Monitoring and Evaluation of Building Ventilation System Fans Operation using Performance Curves

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Published in:
Energy and Built Environment

DOI:
10.1016/j.enbenv.2020.04.001

Publication date:
2020

Document version:
Final published version

Document license:
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Citation for published version (APA):
Monitoring and evaluation of building ventilation system fans operation using performance curves

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ARTICLE INFO

Keywords:
Buildings
Ventilation system
Fan unit
Performance curve
Modeling
Fan efficiency
Energy consumption
HVAC
Performance testing
Support vector regression (SVR)
Polynomial regression

ABSTRACT

Ventilation fans are an important component of any mechanically ventilated building. Poor fan performance could significantly affect the whole building performance metrics. There are several issues such as dirty blades, mechanical wear, aging of fans could impact the fan’s performance. In present work, a novel, indirect and data-driven methodology is introduced to monitor the ventilation fan unit performance. The proposed method is able to perform continuous monitoring of ventilation fan unit in real-time. The real-time performance of 3 Air handling unit (AHU) fans is examined in an academic building. Expected fan performance is modeled with the help of manufacturer data and compared against the real-time performance. Two data-driven models are developed and implemented. The first model is used to compute expected total fan pressure at a given airflow rate while second is a Support Vector Regression (SVR) model, to predict the fan efficiency. The performance monitoring of the ventilation fan unit is determined in terms of expected and actual fan energy consumption. Findings indicated a significant performance gap in three ventilation fan unit in a case building known as OU44, located in city Odense, Denmark. The advantage of this method comprises simplicity, no direct human intervention and scalability to the series of ventilation units.

1. Introduction

Existing passive house standards vouch for a high thermal comfort with minimum energy consumption [1]. An efficient building envelop, sustainable construction materials along with a mechanical ventilation system, are the key components of a passive house design. Moreover, an efficient operation of mechanical ventilation will also help to achieve desired energy consumption levels of such buildings.

A poorly ventilated or managed building may cause a serious health issue to occupants or building users. A series of components such as heating, ventilation and air conditioning (HVAC), controllers and building management system (BMS) operate in parallel to maintain a satisfactory operation after the post commissioning of the building automation system. Nevertheless, each component has its own performance indexes and needs to be monitored carefully. Moreover, buildings are also responsible for a significant amount of energy waste that increases the actual operational cost of the whole building operation [2]. As the matter of fact, performance monitoring of different HVAC components is noteworthy in terms of dweller’s comfort and energy-saving [3,4]. A typical air handling unit (AHU) system consists of supply and return fans, an electric motor, ducts, flow control devices, filters, heat exchanger and cooling coils etc. Fans are an essential component of any AHU system in a mechanically ventilated building. A considerable amount of energy goes to the fan consumption. Indeed, AHU fans are responsible for approximately 35–40% of all electricity consumption in a HVAC system [5,6].

In practice, two types of fans i.e., centrifugal and axial are used for ventilation purpose. In HVAC system two fans with almost similar capacity are used as inlet (supply) and outlet (return) fan. An inlet fan is responsible for moving air inside while the outlet fan is for air distribution to the main duct. In order to meet the desired performance level of the ventilation system, the actual fan performance should follow the expected or ideal fan performance. However, a certain level of the mismatch is acceptable due to changes in operating conditions. Tracking fan energy performance could also give an indication about different faults and failures in buildings. For example,

• A fan reporting over-consumption could indicate a rise in static pressure due to a blocked filter.

Abbreviations: SVR, Support Vector Regression; BMS, Building Management System; HVAC, Heating, Ventilation, and Air conditioning; AHU, Air Handling Unit; FDD, Fault Detection and Diagnosis; FPC, Fan Performance Curve; t.p, Total Pressure; rpm, Revolutions Per Unit; VE02, Ventilation Unit 2; VE03, Ventilation Unit 3; VE04, Ventilation Unit 4; PT, Performance test.

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https://doi.org/10.1016/j.enbenv.2020.04.001
Received 12 February 2020; Received in revised form 2 April 2020; Accepted 3 April 2020
Available online 30 April 2020
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Lastly, design order also, posed.

In this research, the main focus is given to:

- temperature profile in the room
- air distribution effectiveness
- energy consumption

In [13] authors reviewed performance of different ventilation system along with air distribution systems in buildings. Monitoring and tracking of individual HVAC components could improve building system performance also ease the building’s fault diagnostic process. There are several guidelines, and recommendations already exists for the pre-commissioning AHU fan [14,15]. However, post-commission performance evaluation of a fan system is a notable concern for the building maintenance team. In [16] authors have discussed different issues and possible solutions for an under performing fan. This study has identified poor fan efficiency along with improper design measure is responsible for performance gap.

In this regard, a range of studies also have shown the importance of ventilation fan unit performance monitoring. In [17,18], various methods and techniques are proposed to monitor fan’s performance using basic preventive maintenance and by selecting proper fan type. Further, [19] investigated the performance of exhaust only ventilation system. In an interesting work, fan performance is estimated for a leaky duct [20].

In addition to the above, few studies were performed over the ventilation fan for the different building types. For instance, in [21] ventilation fans performance is analyzed in a farm. Similarly, in [22,23] ventilation fan performance is evaluated for a mine, and an animal building, respectively. These methods require a complex mathematical model such as computational fluid dynamics (CFD) analysis and test set-up.

2. State-of-the-art

Buildings designed for centralized comfort management heavily rely on HVAC performance. HVAC designing and commissioning is always a central research topic for building researchers and industry practitioners. In literature, there are few work that consider the whole ventilation system performance [8,9]. The main focus is given to:

- temperature profile in the room
- air distribution effectiveness
- energy consumption

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2.1. Contribution and objective:

The objective of this work is to develop a simple, indirect and practical performance test for a ventilation fan unit, using real-time airflow rate and power consumption data.

The initial literature review about the present research work had suggested following two major category to monitor the ventilation system performance.

- Direct method: it includes monitoring and measuring airflow at inlet and outlet or total pressure measurement in the ventilation unit.
- Indirect method: such as CO₂ mass balance, Tracer gas techniques, H₂O mass balance and heat balance inside the dwelling [24].

Both methods have their own pros and cons. For instance, direct methods offer simplicity and easy validation with the help of large number of sensors [25]. Nevertheless, simplicity requires initial investment. Often, direct methods ignore the correlation between other variables that could also influence the measurement.

Indirect methods are widely accepted and practiced in the scientific community [24,26]. Existing, indirect method are mainly rely on measurement of physical variables like indoor CO₂ concentration, heat produced and H₂O mass. In reality, these physical variables has direct correlation with usually unmeasured variables e.g occupancy level (people count), activity and building door or window opening. Further, measuring only physical variables are not enough to understand the faulty or abnormal behavior of ventilation system.

The proposed method is indirect and uses data-driven models to predict the real-time performance of ventilation system. Moreover, in this method unmeasured variables are considered as possible explanations of abnormal behavior of ventilation system. Performance gap is
measured with respect to manufacturer data and post-commissioning knowledge (e.g. design number). The discussed methodology will definitely help to improve understanding of building maintenance team.

Thanks to the available fan’s performance curves from the manufacturer that allow an easy modeling and performance evaluation. To design a performance test for a ventilation fan, the fundamental challenges are summarized below:

- Ideal fan performance curves (Fig. 2) comes with different set of characteristics and it is not easy to implement a single model that could easily relate all parameters.
- How to establish a link between current operating conditions and operational parameters such as airflow, efficiency, etc.
- Estimating the expected performance under the actual operating conditions and assessing energy consumption with respect to actual performance.
- Analyzing operating data along with fan’s performance curves to model the fan operation.
- Continuous commissioning of HVAC system and real-time performance testing.

To address the above challenges, rest of the paper proposes modeling of the performance test for a ventilation fan unit. The main contribution of the present work is to propose a performance test for the ventilation unit fan using on-site measured data and a model explaining the expected behavior of the fan unit. Proposed performance test could help building consultant and practitioners to test the energy performance of ventilation fan unit.

3. Performance test design for a ventilation fan unit

To estimate expected fan energy consumption of ventilation system fan using airflow measurement it is necessary to model total fan pressure \((t.p)\) in the terms of measured airflow. A second model requires to estimate expected fan efficiency followed by the expected fan energy consumption. Further the following performance test (Eq. (1)) is formalized to monitor the normal and abnormal behavior of ventilation fan unit.

\[
\text{Performance test} (PT) = \begin{cases} 
\text{normal behaviour} & \text{if } (E_{\text{expected}} - DN^- + E_{\text{measured}} < E_{\text{expected}} + DN^+) \\
\text{abnormal behaviour} & \text{otherwise} 
\end{cases}
\]

(1)

In above equation, \(DN^+\) and \(DN^-\) are upper and lower value of performance design number and can be obtained from the ventilation commissioning team. \(E_{\text{expected}}\) and \(E_{\text{measured}}\) are expected and measured energy consumption receptively.

Definition 1. (Design number): Design number (DN) is a performance indicator that reports the acceptable and non-faulty behavior of a ventilation unit within the maximum and minimum operational threshold i.e. \(DN^+\) and \(DN^-\).

The fan operational data sheets are a well-established methodology used by the majority of energy consultants in commissioning processes to ensure that energy systems are operating as expected. Fan performance curve (FPC) is a graphical representation of total fan pressure and fan power requirements over an airflow volume range operation. A set of fan performance curve, provided by NK Industri (Fig. 2) is used for the modeling purpose. Furthermore, these models are applied and analyzed for a case building in Section 4. In the following discussion, the detailed modeling of performance test is discussed.

3.1. Total pressure model in terms of airflow rate of the fan

In order to model the fan characteristic equation, airflow rate of the fan and corresponding total fan pressure data is taken from the ideal fan performance curve, (Fig. 2). An example of such data set is given in the Table 1.

Where airflow rate \((Q)\) is defined as the volume of air moved per unit of time and measured in terms of cubic feet of air per minute (cfm), cubic meters of air per minute \((m^3/min)\), or litres of air per second \((l/s)\). The first fan law states that fan airflow rate varies with the fan’s rotational speed and also influenced by the aerodynamic resistance of the installation. Similarly, total fan pressure \((t.p)\) measures the difference between total pressures in the fan outlet and inlet openings. Fan rotational speed is usually measured in revolutions per minute (rpm).
Fig. 2. Ventilation unit fan performance curve provided by NK Industri [27].
Table 1
Data used for total pressure estimation.

<table>
<thead>
<tr>
<th>Airflow rate (Q) of the fan (m³/hour)</th>
<th>Total fan pressure (t.p) in pascal</th>
</tr>
</thead>
<tbody>
<tr>
<td>36,000</td>
<td>80</td>
</tr>
<tr>
<td>35,280</td>
<td>90</td>
</tr>
<tr>
<td>34,560</td>
<td>100</td>
</tr>
<tr>
<td>33,840</td>
<td>120</td>
</tr>
<tr>
<td>33,120</td>
<td>140</td>
</tr>
<tr>
<td>32,400</td>
<td>160</td>
</tr>
<tr>
<td>30,600</td>
<td>200</td>
</tr>
<tr>
<td>28,080</td>
<td>250</td>
</tr>
<tr>
<td>25,200</td>
<td>300</td>
</tr>
<tr>
<td>21,600</td>
<td>350</td>
</tr>
<tr>
<td>14,400</td>
<td>390</td>
</tr>
<tr>
<td>6,000</td>
<td>360</td>
</tr>
</tbody>
</table>

† Data set is obtained from the first performance curve i.e 600 rpm of Fig. 2.

In fact, total fan pressure is the sum of velocity pressure (v.p) and static pressure (s.p).

total pressure (t.p) = (v.p) + (s.p)

(2)

In many cases, measurements for v.p and s.p is not easily available and difficult to obtain on-site total pressure values. Further, the relation between airflow rate of the fan and total fan pressure represented by a polynomial expression is mentioned in the Eq. (3), [28,29]. Total pressure is expressed in terms of measured airflow.

total pressure (t.p) = f(K_1Q^0 + K_2Q^2 + ... + K_n) = (3)

In this equation K_1, K_2, ..., K_n are polynomial coefficients and p is the polynomial order. Generally, a third order polynomial fits best between the fan total pressure and airflow. However, high order polynomial could be expected for a fan running at higher rpm values.

The polynomial coefficients and order are estimated using the curve fitting technique. It uses the least-square method to minimize residuals between the actual value and prediction to estimate polynomial coefficients. It is assumed that the manufacturer data is reliable and the fan is operating on a single curve that relates the total fan pressure and airflow rate.

Moreover, each performance curve is modeled for a fixed rpm value. Fig. 3a-d illustrates the estimated fan performance curve at different rpm values. For example, Fig. 3a illustrates the estimated total fan pressure using Eq. (2)a and corresponds to performance curve (Fig. 2) at rotational speed 600 rpm. Similarly, Fig. 3b-d shows estimated total fan pressure taking Fig. 4 shows the estimated fan efficiency

i.e, for the estimated value (t.p) of the fan: (5.12e - 12)Q^3 + (-9.44e - 07)Q^2 + (2.21e - 02)Q + 258.12

(2a)

t_{Estimated} = (3.92e - 12)Q^3 + (-8.60e - 07)Q^2 + (2.04e - 02)Q + 266.27

(2b)

t_{Estimated} = (1.19e - 11)Q^3 + (-1.58e - 06)Q^2 + (4.22e - 02)Q + 420.93

(2c)

t_{Estimated} = (1.34e - 16)Q^3 + (-5.13e - 12)Q^2 + (-9.31e - 07)Q^2 + (3.73e - 02)Q + 782.37

(2d)

Table 2
Error analysis: Goodness-to-fit.

<table>
<thead>
<tr>
<th>Airflow rate (m³/hour)</th>
<th>Total fan pressure (t.p) in pascal</th>
</tr>
</thead>
<tbody>
<tr>
<td>36,000</td>
<td>80</td>
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<td>21,600</td>
<td>350</td>
</tr>
<tr>
<td>14,400</td>
<td>390</td>
</tr>
</tbody>
</table>

† Data set is obtained from the first performance curve i.e 600 rpm of Fig. 2.

Table 3
Data used for fan efficiency estimation.

<table>
<thead>
<tr>
<th>Airflow rate (m³/hour)</th>
<th>Total fan pressure (t.p) in pascal</th>
<th>Fan efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>36,000</td>
<td>80</td>
<td>30</td>
</tr>
<tr>
<td>33,120</td>
<td>140</td>
<td>46</td>
</tr>
<tr>
<td>28,080</td>
<td>220</td>
<td>64</td>
</tr>
<tr>
<td>21,600</td>
<td>355</td>
<td>83</td>
</tr>
<tr>
<td>14,400</td>
<td>390</td>
<td>71</td>
</tr>
</tbody>
</table>

† Data set is obtained from the first performance curve i.e 600 rpm of Fig. 2.

3.2. Ventilation fan efficiency calculation

Fan efficiency (μ) is a parameter to estimate the expected energy consumption. And, defined as the ratio of the power input to the airflow rate to the power delivered by the motor. The power of the airflow rate is the product of the total fan pressure and the airflow-rate.

 efficiency(μ) = \frac{\text{total pressure}(t.p) \times \text{airflow rate}(Q)}{P}

(4)

Where P is the power required to move the fan under the normal operating conditions. Fan efficiency is estimated with the help of a regression model. Expected efficiency is computed using given airflow rate and total pressure. Table 3 shows an example of such data set for the fan running at 600 rpm. Again, the data in Table 3 is obtained from the ideal fan curve, (Fig. 2).

3.2.1. Support Vector Regression (SVR)

Support Vector Regression (SVR) is used to predict the fan efficiency values. SVR is a popular regression technique coming from the machine learning research community [30]. It uses a set of labelled training data, that consist of feature vector and target output.

- Support Vector: The training data points that are closest to the hyperplane i.e. the separation line between the data classes are called support vectors.
- Kernel: A kernel function transforms the data into a higher dimensional feature space to perform the linear separation.

The underlying idea behind the SVR is to compute a linear regression function in a high dimensional feature space, where the input data points are mapped via a non-linear function.

SVR offers certain advantages over other modeling techniques such as Simple linear regression (SLR) and Ordinary least square (OLS). It belongs to the Support vector machine (SVM) classification algorithm.
The advantage of SVR is that it predicts the real values rather than a class. Besides, SVR acknowledges the presence of non-linearity attributes in data points. Contrarily, other modeling techniques have limitations in this context. Moreover, the kernel function in SVR specifies which type of algorithm is to be used. For example, a polynomial kernel is preferred when input and output data have a non-linear relationship, [30].

\[
\mu_{estimated} = f(\text{airflow rate}, \text{total fan pressure})
\]  

(5)

In the present case, efficiency is estimated in terms of airflow rate of the fan and total fan pressure (Eq. (5)). Airflow rate and total pressure is defined as features and estimated fan efficiency is considered as the output target. A third order polynomial relation is observed as the best fit between fan efficiency, airflow and total fan pressure. Figure below shows the estimated efficiency using measured airflow and total pressure as input to SVR.

Error analysis of model gives a minimum root mean square value RMSE=1.35 and Rsquared error=1.0 for a 3 degree polynomial.
Moreover predicted efficiency is relatively close to the actual efficiency provided by the manufacturer.

3.3. Expected fan energy consumption

Estimated fan energy ($E_{\text{expected}}$) consumption is computed with the help of measured airflow rate ($Q_{\text{measured}}$), estimated total pressure ($tp$), estimated efficiency ($\mu_{\text{estimated}}$) and the number of operational hours ($t_h$). In the proposed methodology, measured fan energy consumption ($E_{\text{measured}}$) has been compared against the estimated fan energy consumption. Measured values of fan energy consumption ($E_{\text{measured}}$) can be easily obtained from the installed energy meters. Further, in order to estimate an expected energy consumption following equation is used.

$$E_{\text{expected}} = \frac{(1 \times \mu_{\text{estimated}} \times Q_{\text{measured}})}{\mu_{\text{estimated}}} \times t_h$$

Eq. (6) yields the expected fan energy consumption in Kilowatt-Hour. In above equation $t_h$ is computed from the energy meter reading and represent the total number of hours of active meter reading i.e., use of ventilation system. Notwithstanding, the relation between different variables in Eq. (6) is dependent. To address the simplicity in error propagation the higher terms with correlations are ignored. Error, in $E_{\text{expected}}$ could be calculated by the Eq. (7) considering the error free measurement of $t_h$.

$$\delta E_{\text{expected}} = |E_{\text{expected}}| \sqrt{\left( \frac{\delta Q_{\text{measured}}}{Q_{\text{measured}}} \right)^2 + \left( \frac{\delta Q_{\text{measured}}}{Q_{\text{measured}}} \right)^2 + \left( \frac{\delta Q_{\text{measured}}}{Q_{\text{measured}}} \right)^2}$$

Where, $\delta (Q_{\text{measured}})$, $\delta (Q_{\text{measured}})$, are difference error value between manufacturer data and estimation, while $\delta (Q_{\text{measured}})$ is accounts for the error in airflow measurement (Fig. 8). In the next section, a case-study is presented to test the performance of different fan units in OU44 building.

4. A case-study: OU44 building

A highly energy efficient building, called OU44 (Fig. 5) have been considered as an experimental platform. Building OU44 is an academic building and located in the campus of University of Southern Denmark, SDU. A succinct description of the building OU44 is given below.

- Building Name: OU44
- Area: 9600 square-feet
- Building type: Academic building
- Operating hours/week (Max 168)
- Location: Odense, Denmark
- Year of construction: 2015

Building OU44 is relatively a newly constructed building in the campus of University of Southern Denmark. The construction project was completed in 2015, however, the building became fully functional since February 2016. In addition, OU44 is meeting the requirement of Danish Building Low energy class 2015. Several sensors and communication protocols are installed to assess the efficient data measurements and performance monitoring. Moreover, 11 performance tests are implemented to assure the continuous performance of building. [31]. OU44 is divided into 4 quadrants with essentially the same ducting and the same size of ventilation. Ventilation channels are routed from units in basements via installation shafts to the individual floors, from which ducts are routed around the floors over suspended ceilings. Ventilation unit namely, VE01, VE02, VE03 and VE04 cover most of the premise in SDU, OU44. The ventilation systems are equipped with rotatory heat-exchanger, which recovers heat and cooling.

In Fig. 6 a schematic representation of the Ventilation unit VE02 is provided, taking into consideration that other units have similar representation. However, unit VE01 is not considered in present case study, due lack of measured data.

The ventilation systems at OU44 are of the type VAV (Variable Air Volume) which serves three floors called the ground floor, living room and 1st floor. Living room and ground floor are divided into zones with one or more VAV dampers. The first floor in the same way, but further there is an office area where the offices are provided with VAV dampers and common exhaust with a pressure holding damper which regulates the total extraction in relation to the total supply air. Each AHU unit has an exhaust fan, outside and supply airflow measuring stations, mixing box, pre-filter, final filter, heating hot water coil, chilled water coil, and supply fan.

The use of ventilation units is CO2 driven and controlled by the indoor CO2 sensor and damper control signal. Except, weekend and official vacation in SDU campus all ventilation units runs year-long with scheduled 8–9 h in a day.

4.1. Description of fan unit in OU44 ventilation unit

A centrifugal fan (Fig. 7) provided by NK Industri (NKI) is installed in ventilation unit. NKI climate control units are integrated with either centrifugal fans, axial fans or chamber fans.

The centrifugal fans can include 2 more variants:

- BK wheels are provided with backward curved blades which are used at pressures up to 1600 Pa. The fans have a high efficiency and thus good operating economy. This fan type is suitable for plants with changes in air performance and energy consumption.
- BK/K wheels are equipped with rear curved blades in extra reinforced version for pressures up to 3000 Pa. The work area is indicated on the fan curves with colors.

The BK and BK/K wheels are driven by a jacket-cooled norm motor via an adjustable V-belt drive, which is mounted on the mounting frame, separated from the panel construction via elastic connections and vibration dampers. These fans have a high efficiency and thus economical. This fan type is suitable for installations, with changes in air performance and energy consumption. At the start of the HVAC, the main damper is opened. When both end stop switches indicate open damper, the fans are started via a ramp mode in the frequency inverters and the controls are released. The airflow for each fan is calculated in CTS (Clear-to-send) programs based on pressure measurements at the input rings for supply and return fan, respectively. Fan electricity consumption (absorbed electrical power) should be provided in the CTS system with a high temporal resolution in conjunction with continuous exercising.

4.2. Airflow rate data acquisition and total pressure estimation

Building OU44 introduced earlier is being considered as an experimental platform. Three ventilation units VE02, VE03, and VE04 are considered for the analysis. Airflow sensors are installed inside the airflow measuring stations in the Schneider BMS system to record the airflow.
rate for three ventilation fan units. Accuracy of the airflow measuring satiation is marked as $\pm 2\%$ at 6000 feet per minute $\pm 0.5\%$ at 2000 feet per minute. A graphical user interface sMAP 2.0 is a plotting engine to display the raw data. In order to deal with missing data and ambiguity in measurements, the measured data is re-sampled with the one minute sample period.

Moreover, measured airflow data between the dates 03-May-2017 to 30-May-2017 is utilized to model the fan performance. Fig. 9 shows on-site measured airflow rate from three fan units. In-fact, the measured airflow values range between (0 and 25,000) m$^3$/h. Fan’s rotational speed is also measured in revolution per minutes (rpm). Except few outlier values, fan speed varies between the 600 and 800 rpm. Also, ventilation fans follow the 600 rpm performance curve (Fig. 2), expect few peak values.

Further, fan’s energy consumption is measured with the help of on-site installed energy meters. These energy meters are dedicated to measure the power consumption of fan at every two minute time sample. Furthermore, total fan pressure is used to define the fan performance requirement. Total pressure across the fans is estimated using the Eq. (2a) and shown in Fig. 10.
Fig. 9. Airflow (supply fan) from ventilation unit (a) VE02 (b) VE03 (c) VE04.

Fig. 10. Estimated total pressure for ventilation fan unit VE02, VE03, VE04.
Fig. 11. Expected and actual fan energy consumption of ventilation unit (a) VE02 (b) VE03 (c) VE04.

Expected total pressure difference and airflow rate follow a non-linear relation. At a certain point maximum total pressure difference is observed and after this peak pressure starts decreasing even for increasing airflow rate. This is the point of maximum performance for the corresponding fan unit.

Comparing the estimated total fan pressure with the performance curve provided in Fig. 2, it is very obvious that each fan unit is operating between the total pressure range 260–400 pascal at 600 rpm. Further, estimated pressure difference is used to compute the expected energy consumption of the respective fan units.

5. Test result and Fan’s performance gap analysis

The methodology proposed in Section 3 is applied to compute the expected energy consumption. Measured energy consumption is obtained from the energy meter data. Recalling Eq. (6) the expected energy is
computed for a given period. Further, Eq. (1) computes the performance gap.

Nevertheless, during the building commissioning of OU44 is was assumed that $\pm 30\%$ (i.e., $DN^+ = +30\%$ and $DN^- = -30\%$ of expected consumption) difference in expected and actual energy consumption is accepted. Indeed, this difference is considered as a design number (DN) for the acceptable performance region. It is an acceptance margin. If the operation lies between this margin the operation is set to be acceptable, in contrary, if the operation gap goes beyond that margin, an anomaly is detected and this persists a chance of failure is likely. Fig. 11 compares the expected and actual energy consumption. Indeed, during the several operation days, it is found that actual energy consumption is significantly higher than expected consumption for unit VE03 and VE04. Zero performance gap is observed during the weekend operation.

A certain level of uncertainty in expected energy consumption calculation is also anticipated. Estimation error analysis in estimated energy consumption for three ventilation unit is computed with the help of Eq. (7). Fig. 12 explain the estimation error analysis. Regardless the values that have no error, the error values are distributed between 0.1 and 0.5 KWh-day.

A fan operating beyond the accepted performance region clearly indicates an anomaly in the fan unit. The maintenance services need to be informed if a ventilation fan unit consuming beyond the accepted performance gap for the several days.

The difference between expected and actual performance for the whole period is illustrated in Fig. 13. Fan in the ventilation unit VE03 is showing the maximum performance gap i.e (40.2%) followed by VE04 (20.4%), while VE02 reports the least performance gap, 1.4%. The issue with VE03 and VE04 was unnoticed due to the lack of available performance test of the ventilation fan unit. Often, building maintenance team perform a scheduled maintenance to monitor the performance of the ventilation unit in building OU44. However, in present scenario a meaningful amount of energy waste is reported because of poor fan unit performance. Though, above difference in energy consumption is noticed only for the supply fans. Assuming that return fans have similar capacity, this difference could be also expected for the return fans as well.

5.1. Discussion

Fan unit VE03 and VE04 have reported poor performance test result for the whole month, clearly indicates an abnormal behavior of ventilation units. Aforesaid, there are several possible causes for a over and under performing fan unit. Moreover, the fault diagnosis and isolation is not the primary concern for this work. Proposed performance test could be a starting point to commence a deeper diagnosis of internal fan components. Apart from the faulty components there are several other issues such as clogged filter, broken duct or aging of fans could be responsible for the poor performance. Nonetheless, OU44 is newly commissioned building and aging of fans could not be a potential cause for performance gap. The other most common issue related to fan performance is dampers are not following the control logic and creates an additional effort to move fan unit. Moreover, fan performance could be improved by improvising duct, fan filter cleaning. Installing proper diffusers is the most efficient and economical way to improve fan performance. It
evenly distribute the flow of air, in the desired directions of building and reducing the total pressure across the fan.

6. Conclusion

Mechanical ventilation plays an critical role in achieving desired level of indoor comfort in both active and passive buildings. Often, building maintenance teams are unable to monitor the poor performing ventilation fan unit. A systematic approach to performance monitoring requires different tests explaining the normal and abnormal behavior of a particular component. Ventilation fan unit is an essential component to test. Research work in this paper compares the expected and actual ventilation fan unit performance. Proposed test utilize the fan performance curve to model the expected fan performance. Further, the proposed methodology uses two data driven models to compute the total fan pressure and expected fan efficiency. Moreover, Support vector regression (SVR) model is used to estimate the expected fan efficiency. The results demonstrate a real scenario in building and have confidence in on-site measured data. The proposed methodology and analysis can help building facility managers to understand the fan performance in a mechanically ventilated building. Further, this performance test could be integrated with building performance monitoring dashboard to analyse actual performance of a fan unit. The limitation of this method is that it requires manufactures data to model performance curves, however, in some cases it is not available easily.

In future emphasis will be given to develop performance test for other components like dampers, heat exchanger, heating loops, and ductwork. Developing different performance tests, will also facilitate the fault isolation issue by narrow down the other possibilities of faults. Diagnostic explanation and cause isolation is also considered as a future challenge. Indeed, the global aim of the future work is to generate a minimum set of faults or misuses explanation by combing the performance tests, expert-knowledge and diagnostic algorithm such as logical diagnosis or diagnostic from the first principal reasoning. The another objective of this work is to combine this test with other performance tests to develop a complete whole building diagnostic framework.

Sample availability

Sample data analysed during experiment and modeling are available from the corresponding authors.

Conflict of interest

The authors declare that there is no conflicts of interest.

Acknowledgments

Authors would like to thank to NK Industri for sharing ventilation fan data.

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[21] ISSN 0886-7798.