International Journal of Emerging Technologies in Engineering Research (IJETER)
Volume 6, Issue 5, May (2018) www.ijeter.everscience.org

Enhancement of Performance of Axial Fans by Identifying and Resolving Stalling

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Abstract – Axial fans are used in almost all forms of built environment where life exists. The selection of axial fan is based on several factors such as pressure, airflow and efficiency. The environment of the location of the axial fans play a major role in the efficiency and the life period of the fan. Some the external factors such as increase in pressure and pollution cannot be eliminated in the environment which might lead to stalling condition. Although stalling condition cannot be eliminated in axial fans, it can be detected in early stages and external sources or change in designs could reduce the probability of fan getting induced to stall condition. This paper explains the method calculation the performance of the fan and analyzing its operating condition and solutions to overcome the stalling the fan might accidentally get into which reduces the efficiency or sometimes the fan itself.

Index Terms – Anti-stall rings, Axial fans, Fan performance, Fan stalling.

1. INTRODUCTION

Ventilation is a very important when it comes to any livable environment for both humans and for most mechanical, electrical or electronic components or systems. And hence, all built environment will be having a ventilation system suitable for the application and the purpose of the built environment. Although there are several kinds of ventilation systems, this paper is about mechanical ventilation systems. Mechanical ventilations systems can also be referred to as Heat Ventilation and Air Conditioning (HVAC) or Air Conditioning and Mechanical Ventilation (ACMV). Ventilation is the intentional introduction of processed air or ambient air into a volume or space particularly to control the air quality of the indoor environment by reducing the indoor pollutants and to improve thermal comfort. The proper introduction of processed or ambient air will aid in achieving a desired indoor comfort levels although the measure of an ideal comfort level varies from individual to individual. The mechanical ventilation systems consist of inlet, exit and connector ducts, weather louvre, humidifier and dehumidifier, heating coil and cooling coil, control dampers and flow rate controller, silencers, filter and fans but this paper deals with more about fans used in ventilation. Although, there are different types of fans like centrifugal fans, jet fans, contra-rotating fans, we will discuss about only axial fans. An axial fan consists of three major components which are casing, impeller and motor. The components of an axial fan is shown in Fig. 1. The motor is determined by its power rating and the power consumption to

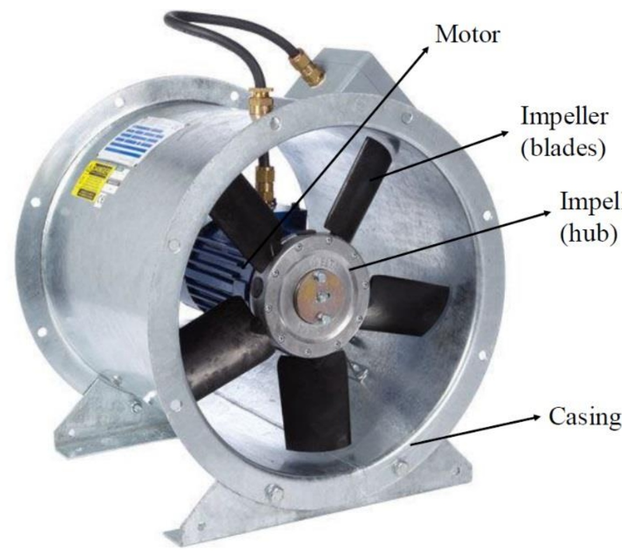

Figure 1. Components of axial fan [1].

circulate certain volume of air. The design of the casing is done based on the diameter and tip clearance of the fan, the value of tip clearance depends on the required performance and the application [2]. The impeller is the major component responsible for the air flow and they have two sub-components namely blade and hub. They both are made of similar or dissimilar materials such as aluminum (Al), glass reinforced polypropylene (PPG), glass reinforced polyamilde (PAG) and antistatic glass reinforced polyamide (PAGAS). The blades are of different blade profiles which include sickle shaped, airfoil shaped, increasing arc and broad paddle which is selected based on the performance required and the application of the axial fan. The number of blades in the axial fan also plays a major role in the performance. Increasing the number of blades in the fan increases the aerodynamic efficiency of the fans [3 – 4]. The pitch angles in the blades of the axial fans can be varied and this variation increases the performance of the axial fans in terms of both airflow and static pressure [3, 5].

1.1. Fan laws

All Fan laws are used to calculate the volumetric air flow, pressure and absorbed power. First fan law states that

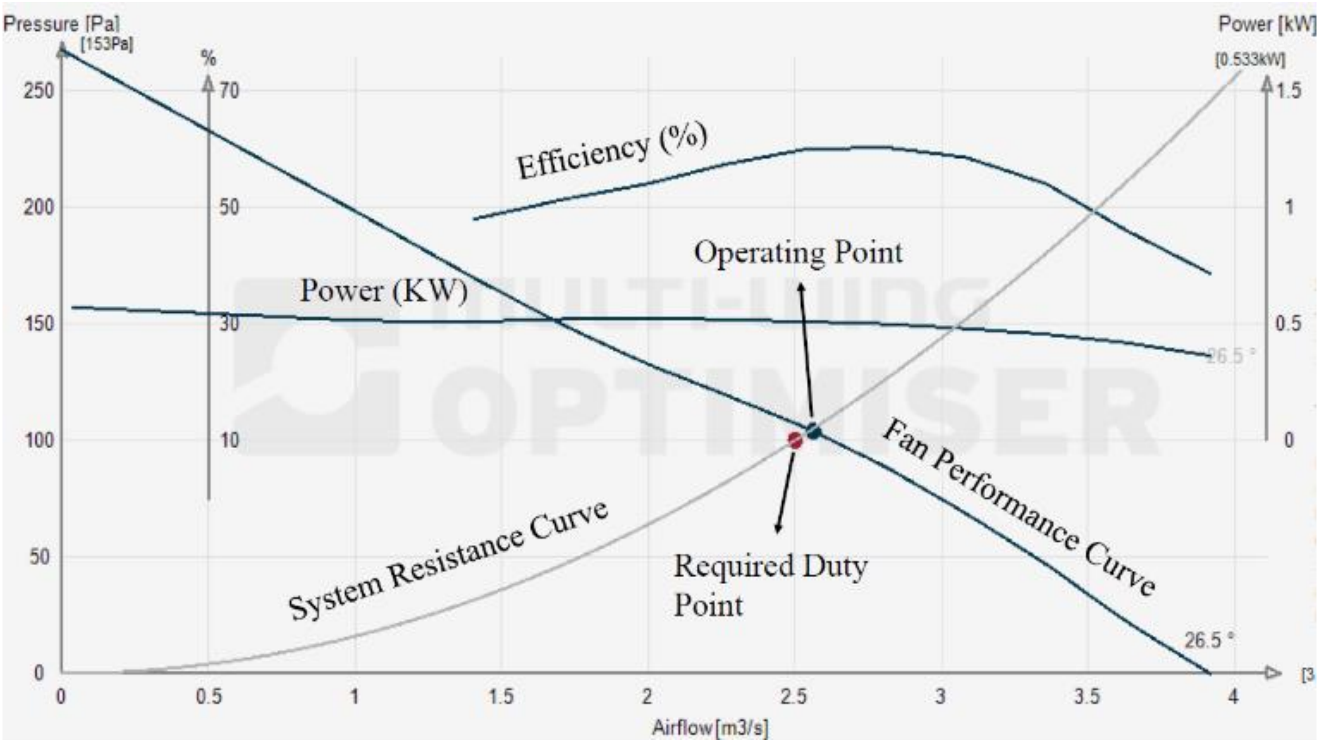

Figure 2. Fan performance curve (ideal).

volumetric air flow rate is proportional to the speed of the fan and cube of the diameter of the fan.

$$Q \propto N.D^3 \quad (1)$$

Where Q is the volumetric air flow, N is the speed of axial fan and D is the diameter of the axial fan. Second fan law states that pressure is proportional to density of fluid flowing through the fan and square of the speed of the fan and cube of the diameter of the fan.

$$P \propto N^2.D^3.\rho \quad (2)$$

Where P is the pressure of the fluid in the fan and ρ is the density of the fluid flowing through the axial fan. Third fan law states that power absorbed by the fan is proportional to density of fluid flowing through the fan and cube of the speed of the fan and fifth power of the diameter of the fan.

$$W \propto N^3.D^5.\rho \quad (3)$$

Where W is the fan absorbed power. The most important use of fan laws in industrial applications can be used to interpret the values of a fan that can run in multiple speeds. Since the multiple speed fans run in the same application, there is no change in the density of the fluid medium and the diameter of the fan does not change and hence the volumetric air flow, pressure and absorbed power values depend only on the speed of the fans. Given the values of volumetric air flow, pressure and absorbed power for one speed of the fan, the values of volumetric air flow, pressure and absorbed power of other speeds of the fan can be determined using fan laws. Although adding or deleting system components such as dampers, or incurring density changes, will create completely new system curves. Changing fan accessories such as inlet boxes, evases, or inlet dampers will alter the fans performance curve from standard. These variables must be considered before the fan laws can be applied.

Since the fan laws are only valid within a fixed system with no change in the aerodynamics or airflow characteristics of the system, these laws can also be referred to as "system laws" [6].

2. PERFORMANCE OF AXIAL FANS

Performance of axial fans can be explained easily with the aid of fan performance curves. An ideal fan performance curve was generated for an axial fan to operate at 25 *℃*, airflow rate of 2.5 m^3/s, static pressure of 100 *Pa*, motor operating speed of 920 *RPM* using Multi-Wing™ Optimiser 10 software and shown in Fig. 2. An 800 *mm* diameter, 7 blade fan with a pitch angle of 26.5◦ and a tip clearance of 1% was selected from the software to operate at point closer to the required duty point and the details of the operating point is shown in Table 1. The fan performance curve is generated with airflow rate on X–axis and pressure on Y–axis. The fan operating point is the point where the system resistance curve and fan performance curve meet, and this point is selected as close as possible to the required duty point. The efficiency and power curves is also generated in the same workspace.

Table 1. Operating point data of axial fan (ideal).

Parameter	Values
Tip speed (*m/s*)	39
Air velocity (*m/s*)	5.1
Torque (*N-m*)	5.28
Axial force (*N*)	60
Air flow (m^3/s)	2.56
Static pressure (*Pa*)	104
Dynamic pressure (*Pa*)	15.4
Total pressure (*Pa*)	119.4
Power (*KW*)	0.509
Efficiency (*%*)	60
Sound (*LW DB*)	88.7
Density (kg/m^3)	1.184
Blade centrifugal force (*N*)	1190
Hub/Diameter ratio	0.233

2.1. Fan curve

All When we put a fan on the test chamber, we have the ability to change the resistance against the fan, through a combination of dampers and an auxiliary fan. We usually set up the test with eleven points that are equally spaced, giving ten flow increments. To get the test fan to zero pressure, we speed up the auxiliary fan high enough to overcome all the internal losses in the test chamber. Then we slow down the auxiliary fan, or close a damper slightly (or a combination of both) to force the fan to approximately 10% less airflow. This process is followed until the damper is completely closed and there is zero airflow.

At each of the test points, we record the airflow, pressure, power, and several pieces of information about the air stream (temperature, pressures, barometric pressure, etc.). These values are used to calculate the fan performance at standard conditions, which is 1.225 kg/m^3 density as per ISA [7], or to any other density required.

The results of the calculations are displayed on a graph with the airflow on the X-axis, the pressure on the left side of Y-axis, and the power on the right side of Y-axis, as shown below.

2.2. System curve

The system resistance is the sum of all pressure losses happening through the design of the systems such as the presence of duct, elbows, filters, dampers, coils and other devices that resists the flow of the fluid. System resistance curves are a graphical representation of how a system reacts to a given airflow.

Fig. 2 shows that the system curve always starts at the origin where flow and pressure are zero. The fan will operate at the point where the system resistance curve intersects the fan curve. For a constant system, the pressure at a given flow varies as the square of the airflow.

The only time the shape of the system resistance curve changes is when the system physically changes. For instance, if a damper is closed, the system resistance is increased. The result is a pressure rise. Similarly, opening a damper reduces the systems resistance.

As stated previously, a system curve can be plotted to show all possible combinations of pressure and airflow rate for a given fixed system. Any fan used on that system must operate somewhere on that system curve. Fan performance is determined by laboratory testing and is presented graphically in the form of fan curves. Unless it is physically altered in some way, a fan must operate somewhere on its Pressure-Air flow rate curve. The relative shape of that curve will not change, regardless of fan speed. Because the fan and system can each only operate somewhere on their own respective curves, a fan used on a fixed system can only have one point of operation. The point of operation, as shown in Fig. 2, is the intersection of the system curve and the fan Pressure-Air flow rate curve.

If the fan speed is increased or decreased, the point of operation will move up or down the existing system curve. This is shown in Fig. 2. The following are examples of how the fan curve can be used to calculate changes to flow and pressure requirements.

2.3. Fan efficiency

The fan efficiency can be calculated either from the design of the fan or from the design of the room for which the fan is installed to serve. The total fan efficiency (η_{total}) calculated based on the design of axial fan is [8]:

$$\eta_{total} = \frac{\frac{\pi}{4} d^2 v (P + \rho v^2)}{\sqrt{n} V I cos\varphi} \quad (4)$$

Where d is the diameter of the axial fan, v is the flow velocity of the air, P is the static pressure of the air, ρ is the density of air, n is the phase of ac supply of motor (usually 3 phase), V is the voltage of the motor, I is the current of the motor and φ is

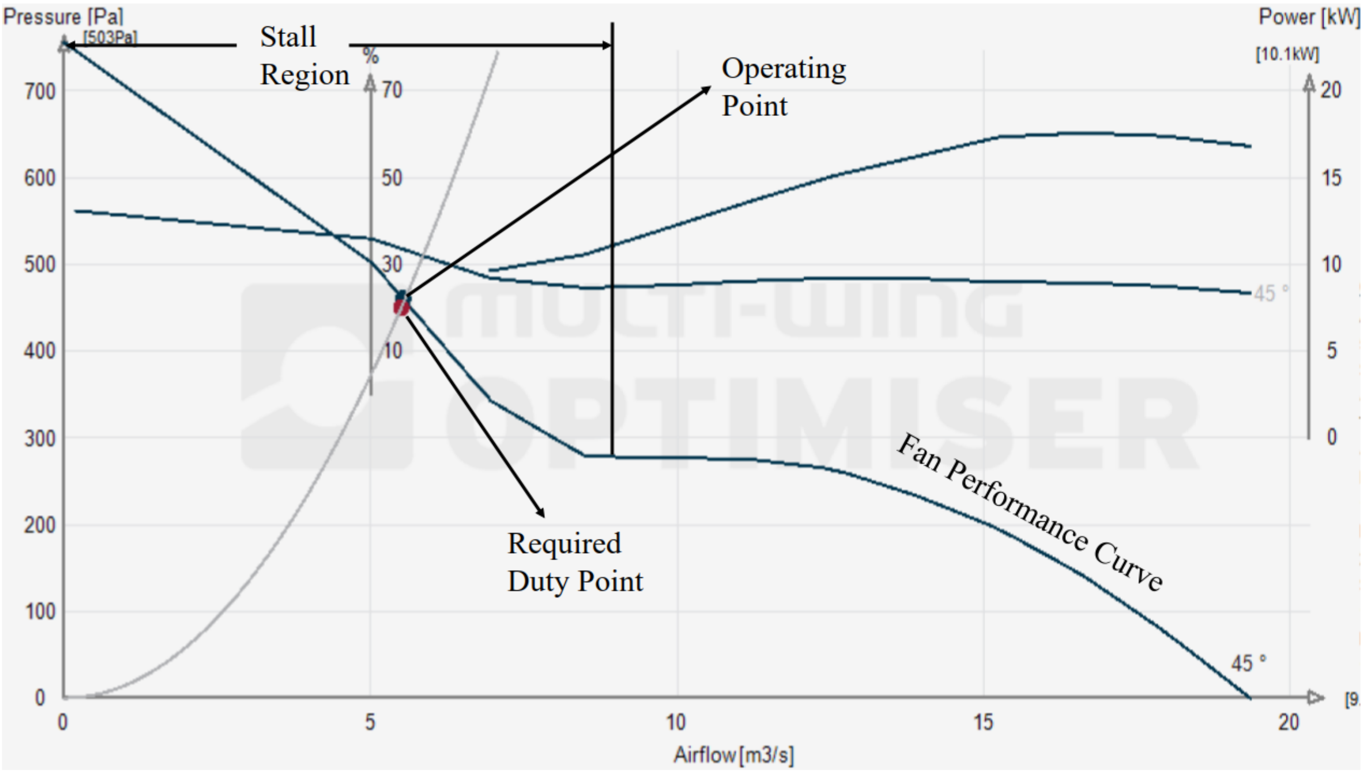

Figure 3. Fan performance curve (stalling).

the phase angle. Electrical motors generally used to drive the axial fans have an efficiency rating of IE1, IE2 and IE3 specified by IEC 60034-30 [9] which are selected depending on the application. The total fan efficiency (η_{total}) calculated based on the design of the room for which the axial fan is installed to serve:

$$\eta_{total} = \frac{a \times L_{room} \times B_{room} \times H_{room} \times (P + \frac{1}{2}\rho v^2)}{3600 \times \sqrt{n} V I cos\varphi} \quad (5)$$

Where a is the air changes per hour which depends of the application of the room, L_{room} is the length of the room, Broom is the breadth of the room, H_{room} is the height of the room, v is the flow velocity of the air, P is the static pressure of the air calculated based on the duct design.

3. STALLING IN AXIAL FANS

One of the main problems that could be suffered by the fans installed in the definitive ventilation systems is stalling, this being one of the major causes of concern for the operation contractors in charge of the ventilation systems of tunnels.

Stalling in axial fans is a phenomenon that can be compared with the situation experienced by aircraft wings where angle of incidence of the airflow is increased, the lift force increases first, but falls abruptly when a certain critical angle is exceeded [10].

In the case of the fan blades, severe separation of the flow lines along the profile of the blade occurs, and this induces a strong decrease in the increasing pressure given by the fan, impacting negatively on the fan efficiency.

The stalling of axial fans can be visualized easily with the aid of fan performance curves. A fan performance curve was generated for an axial fan to operate at 25 *°C*, airflow rate of 5.5 m^3/s, static pressure of 450 Pa, motor operating speed of 920 *RPM* using Multi-Wing™ Optimiser 10 software and shown in Fig. 3. A 1100 *mm* diameter, 6 blade fan with a pitch angle of 45° and a tip clearance of 1% was selected from the software to operate at point closer to the required duty point and the details of the operating point is shown in Table 2. The fan performance curve is generated with airflow rate on X-axis and pressure on Y-axis. The fan operating point is the point where the system resistance curve and fan performance curve meet and this point is selected as close as possible to the required duty point which was found to be operating in the stall region. The efficiency and power curves is also generated in the same workspace. The difference in the airflow pattern when fan operating under normal condition and stall condition can be seen in Fig. 4 and Fig. 5.

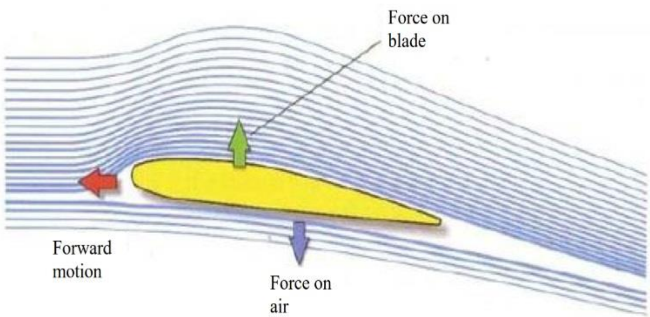

Figure 4. Blade operating in ideal condition [10].

Table 2. Operating point data of axial fan (stalling).

Parameter	Values
Tip speed (*m/s*)	53
Air velocity (*m/s*)	5.82
Torque (*N-m*)	113
Axial force (*N*)	457
Air flow (m^3/s)	5.53
Static pressure (*Pa*)	460
Dynamic pressure (*Pa*)	20.5
Total pressure (*Pa*)	480.5
Power (*KW*)	10.8
Efficiency (*%*)	24
Sound (*LW DB*)	104
Density (kg/m^3)	1.184
Blade centrifugal force (*N*)	6100
Hub/Diameter ratio	0.249

From Fig. 3 and Table. 1, it was observed that the efficiency of the fan fell drastically and the sound of the fan has increased enormously. This is because the fan is operated in the stall region. The system resistance curve also increases as the dust starts to form in the fan blades after some time of operation of the fan, this will cause an increase in the power of the motor and decrease the efficiency even more while causing further increase in sound of the fan and ultimately fracture of the impeller blades. The fan stalling is a situation that should always be avoided. Potential risk of serious damage due to blade fatigue are [10],

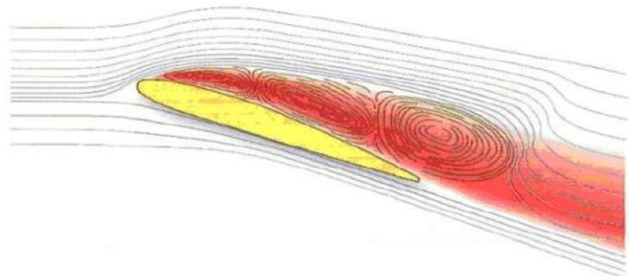

Figure 5. Blade operating in stall condition [10].

- Fan does not develop the design performance, air flow and pressure (Lower safety level of the system).
- Efficiency is lower and hence power consumption is higher.
- Dramatic increase in noise. Higher vibration levels than at normal operation.

3.1. Anti-stall rings

There are different methods to keep the fan operating in the stall mitigating the risk of blade rupture using anti-stall rings. The anti-stall rings consists in a chamber around the impeller. This chamber is fitted with internal guide vanes that catch the turbulent flow generated at the blade tips during the stall. The turbulent flow is stabilized and returned to the main volume flow which is circulating through the impeller [10]. The image of anti-stall rings showing the flow pattern and anti-stall chamber is shown in Fig. 6. This system could seem advantageous but once it is analyzed in detail, some disadvantages were found. The anti-stall ring system reduces the efficiency drastically, therefore the power consumption all along the fan design life will be higher than really required to deliver the design duty point [10].

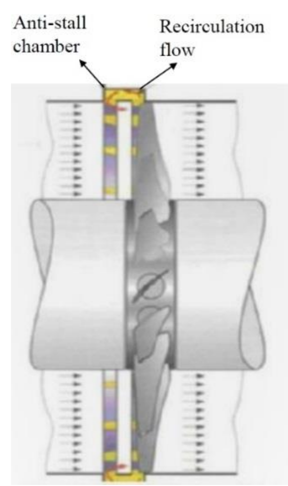

Figure 6. Anti-stall rings [10].

3.2. Vane axial fans

Vane axial fans are mostly used for high pressure ventilation due to its non-stalling advantages [11]. The vane axial fans has vanes or broad blades which are attached permanently to the fan casing and do not rotate with the motor or at any cost. The vanes are parallel to the direction of flow and are placed after the blades of the axial fan and before the motor. When the high pressure air flow coming from the blades, angle of incidence of the airflow is increased beyond the critical angle and the lift force increases first, but falls abruptly. Due to the presence of the vanes behind the blades, this stops the increased lift force to fall abruptly and rather smoothens the flow of the air and guides an efficient flow through the motor and the other end of axial fan. The image of vane axial fans showing its parts is shown in Fig. 7.

The number of vanes present in the axial fan depends on several factors including the pressure, air-flow rate, efficiency, blade number and blade angles. But the most important factor is the number of blades of the axial fan. The number of vanes are usually as close as the number of blades in the axial fan and are usually in odd numbers. For example for a 8 blade axial fan, the suitable number of vanes would be 7 or 9.

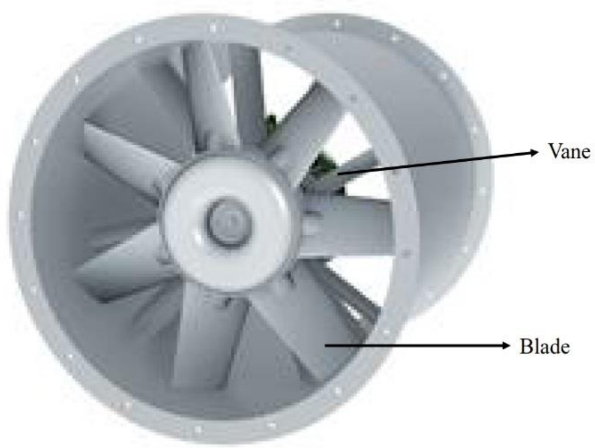

Figure 7. Vane axial fans [11].

3.3. Fan stall detection

Although installation of anti-stall rings in the fan reduce the chances of axial fan to operate in the stall region, it is impossible to detect if the fan accidentally happens to move towards the stalling region due to other reasons such as blade damage due to dust or particle collection. This can be detected and notified to the operator by installing a fan stall detection device or a system.

The vibration of the axial fan setup could be calculated in real time by installing sensors either along all the axis and all directions or along the axis and direction prone to high vibrations (depends on the design, setup and application of the fan). The vibration can be detected based on ISO 14694 [12] and suitable steps could be taken based on applications and also this could help in determining the change in the vibration level of the operating fans in real time and help in detecting stall.

Similar to vibration other huge change in fan operation that can be identified to detect stalling in axial fans is the sound or noise level. The sound of the axial fan is usually detected based on BS 848 standards [13] and verified based on the application of the fan. The real time data obtained for the sound could be used to detect whether is fan is getting close to the stall region or in the safe and ideal operation regions. An alarm could be set to stop the fan before starting to operate in the stall region of the curve.

Also increase in the input power or fall in the efficiency could be calculated easily by acquiring data over a certain time and safety alarm could be activated before the fan starts to operate in the stall region.

4. CONCLUSION

The laws behind the operation of fan and the method of selecting axial fan for the application based on the performance and analyzing the performance of axial fan is explained in the paper with the help of fan performance curves. The fan performance curve also showed the difference between stalling and ideal or normal operation condition of axial fans. The causes and effects of stalling in axial fans and possible methods to detect and overcome the stalling operating conditions by custom changing the design of the fan or introducing additional instruments to the axial fan assembly. Sometimes even reduction of additional pressure inducing components in the system could be eliminated to reduce the possibility of fan operating in stall. Also running the fan at lower speeds will reduce the stalling condition to occur in the axial fan.

Usage of addition components in the axial fan like anti-stall rings or vanes will reduce the efficiency of the fan. To overcome that an alternative method such as automatic or active adjusting of fan blade angle or pitch angle could be done. Due to the high reliability and energy friendliness of automatic blade pitch angle method, it should be preferred over introduction of anti-stall components which reduce the efficiency of the system.

Future works will be to conduct more research to reduce and eliminate the stalling in axial fans without compensating on the efficiency of the system. This can be done by changing profile of the blade angle and analyzing the performance and resistance to stalling. Also, to use a different form of fan other than axial fan which will eliminate stalling and at the same time will have equal performance as axial fans and will as cheap as possible to the axial fans.

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