Development of Power-head Based Fan Airflow Station

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Abstract

Fan airflow measurement is critical for heating ventilation and air conditioning (HVAC) system operation, control, and fault detection. It has been a challenge for HVAC professional. Since fan curves under a given fan speed can relate fan airflow to fan head or fan power, both fan head based and fan power based fan airflow stations have been developed and implemented in many air handling units (AHUs). The fan airflow station obtains the airflow based on the measured fan curve, fan speed and fan head or fan power. However, it is hard to obtain accurate fan curves since airflow measurement is still required to determine fan curves. On the other hand, the fan airflow can be obtained by measured fan power and fan head with fan efficiency curve. Since the fan efficiency varies slightly when the HVAC system airflow changes, the power-head based fan airflow station mainly depends on fan head and fan power measurement. The paper presents the theoretical models and the experiments of the power-head based fan airflow station.

Introduction

In a variable air volume (VAV) air handling unit system, the supply airflow varies with building load using variable frequency drive (VFD) to modulate supply fan speed to maintain a static pressure set point. To maintain the appropriate positive building pressure, the return airflow must be properly tracked with the supply airflow. The return airflow should be slightly less than the supply airflow. The difference between the supply and return airflow depends on building exhaust airflow and envelope tightness. One of tracking measures is to modulate the return fan speed to maintain the difference between the supply airflow and return airflow. The airflow is measured using flow stations in the main supply duct and in the main return duct [1].

In a laboratory exhaust system, the exhaust airflow varies with the fume hood sash position. Therefore the laboratory exhaust system is a VAV system. On the other hand, the stack exit velocity should be controlled for adequate dilution. Therefore multi-stack system is developed for the requirement of exit velocity. The exit velocity can be controlled in a required range by using different stack combination based on the measured actual building exhaust airflow [2].

The airflow measurement plays an important role in the HVAC system operation. However, the airflow station requires a straight duct for 6-10 duct diameters upstream and 3 duct diameters downstream. There are very few systems that have such duct run in the main ducts. In order to obtain accurate airflow, Liu developed a fan airflow station to obtain the fan airflow using the fan speed and head based on the regressed fan curve [1]. The experiment was conducted to verify the fan station and an excellent agreement between the model and the experimental values was found [3]. The accuracy of the fan airflow station depends on the accuracy of the fan curve. Since the fan installation configuration is different with the testing condition, the actual fan curve is

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different with the manufacturer's fan curve. An in-site fan curve measurement was developed for VAV AHU System [4].

The fan airflow station works very well in the high airflow range where the fan head is sensitive to the fan airflow. However, the fan head varies slightly in the small airflow range. Therefore, it is difficult to obtain the fan airflow using the fan head in the smaller airflow range. Unfortunately, the fan may works in this airflow range under partial loads. On the other hand, in most of airflow range, the power curve varies exquisitely. Wang and Liu developed the VFD airflow station to obtain the fan airflow using the power and speed based on the power curve.

Both the fan airflow station and the VFD airflow station depend on measured fan head curve or fan power curve and measured fan speed. First, the airflow measurement is required to obtain the fan curve. As we mentioned previously, it is difficult to obtain accurate airflow in systems. It may result in an inaccurate fan curves. Secondly, the measured airflow is proportional to square of the measure fan speed using the fan head curve or cube of the measured fan speed using power curve. The accuracy is mainly related to the measured fan speed. Actually the measured fan speed is assumed to equal the motor synchronous speed, which is proportional to the VFD frequency. Theoretically it is not true. The difference between the synchronous speed and motor speed depends on the motor load. The less motor load results in the less speed differential. Therefore, it is hard to accurate fan curve and fan speed. Finally the fan curve based fan airflow has accurate problems.

On the other hand, the fan efficiency does not change much around design working point when the fan airflow changes. This gives us an opportunity to obtain fan airflow using the measured fan power and fan head directly without the fan speed and fan curve

involved. The paper presents the basic theory, experiment and results of the power-head based airflow station.

Theory

Figure 1 shows variable speed fan connection schematic. VFD is normally installed on the motor to adjust the motor speed by modulating frequency. Typically the motor power input can be obtained from VFD output terminal. Both motor and fan have the mechanical energy loss, such as heat generation loss and friction loss. So the fan output mechanical energy can be expressed as:

$$Q \cdot H_{fan} = W_{fan} \cdot \eta_{fan} = W_{motor} \cdot \eta_{motor} \cdot \eta_{fan} \quad (1)$$
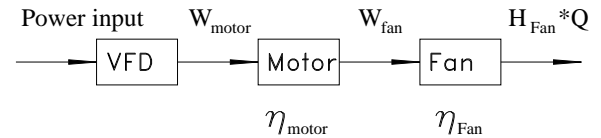

Figure 1: mechanical connection

Since the motor input power can be provided by VFD and the fan head is easy to be measured, the fan airflow can be obtained using this relationship if the motor and fan efficiency is known.

$$Q = \frac{W_{fan} \cdot \eta_{fan}}{H_{fan}} = \frac{W_{motor} \cdot \eta_{motor} \cdot \eta_{fan}}{H_{fan}} \quad (2)$$

Based on the motor theory, the motor efficiency is the function of the motor power.

$$\eta_{motor} = f_1(W_{motor}) \quad (3)$$

Typically the motor efficiency can be considered as a constant when the motor power changes from 25% to fully load. Figure 2 gives the motor efficiency

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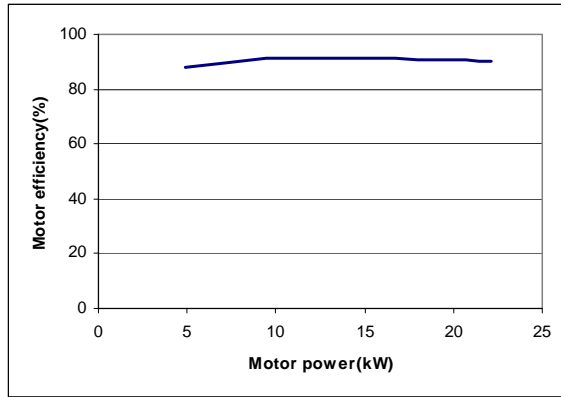curve with the motor power provided by motor manufacture.

Figure 2: Motor efficiency with motor power

Typically the fan head and fan power curve under a given fan speed are provided by fan manufacture. Then the fan efficiency curve can be easily achieved from the fan head and the fan power curve. Figure 3 shows the fan head curve and efficiency curve with the fan airflow under given fan speed for the backward centrifugal fan.
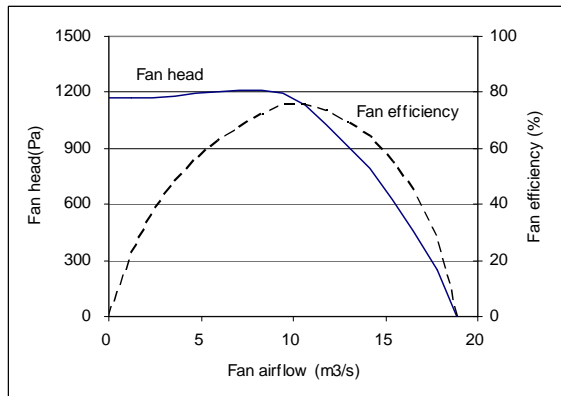

Figure 3: fan head and efficiency with fan airflow under a given fan speed

Figure 3 also shows that fan efficiency is the function of fan airflow and fan speed. In order to eliminate the fan speed, the fan law is applied. It can be proved that the fan has a same efficient under a

same ratio H_{fan}/Q^2 no matter what the fan speed is. In other words, the fan efficiency is the function of H_{fan}/Q^2.

$$\eta_{fan} = f_2(\frac{H_{fan}}{Q^2}) \qquad (4)$$

For any fan airflow under a given fan speed, the fan head can be obtained from the fan head curve and the ratio H_{fan}/Q^2 can be easily obtained. Then the fan efficiency curve can be redrawn with the ratio H_{fan}/Q^2 in figure 4.
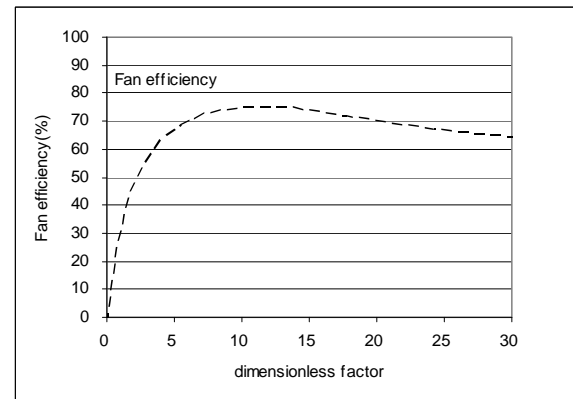

Figure 4: fan efficiency versus H_{fan}/Q^2

Substitute Eqs. (3) and (4) into Eq. (1).

$$Q = \frac{W_{motor} \cdot f_2(W_{motor}) \cdot f_1(\frac{H_{fan}}{Q^2})}{H_{fan}} \qquad (5)$$

Therefore, the fan airflow can be obtained from the measured motor power and the measured fan head.

The actual motor efficiency and fan efficiency

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will change based on the system operation. Normally in the VAV system, the fan speed is modulated to maintain the duct static pressure at its set point when airflow changes. The curve control curve depends on the chosen design fan head and the static pressure set point. If the design working point is chosen to have the high efficiency and the static pressure set point is 10% and 25% of the design fan head respectively, the system control curves are shown in figure 5.
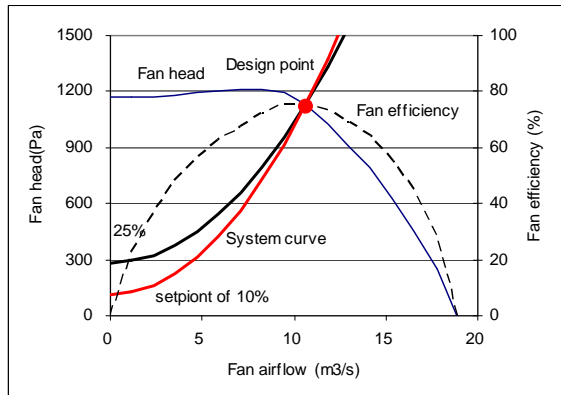

Figure 5: System control curve with different static pressure set points

Since the fan efficiency is a function of ratio H_{fan}/Q^2, these system curves are redrawn in Figure 6 with coordinates of fan airflow and ratio of H_{fan}/Q^2. The fan efficiency is also drawn in the same chart. The ratio H_{fan}/Q^2 under different airflow can be obtained by following different system control curves and then the fan efficiency can be obtained by the ratio H_{fan}/Q^2. With a setpoint of 10% of the design fan head, the ratio H_{fan}/Q^2 changes from 10 to 15 (from A0 to A1) when airflow decreases from the design airflow to the half. With a setpoint of 25%, the ratio changes from 10 to 20 (from A0 to A2). As results, the fan

efficiency changes from 75.4% to 73.7% (from B0 to B1) for 10% setpoint and from 75.4% to 70% (from B0 to B2) for 25% of setpoint. It can be seen that the fan efficiency is not sensitive to the airflow change. The fan efficiency slightly deceases as the fan airflow decreases.
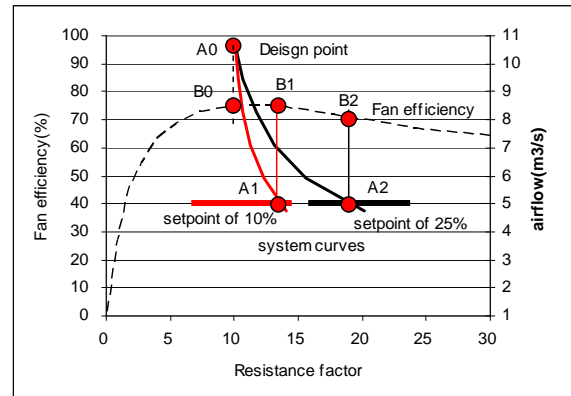

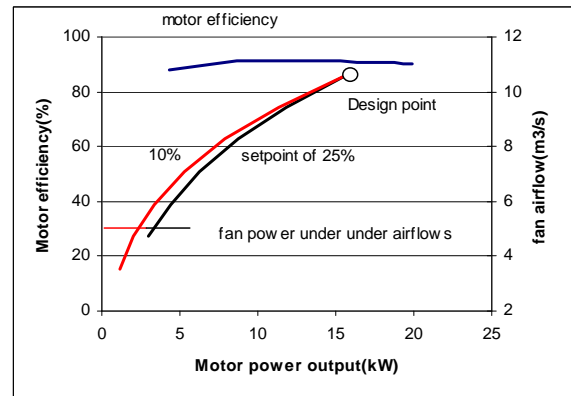**Figure 6**: Fan efficiency versus with fan airflow

Figure 7: Motor efficiency versus fan airflow

Fan head under different airflows can be obtained based on the different system control curves, then the ratio H_{fan}/Q^2 can be used to calculate the fan efficiency, and finally the fan power or motor power input can be obtained. On the other hand, the fan efficiency also can be expressed as the function of the motor input power instead of the motor output. Figure 7 shows the fan required power with the airflow change and the motor efficiency with the fan

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power. The required fan power decreases from 15.7kW to 3.5kW with a setpoint of 25% of the design fan head and from 15.7 kW to 2.0 kW when the fan airflow changes form design value to the half. It can be seen that the motor efficiency is also not sensitive to the airflow change and slight deceases as the airflow decreases.

In reality, the measured static pressure differential is not the fan head. The equivalent efficiency should replace the fan efficiency. The measured static pressure is the fan head minus the dynamics pressure and the pressure loss. So the measured static pressure differential can be expressed:

$$\Delta H = H_{fan} - SQ^2 \qquad (6)$$

The equivalent fan efficiency is expressed as:

$$\eta = \frac{Q \cdot \Delta H}{W_{fan}} = \frac{Q(H_{fan} - SQ^2)}{QH_{fan}/\eta_{fan}}$$

$$= \eta_{fan} \cdot (1 - S\frac{Q^2}{H_{fan}}) = f_2(\frac{H_{fan}}{Q^2}) \cdot (1 - S\frac{Q^2}{H_{fan}}) \quad (7)$$

Replace the fan head by the measured pressure differential.

$$\eta = f_2(\frac{\Delta H + SQ^2}{Q^2}) \cdot (1 - S\frac{Q^2}{\Delta H + SQ^2})$$

$$= f_2(\frac{\Delta H}{Q^2} + S) \cdot (1 - \frac{S}{\frac{\Delta H}{Q^2} + S}) = f_3(\frac{\Delta H}{Q^2}) \quad (8)$$

The factor S depends on the pressure sensor location. For a fixed location, S is constant. The equivalent fan efficiency is still determined by the ratio $\Delta H / Q^2$. Therefore, all equation can be used for the measured pressure differential and the equivalent fan efficiency. The fan airflow can be obtained by the measured motor power and measured pressured

differential with the motor efficiency and the equivalent fan efficiency.

$$Q = \frac{W_{motor} \cdot f_1(W_{motor}) \cdot f_3(\frac{H}{Q^2})}{H} \qquad (9)$$

Experiments

In order to develop the power-head based airflow station, both the motor efficiency and fan efficiency should be known. The motor efficiency can be obtained from motor manufacture and the fan efficiency need be evaluated by experiments.

The experiments were conducted on a laboratory fume hood exhaust system to validate the theory. The exhaust system has a fan with VFD. The VFD modulates the fan speed to maintain the duct static pressure at 1.4 inch of water. The system airflow changes from 5.2m³/s to 6.7m³/s and the motor speed changes from 66% to 74% of the design speed when all fume hood sashes change from full closed position to full open position. The two stacks were designed in the system to ensure the required exit velocity all the time. Two stack are used when the airflow is higher than 5.3m³/s and one stack is used when the airflow is lower than 5.3m³/s. Since the system has a 15 meter long main duct without any branches, the airflow is measured based on the pressure drop through the main duct and then the stack damper is controlled by the measured airflow.

During the measurement the airflow was obtained by the measured duct pressure drop and the motor power were obtained from VDF. Meanwhile, the fan head was measured using the pressure sensor. All the measured parameters are recorded in computer with a time interval. The measurements were conducted under three different speeds, 85%, 75% and 65% of design fan speed. Under each fan speed, the fan airflow was adjusted by changing fume hood sashes from full open position to full closed position.

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Figure 8 shows the average fan head via the fan airflow under 85%, 75% and 65% of design fan speed when the sash positions were changed from closed to full open position. Figure 9 shows the motor power via the fan airflow under same conditions.
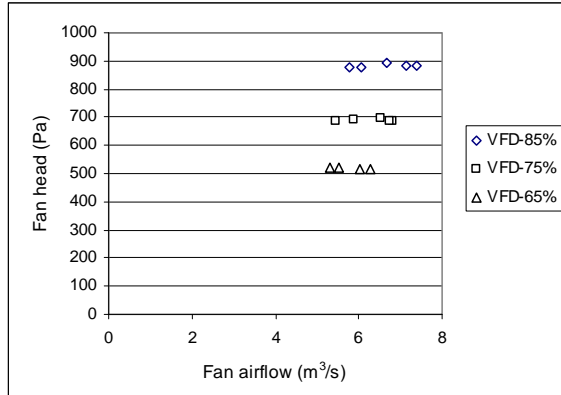

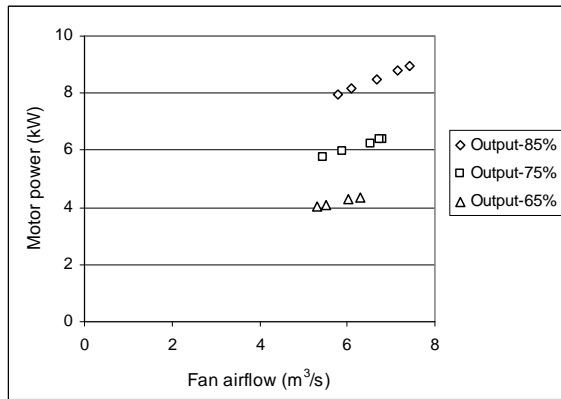**Figure 8:** Fan head under different fan speeds

Figure 9: Motor power under different fan speeds

It is found that the motor efficiencies in the actual motor power range can be regressed as a function of the motor power.

$$\eta_{motor} = f_1(W_{motor}) = 0.87 W_{motor}^{0.04} \qquad (10)$$

The equivalent fan efficiency curve can be obtained introducing Eq.(10) into Eq.(9),

$$f_3\left(\frac{H}{Q^2}\right) = \frac{Q \cdot \Delta H}{W_{motor} \cdot f_1(W_{motor})} = \frac{Q \cdot \Delta H}{W_{motor} \cdot 0.87 W_{motot}^{0.04}} \qquad (11)$$
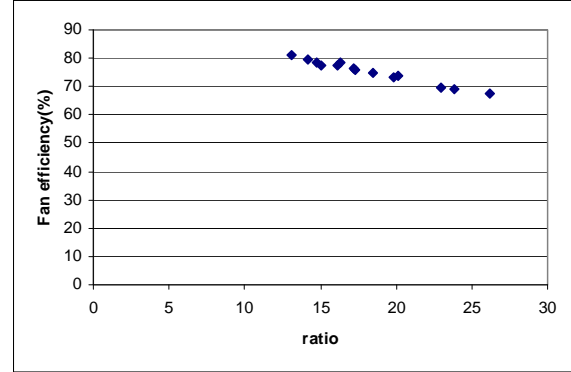

Figure 10: Motor efficiency curve versus

dimensionless factor $\Delta H / Q^2$

Figure 10 shows the motor efficiency curve verse dimensionless factor $\Delta H / Q^2$ based on the measured data in figure 8 and 9. The fan efficiency curve can be regressed using linear expression with the dimensionless factor.

$$\eta = 0.94 - 0.0104 \frac{\Delta H}{Q^2} \qquad (12)$$

Finally the fan airflow can be expressed as the function of the measured motor power and fan head.

$$Q = \frac{W_{motor} \cdot W_{motor}^{0.04} \cdot \left(0.94 - 0.0104 \frac{H}{Q^2}\right)}{H} \qquad (13)$$

Conclusions

The power-head based airflow station theory has been deduced that the airflow can be obtained using the motor power and fan head. A power-head based airflow station was developed in an existing exhaust system. The airflow station mainly depends on the motor power and fan head measurement, so the

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accurate fan airflow can be obtained.

Nomenclature

H - fan head, Pa;

Q - airflow, m^3/s

W - power, kw;

η - efficiency

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