Investigation of the energy consumption in regulating the flow rate of fan systems

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Abstract. The ensuring of the required parameters of the air, used in air-conditioning systems, is directly related to the change of the flow rate of each fan that is installed in these systems. This change can be achieved by using different methods of flow rate regulation. However, it is well-known that the selected method determines the energy efficiency of the given fan system. This work represents a comparative theoretical analysis, concerning the energy efficiency of three different methods of regulating a fan’s flow rate: by throttling, by using inlet guide vanes and by changing the voltage frequency - the motor’s speed of rotation has been changed with the help of a variable frequency drive (VFD). For the aims of this research, the change of the coefficient of efficiency for some of the key system elements – fan, motor and VFD, at different work regimes, have also been indicated. To fulfil the objectives of this research a given number of fans, having different specific speeds of rotations: \( n_q = 3.31; 7.11 \) and \( 8.82 \text{ min}^{-1} \), have been selected. As a criteria of effectiveness, concerning the different methods of flow rate regulation, the specific fan power \( P_{SFP} \) - the invested energy in transporting a unit volume of fluid (gas), has been used: \( P_{SFP} = \frac{p}{\eta_{tot}} \left[ \frac{\text{kw}}{\text{m}^3/\text{h}} \right] \), where \( p \) is the total pressure of the fan; \( \eta_{tot} \) is the overall efficiency of the fan. As a result of this theoretical investigation some graphics representing the change of the specific energy consumption, when the three different methods of flow rate regulation are used and indicating the fan’s initial work regime and its specific speed of rotation, have been given.

1. Introduction
Ventilation systems are widely used in practice. They are involved in different technological processes related to the transportation of gas fluids – most often air flows. The achieving of steady-state operating (work) regimes of these systems, providing the corresponding technological requirements, is a present-day applied engineering problem. This requires the using of specialized devices, such as throttle, inlet guide vane, VFD, etc., enabling the continuous changing of a fan’s aerodynamic parameters. This change is known as “regulation”.

There is a good number of contemporary (new) research works concerning the investigation of the effectiveness of the different methods of flow rate regulation, in terms of energy efficiency, of trubopump systems. In his PhD Thesis [1], Bakman has presented a method of high-efficiency frequency (VFD) regulation of pumps, working in parallel. A similar investigation has been presented by Kostov in his PhD Thesis. In the following literature sources [4], [7], [8] and [11], the authors have proven the advantages of using VFD, instead of other methods of regulating the flow rate of a pump system. In [8], the authors have presented a number of system operating conditions, whose implementation leads to the decreasing of the effectiveness in using the frequency method of flow rate regulation. Source [3] compares the effectiveness, in terms of energy efficiency, where an inlet vane
fan is used, instead of a flap-adjustment based centrifugal fan. This research indicates that where the inlet vane is used the fan operates less effectively in a wider range.

This work represents a comparative investigation concerning the effectiveness, in terms of energy efficiency, of three different methods of flow rate regulation of a centrifugal fan system: by using a VFD, by using an inlet guide vane (IVC) and by throttling. The main purpose is to determine how much more effective, in terms of energy efficiency, it is to use VFD, instead of inlet guide vane or throttling for the regulation of a fan system’s flow rate. A comparison between the effectiveness in applying the last two methods has also been done. In addition to that, the impact of a fan’s specific speed of rotation on the effectiveness of the selected methods for flow rate regulation is investigated. This research investigated three centrifugal fans named C8-18, C5-40 and C4-50, which are produced by Central Aerohydrodynamic Institute (TsAGI) of Moscow. Each fan has a different value for its specific speed of rotation, respectively: C8-18 - \( n_q = 3.31 \text{ min}^{-1} \); C5-40 - \( n_q = 7.11 \text{ min}^{-1} \); C4-50 - \( n_q = 8.82 \text{ min}^{-1} \), where \( n_q \) has been estimated by the following equation:

\[
n_q = \frac{n g^{0.5}}{p^{0.75}}, [\text{min}^{-1}]
\]  

(1)

where: \( n_q \) is the fan’s specific speed of rotation; \( n \), \( [\text{min}^{-1}] \) – the fan’s speed of rotation; \( Q, [\text{m}^3/\text{s}] \) – the fan’s volumetric flow rate at best efficiency point (BEP); \( p, [\text{Pa}] \) – the fan’s total pressure at BEP. The fan’s operating curves are given in [13].

2. Methodology of the investigation

In [10] it has been presented a methodology to investigate the effectiveness of three different methods, used in regulating the flow rate of pump systems. As a criteria of effectiveness the specific energy consumption \( e_v \) has been used:

\[
e_v = \frac{g H}{3600 \eta} [\text{kWh/m}^3]
\]  

(2)

where: \( g, [\text{m/s}^2] \) is the gravity acceleration; \( H, [\text{m}] \) – pump’s head; \( \eta \) – the total pump system’s coefficient of efficiency [10].

According to the standard prEN 13779:2006 (E) „Ventilation for non-residential buildings — Performance requirements for ventilation and room-conditioning systems“, as a criteria of effectiveness of a fan system the “specific fan power” has been given [12]. For its estimation the following equation can be used:

\[
P_{SFP} = \frac{p}{\eta_{tot}} \left[ \frac{\text{kw}}{\text{m}^3/\text{s}} \right]
\]  

(3)

where \( p \) is the total fan’s pressure; \( \eta_{tot} \) – total coefficient of efficiency of the fan system, including the coefficients of efficiency of the fan and system’s drive (mechanical transmission, motor and VFD).

The physical importance (meaning) of the parameters \( e_v \) and \( P_{SFP} \) is the same – the electrical energy, used for the transportation of a cubic meter of fluid in a pump or fan system. In this research the “specific fan power” [12], is used.

The methodology, presented in [10], determining the specific energy consumption in case of flow rate regulation, is accomplished by using three different methods, requiring information about the equations describing the pump’s operating curves: \( H = f(Q) \) and \( \eta = f(Q) \). The operating curves of the fans, which are objects of this investigation, are presented in a dimensionless form in [13]. It has to be indicated that the methodology, given in [10], takes into account the including of a static head. At the same time, it is a well-known fact that the fan systems usually work without static head, which requires the accomplishing of a simplification of the equations before they can be used in this work. As it is mentioned above, source [13] provides detailed information about the fans’ dimensionless operating curves (characteristics) - \( \psi = f(\varphi) \) and \( \eta_f = f(\varphi) \), where:

\[
\psi = \frac{2p}{\rho u^2}
\]  

(4)

is the coefficient of fan’s pressure; \( \rho = 1.2 \text{ kg/m}^3 \) – the air’s density at given atmosphere pressure - \( p_{atm} = 101325 \text{ Pa} \); air’s temperature \( T = 293.15 \text{ K} \) and relative humidity \( hu = 0.5 \) (these
are the conditions at which the operating curves have been determined; \( u_2 = \frac{mD_2}{60}, \text{[m/s]} \) – transmitted velocity at the fan impeller’s outlet; \( D_2, \text{[m]} \) – outer diameter of the fan’s impeller.

The flow rate coefficient - \( \varphi \), for each fan, can be estimated by using the following equation:

\[
\varphi = \frac{4Q}{\pi D^2 u_2},
\]

(5)

where \( Q, \text{[m}^3\text{s}^{-1}] \) comes from (5) and is the fan’s volumetric flow rate. The fan’s coefficient of efficiency is given with \( \eta_f \).

The functions: \( \psi_i = f(\varphi_i) \) and \( \eta_{f,i} = f(\varphi_i) \), can be approximated by using the equations (6) and (7):

\[
\psi_i = a_i + b_i \varphi_i + c_i \varphi_i^2
\]

and

\[
\eta_{f,i} = d_i + e_i \varphi_i + f_i \varphi_i^2.
\]

(6)

(7)

The coefficients \( a_i, b_i, c_i, d_i, e_i \) and \( f_i \), used in equations (6) and (7), have been preliminary determined in case that each of the investigated fans works with an inlet vane whose blades are fixed at different angular: \( \alpha_i = 0, 20, 40 \) and \( 60^\circ \). The corresponding values of these coefficients are given in Table 1. This theoretically found data has been used to accomplish the aims of this research.

| \( \alpha_i, \text{deg} \) | \( a \) | \( b \) | \( c \) | \( d \) | \( e \) | \( f \) |
|----------------|---------|---------|---------|---------|---------|---------|
| Fan C8 – 18; \( n_q = 3.31 \text{ min}^{-1} \); \( \varphi_0 = 0.038 \) | 0 | 0.8788 | 41.708 | -536.78 | 0.2903 | 18.561 | -240.19 |
| | 20 | 1.0113 | 35.346 | -570.84 | 0.1537 | 26.023 | -357.37 |
| | 40 | 0.8687 | 44.299 | -925.58 | 0.1083 | 31.93 | -538.99 |
| | 60 | 0.9837 | 39.163 | -1751.9 | 0.0644 | 40.238 | -1099.7 |
| Fan C5 – 40; \( n_q = 7.11 \text{ min}^{-1} \); \( \varphi_0 = 0.1 \) | 0 | 1.2317 | -0.8062 | -28.158 | 0.3788 | 7.8764 | -41.376 |
| | 20 | 1.0874 | 2.7172 | -63.287 | 0.1639 | 13.08 | -73.322 |
| | 40 | 1.0946 | 2.2013 | -80.172 | 0.134 | 16.125 | -108.89 |
| | 60 | 1.0584 | 3.1995 | -167.35 | 0.029 | 21.957 | -215.96 |
| Fan C4 – 50; \( n_q = 8.82 \text{ min}^{-1} \); \( \varphi_0 = 0.072 \) | 0 | 1.1741 | 0.4603 | -54.674 | 0.3154 | 12.03 | -84.364 |
| | 20 | 0.9875 | 4.5191 | -103.71 | 0.1576 | 16.113 | -117.2 |
| | 40 | 0.9767 | 5.153 | -160.17 | 0.1028 | 20.78 | -193.06 |
| | 60 | 0.9998 | 0.6827 | -250.77 | 0.0597 | 26.244 | -374.99 |

To compare the effectiveness of the selected different methods of a fan system’s flow rate regulation, the following equation is used:

\[
P_{\text{SFP,i}} \frac{P_{\text{SFP,0}}}{P_{\text{SFP,0}}} = f\left(\frac{Q_i}{Q_0}\right),
\]

(8)

where \( P_{\text{SFP,i}} \) is the current value of SFP at given flow rate \( Q \); \( P_{\text{SFP,0}} \) is the value of SFP at the initial operating regime concerning the relevant method of flow rate regulation, corresponding to the provided flow rate \( Q_0 \). In defining the equation (8), the ratio \( \frac{Q_i}{Q_0} \) for a given fan, can be replaced by the ratio \( \frac{\varphi_i}{\varphi_0} \). For an initial operating regime in this research the nominal regime of each fan, given in [13], has been selected. To provide the graphically presented results, concerning a comparative analysis of the energy effectiveness for the three selected methods, equation (8) is used.
3. Throttle method of flow rate regulation

When the throttle method of flow rate regulation is used, the ratio \( \frac{P_{\text{SFP}}}{P_{\text{SFP},0}} \) can be determined by using the following equation:

\[
\frac{P_{\text{SFP}}}{P_{\text{SFP},0}} = \frac{\psi_i \eta_{\text{tot},0}}{\psi_i \eta_{\text{tot},i}},
\]

where the relevant coefficient of efficiency \( \eta_{\text{tot}} \) represents the multiplication of the coefficients of efficiency respectively of the fan \( \eta_f \) and motor \( \eta_m \):

\[
\eta_{\text{tot}} = \eta_f \eta_m.
\]

It is assumed that the fan’s impeller has been installed (mounted) directly on the motor’s shaft, i.e. this excludes the existence of mechanical transmission between the fan and motor. In case that the flow rate has been regulated by throttling the work points belong to the fan’s operating characteristic when it works with inlet guide vane and its blades are fixed at an angle \( \alpha_0 = 0^\circ \). In this regard, by using the equations (6) and (7), the following equation - (9), is found:

\[
\frac{P_{\text{SFP}}}{P_{\text{SFP},0}} = \frac{a_0 + b_0 \varphi_i + c_0 \varphi_i^2 + d_0 + e_0 \varphi_i + f_0 \varphi_i^2}{a_0 + b_0 \varphi_0 + c_0 \varphi_0^2 + d_0 + e_0 \varphi_0 + f_0 \varphi_0^2} \frac{1}{\eta_{\text{tot},i}/\eta_{\text{tot},0}}.
\]

The coefficients \( a_0, b_0, c_0, d_0, e_0 \) and \( f_0 \), belonging to equation (11), are valid only in case that the investigated fans work with inlet guide vanes, whose blades are fixed at a given angular - \( \alpha_0 = 0^\circ \).

The literature sources [2] and [9] provides the necessity information, concerning the change of a motor’s coefficient of efficiency as a function of load. In the accomplishing of this research, some data found for a 10 kW motor, given in [9], is used. The literature source [9] provides an equation, used for the estimation of a motor’s nominal speed of rotation:

\[
\frac{\eta_{\text{m},i}}{\eta_{\text{m},0}} = f(\mu_i),
\]

where \( \mu_i = \frac{\psi_i \varphi_i}{\eta_{f,i}} \) is the fan’s power coefficient.

By using the equations (11) and (12), it can be estimated the ratio \( \frac{P_{\text{SFP}}}{P_{\text{SFP},0}} \) at different values of the flow rate’s relative coefficient - \( \frac{\varphi_i}{\varphi_0} \) (or respectively \( \frac{Q_i}{Q_0} \)).

4. Flow rate regulation by using an inlet guide vane

A well-know fact is that usually the fans are used in systems without static head. The resistance characteristic of such a system, containing a point whose coordinates respectively are: \( \varphi_0; \psi_0 \), can be presented in the following way:

\[
\psi = \kappa \varphi_0^2,
\]

where \( \kappa = \psi_0/\varphi_0^2 \) (a coefficient). The work points, corresponding to the achieved after flow rate regulation operating regimes, belong to a curve that has been described by using equation (13). The values of the flow rate’s coefficient \( \varphi_i \), when the inlet guide vane’s blades are installed at different angle \( \alpha_i \), can be found by using the following equation:

\[
\varphi_i = a_i + b_i \varphi_i + c_i \varphi_i^2
\]

and its final solution is:

\[
\varphi_i = \frac{-b_i \pm \sqrt{b_i^2 - 4a_i(c_i \varphi_0 - \varphi_i)}}{2(c_i \varphi_0 - \varphi_i)}
\]

After the determination of the flow rate coefficient \( \varphi_i \) for each of the achieved operating regimes is accomplished, the ratio \( \frac{P_{\text{SFP}}}{P_{\text{SFP},0}} \) can also be determined:

\[
\frac{P_{\text{SFP}}}{P_{\text{SFP},0}} = \frac{\psi_i \eta_{\text{tot},0}}{\psi_0 \eta_{\text{tot},i}} = \frac{a_i + b_i \varphi_i + c_i \varphi_i^2 + d_i + e_i \varphi_i + f_i \varphi_i^2}{a_0 + b_0 \varphi_0 + c_0 \varphi_0^2 + d_0 + e_0 \varphi_0 + f_0 \varphi_0^2} \frac{1}{\eta_{\text{m},i}/\eta_{\text{m},0}}.
\]
5. Flow rate regulation by using VFD (frequency method)

When the flow rate regulation is accomplished by using VFD the work points, corresponding to the achieved operating regimes, belong to the system’s curve described by equation (13). In this case, the mentioned curve coincides with the parabola of similarity. According to the “Theory of similarity” when the gas’ density has a constant value, the following relation is valid:

\[ \psi_1 \psi_0 = \frac{\psi_1^2}{\psi_0^2} \]

Indicating the previous statement, equation (9) can be presented the following way:

\[ \frac{P_{SFP,1}}{P_{SFP,0}} = \frac{\eta_1}{\eta_0} \frac{\eta_{tot,0}}{\eta_{tot,1}} \]  

(16)

The fan system’s total coefficient of efficiency is the multiplication between the coefficients of efficiency respectively of the fan (\( \eta_f \)), motor (\( \eta_m \)) and VFD (\( \eta_{VFD} \)). For the determination of a fan’s coefficient of efficiency operating at different Reynolds numbers (Re) the methodology given in [13] can be used:

\[ \eta_{f,i} = 1 - \frac{2(1-\eta_{f,0})}{14(Re_i/Re_0)} \]  

(17)

Taking into account that: \( \frac{Re_i}{Re_0} = \frac{\chi_i}{\chi_0} = \frac{\phi_i}{\phi_0} \) then equation (17) can be given the following way:

\[ \eta_{f,i} = 1 - \frac{2(1-\eta_{f,0})}{14(\phi_i/\phi_0)} \]  

(18)

For the determination of the motor’s coefficient of efficiency, equation (12) was used:

In [5] and [6] the authors are given equations that can be used to estimate a VFD’s coefficient of efficiency. For the aims of this work, an equation given in [5] is used.

\[ \eta_{VFD,i} = \frac{aX_{VFD}}{b+X_{VFD}} + cX_{VFD} \]  

(19)

where in case the VFD works at output power \( P = 14.91 \text{ kW} \) (20 hP) the values of the coefficients are: \( a = 0.9850, b = 0.0175, c = -0.0005 \) and the parameter \( X_{VFD} \) represents the ratio between the current and maximal output power. If the values of \( \frac{\eta_{f,i}}{\eta_{f,0}} \) and \( \frac{\eta_{m,i}}{\eta_{m,0}} \) are preliminary known, the parameter \( X_{VFD} \) can be determined by using the following equation:

\[ X_{VFD,i} = \frac{\psi_i \psi_0}{\eta_{f,i}\eta_{m,i}} \frac{\eta_{f,0}\eta_{m,0}}{\psi_0} = \frac{\phi_i^3}{\phi_0^3} \frac{1}{\eta_{f,i}\eta_{m,i}} \]  

(20)

6. Results and discussion

Figure 1 shows the change of the specific fan power as a function of the relative flow rate’s change when the flow rate of a fan (C8-18) system, has been regulated by the three selected methods. The curves describing these methods are named as it follows: TH – throttle, IVC – Inlet (Guide) Vane Control and VFD – Variable Frequncy Drive.

The results concerning the investigated fan systems are similar with the results (related to pump systems) given in [11]. Therefore, the using of VFD regulation is most effective in terms of energy efficiency. In this case, the decreasing of the relative flow rate \( \frac{Q}{Q_0} \) (i.e. increasing of the range of regulation: \( \frac{Q_0}{Q_0} = 1 - \frac{Q}{Q_0} \)) leads to decreasing of the relative energy consumption, used for the transportation of a cubic meter of air. The reason is that the system’s pressure decreases with the decreasing of the flow rate squared.

In applying the flow rate regulation by throttling the relative coefficient SFP increases with the decreasing of the relative flow rate and has highest values compared with the coefficients achieved by applying the other two methods. In case of applying the IVC regulation, it is indicated that the relative energy consumption decreases and this continues until the relative flow rate has a value of \( \frac{Q}{Q_0} \approx 0.9 \).
At the same time the relative coefficient SFP has also been decreased to \( \frac{P_{\text{SFP},i}}{P_{\text{SFP},0}} \approx 0.9 \). If the decreasing of the relative flow rate continues, the relative coefficient SFP stays constant.

The trends describing the change of the relative energy consumption concerning the three selected methods of flow rate regulation are identical for the other two fans that are object of this research. The quantitative deviations depending on the fan’s type and its specific speed of rotation are graphically presented in the figures 2, 3 and 4.

Figure 2 illustrates the results found for the relation: \( \frac{P_{\text{SFP},i}}{P_{\text{SFP},0}} = f\left(\frac{Q_i}{Q_0}\right) \) in case that the three investigated fans are regulated by using VFD. Actually, the three curves have to coincide with each other because in using this method of regulation the operating point “moves” along the fan’s curve, which is the same in the three cases and the change of the relative coefficient SFP is described by the same equation – (16). In this case, the fan’s type do not affect the change of \( \frac{P_{\text{SFP},i}}{P_{\text{SFP},0}} \) in the process of regulation.
Figure 3 illustrates the results found the relation: \( P_{\text{SFPI}} = f\left(\frac{Q_i}{Q_0}\right) \), in case that the three investigated fans are regulated by throttling. In this case, it can be seen that the specific speed of rotation \( n_q \) has a significant impact on the change of the relative energy consumption in regulating the fan’s flow rate. For the fan having the lowest specific speed of rotation \( n_q = 3.31 \text{ min}^{-1} \) the value of the relative coefficient increases with about 5% at \( \frac{Q_i}{Q_0} = 0.7 \), as for the fans whose speed of rotations respectively are \( n_q = 7.11 \text{ min}^{-1} \) and \( n_q = 8.82 \text{ min}^{-1} \), this increase is about 25%.

According to the results given in fig.4, it can be seen that the relative coefficient SFP decreases most intensively (about 20%, at \( \frac{Q_i}{Q_0} = 0.7 \)) in case of the fan with highest specific speed of rotation operates, as for the fan with the lowest specific speed of rotation this decrease is about 10%. As a general conclusion concerning the three selected fans, it can be indicated that the fan’s relative flow rate decreases intensively until it comes to \( \frac{Q_i}{Q_0} = 0.9 \), and then its value stays almost constant.

Summarizing the above-mentioned conclusions, it is clear that the most effective method of flow rate regulation is by using VFD and as most inefficient it can be indicated the throtteling. In order to assess the superiority, in terms of effectiveness, of a given method of flow rate regulation compared with the other selected methods by indicating the impact of the fan’s type the graphical relations given in the figures 5, 6 and 7, is used.

The abscissa axis represents the relative flow rate \( \frac{Q_i}{Q_0} \), and the ordinate axis represents the relative difference (RD), which can be estimated by using the following equation:

\[
RD = \frac{\left(\frac{P_{\text{SFPI}}}{P_{\text{SFPI},0}}\right)_{\text{IVC}} - \left(\frac{P_{\text{SFPI}}}{P_{\text{SFPI},0}}\right)_{\text{VFD}}}{\left(\frac{P_{\text{SFPI}}}{P_{\text{SFPI},0}}\right)_{\text{VFD}}} \times 100\% 
\]

\[
RD = \frac{\left(\frac{P_{\text{SFPI}}}{P_{\text{SFPI},0}}\right)_{\text{TH}} - \left(\frac{P_{\text{SFPI}}}{P_{\text{SFPI},0}}\right)_{\text{VFD}}}{\left(\frac{P_{\text{SFPI}}}{P_{\text{SFPI},0}}\right)_{\text{VFD}}} \times 100\% 
\]

\[
RD = \frac{\left(\frac{P_{\text{SFPI}}}{P_{\text{SFPI},0}}\right)_{\text{IVC}} - \left(\frac{P_{\text{SFPI}}}{P_{\text{SFPI},0}}\right)_{\text{VFD}}}{\left(\frac{P_{\text{SFPI}}}{P_{\text{SFPI},0}}\right)_{\text{IVC}}} \times 100\% 
\]

Figures 5, 6 and 7 illustrate the results found for the relation: \( RD = f\left(\frac{Q_i}{Q_0}\right) \), concerning the three investigated fans.
Figure 5 illustrates the change of the relative difference $RD$ for the three investigated fans, estimated by using the equation (21), given as a function of the fan’s relative flow rate. A comparison between the effectiveness of regulation by using VFD or IVC shows similarity when the relative flow rate $\frac{Q_i}{Q_0}$ is less than 0.9. For the same range ($\frac{Q_i}{Q_0}=0...0.9$) the fan whose $n_q = 8.82 \text{ min}^{-1}$ has almost no relative difference $RD \approx 0$, as for the other two fans its value reaches 6-7%. In the range of: $0.7 \leq \frac{Q_i}{Q_0} \leq 0.9$, the relative difference $RD$ of the fan with $n_q = 8.82 \text{ min}^{-1}$ increases to 35% and for the fan with $n_q = 3.31 \text{ min}^{-1}$ this value increases up to 50%.

Figure 6 illustrates a comparison between the using of throttle and VFD flow rate regulation and it can be clearly seen that relative difference $RD$ increases almost linear and this is valid for the investigated full range of changing the relative flow rate. For the fan with the lowest specific speed of rotation $n_q$ the value of $RD$ reaches about 70%, as for the other fans with higher values of $n_q$ the $RD$ is over 100%.

The comparison between the throttle and IVC methods, given in figure 7, gives a clear indications that in case a fan has a higher value of $n_q$ the value of $RD$ increases. The indicated maximal value of $RD$ for the investigated fans with $n_q = 7.11 \text{ min}^{-1}$ and $n_q = 8.82 \text{ min}^{-1}$ is about 50% at $\frac{Q_i}{Q_0} = 0.7$. For the fan with the lowest value of $n_q$ the value of $RD$ reaches about 15%. In this case, the increasing of $RD$ is more intensive in the range of $0.9 \leq \frac{Q_i}{Q_0} \leq 1$ and the change is much less in the range of $0.7 \leq \frac{Q_i}{Q_0} \leq 0.9$. The last statement can be explained by paying attention to the type of the same fan’s curve, given in figure 4, that is described by the relation $\frac{P_{SPP,i}}{P_{SPP,0}} = f(\frac{Q_i}{Q_0})$.

7. Conclusion
The accomplishment of this research work leads to the following significant conclusions:

- The using of VFD method of flow rate regulation is more efficient, in terms of energy efficiency, than using the other two methods - throttle and IVC, independently of the fan’s specific speed of rotation;
- The regulation of a fan system’s flow rate by using IVC is more efficient, in terms of energy efficiency, than throtteling, independently of the fan’s specific speed of rotation;
- In case of using VFD to regulate the flow rate the specific speed of rotation does not affect the effectivness of this selected method;
- The using of throttling for regulating a fan system’s flow rate is more efficient, in terms of energy efficiency, in case that the fan has a lower value of specific speed of rotation;
- The using of IVC for regulating a fan system’s flow rate is more efficient, in terms of energy efficiency, in case that the fan has a higher value of specific speed of rotation;
- In case the applying of a fan system’s flow rate regulation is in the range of $\frac{Q_0-Q}{Q_0} \leq 0.1$, the energy efficiency of using the two selected methods – IVC and VFD, is similar.
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