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## A New Constant Air Volume Flow Regulation Method for Blowers Used in HVAC&R Systems

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### ABSTRACT

Accurate constant air volume flow rate regulation is essential in HVAC&R systems to provide comfort and required system performance. In the motor which drives a forward curved blower, the torque is regulated to provide the required air volume flow rate by monitoring the motor rotational speed. Various correlations including exponential functions and high order of polynomials used to regulate the torque in terms of motor speed and air volume flow rate are presented in the literature. However, none of these formulas has addressed the issue of inaccuracy of the air volume flow control in areas where the air density is different. Therefore, a new 5-coefficient formula is proposed in this paper to maintain the constant air volume flow rate regardless of the changes in air density.

### 1. INTRODUCTION

In the residential heating, ventilating and air conditioning systems, the constant air flow control method provides thermal comfort and energy savings to customers. The motor used to drive an indoor centrifugal blower receives air flow rate demand from the OEM system control board. The motor is operating in the torque control mode. With the air flow rate demand, the motor torque is regulated along with the monitored instantaneous motor rotational speed, to provide the required air flow rate.

There are several torque(power)-speed-volume flow rate correlations presented in the literature. Sasaki (2017) proposed a 5-coefficients formula to calculate the motor torque in terms of speed and volume flow rate. The torque formula was derived by dividing the target air flow by speed, a square of the speed. Shahi (2009) proposed motor torque formulas in terms of motor speed and volume flow rate. In these formulas, a composite function in the form of  $\Sigma N^m Q^n$  was used. Shahi et. al. (2013) presented a method to correct fluid flow offset for an uncharacterized fluid handling system including a motor. In this method, in order to provide accurate airflow, the motor torque was calculated by a four coefficient correlation using motor speed and volume flow rate. Wang et. al. (2017) disclosed a method to maintain the constant air flow control by equaling the motor power with the target motor power. The motor power and speed were determined based on the static pressure. A target power yielding the target air flow rate was obtained. A five and fewer coefficients correlation was claimed to calculate the motor power in terms of motor speed and volume flow rate.

However, to the authors' knowledge, none of these correlations has addressed the issue of density effect on the motor torque control accuracy yet. When the air density changes, for example, in high altitude regions, the motor torque control accuracy decreases due to the less dense air compared to that when the blower is characterized. In the torque control mode, the relation among torque, speed and volume flow rate is used to regulate the motor torque. Generally, the torque-speed-volume flow rate plane is characterized in the Lab in regions of low altitude. Due to the density change in high altitude regions, the pre-determined torque-speed-volume flow rate relation is not appropriate anymore.

A new 5-coefficient torque correlation is proposed in this paper to address this issue by introducing an explicit density term into the correlation. The air density at a specific application location can be predefined as an input to the correlation.

## 2. AIRFLOW REGULATION IN RESIDENTIAL HVAC SYSTEMS

### 2.1 Fan and Its System

Centrifugal fans (indoor blower, draft inducer) are widely used in residential air handlers to provide required air volume flow to maintain the room temperature and humidity in a certain range. A typical forward curved fan performance curve is shown in Fig. 1. The variation of the fan static pressure over the air volume flow rate is given at a constant speed,  $N_1$ .  $S_1$  is a typical system characteristic curve which is usually approximated as a parabolic curve. The intersection between the fan curve at speed  $N_1$  and system curve  $S_1$  is the fan operating point. At any operating point, the fan static pressure head matches the duct system static head to overcome the system resistance consisting of dampers and any other restrictions in the duct system. If the fan speed is reduced from  $N_1$  to  $N_2$  while the system resistance keeps constant, the fan operating point will move from point A to point B. The air volume flow rate is reduced consequently. If the system resistance increases by any means, the system curve  $S_1$  becomes  $S_2$ . If the fan still runs at the same speed  $N_1$ , the operating point will move from point A to point C, thus, the air volume flow rate is reduced as well.

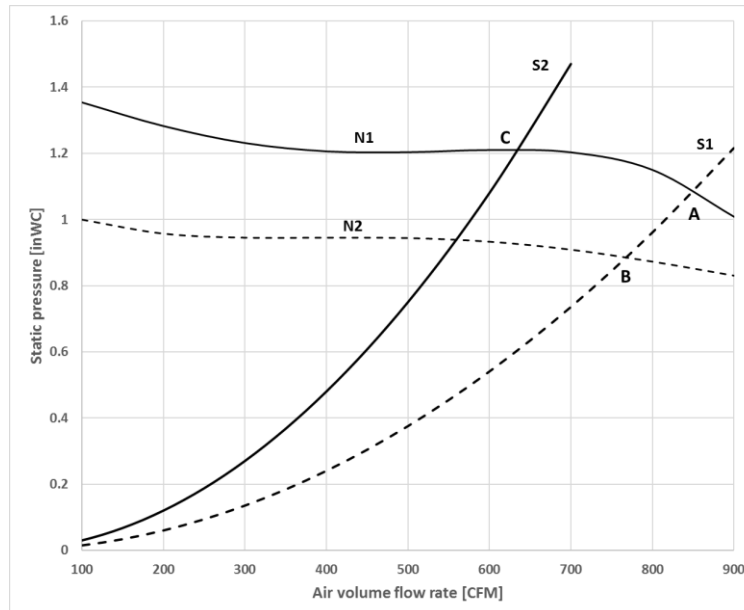


Figure 1: Typical fan curve and system curve

### 2.2 Fan Laws

The fan laws are used in the design and selection of fans. According to the fan performance (static pressure, power, torque, and etc.) at one operating condition, the fan performances at other operating conditions can be predicted as

long as three similarity conditions are satisfied: geometric similarity, kinematic similarity and dynamic similarity. The following fan law equations are generally used.

$$\frac{Q_2}{Q_1} = \frac{N_2}{N_1} \quad (1)$$

$$\frac{T_2}{T_1} = \frac{N_2^2}{N_1^2} = \frac{P_{st,2}}{P_{st,1}} \quad (2)$$

Where,  $T$  is the fan shaft torque,  $N$  is the fan rotating speed. The air volume flow rate,  $Q$  varies linearly with the fan speed as shown in Eq. (1). The static pressure,  $P_{st}$  has a relation of square with the speed,  $N$ .

Using the torque and speed, the shaft power,  $P$  into the fan can be calculated by Eq. (3), which has a relation of cube with the speed.

$$\frac{P_2}{P_1} = \frac{N_2^3}{N_1^3} \quad (3)$$

The portion of shaft power transferred into the air flow is calculated by

$$P_{air} = P_{st} \cdot Q \quad (4)$$

The fan efficiency,  $\eta$  is estimated,

$$\eta = \frac{P_{st} \cdot Q}{T \cdot N} \quad (5)$$

The motor-fan system efficiency,  $\eta_{sys}$  can expressed as,

$$\eta_{sys} = \eta_m \frac{P_{st} \cdot Q}{T \cdot N} = \frac{P_{st} \cdot Q}{P_{input}} \quad (6)$$

Where,  $\eta_m$  is the motor efficiency.  $P_{input}$  is the motor input power.

### 2.3 Constant Air Flow System and Control

In the residential HVAC systems, the blower motor can be set at several discrete speeds to accommodate the system requirements of different air volume flow rates to provide the comfort to the end users. However, as described in Section 2.1, running motor at a constant speed could not detect the change of the system resistance (static pressure) to adjust the air volume flow rate accordingly. The motor is usually designed to provide a certain air volume flow rate at a specified static head. When the system resistance is off the design point, the air volume flow rate either decreases (system resistance increases, e.g. humidifier added) or increases (system resistance decreases, e.g. duct cleaned).

Young (1989) proposed a method to maintain a required air volume flow rate regardless of the change of the system resistance. The constant air volume flow is beneficial to maintain the designed overall heat transfer performance of a refrigerant-air fin-tube heat exchanger.

Fig. 2 shows the variation of the air volume flow with respect to the system resistance (static pressure), driven by constant speed control and constant air volume flow rate control. It is clearly seen that, the air volume flow rate changes significantly with the system static pressure under the constant speed control. In contrast, the air volume flow rate keeps relatively constant regardless of the static pressure variation if the constant air flow control method is used.

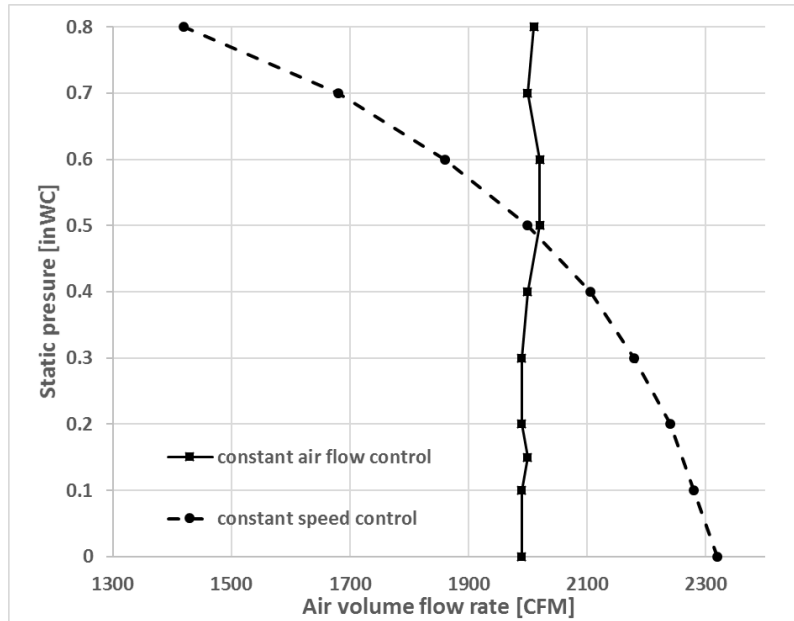


Figure 2: Comparison of air volume flow rate curve using constant speed control and constant air flow control (Becerra and Beifus, 1996)

The constant air volume flow rate control algorithm requires the input torque of the fan and fan speed to be controlled/monitored over the whole Torque-Speed plane. This algorithm can be used with any motor drive which has the torque and speed regulation. However, currently this algorithm is mainly implemented on the ECM (Electronically Commutated Motor) motors.

With the air volume flow rate command from the HVAC system control board, either the motor torque or motor speed is regulated by monitoring its speed or torque to provide the required air flow. Becerra and Beifus (1996) proposed the following four-coefficient torque correlation to regulate the motor torque based on the required air volume flow rate and instantaneous motor speed.

$$T = k_1 \cdot N + k_2 \cdot N^{k_3} \cdot Q^{k_4} \quad (7)$$

Where,  $T$  is the motor torque required to maintain a constant air volume flow rate at a the corresponding motor rotational speed.  $N$  is the motor speed.  $Q$  is the air volume flow rate.  $k_1 \sim k_4$  are constants determined by actual motor torque, speed and delivered air volume flow rate taken at different static pressure levels in the lab.

Other forms of torque correlation formula are also proposed in the literature as mentioned in the introduction section. However, none of these correlations addresses the effect of air density in field application. A new torque correlation with an explicit density term is proposed as follows

$$T = \rho \cdot (k_1 \cdot N \cdot Q + k_2 \cdot Q^2 + k_3 \cdot N + k_4 \cdot N^2 + k_5) \quad (8)$$

Where,  $\rho$  is the air density.  $k_1$ ,  $k_2$ ,  $k_3$ ,  $k_4$  and  $k_5$  are constants for a particular blower to be operated by the motor. This new correlation includes an explicit density term to accommodate the change of air density in various applications.

### 3. RESULTS AND DISCUSSIONS

The use of the proposed 5-coefficient torque calculation formula with density settings was validated against the testing data from two forward curved blowers of different sizes. During the testing, the air density changes little which was

approximated with a constant. The blower was operated to provide different air volume flow rates. For each air volume flow rate, the motor speed and torque varied to provide the required constant CFM under different static pressure levels. The motor torque was regulated as a percentage torque. The relative error of predicted percentage torque calculated from the proposed torque formula was shown in Fig. 3. It is found that, overall, the predicted percentage torque agrees well with the percentage torque recorded in the testing even in the lower percentage torque range. The mean absolute error (MAE) is 1.43% for blower 1 and 1.12% for blower 2.

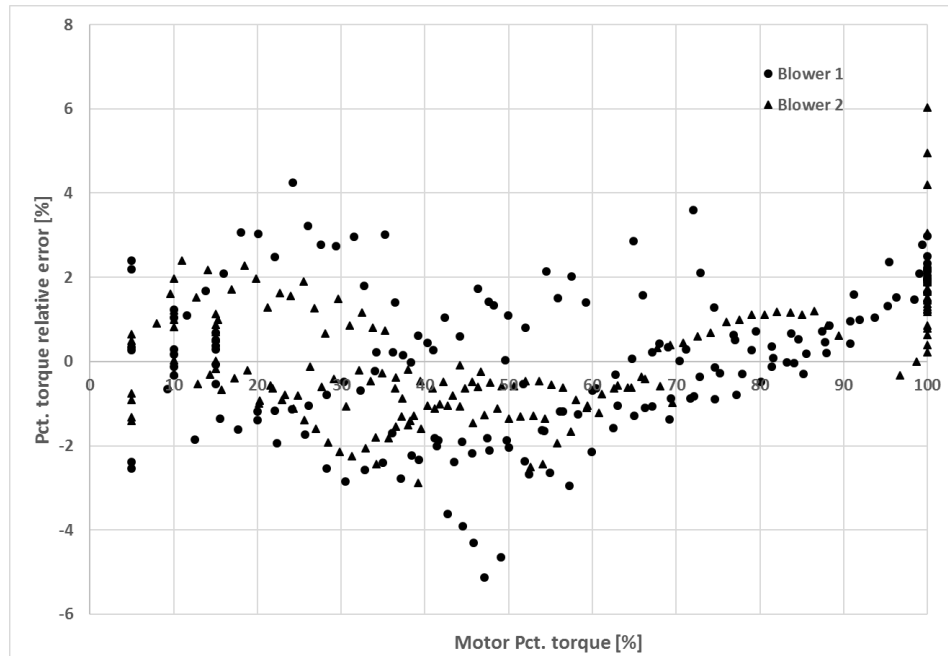


Figure 3: Relative error of predicted percentage torque

Fig. 4 gives the percentage torque-speed-air volume flow rate 3D surface taking the data of one of the blowers as an example. This 3D surface is constructed according to the proposed torque calculation formula. It is found that all the little blue dots which are actual testing points are located well on this surface. Moreover, this new 5-coefficient torque formula generates a surface which is very smooth and flat over a wide range of speed, air volume flow rate and percentage torque. The smoothness and flatness of the surface result in an excellent extrapolation capability of the proposed formula once the actual operating conditions are out of the testing conditions.

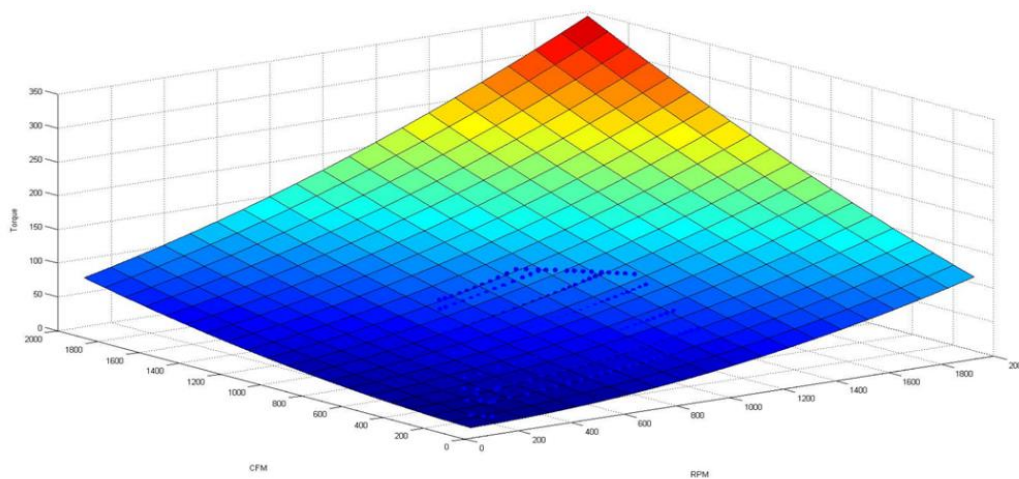


Figure 4: Torque-Speed-Volume Flow Rate 3D surface for blower 2

#### 4. CONCLUSIONS

A new 5-coefficients torque correlation is proposed for the constant air volume rate regulation algorithm used for residential centrifugal fans. An explicit density term is included in the proposed correlation which can address the effect of the air density on the implementation of the torque correlation at different applications, e.g. at different high latitude regions.

The form of the proposed correlation is validated against the testing data of two blowers of different sizes. Overall, the predicted percentage torque agrees well with the actual recorded data.

#### NOMENCLATURE

k	constants	(-)
N	motor speed	(RPM)
Q	air volume flow rate	(CFM)
P	pressure, power	(inWC)/W
T	motor torque	(-)
$\eta$	efficiency	(-)
$\rho$	density	(lb/ft <sup>3</sup> )

#### Subscript

input	motor input
m	motor
st	static
sys	system

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