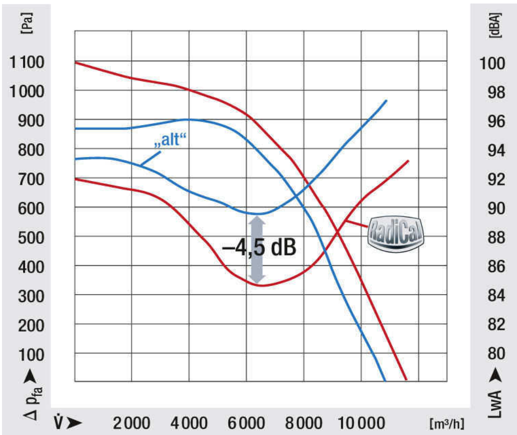


Figure 14b: Noise data of traditional and Radical backward curve impellers after ebm-papst GmbH (12)

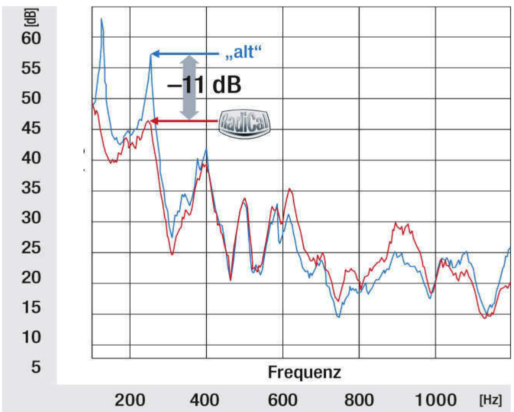


Figure 14c: reduction of primary blade passing frequency at 250Hz of the new Radical backward curve impellers after ebm-papst GmbH (12)

2.2. SYSTEM EFFECTS

2.2.1 "Air on" effects

Efficient fans are important in the developments of better air flow products. However, how the fan is used and how air flows into and out of a fan also has to be considered.

An examination of the effect of obstructions and/or surrounding constructions on the noise characteristics of a backward curve impeller is shown in Figure 15. These investigations clearly show that as the inlet of the fan is constrained, greater average noise results. Indeed, increases of up to 15dB can result from a "bad" assembly.

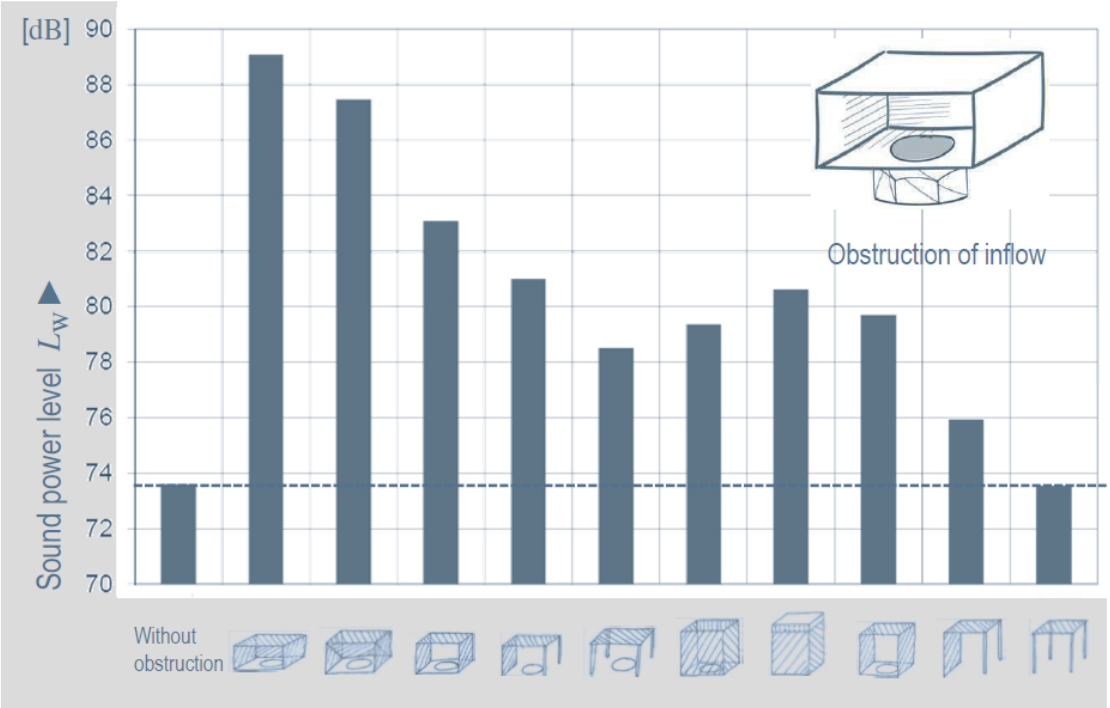


Figure 15: The effect of obstructions on the noise characteristics of single inlet backward curve impellers after ebm-papst GmbH (12)

A common mounting arrangement for axial fans is on a rectangular box, as shown in Figure 16. Examinations have shown that when the positioning of an axial fan is irregular, allowing air to pass into one area of an axial fan preferentially, then pigtails or spigots of high velocity air result. This high velocity air increases turbulence in the areas shown and changes the air performance vectors on the axial fan at the position which correspondingly results in an increase of noise at the blade passing frequency.

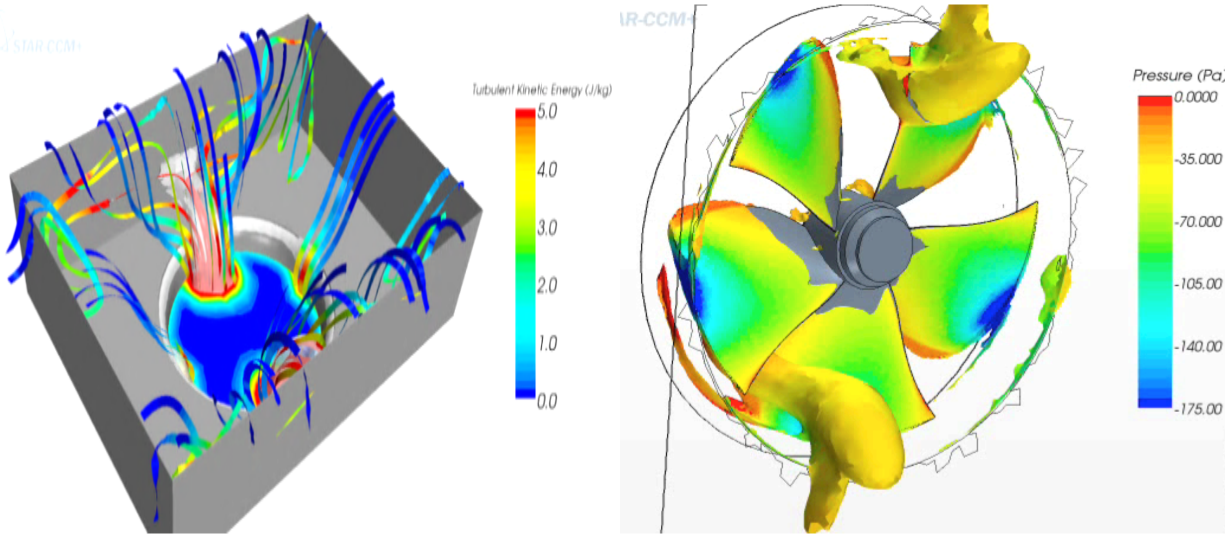


Figure 16: Examination the air flow into an axial fan mounted on the surface of a rectangular box (12)

Many developments have taken place in order to reduce the turbulence of the air flow onto an axial impeller and it is suggested by Woods Guide that several fan distances prior to the blade as well as an inlet venturi should be used. An example of this is reproduced here courtesy of Fantech Pty Ltd, Figure 17.

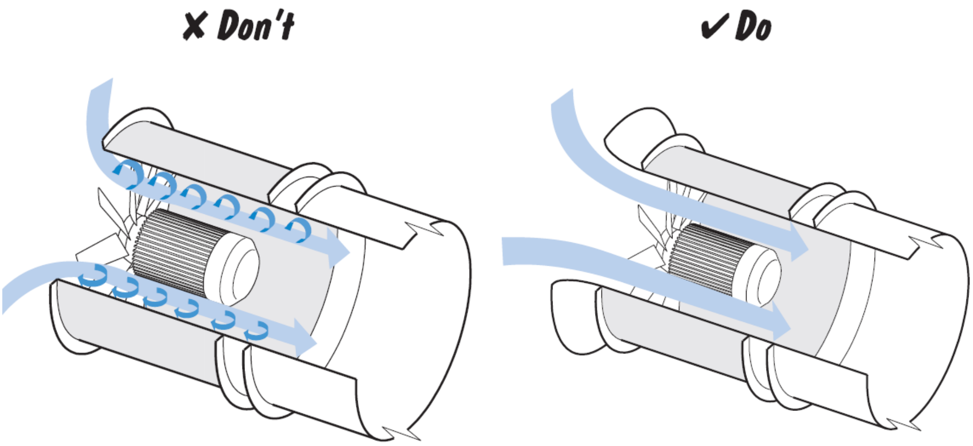


Figure 17: Assembly designs allowing lamellar airflow through an axial fan after Fantech (13)

Although these suggestions work especially in ventilation applications, in practice the costs and dimensional requirements of the system sometimes do not allow this to be a practical solution especially in the type of mounting arrangements as shown in Figure 16. Further investigations based upon the research shown in Figure 16 by the same team have resulted in the development of an inflow grid as shown in Figure 18, which can be used with both axial and centrifugal fans.

Figure 18: The inflow grid as used on axial and plug fans after ebm-papst GmbH (12)

The performance of the inflow grid has been measured in a variety of applications. Improvements in overall noise behaviour and in particular a reduction in noise at the blade passing frequency have been found for both axial and centrifugal fans. Some examples are shown in Figure 19. It should be noted that the inflow grid is reported not to affect air flow performance characteristics.

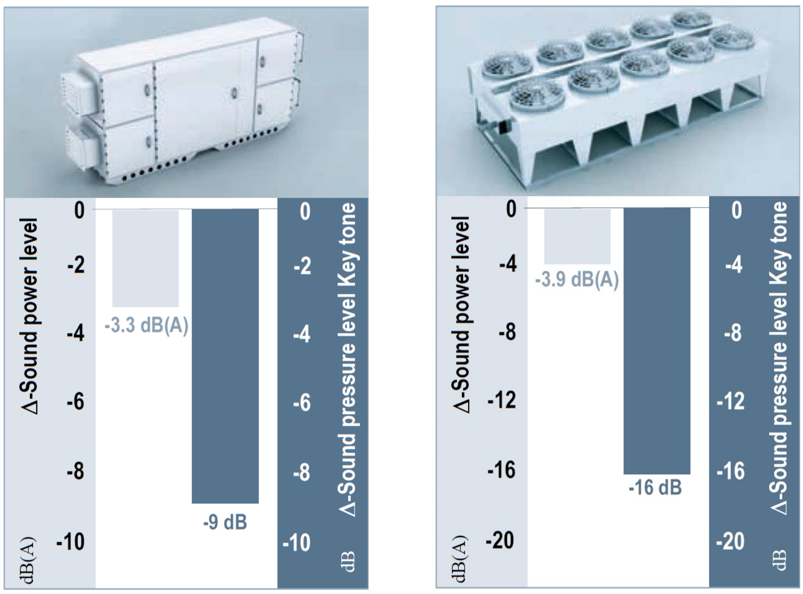


Figure 19: Experimental data of the effects of inflow grid on 710mm diameter axial fans in a condenser and 630mm diameter backward curve centrifugal fan in an air handling unit after ebm-papst GmbH (12)

The experimental data shows different noise results in different applications from which it can be suggested that varying amounts of turbulent air flow exists in each unit.

The extracted data is:

- Axial fans 710mm diameter in a condenser: 3.9dB(A) average reduction and 16dB at key tone

- Backward curve centrifugal fan 630mm diameter in and air handling unit: 3.3dB(A) average reduction and 9dB at key tone

In the examples shown here, it is highlighted that the position of condenser coils too close to the fans and the use of other components such as heat exchangers or electric heaters, all act to increase the amount of turbulent flow inside the unit. In each case reduction of both overall as well as blade passing frequency noise is achieved with the use of the in-flow grid.

For designers, an alternative view is that the use of flow grids will allow product designers to be more flexible with designs and reduce sub component spacing without reducing the average noise of the unit.

2.2.2 “Air off” effects

The flow characteristics on the pressure side of an axial fan can be highly turbulent with considerable swirl dependent upon the impeller design. Air velocities and the resultant dynamic pressure can be high and these combined, can result in high noise as well as low static efficiency. Significantly, in the analysis, a broad area of “back flow” at the hub of the impeller was also discovered. The area of positive pressure near the hum of the impeller is minimal due to the low level of work being performed in this area. Due to the typical use of shafted motor and open hub blade mounting designs, back flow causes considerable turbulence in this region.

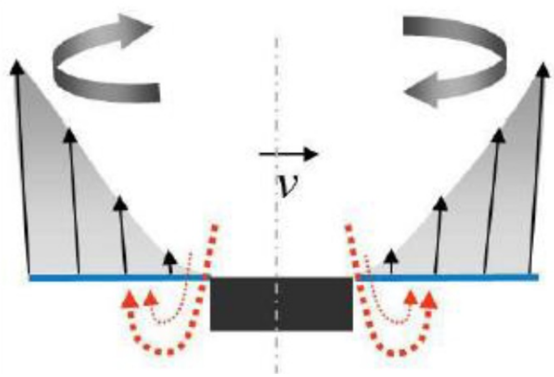


Figure 20: Schematic representation of air flow through axial fans (12).

Traditionally, static regain systems or diffusers have been used in order to improve the performance of axial fans. Figure 21 shows a typical example of a diffuser on an industrial axial fan which is used to increase the static efficiency of the product as well as reduce noise.

Figure 21: Typical industrial cooling towers cooled using axial fans with static regain systems.

These traditional axial fan diffusers do not however address the issues of back flow and only recent development of a combination of inner and outer diffusers, shown in Figure 22, have addressed this.

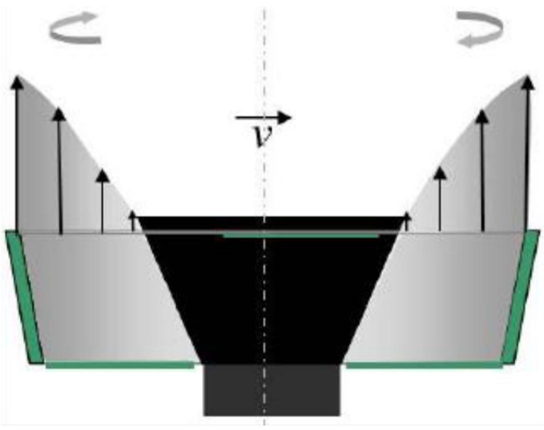


Figure 22: Schematic representation of air flow through axial fans fitted with an inner and outer diffuser (12)

This patented design channels the air vertically up away from the fan as shown in the dynamic analysis in Figure 23.

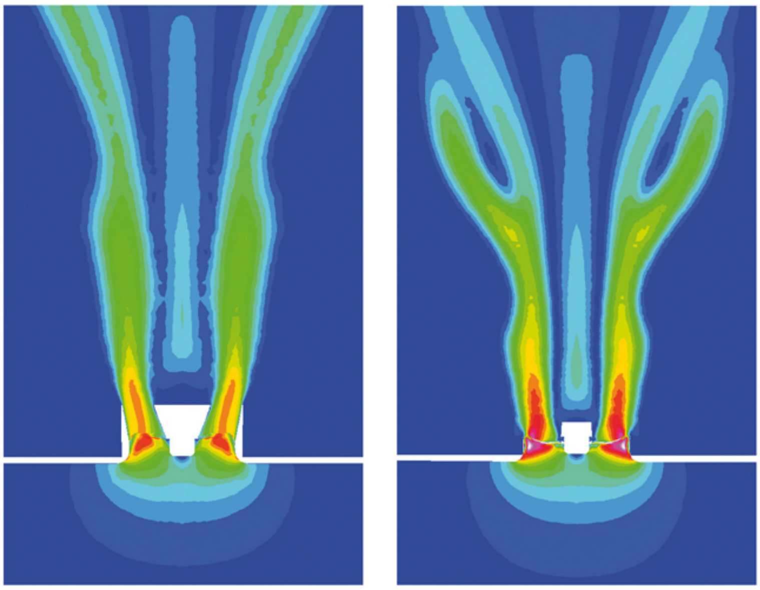


Figure 23: Fluid dynamics analysis of axial fan with (left) and without (right) inner and outer diffuser system (AxiTop) (12).

This new developments has clear advantages for cooling products such as that shown in Figure 24. Typical data for an axial fan with this type of product shows:

- 9% improvement in air flow at maximum performance
- 7 dBA reduction in average noise at the same duty
- 27% reduction in power consumption at the same duty

Figure 24: Typical refrigerative condensing unit using inner and outer diffuser system. (AxiTop)(6).

“Air off” issues of noise and inefficiency associated with the use of backward curve centrifugal impellers arise if the pressure side spacing around the impeller is too small or the air off the impeller is ducted incorrectly. Air exit from a backward curve fan is typically at right angles or in an axial direction and mounting and spacing arrangements in both are important.

Long held beliefs of minimum spacing which be greater than or equal to 40% of the impeller diameter have been replaced by calculations of hydraulic diameter, as shown in Figure 25, as it is most common for these products to be used in non-circular ducts in either ventilation or air handling applications.

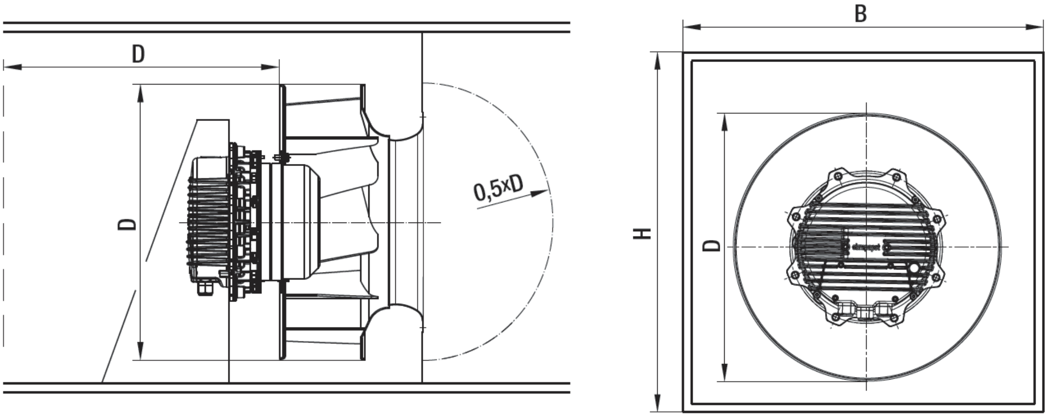


Figure 25a: Box dimensions for the mounting of centrifugal backward curve impellers (6).

where: d_h = hydraulic diameter
and: $d_h = 2*B*H/(B+H)$
where: B = width of box
H = height of box
D = outer diameter of fan

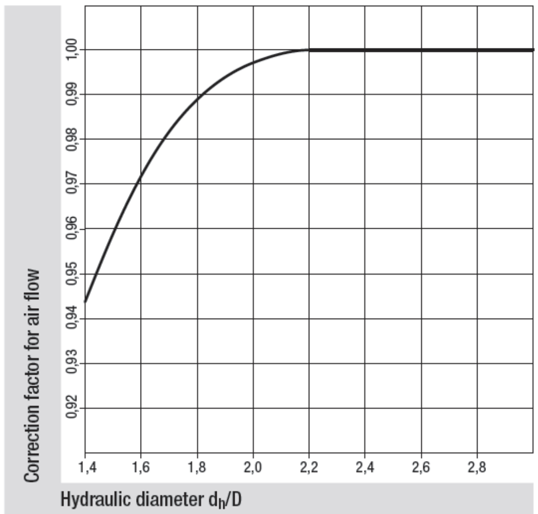


Figure 25b: Correctional factors for flow at varying hydraulic diameters for backward curve centrifugal impellers (6).

Hydraulic diameter surrounding a backward curve centrifugal fan allow for a rectangular system to fit into low height applications. Minimum distances away from the impeller apply such that increased noise doesn't result when the air is exiting in an axial direction along the motor shaft; these distances should be determined empirically.

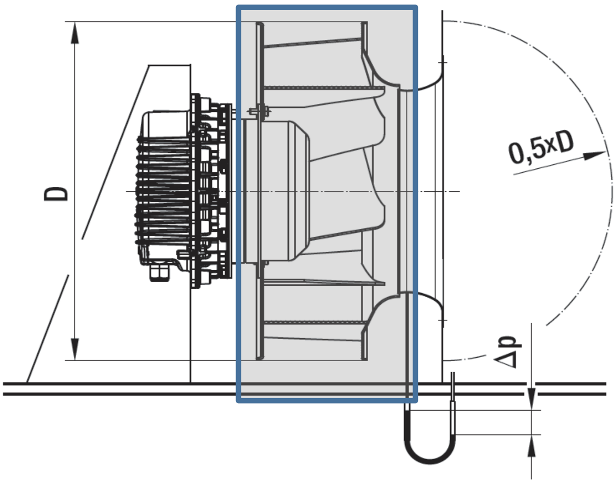


Figure 25: Best practice air exit duct positioning (in grey) design for a backward curve centrifugal fan in a box plenum (12).

Air exit from a backward curve fan at right angles in a 360 degrees direction can be achieved easily. Advantages for this arrangement, in comparison to traditional belt driven supply fans with housings, are that, firstly, the arrangement of the fan does not need to be changed and secondly, the exit velocity of the air is much lower. This lower air velocity consequentially reduces the mechanical services requirements for distances prior to duct turns as well as improves the static efficiency of the supply air.

In considering the design of the air exit from the plenum, positioning of the exit duct is paramount. An example of best practice is shown in Figure 26. Here it can be seen that alignment of the impeller with the exit duct is paramount.

3.0 DISCUSSION AND CONCLUSIONS

Axial and backward curve centrifugal fans without scroll (plug fans) are the most common and growing fan types in the market. The regulation of their use as has been set in Europe according to efficiency levels N and the local markets have drawn up industry codes of practice to assist building and contracting engineers control their use. The noise and performance characteristics of different fan types are shown to be different such that each fan type is used in different applications.

A major contributing factor to both fan efficiency and noise is how the air flow is controlled through both the impeller as well as the air movement system. In this review we have looked at flow through both axial impellers and centrifugal impellers and have highlighted several rules.

1. Impeller design

   Ensuring that air flows efficiently through an impeller requires considerable analysis.   For all impeller designs, the findings of Bernoulli should be used such that the increased lift available with three dimensional impellers is taken advantage of. Commercial considerations must be made here however as costs associated with the manufacture of three dimensional impellers often outweighs the benefits available. Delamination of air away from an impeller at high static pressures should also be monitored and users of axial fans should ensure that the required performance falls within the normal operating ranges.

Centrifugal fans typically turn air through right angles and therefore the route of flow through the impeller has to be controlled. Flat plates and obstructions through an impeller all cause complications to the air flow and design changes such as complex composite impellers and the positioning of motors and or other obstructions have all been implemented by manufacturers to improve performance.

Reverse airflow from positive pressure to negative pressure areas in axial fans blades has been shown to be an issue. The use of physical barriers to stop this flow has been shown to be effective and axial blade designs are now offered to the market with wing tip blades which reduce noise by 2-3dBa.

2. System design

The air onto both axial and centrifugal impellers has been shown to be typically non laminar. Disruption of the air flow onto a fan is shown to be caused by either the box that it is mounted in or by more complex product designs where products such as electric heaters cause disruption of the air flow prior to the fan. System designs such as venturis and extended duct runs that allow air to straighten can be used to provide improvements. Cost implications and or space limitations may affect this solution however and alternative product designs using “in-flow grids” have been shown to be effective.

“In flow grids” have been shown to improve overall noise and in particular blade passing frequencies in both axial and centrifugal fans. The effect of an inflow grid has been shown to be effective in a range of air-conditioning, ventilation and refrigeration product and the grid design is such that more even air flow across the total cross-section of the air inlet area is achieved.

Turbulence created by axial impellers has been shown to be complex such that counter-flow areas can result where the blades and motors join. The use of diffusers to improve static efficiency, reduce air velocities and hence reduce noise has been widely used in industrial systems for many years. Recent designs offering both external and internal diffusers have been shown to reduce turbulence and noise in axial fan assemblies by up to 7dBa.

The positioning of plug fans is explored and the use of hydraulic diameter is defined. Hydraulic diameter calculations provide spacing design details for the use of plug fans in a plenum and considerations of air off ducting are discussed. Lower velocity air resultant of a plug fan allows simple ducting and shorter turns as long as the exit duct is positioned to allow clean and simple airflow off the impeller.

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