Koc. J. Sci. Eng., 6(1): (2023) 26-34 https://doi.org/10.34088/kojose.1134625

Kocaeli University

Kocaeli Journal of Science and Engineering

http://dergipark.org.tr/kojose

Energy Efficiency Research In Fans and Experimental Investigation of the Effect of Motor Frequency

Selman ÇAĞMAN [1, *], Aşkın YILDIZ [2], Alpaslan GÜVEN [3], Ümit ÜNVER [4]

[1] *Department of Energy Systems Engineering, Kocaeli University, Kocaeli, 41001, Turkey,* ***ORCID:*** *0000-0001-9214-7306*
[2] *Department of Energy Systems Engineering, Yalova University, Yalova, 77200, Turkey,* ***ORCID:*** *0000-0002-2409-2136*
[3] *Chamber of Mechanical Engineers Kocaeli Branch, Kocaeli, Turkey,* ***ORCID:*** *0000-0003-1623-1682*
[4] *Department of Energy Systems Engineering, Yalova University, Yalova, 77200, Turkey,* ***ORCID:*** *0000-0002-6968-6181*

Article Info

Research paper

Received : *June 23, 2022*
Accepted : *September 20, 2022*

Keywords

Energy Efficiency
Variable Speed Drive,
Fan Efficiency
Sustainability
Industrial Energy Efficiency

Abstract

Fans are widely used in the industry, and they have a potential in energy efficiency studies. The aim of this paper is to introduce the fan systems and the energy efficiency studies on fan systems. The parameters like flow rate, active power, fluid power and pressure difference were explained and used in the investigations together with the experimental data obtained in the energy audits. The effects of air temperature, velocity, and frequency parameters on fan efficiency were studied. The results showed that the temperature increment negatively affects the fan efficiency, and 1 m/s increase in the air velocity reduces the system efficiency by % 1,088. Finally, according to achievements of this paper, reducing the frequency with Variable Speed Drive means less fan power and Variable Speed Drive provides energy-savings but not energy efficiency.

1. Introduction

Today in developed countries, there is a tendency to reduce greenhouse gas emissions due to global warming and other environmental problems. For this goal, a global energy policy is determined that indicates a preference for renewable energy sources over fossil fuels such as solar, wind and so on [1, 2]. However, renewable energy systems are low efficient and expensive compared to conventional systems [3]. At this point, energy efficiency appears to be a desirable alternative as it is accepted "the cheapest renewable energy source". In Energy Efficiency Law No: 5627 in Turkey, energy efficiency is defined as efficient use of energy, prevention of waste, reducing the burden of energy costs on the economy, and increasing efficiency to protect the environment while using energy resources [4]. Energy efficiency is extremely important also in reducing dependency on imported energy [5, 6, 7].

The energy efficiency potential of Turkey is stated as 15%, approximately 33 million Tons of Oil Equivalent (TOE), against 222 million TOE primary energy demand for 2020 in a report conducted by the General Directorate of Renewable Energy (YEGM) [8]. The breakdown of energy saving potential of Turkey is 30% in residences [9], 20% in industry, and 15% in transportation [10]. 40% of Turkey's total industrial electricity consumption is diversed like: 22% fan, 29% pump, 7% compressor and 42% other utilities [11].

Approximately 65-70% of the electrical energy is consumed by electric motors in the industry, where 20% of this energy is consumed by the fans [11]. According to the data provided by the Ministry of Energy and Natural Resources (MENR), there are some ways to avoid this excessive energy consumption by fans. There is an energy saving potential of 2-8% through preventing losses and leakages in fans, 70% by using high-efficiency fans, and 50% in Variable Speed Drive (VSD) application [12].

The ratio of the energy efficiency potential of fan motors in the total energy efficiency potential in the

[*] Corresponding Author: selmancagman@gmail.com

industry is 2,60%. Although control and drivers have a very important place in high-efficiency fan systems [13], system efficiency does not simply mean a highly efficient motor. The entire system components have impact on the efficiency, such as design, sizing, ducts, and dampers etc [14]. An efficient fan system requires accurate investment, maintenance, and operation. Decision makers often consider initial investment cost but not operating or maintenance costs. They purchase the cheapest fan and the cheapest fan is generally the less efficient one. Nevertheless, the operational cost difference between these two fans systems; the cheapest and the efficient, is much higher than the initial investment cost difference throughout the fan's life span [15].

Improvements in the applications of the control systems affect energy efficiency of the fan systems positively. Wang modeled a proportional damper for a coal power plant and reduced power consumption by 15% [16]. In another study, conventional and novel damper control systems are experimentally compared. The authors claimed that they have achieved 20% reduction in the fan power [17]. The conventional method with Rule-Based Fuzzy Control Method (RBFCM) in air conditioning (AC) systems are investigated in an experimental study, and RBFCM provides 33% energy savings [18]. Sjöström et al. have developed a control strategy considering airflow set values, the differential pressure difference etc for fans operating in the mining industry. The results show a 40% reduction in energy consumption and a 15% reduction in the demand of air inflow to the mine [19].

Correcting installation and maintenance problems within a production facility can also save energy. The fan efficiency can be boosted up to 80% with a proper installation [20]. Doğan says, power consumption decreases 5% with the replacement of the inefficient fan blades with efficient ones and the payback period of this investment is 2 or 3 years [10]. A research carried out in a paint shop of automobile factory states that 5 fans were replaced with new efficient ones, and the payback time of this investment was 1,69 years [21].

When a VSD is used in a 3,72 kW fan motor, if the speed is reduced by 30%, there is a 44% energy saving with an annual cost advantage of $ 543. They proved that as speed decreases, energy saving and cost advantage increase [22]. As a result of long-term performance analysis in Heating, Ventilation, and Air Conditioning (HVAC) systems, with the application of VSD in a public building in Italy, an annual energy saving of 38,9% was achieved [23]. Instead of adjusting the fan flow rate with throttling inlet vane, a VSD does the same effect with less energy consumption. According to this study, VSD energy saves vs vane throttling (VT) are as following; 37% VSD vs 20% VT, % 51 VSD vs 30% VT, 61% VSD vs 40% VT, and 61% VSD vs 50% VT [24]. Another study states that energy consumption of 2.679 kWh decreases to 2.226 kWh in a power plant by using a VSD instead of throttling fans with a suction vane/flap [25]. Similarly, in an iron and steel factory, 960 TOE/year is saved by using VSD instead of flap control of 2.500 kW fan and the payback period of VSD investment is 0,5 years [10].

The energy consumptions of a forced draft fan (FDF) and a primary air fan (PAF) runned for 1 year were analyzed. The consumption without VSD was 25.645.627 kWh, and after utilization of VSD the consumption decreased to 17.412.053 kWh with a saving ratio of 32,1% [26]. Nel et al. have conducted an energy efficiency study of high-capacity power fans operating in a mine in South Africa. This study shows that if a VSD is used in fan motors, the return of investment is 9 months, and it causes a 53% reduction in greenhouse gas [27]. The VSD application to the fan coil system in the two library reading rooms has provided annual energy saving of 38,9% compared to the same system at a constant flow rate [28]. The VSD and variable pitch (VP) fan control methods were applied to air handling units with axial fans in a hospital in Seoul, South Korea. They reported that the VSD is suitable for an axial fan driven with low output per year while VP is an energy-efficient control method when high output is frequent. VSD reduces approximately 20–30% overall energy consumption of the ventilation system [29]. VSD also provides energy-saving rather than other conventional control techniques in the parallel fan system [30]. As can be seen from literature, fan usage in the industry with or without VSD is very common. Fans are widely used in AC systems, smoke evacuation fire systems, ventilation systems, the exhaust of drying and painting booths, vacuum systems, cooling towers, and combustion processes so the energy efficiency potential of fans is quite high. The flow control system with VSD is the best among all of the flow control systems (outlet damper control, inlet guide vane control eddy current control, and VSD) used in the industry. One of the most well known control methodology reducing energy consumption is VSD [31].

Fan systems have an important role in reducing the amount of energy consumed, energy cost and carbon emissions. The energy efficiency potential of the fans, the factors affecting this potential efficiency and the importance of the use of VSD are presented within this paper. Besides the effect of VSDs on efficiency, other energy efficiency possibilities in fans have also been investigated. The data obtained from a detailed energy audit completed within a factory that has actively operating 13 fans.

An energy audit targets to find saving opportunities. The data obtained from an ongoing system makes the study more valuable. In its normal conditions, fans are measured with calibrated measurement devices. There are not enough resources and studies about energy savings by using VSDs or other techniques in fan applications. This paper specifically offers valuable information to engineers in the field.

Accordingly, the paper is structured as follows. The method and the data are described in section 2. The results of the calculations are provided in section 3. Section 4 includes the conclusions and the references.

2. Material and Method

2.1. Fan System Description

13 operating fans were examined within the scope of the study including dust extraction (6 pieces), dust transfer (2 pieces), chimney (2 pieces), cooling (1 piece), drying (1 piece), material transfer (1 piece) in various factories. The power of the measured fans varies between 15 and 326 kW. Examining different kinds of fans with varying capacities and sizes provides opportunity to evaluate and compare the effect of sizes on tbe characteristic performance. The relationships between flow rate and active/fluid power, differential pressure and fluid power are interpreted with the obtained measurements. In this paper, measurements were also taken into account to examine the effects of frequency, as one of the most important fan characteristic parameters of fan performance.

Since it would not be appropriate to compare the frequencies of different fans, the measurements were repeated and interpreted by operating a single fan at different frequencies. In order to examine the variable frequency situation, the analysed fan details are given in Table 1.

In this study, flow rate, pressure (inlet and outlet), temperature, engine speed and energy consumption values were measured. Air velocity, flow rate and inlet-outlet pressures were measured with a pitot tube anemometer, air inlet and outlet temperatures were measured with a thermometer, engine speed was measured with by tachometer. Furthermore, electric current, voltage, power, and power factor were measured with an energy analyzer. The measurement devices are given in Table 2.

Table 1. Fan-motor system data

Fan information		Electric motor information	
Brand	New York	Brand	Reliance Electric
Type	Plug Fan	Type	OMAN53348
Flow (m^3/h)	84.950	Current (A)	73,9 A
Flow (kg/s)	28,32	Voltage (V)	380 V
Power (kW)	53,76 HP	Power (kW)	50 HP
Head (Pa)	1,12 kPa	Frequency (Hz)	50
Revolution (rpm)	1.006	Revolution (rpm)	1.475

Table 2. Measurement devices and their characteristics

Pitot tube anemometer		***Thermometer***	
Brand and type	Fluke 922	Brand and type	Testo 830
Measuring range (m/s)	0,5/80	Measuring range (sec)	1,75
Working temperature (°C)	0-50	Working temperature (°C)	-50/500
Max humidity	%90 RH		
Energy analyzer		***Tachometer***	
Brand and type	Fluke 435	Brand and type	Testo 470
Measuring range (mm)	1-1000 V rms	Measuring range (RPM)	1/99999
AC current probe Brand	Fluke /I 430 Flex	Measurement method	infrared / contact
Current Probe Measurement Range	3000 A	Measuring precision	±0,2%
Test Conductors	TLS430 1000 V		

The duct dimensions vary according to the place where the fan is used. For more detailed information and evaluation, please refer to [32], [33]. Measurements were made in the process conditions of the factories. The measured values were recorded at a steady state when the values remained constant. The velocity measurements were taken from the center of the duct after a distance of 5 times the duct diameter from the fan outlet. The measurements were repeated for 2 different frequency values, 40,5 Hz and 45,4 Hz, to be able to examine the effect of frequency. A schematic diagram of the measurement procedure of audit is given in Figure 1.

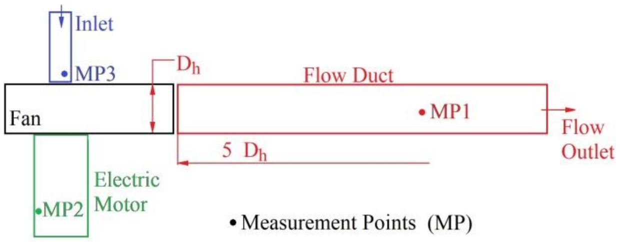

Figure 1. Schematic illustration of metering in energy efficiency audits

The temperature (T), pressure (P) and Velocity (V) parameters were measured from the duct during an energy audit measurement. If the inlet of the system was atmospheric, no measurement was taken. Atmospheric inlet conditions were used in the calculations. But if the air was sucked, then the temperature and pressure are measured. In addition, the speed of the electric motor, electric current (I) and potential (V) and power factor (PF) was measured. In energy efficiency audits, measurements are generally taken about 5 D_h from the entrance of the channels. This depends on the availability of the place of the measurement. It must be noted that, since the Re >>2.300 in the systems, the fully developed flow could be provided closer to the inlet. The measured parameters at the measurement points were shown in Table 3.

Table 3. Measured parameters at the measurement points

Measuring Point	Parameter	Unit
MP 1	T	C
	P	kPa
	V	m/s
MP 2	I	A
	V'	V
	S	Rpm
	PF	-
MP 3	P	kPa
	T	C

2.2. Fan Equations

Analyses were performed by using equations for fans known as the Fan Affinity Laws. The equations expressed as the Fan Laws are considering volumetric flow rate (Q), fan pressure P (fan total pressure P_{tf} or fan static pressure P_{sf}) and effective (shaft) power N_e. The equations are given as;

$$Q_2 = \left(\frac{n_2}{n_1}\right) \cdot Q_1 \tag{1}$$

$$P_{t_2} = P_{t_1} \left(\frac{n_2}{n_1}\right)^3 \frac{\rho_2}{\rho_1} \tag{2}$$

The Head can be calculated by;

$$\mathrm{H} = \mathrm{P_o} - \mathrm{P_i} \tag{3}$$

Here, H (kPa) is the Head in pressure difference, P_o and P_i (kPa) is the air pressure at the fan outlet and inlet. The theoretical power for the required pressure (kW) is calculated by:

$$P_t = \frac{Q \cdot H}{60} \tag{4}$$

The flow rate is calculated with Equation (5) by using velocity, pressure and temperature measured in the channel.

$$Q = V \cdot A \cdot \frac{101{,}3 + P_o}{101{,}3} \cdot \frac{273}{273 + T_o} \tag{5}$$

In this equation V (m/s) is the air velocity flowing through the cross-sectional area A (m^2). T_i and T_o are the air temperature at the fan inlet and outlet in (°C). Please note that Equation (5) considers the variation of fluid density with respect to temperature. The expression related to P_o and T_o in the last part of the equation is normalization with respect to 1 atm and 0 °C. After measuring the electric power P (kW), the specific power consumption (kW/Nm^3) value is calculated by:

$$St = \frac{P}{Q} \tag{6}$$

Finally, the ratio of theoretical compression power to measured power that is the system efficiency is calculated by [27], [32], [34].

$$\eta = \frac{P_t}{P} \tag{7}$$

And Reynolds number can be calculated by;

$$Re = \frac{V.D_h}{\nu} \tag{8}$$

Where υ is the kinematic viscosity and D_h is the hydrolic diameter. By utilizing dimensionless Re number, variation in the size of fan systems is considered because Re includes the size of the system, since the equation employs D_h as the size of the system. Similarly, the temeperature variations of the fluid are also included in Re since $\upsilon = \mu/\rho$, where density (ρ) of the fluid depends on the temperature of the fluid. By utilizing a dimensionless number, the analyses become free of system size and operating parameters.

3. Results and Discussion

Fan power is the amount of electric power required to transport a desired air volume. The required power depends on the flow rate, the resistance of the flow area and efficiency of fan system. Energy consumption reduces at lower airflow rates. Moreover, the fan airpower is equivalent to the product of the intake volumetric airflow rate, total pressure difference across the fan and the power frequency [33], [35], [36]. Figure 2 shows the relationship between flow rate and fluid power and active power. As seen in the figure, flow rate is directly proportional to the fluid power, and active power. As the flow rate increases, both fluid power and active power increase. Figure 2 indicates that active power and fluid power differs according to flow rate. This difference stems from the efficiency of the fan and motor. Since the sizes of each fan system are different, the difference between active power and fluid power is also variable. Fans, turbo compressors and turbo pumps are called volumetric machines. The reason why they are called volumetric is that the volume between the blades that impuls the fluid does not change. Increasing volumetric flow rate means higher fluid power and parallel to this, more active power consumption according to Equation (4).

Figure 2 also proves that Equation (4) provides the same results in practice. Trend lines added to fluid power and active power data, which have different slopes. As it can be seen in the figure, the slope of the active power line is higher. Similar to specific power consumption, both lines illustrates the required energy to impuls the unit volume of the fluid in terms of $kW/m^3/s = kJ/m^3$. In this case, the highness of the slope of the active power line can be interpreted that as more powerful system is used, the fan and motor efficiencies decrease.

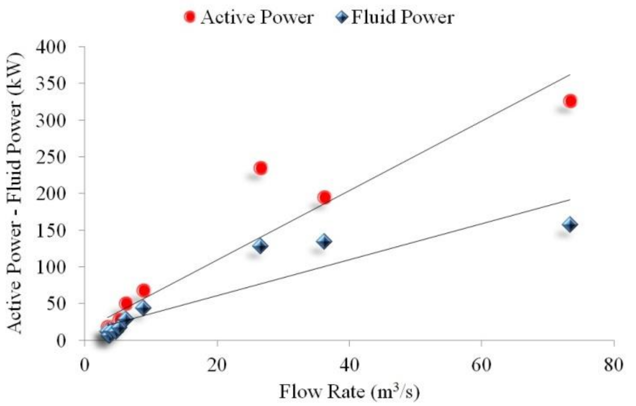

Figure 2. Relationship between Flow - Active Power - Fluid Power

Figure 3 depicts the effect of differantial pressure difference on fluid power. In order to avoid errors because of the size and purposes of the system, identical fans are considered in the analysis. The figure shows the directly proportional relationship between differential pressure and fluid power. The differential pressure specified here is the head calculated in Equation (3). Therefore, the slope in Figure 3 stems from the power expression calculated by Equation (4). The slope of the line given in this graph provides the volumetric flow in (m^3/s). The fluid power boosts with the increase of the differential pressure in the case of a constant volume flow. It can be evaluated in terms of energy efficiency as, as higher differential pressure is required, the larger the fan is needed. This cause more friction losses meaning less efficient system. In this case, the most appropriate choice would be utilizing the smallest fan to provide the same flow rate with the lowest energy.

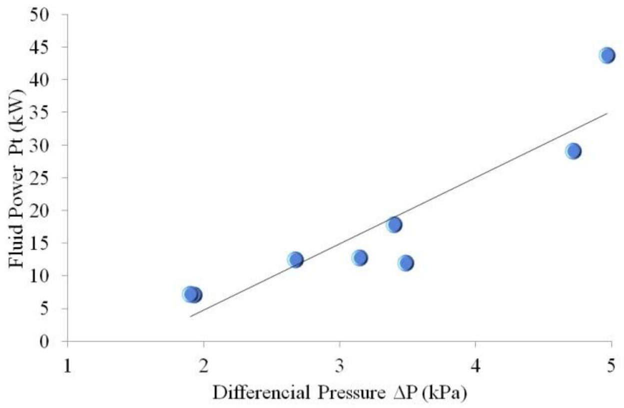

Figure 3. Relationship between Differential Pressure-Fluid Power

In Figure 4, temperature and fan efficiency relationships are provided for the examined fans. Fan efficiency tends to decrease with the increasing temperature. If the temperature of the air entering the blades increases, its density increases. If the density increases, the mass flow rate of the air within the same volume decreases. In this case, the efficiency decreases as less mass flow is directed to the outlet ducts with the same energy. Such applications are frequently encountered in chimney fans. In such cases, placing the fan at the highest point where the flue gases are the coldest is recommended to ensure the highest efficiency.

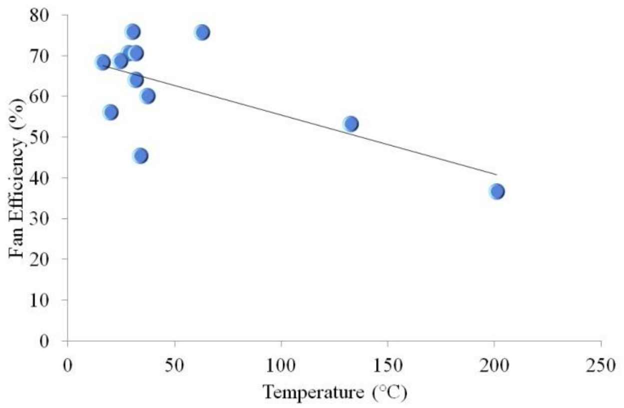

Figure 4. Temperature - Fan Efficiency relationship

The relationship between Re and the fan efficiency is provided in Figure 5. As it is seen from Figure 5, Re>>2.300, that means very high turbulence exists in the flow area. This is an obviously expected result since the flow field is in downstream of an industrial fan. The figure depicts that the system efficiency decreases as Re increases. Because, friction losses increase with the speed and fan must compensate the increased losses. Therefore, it is recommended to transfer the air with the least possible velocity through the ducts [37].

In Figure 5, an inverse relationship is seen between Re and fan efficiency. The relationship can be represented by a V-η coefficient that is –1,088 (%/m/sn). This coefficient can be considered as the effect of fluid velocity to the fan efficiency.

In duct systems, sharp elbows create turbulent areas resulting vortexes that prevent the fluid flow. In other words, sharp turns such as 90° miter bends create counter pressure. Utilizing the fan system for suction may be more efficient instead of pressurizing the flow. In such cases, making the air duct larger to reduce the speed may be recommnded. However, the larger the channel, the greater the initial investment cost would be. Therefore, size selection should be performed considering the initial investment and operational costs for the system's life span.

The measurements of frequency evaluation are given in Table 4. Power factor is measured 0,82 for both frequency values. It is observed that a 12% reduction in frequency (from 45,4 Hz to 40,5 Hz) results in 11,8% decrease in the speed (rpm). Frequency and speed ratios have decreased approximately at the same rate. Flow rate decreases by 4,58% from 17,72 Nm^3/s to 16,94 Nm^3/s. Power demand decreases 37,7% from 32,9 kW to 23,9 kW. A significant energy saving has been achieved in the required flow rate by reducing the fan operating speed. This example shows the difference in the energy efficiency of operating at suitable speeds in fans. Significant energy savings can be made with frequency/speed adjustment according to operating conditions instead of 50 Hz grid frequency.

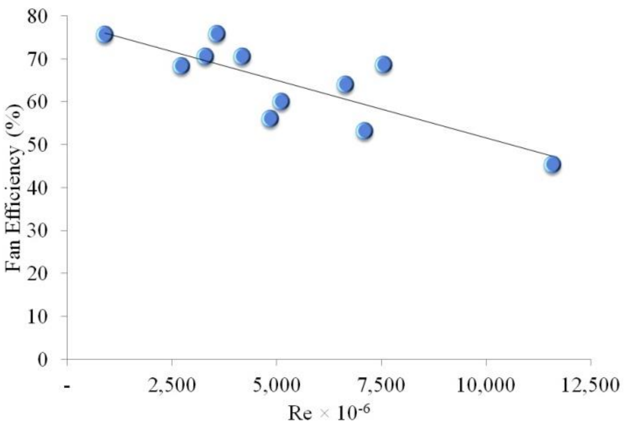

Figure 5. Air Velocity-Fan efficiency relationship

Table 4. Measurement results

Frequency	Revolution	Av. Speed	Power	Input Pressure	Output Pressure	Pressure Difference	Input Temp.	Output Temp.
F		V	P	Pin	Pout	H	Tin	Tout
Hz	rpm	m/s	kW	kPa	kPa	kPa	°C	°C
45,4	1335	10,71	32,9	-0,35	0,28	0,63	23	24,8
40,5	1197	10,18	23,9	-0,284	0,2	0,484	21,8	22,8

Table 5 shows the frequency of specific energy consumption and total efficiency values. As can be seen from Table 5, efficiencies at two frequency values are very close. However, while the specific energy consumption at 45,4 Hz is calculated as 1,86 kPa, 1,41 kPa is obtained at 40,5 Hz. With the 12% decrease in frequency, the specific energy consumption decreases by 24%. This result is proportional to reference [32] and agrees with reference [38].

Table 5. Variation of fan system efficiency depending on the frequency

	Airflow	Theoretical Power	Specific energy consumption	Total Efficiency
f	Q	P_t	P/Q	η
Hz	Nm³/s	kW	kPa	%
45,4	17,72	12,15	1,86	36,92
40,5	16,94	8,87	1,41	37,11
*40,5	17,3	8,81	1,5	36,85

*First two lines are experimental results, and the third line is based on the theoretical calculation.

In Table 5, flow rate, power, specific energy consumption, and total efficiency values calculated theoretically according to the fan laws are given in the bottom line. The most important side of this table is the effect of frequency on fan efficiency. Reduction of the frequency reduces the consumed power since it decreases the motor revolution speed. At low speeds, the motor consumes less energy. In this case, the power conducted to the air reduces proportionally. Thus, the efficiency, which is the ratio of these two magnitudes, does not change. The resulting remark of this study is contrary to the literature that the frequency does not have any effect on the fan efficiency.

In Table 5, there are differences between the values obtained by analytical calculation. For example, while the flow rate calculated with Eq. (1) is 17,3 Nm^3/s, the measured flow rate is 16,94 Nm^3/s. The experimental value is 5,67% lower than the value calculated according to the fan laws. The reason for this is that Equation (1) states that there is a linear proportion between revolution and flow rates. If the measured air duct were a straight and short duct, then perhaps the value calculated with the help of Equation (1) could be obtained. However, air ducts usually have sharp turns and elbows that cause counter pressure, depending on the structure of the installation. The counter-pressure decreases if the speed is decreased. Equation (1) does not include the reduction in counter pressure, it only considers the speed of rotation. As a result, the flow rate measured in the operational air duct is theoretically less than the flow calculated for a duct without losses and counter pressures. However, it is not the case for the power calculated by Equation (2). The power calculated by using the velocity measured from the air duct, theoretically represents the required power in an ideal installation without irreversibilities. That means, both are lossless-theoretical power. Therefore, they are calculated with a small difference of 0,67%.

Fans should be designed to meet the required flow rate. Unnecessarily high flow rates should be avoided because higher mass/volumetric flows require more energy. The smallest possible fan should be selected. Discharge temperatures should be chosen as low as possible. If possible, hot gases should be cooled with a heat exchanger before it enters the fan. According to the fan law, efficiency is calculated as the ratio of required power to measured power. Therefore, the calculated efficiencies are very close with a negligible difference. However, the variation of the flow rate is reflected in the specific energy consumption. The specific energy consumption calculated according to the fan laws and the experimental data are achieved 1,5, and 1,41 respectively. The difference is due to the irreversibilities such as pressure losses, friction losses, and the leaks etc. It is understood that a correction factor should be used in calculations to be made according to the fan laws in fan systems.

In the case of a variable flow system, a VSD driven high-capacity fan, can be expensive and/or inefficient. High-capacity fans can enter the unstable state easier at low flow rates. If there is a variable flow rate requirement, the use of multiple fans instead of a VSD driven high-capacity fan may be more appropriate. But this selection requires more space for multiple fans installation. Therefore, fan capacity should be calculated carefully as it affects the initial investment cost.

4. Conclusions

Energy efficiency should be treated as a new renewable energy source to reduce dependency on imported energy. Fan systems have a huge energy efficiency, reducing the energy consumption, energy cost and carbon emissions potential in the industry. Generally decision makers prefer the cheapest fan and unfortunately the cheapest fans operate with a low efficiency. Sometimes larger fan capacities lead to a less efficient system. In this study, the energy efficiency potentials of the fans are highlighted. One of the most important parameters, utilization of VSD in fan systems, is presented by adding a case study.

There is an energy savings potential between 15% and 40% by enhancing control strategies. In fan systems, particular attention should be paid to productivity in design, assembly, operation, and maintenance with a holistic approach. In this paper, it is concluded that,

I-The air temperature and velocity have a negative effect on the fan efficiency.

II-The improvements made by frequency control do not significantly affect the efficiency.

III-However, one of the most valuable findings of this precise study is that for every 1 Hz reduction in frequency, the revolution of the fan decreases by 28, the power decreases by 1,84 kW, and the specific energy consumption decreases by 91 W (4.9%).

Finally, it should be noted that VSD systems should be used carefully since the reduction of the fan speed may cause over heating in fan motors. Additionally, the results of this study will provide a guidance to the engineers and researchers, who would consider using VSD in their fan systems.

Declaration of Ethical Standards

The authors of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] Kılıç G. A., Al K., Dağtekin E., and Unver U., 2020. Technical, Economic and Environmental Investigation of Grid-Independent Hybrid Energy Systems Applicability: A Case Study, Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, pp. 1-16.

[2] Selimli S. , Shtewi F. A. , Fahed A. K. A. , Yaman Koymatcık Ç. & Özkaymak P. D. M., 2021. Investigation Of Wind Energy Potential Of Four Different Sites Of Libya By Using Weibull Distribution, Konya Mühendislik Bilimleri Dergisi, **9** (3), 766-786. DOI: 10.36306/konjes.915428

[3] Ünver Ü., Bilgin H., Güven A., 2015. Pompaj Depolamalı Hidroelektrik Sistemler, Mühendis ve Makine, **56**, pp. 57-64.

[4] Enerji ve Tabii Kaynaklar Bakanlığı, Enerji Verimliliği Kanunu, 2007, https://www.resmigazete.gov.tr/eskiler/2007/05/20070502-2.htm

[5] Demir H., Çıracı G., Kaya R., Ünver Ü., 2020. Aydınlatmada Enerji Verimliliği: Yalova Üniversitesi Mühendislik Fakültesi Durum Değerlendirmesi. Uludağ University Journal of the Faculty of Eng., **25** (3), pp.1637-1652.

[6] Turan H.H., Unver U., Kara O., Beşirli I., 2014. HORUS: A Decision Support Tool For Energy Efficiency Management". Energy Technologies Conference. Proceedings Book. pp. 419-428, ISBN:978-605-5120-98-6. 22-24 December 2014 İstanbul

[7] Unver U., Kara O., 2019. Energy Efficiency by Determining the Production Process with the Lowest Energy Consumption in a Steel Forging Facility, Journal of Cleaner Production, **215**, pp: 1362-1370. Doi: 10.1016/j.jclepro.2019.01.168

[8] Energy Efficiency in World and in Turkey (In Turkish) Dünya'da ve Türkiye'de Enerji Verimliliği Oda Raporu, 2012. TMMOB

[9] Ünver Ü., Adıgüzel E., Adıgüzel E., Çivi S., Roshanaei K., 2020. Application of Thermal Insulation in Buildings by Climate Zones in Turkey (In Turkish) "Türkiye'deki İklim Bölgelerine Göre Binalarda Isı Yalıtım Uygulamaları", İleri Mühendislik Çalışmaları ve Teknolojileri Dergisi, **1**, pp. 171-187.

[10] Doğan H., 2015. Türkiye'nin Enerji Verimliliği Potansiyeli ve Projeksiyonu, Gazi Üniversitesi Fen Bilimleri Dergisi Part:C, Tasarım Ve Teknoloji, **3**, pp. 375 – 384.

[11] Türkiye Enerji ve Enerji Verimliliği Çalışmaları Raporu, 2010. ENVER Enerji Verimliliği Derneği, https://www.tskb.com.tr/i/content/486_1_turkiye-enerji-ve-enerji-verimliligi-calismalari-raporu-Temmuz-2010.pdf

[12] Sanayi'de Enerji Verimli Projeler, T.C Enerji ve Tabii Kaynaklar Bakanlığı web sayfası yayınlar bölümü, Bilgi merkezi, Enerji Verimliliği,

[13] İşler T., 2009. Dünyada ve Türkiye'de Enerji Verimliliği. Ege Bölgesi Enerji Forumu, 12-13

[14] Aynsley R., 2002. Fan size and energy efficiency. International Journal of Ventilation, **1**, pp. 33-38

[15] Improving fan system performance, a sourcebook for industry, 1989. AMCA (Air movement and control association int), The United States Department of Energy Air Movement and Control Association International, Inc. Washington, DC, USA

[16] Wang Y., 2016. A power-saving control strategy for reducing the total pressure applied by the primary air fan of a coal-fired power plant, Applied Energy, **175**, pp. 380-388.

[17] Rahnama S., 2017. Experimental study of the pressure reset control strategy for energy-efficient fan operation: Part 1: Variable air volume ventilation system with dampers, Energy and Buildings, **139**, pp. 72-77

[18] Li X., Zhao T., Fan P., Zhang J., 2019. Rule-based fuzzy control method for static pressure reset using improved Mamdani model in VAV systems, Journal of Building Engineering, **22**, pp. 192-199

[19] Sjöström S., Klintenäs E., Johansson P., Nyqvist J., 2020. Optimized model-based control of main mine ventilation airflows with minimized energy consumption, International Journal of Mining Science and Technology, **30**, pp. 533-539

[20] De Souza E., 2015. Improving the energy efficiency of mine fan assemblages, Applied Thermal Engineering, **90**, pp. 1092-1097

[21] Akbaş B., Kaya D., Eyidoğan M., 2018. Bir Otomobil Montaj Fabrikasının Enerji Tüketim Analizi ve Enerji Tasarrufu Potansiyelinin Değerlendirilmesi, Mühendis ve Makina, **59**, pp. 85-100.

[22] Saidur R., Mekhilef S., Ali M.B., Safari A., Mohammed H.A., 2012. Applications of variable speed drive (VSD) in electrical motors energy savings, Renewable and Sustainable Energy Reviews, **16**, pp. 543-550

[23] Schibuola L., Scarpa M., Tambani C., 2018. Variable speed drive (VSD) technology applied to HVAC systems for energy saving: an experimental investigation. 73rd Conference of the Italian Thermal Machines Engineering Association (ATI 2018), Pisa, Italy, 12–14 September 2018.

[24] Kalpar M., 2015. Fanlarda Akış Kontrolünün Emiş Klapesi Yerine Değişken Hız Sürücüsü ile Gerçekleştirilmesinin Enerji Verimliliği Bakış Açısıyla İncelenmesi, Siemens Sanayi ve Ticaret A.Ş., EMO Yayınları, https://www.emo.org.tr/ekler/9462515dcc24e9a_ek.pdf

[25] Kalpar M., 2017. Enerji Santrallerinde İç Tüketimi Azaltıcı Tedbirlerden Taze Hava, Sekonder Hava Ve ID Fanlarda Enerji Verimliliğinin Artırılması, Siemens Sanayi ve Ticaret A.Ş., IV. Enerji Verimliliği Kongresi, 14 Ekim 2017.

[26] Wibowo P., M., Haddin M., Marwanto A., 2021. Energy saving analysis of air fan motor in power plant boiler controlled by variable frequency drive, International Journal of Power Electronics and Drive Systems; Yogyakarta **12**, pp.2059-2069. DOI:10.11591/ijpeds.v12.i4.pp2059-2069

[27] Nel A., Arndt D., Vosloo J., Mathews M., 2019. Achieving energy efficiency with medium voltage variable speed drives for ventilation-on-demand in South African mines, Journal of Cleaner Production, **232**, pp. 379-390.

[28] Schibuolaa L., Scarpaa M., Tambania C., 2018. Variable speed drive (VSD) technology applied to HVAC systems for energy saving: an experimental investigation, Energy Procedia, **148**, pp. 806–813

[29] Song I. H., Lhee J., H., and Jeong J. W., 2021. Energy efficiency and economic analysis of variable frequency drive and variable pitch system: A case study of axial fan in hospital, Journal of Building Engineering, **43**, 103213. doi:10.1016/j.jobe.2021.103213

[30] Prince and Hati A. S., 2021. A comprehensive review of energy-efficiency of ventilation system using Artificial Intelligence. Renewable and Sustainable Energy Reviews, **146**, 111153. doi:10.1016/j.rser.2021.111153

[31] Jena M.C., Mishra S.K., Moharana H.S., 2020. Experimental investigation on power consumption of an industrial fan with different flow control methods. Environ Prog Sustainable Energy. 2020; 39:e13237. https://doi.org/10.1002/ep.13237

[32] Mahendra Singh M., Jradi M., Shaker H. R., 2020. Monitoring and evaluation of building ventilation system fans operation using performance curves, Energy and Built Environment **1**, pp. 307–318

[33] Güven A., 2016. Sirkülasyon Fanı Performans Değerlendirmesi, TMMOB Makine Mühendisleri Odası Kocaeli Şubesi

[34] Wang Z., Han Z., Ding L. & Wang G., 2021. Development of an efficiency model for electronically commutated motor fan systems in air handling units, Science and Technology for the Built Environment, **27**(3), pp. 329-340

[35] Pöyhönen S., Ahola J., Niemelä M., Hammo S., Punnonen P., 2021. Variable-speed-drive-based method for the cost optimization of air filter replacement timing, Energy & Buildings, **240**, 110904

[36] De Villiers D. J., Mathews M.J., Maré P., Kleingeld M., Arndt D., 2019. Evaluating the impact of auxiliary fan practices on localised subsurface ventilation, International Journal of Mining Science and Technology, **29**, pp. 933–941

[37] Canbazoğlu F., 2020. Fan Mühendisliği, AIRONN Teknik Yayınları, ISBN: 978-975-6263-41-9

[38] Teitel M., Levi A., Zhao Y., Barak M., Barlev E., Shmuel D., 2007. Energy saving in agricultural buildings through fan motor control by variable frequency drives, Energy and Buildings, **40**, pp. 953–960