How to improve energy efficiency of fans for air handling units

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Introduction

Fans use approximately 40% of all electricity in HVAC systems. Despite all the textbooks and handbooks, which describe the proper procedure for selection of fans, practice shows that fans in existing HVAC systems have very low total efficiency. In Sweden, ECiS AB (Energy Concept in Sweden) performed performance measurements of 767 fans in existing HVAC systems between the years 2005 and 2009. The average total efficiency[1] of all the fans was only 33% (**Figure 1**). Only a minor share of the fans had the efficiency in the range 50–60%, which is below the requirements of the EU regulation on efficiency of fans. It is most likely that the data from Sweden represent better than average practice in EU countries. It is evident that on average, fans have a huge energy improvement potential. Up to 50% of electricity for fans could be saved just by designing and installing more energy efficient fans and introducing better control strategies.

Best technology products

Today's best fans include an electric motor in brushless direct current (DC) technology, also known as electronically commutated motors (EC motor), with an integrated frequency converter for step-less load control and an impeller with low aerodynamic losses. Fans should be direct-driven, i.e. the fan impeller is directly mounted on the electric motor shaft. In the range of higher flows and pressures, the EC motors are not yet available. In that range the best available technology of motor is an AC electric motor of the efficiency rating IE3 with a variable frequency drive.

1 Total efficiency is measured by comparing the electric power consumption to the mechanical power of the fan.

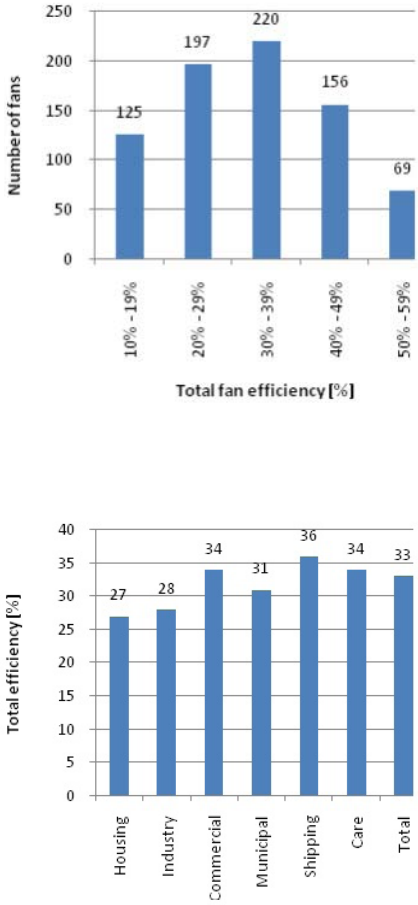


Figure 1. Results of total efficiency measurements of 779 fans in Sweden. Most of the fans had total efficiency between 30–39%. Efficiency is comparable in different building sectors (top), but the lowest in residential sector (bottom).

Requirements for the minimum energy efficiency of fans are presented in the mandatory European regulation on fans based on Ecodesign directive (EC, 2011). The fan regulation (**Figure 2**) only set limits for the lowest fan efficiency of the products sold or manufactured in EU. Already today in 2012, the products with better efficiencies than those required by the directive are available in the market.

According to the regulation on fans, the efficiency of fans must be always given as a total efficiency of the fan assembly, i.e. including losses of all the components of

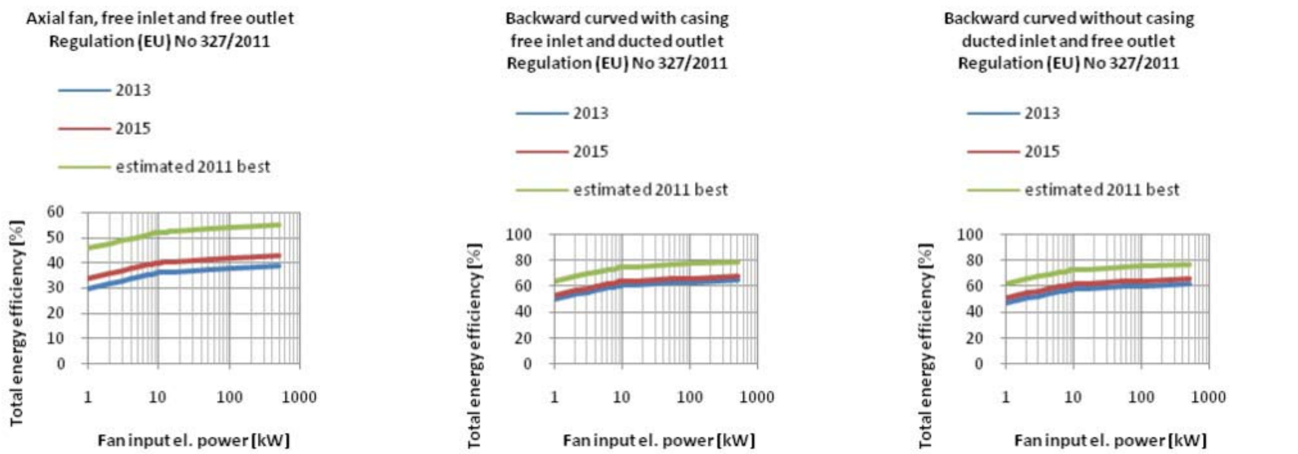
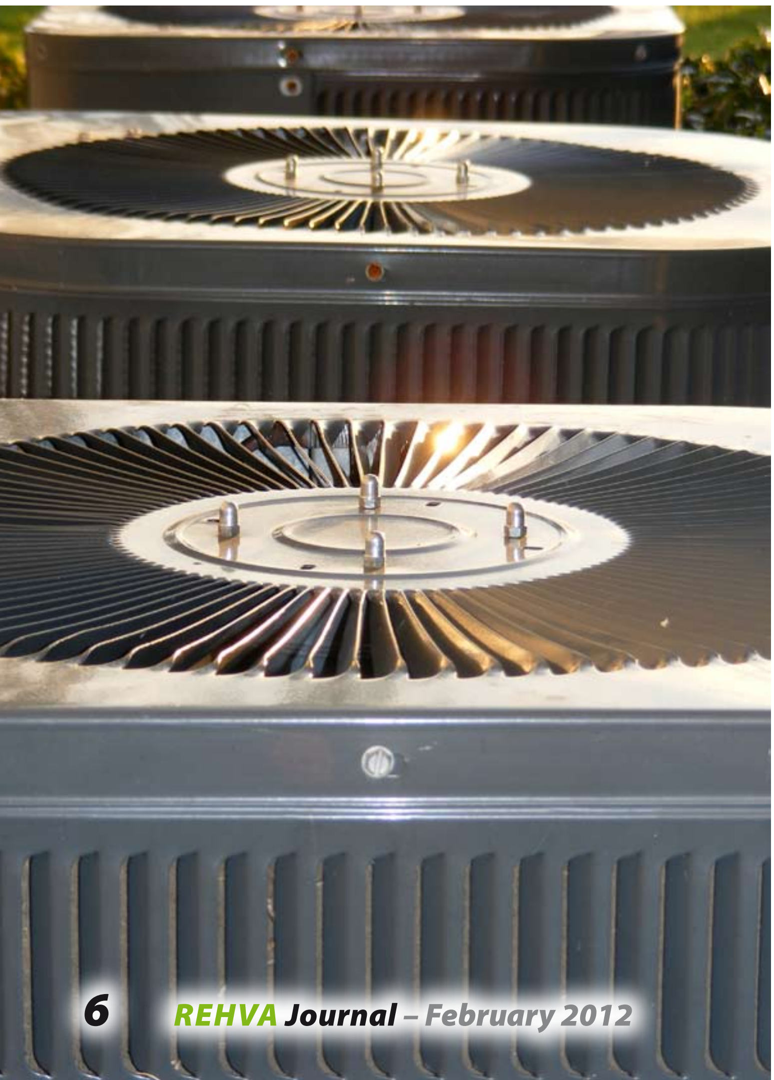


Figure 2. Target total efficiency of fans according to requirements of EU fan regulation. The charts indicate that the requirements for 2015 are stricter that the requirements for 2013.



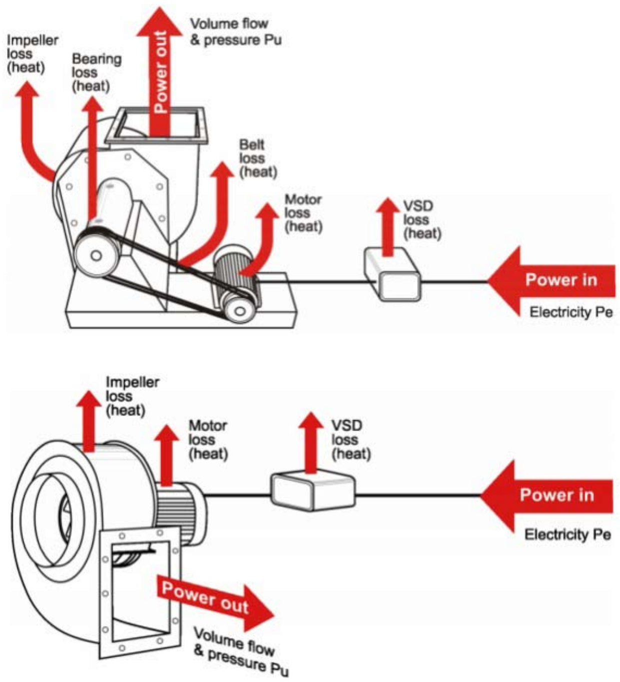


Figure 3. Breakdown of efficiency losses in fans. Belt-driven centrifugal fan (top). Direct-driven centrifugal fan (bottom). There are less steps of energy conversion in direct-driven fans, which makes them more efficient.

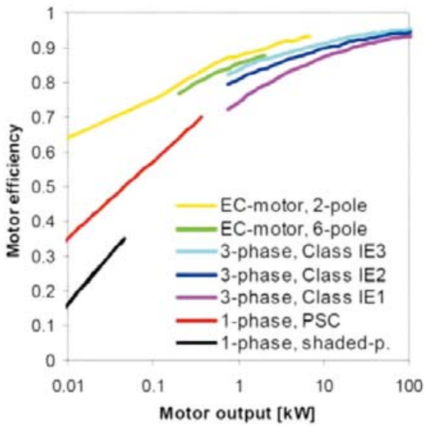


Figure 4. Efficiency of different motor types. EC motors have the highest efficiency, especially in the range of low motor output.

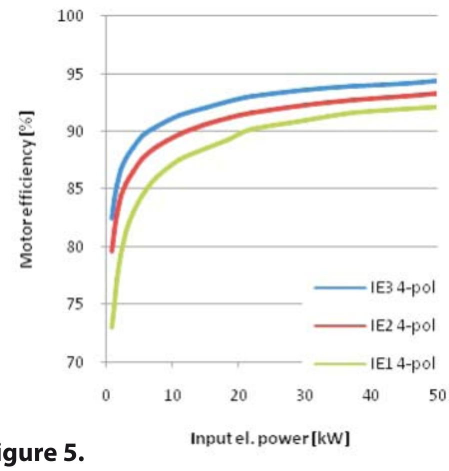


Figure 5. Efficiency classes of AC motors. IE3 class is the most stringent.

the assembly: the electric motor, the frequency converter, the belt drive (if given), the aerodynamic design, and the efficiency of the fan wheel.

The total efficiency is measured by comparing the electric power consumption to the mechanical power of the fan. The total efficiency of a fan is given as a product of all the partial efficiencies of the fan assembly:

$$\eta_{total} = \eta_{motor} \times \eta_{frequency\ converter} \times \eta_{belt\ gear} \times \eta_{dynamic\ loss} \times \eta_{fan\ wheel}$$

It is evident from the equation that in order to have a high total efficiency, all the efficiency of each component should be as high as possible. One weak link in the system can considerably reduce the efficiency of the entire fan assembly.

Motors (η_{motor}) are a crucial link in the efficiency chain of every fan. The best electric motors are brushless DC motors, otherwise known also as the EC motors because they are electronically commutated. The commutation is the application of current to motor phases for production of an optimum motor torque. With an electronic commutation, a motor can operate with e.g. 1.4 poles to find the right speed. The EC motors are currently available in the low power ranges but they are slowly penetrating into the market of the higher motor powers. The advantage of EC motors in comparison to an AC squirrel-cage induction motors is not as outstanding in the high power ranges, but it is the part-load efficiency that gives advantage the EC motor technology (**Figure 4**). The AC motors are classified into the three efficiency classes (**Figure 5**). As from 16th June 2011, motors of the class IE1 should not be sold on the market. Class IE4 (Super-Premium Efficiency) is expected to be officially defined in the future and will take into account also non-AC motors, like EC motors. The IE3 motors are already available on the market today, and some EC motors already fulfil the requirements of the proposed IE4 class.

Variable frequency drive – VFD ($\eta_{frequency\ converter}$) adjusts the speed of the electric motor according to the load, which results in a lower motor speed and an energy saving. The frequency drive itself has an efficiency rating that needs to be taken into account, because it depends on the nominal output and the partial load. The VFD losses are typically 2…5% at the nominal torque and speed, and 10…30% at 25% torque and speed.

Belt drive ($\eta_{belt\ gear}$) imposes considerable efficiency loss. The efficiency depends on the calculation of the belt gear, type of the belt, and the complete gear adjustment. Normally an expected efficiency of a belt drive is 90% at medium power (3–15 kW), but it can easily slip to 60–70% if the gear adjustment is incorrect. The newly designed AHUs must avoid belt-driven fans and should always use direct driven fans, whose transmission efficiency is 100%.

Aerodynamic design ($\eta_{dynamic\ loss}$). There is always a dynamic pressure loss in a fan. The size of the loss is dictated by the aerodynamics of the fan hood (or the AHU chamber in the case when a hood is not used). A well designed fan hood always gives less dynamic pressure loss than a chamber does.

Fan wheel ($\eta_{fan\ wheel}$). Depending on the type and design of the blades of the wheel, the efficiency will be different. The highest efficiency of up to 85% is achieved with backward curved blades (wheel type B). The forward type wheel is often used because it delivers greater airflow at smaller sizes of the wheel but at a cost of lower efficiency. In practice, fan wheels with backward curved blades should be used in AHUs.

Selection of a fan type and size

In selecting a fan for HVAC applications it is often found that several fans of different types and sizes provide the required performance. Considering that an engineer already defined the required performance of the fan (airflow requirement, pressure, size restrictions, ambient temperature and other special requirements), the first step in a selection process is to select fan type. If that the fan is to be installed into an AHU, the most common question is whether to select a centrifugal fan in casing or without casing. Centrifugal fan in casing usually has slightly higher efficiency than a fan without casing, but in an AHU it is more vulnerable to the installation effect, which reduces its efficiency. Therefore, for AHUs, a backward curved centrifugal fan without casing is the preferred option for majority of AHUs.

The next step is to select a fan motor. Because of the high efficiency, EC motors should be used whenever possible. Asynchronous AC motors with variable frequency drives as are the second option. When selecting the fan size, several sizes are usually able to provide the required airflow and pressure in the operating point. The size, where the operating point is closest to the best efficiency point and motor electrical input is the lowest, should be selected.

However, if the fan is going to operate in a variable flow system, and it is selected using "worst case" (design) operating point near the point of highest efficiency, such fan may operate at lower efficiency in the part load. Knowing that in variable flow systems fans operate most of the time with less than the "worst case" flow, such a fan will not have the lowest LCC. For variable flow cases, a selection should also consider efficiency and operating time in part-load range. The best efficiency point is by no means close to the 70% of maximum airflow, like suggested in EN 13779, but considerably varies with flow rate and pressure.

Another problem that will probably appear in fans, operating in variable flow but selected for the "worst case" flow is the low frequency noise problem (rumbling), which appears in part load range. This noise is difficult and costly to attenuate. It is better to select a fan size such that peak efficiency is achieved at the most common flow rate, but fan should still be able to deliver the "worst case" flow. During the short periods of maximum flow demand, the increased fan noise will have a higher frequency, which is easier to attenuate, using less expensive silencers.

Importance of good specification

Specification of a fan is an equally important step in a HVAC system design as the selection process. In many EU countries, designers only specify the needed airflow and pressure of a fan in an AHU assembly. The contractor, responsible for ventilation installations, orders equipment on the base of criteria, which is given in the project specification. If total fan efficiency or motor input power is not given in the specification, the contractor can choose any fan that fulfils the basic requirements which are given, i.e. usually airflow and external pressure. In such situation, the contractors select the fan with lowest first cost, which still fulfils the specified requirements. Due to the fact that one fan can cover a wide range of airflows and pressure, especially in combination with a variable frequency drive, it is relatively easy to choose a smaller (and cheaper) fan instead of a larger (and more expensive) fan. **Figure 6** shows how two different fans can operate at the same operating point but one fan has more than 20% lower total efficiency. The fan with the lower efficiency is two nominal sizes smaller and thus less expensive to install than the fan operating with the higher efficiency. The current EU fan regulation does not prevent such situation

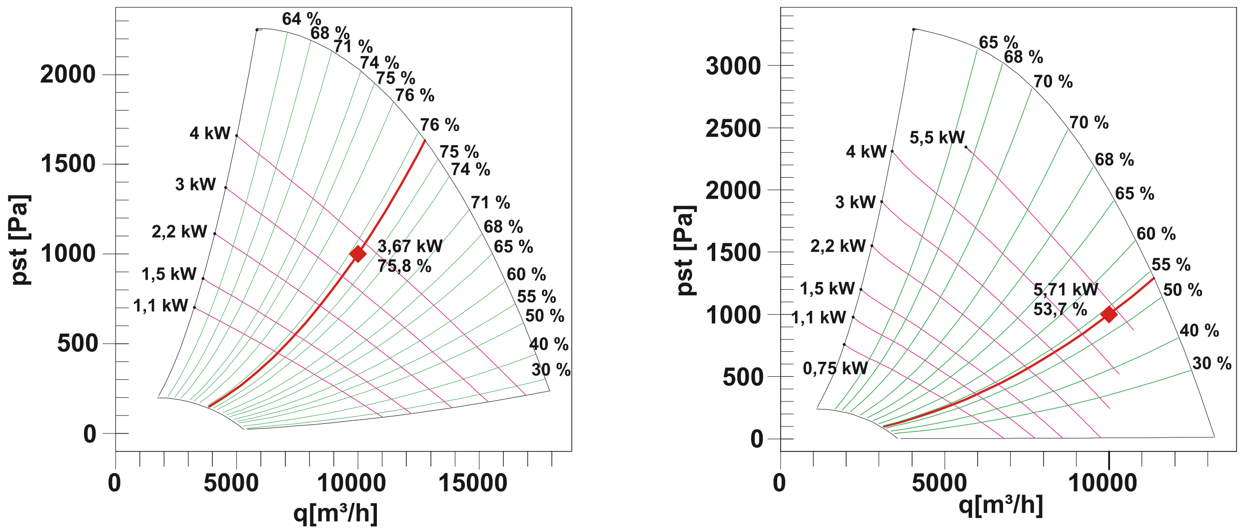


Figure 6. Comparison of two fans of different sizes operating at the same operating point but with different efficiency. The left diagram is nominal size 500 mm and the right one for a fan of nominal size 400 mm.

because it only limits the minimum total fan efficiency at the best efficiency point, which can be in practice far away from the real operating point, where efficiency is considerably lower.

If a contractor installs the fan from the **Figure 6** (right) into a system that operates 4000 hours per year, it will use 22 840 kWh of electricity. The electricity cost per year at a price of 0.10 €/kWh will be 2 284 €. If a contractor would install the more efficient fan (**Figure 6** left) it would use 14 680 kWh of electricity at a cost of 1 460 € per year. A specification of the more efficient fan would save the building owner or tenant 816 € per year or 12 240 € in 15 years. It is evident, that the installation of a ca. 500 € cheaper fan will cause considerably higher electricity use and costs to the owner or tenant.

In order to prevent such situation from occurring in practice, an engineer should always specify at least the following data; airflow, external pressure, total fan efficiency, grid power, air temperature rise. Besides that, voltage and type of motor should also be specified in order to eliminate the problem of compatibility between the fan end the electric network.

Control strategies

Control allows a fan to adapt airflow and/or pressure to the needs of a system. If we consider that the suggested SFP for new building is 2.0 kW/(m³/s) or 2.0 W/(l/s), for every litre of air per second that is moved around without purpose, 2 W of energy is wasted just for the transport its transport. The energy wasting can be several times higher if heating and cooling of the air are also considered.

Traditionally fans were usually not equipped with any of the control strategies and run at constant speed. Some belt driven fans have relied on gear mechanisms to change the fan speed and thus control air flow in steps. Other control types included pressure dampers, vane angle and bypass to control volume flow in the system. However, these systems are not energy efficient because the fan speed is not reduced.

According to the fan affinity laws, fan power is proportional to the third power of the ratio of fan speed:

$$P_{r2} = P_{r1} \times (n_2 / n_2)^3 \qquad \textbf{(Equation 1)}$$

where P_r is the mechanical input to the impeller and n is the fan rotational speed. That means, if fan rotation speed is reduced by 10%, the fan power will reduce 27%. The most efficient way to reduce fan energy use in variable flow is to reduce fan rotation speed, which can be most efficiently achieved with frequency controlled electric motors.

The biggest advantage of using speed-controlled fans is when they are used in variable air volume flow systems (VAV). Fan power can be considerably reduced in the part-load range if air volume flow is reduced:

$$P_{input} = \frac{p_{tot} \cdot \dot{V}}{\eta_{tot}} \qquad \textbf{(Equation 2)}$$

where P_{input} is electrical power absorbed by the motor from the grid (W), ptot is total pressure across fan (Pa), $\dot{V}$ is air volume flow (m³/s) and η_{tot} is total fan efficiency (%).

The relation in **Equation 2** between fan input power and air volume flow is linear if total pressure and efficiency are constant. In practice, total fan efficiency and pressure vary if volume flow is changing. For a fixed system, it may be said that the system resistance (equal to the pressure required to pass a given volume of air through the system) will vary as the square of the volume flow rate, i.e. $p_f \propto q_v^2$. Therefore, to double the airflow, a pressure four times greater is required from the fan. This is only true for a static system and constant air density. If the resistance of the system can be altered, e.g. by closure of a damper, then the above laws do not apply and the relation between pressure and flow is much more complicated. The efficiency in **Equation 2** is also reduced by decreasing airflow due to the part-load losses in electric motor and variable speed drive (**Figure 7**). The decrease in efficiency is greater in the case of AC motor controlled by a VFD because they have lower part load efficiencies than EC motors. This Figure also suggests that fan should not be sized with a reserve on air volume flow side. In contrast to reserve on the pressure side, reducing volume flow does considerably affect efficiency of a fan.

All new fans are suggested to be speed controlled by using EC motors, which have integrated VFD, or AC motors with an external VFD. On the first sight it may seem that a VFD in addition to an AC motor is useless or even unfavourable due to its losses in constant air volume flow systems (CAV). However, pressure conditions vary in every ventilation system which is equipped with filters, because filter pressure drop changes through time as filters get soiled. Buildings are rarely static systems. There may be significant alterations in the function or capacity of ventilation systems, which often require reset of fan operation point. Another advantage of variable frequency drives is that they allow for small pressure reserve on the fan size during the design phase. If pressure reserve is used when selecting single speed fan but the resistance of a real system is lower, a fan will operate at a higher flow rate and thus waste energy. If a variable EC motor or VFD is used in such situation, it will allow for changes of the fan speed and thus pressure of fan – air volume flow can easily be adapted to the designed air flow and energy waste is avoided. An example in **Figure 8** shows that the efficiency does not decrease dramatically when the static pressure of an EC fan is decreased (in case when a fan was selected with some pressure reserve).

Conclusion

Fans are one of the major electricity users in HVAC systems. In order to achieve good efficiency of fans once they are installed, it is not enough just to select best products on the market, but also to change design and

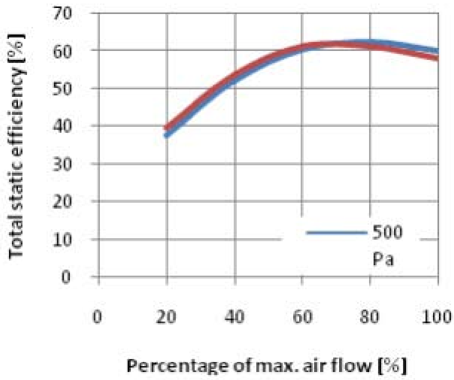


Figure 7. Total static fan efficiency of a backward curved EC fan without casing (100% = 10 000 m³/h). By reducing the airflow, efficiency first increases because the 100% operating point was selected on the right side of the best efficiency point. (Calculated with Ziehl-Abbeg fan selector)

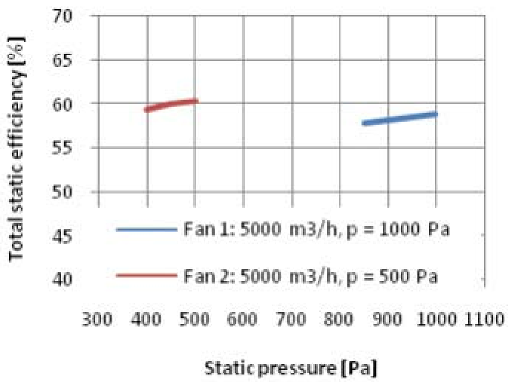


Figure 8. Total static efficiency decrease of the same fan as on the left chart due to the lower operational static pressure (Calculated with Ziehl-Abbeg fan selector).

and selection procedure to fit such technology. With increased number of variable air volume systems entering the market, old principles of design that are embeded in minds of engineers have to be changed and alligned with the development of technology.

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