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An innovative analysis and experimental investigation on energy savings of a VAV system in hot and humid climates

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Abstract

An innovative calculation methodology is proposed in this paper which retains the accuracy of sophisticated computer simulation programs, such as DOE 2.1, but maintains the simplicity of simplified building energy calculation methods, such as the Modified Bin method.

The entire calculation procedure is discussed and followed by a full-scale experiment on a VAV (Variable Air Volume) system which successfully demonstrated its effectiveness. This method is now proposed to be adapted as the main part of the national building energy code or PACS index in Taiwan. © 1999 Elsevier Science Ltd. All rights reserved.

1. Introduction

A VAV system automatically supplies less air to the indoor environment when the cooling load is reduced and thus saves energy. There have been a lot of sophisticated and detailed computer programs, such as DOE 2.1, to evaluate this energy saving effect on a seasonal or annual basis. However, there is a need to establish an efficient calculation method, for use by engineers using handheld calculators, to estimate the energy savings potential quickly while not losing accuracy compared to detailed computer simulation results or a full-scale experiment.

The goal of this study is to establish such a methodology, and involves a full-scale experiment to validate the entire process.

2. Theoretical analysis

The accumulated energy use of a VAV system, denoted as Q_a is the multiplication of the actual power consumption, P_x, under a specific load fraction, X, and its hours of operation, $g(x)$. Or, in equation form:

$$Q_a = \sum_{x=0}^{1} P_x \cdot g(x) \tag{1}$$

Following this, many calculation methods were developed, including the bin method, which correlated linearly power consumption, P_x, directly with outdoor temperatures. Since it is true that it takes more energy to cool down a building when the weather is hotter than heat it when the weather is colder, the linear assumption is over-simplified.

P_x represents a fraction $f(x)$ of the rated power consumption at full load Pn, and can be denoted as:

$$P_x = P_n \cdot f(x) \tag{2}$$

The $f(x)$ can be obtained from an experiment by recording P_x at each load fraction, X, and establishing the characteristic curve.

Re-arranging Eq. (1), we can write:

$$Q_a = P_n \int_0^1 f(x) \cdot g(x)\, dx \tag{3}$$

This is the equation which all sophisticated simulation

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programs, such as DOE 2.1, adapted for doing energy calculations.

3. The significance of defining a mean-value X_c from $f(x)$

$$Q_a = P_n \cdot f(X)_c \cdot \int_0^1 g(x)\,dx \qquad (4)$$

By applying the Mean Value theorem, a critical partial load factor, X_c, can be found, so that Eq. (3) becomes:

Where $0 < X_c < 1$

The significance, of Eq. (4) is that $f(x)$ and $g(x)$ are decoupled. The integration term represents the total operation hours under a specific load fraction, X, or the area under the $g(x)$ curve shown in Fig. 1, which can be readily obtained from computerized weather data.

In conventional designs, a constant air volume (CAV) system is used, where P_n power is always consumed no matter what the load fraction X is. Eq. (4) depicts an important point that the $P_n \cdot \int_0^1 g(x)\,dx$ energy should have been consumed in a CAV system, if VAV is not used. Here $f(X_c)$ represents an energy savings potential or 'discounted' rate for VAV vs CAV systems.

For a VAV system, its characteristic curve $f(x)$ can be found experimentally, and then correlated with the partial load factor X in a second-order polynomial

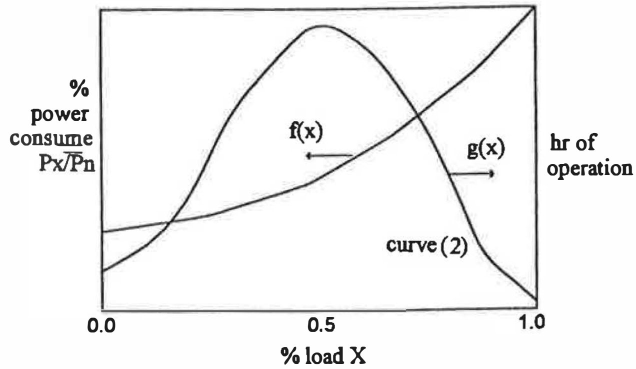
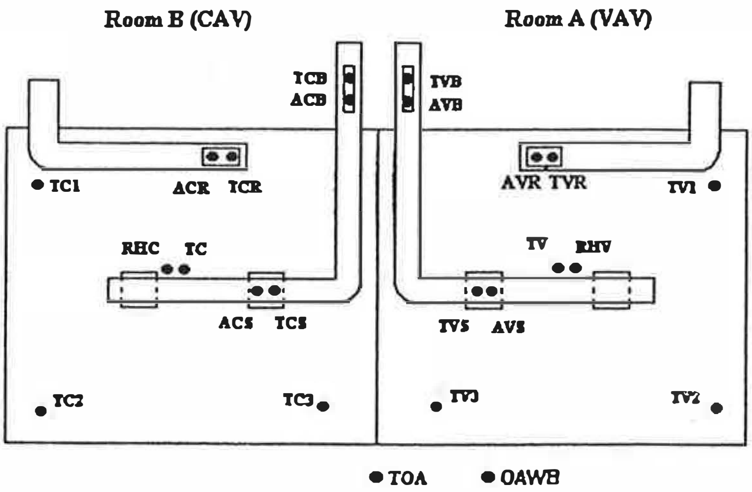


Fig. 1. The relationship of power consumption vs operation time % power consume P_x/P_n.



TCS : CAV supply air temp.
ACS : CAV supply air volume
TCR : CAV return air temp.
ACR : CAV return air volume
TCB : CAV by-pass air temp.
ACB : CAV by-pass air volume
TC1 : CAV indoor dry bulb temp. (1)
TC2 : CAV indoor dry bulb temp. (2)
TC3 : CAV indoor dry bulb temp. (3)
TC : CAV indoor dry bulb temp. (Central)
RCV: CAV indoor RH (Central)
CAVKWH : CAV power consumption

TOA : outdoor dry bulb temp.

TVS : VAV supply air temp.
AVS : VAV supply air volume
TVR : VAV return air temp.
AVR : VAV return air volume
TVB : VAV by-pass air temp.
AVB : VAV by-pass air volume
TV1 : VAV indoor dry bulb temp. (1)
TV2 : VAV indoor dry bulb temp. (2)
TV3 : VAV indoor dry bulb temp. (3)
TV : VAV indoor dry bulb temp. (Central)
RHV: VAV indoor RH (Central)
VAVKWH : VAV power consumption

OAWB : outdoor wet bulb temp.

Fig. 2. Layout of the full-scale experiment with CAV vs VAV systems in NSYSU test building.

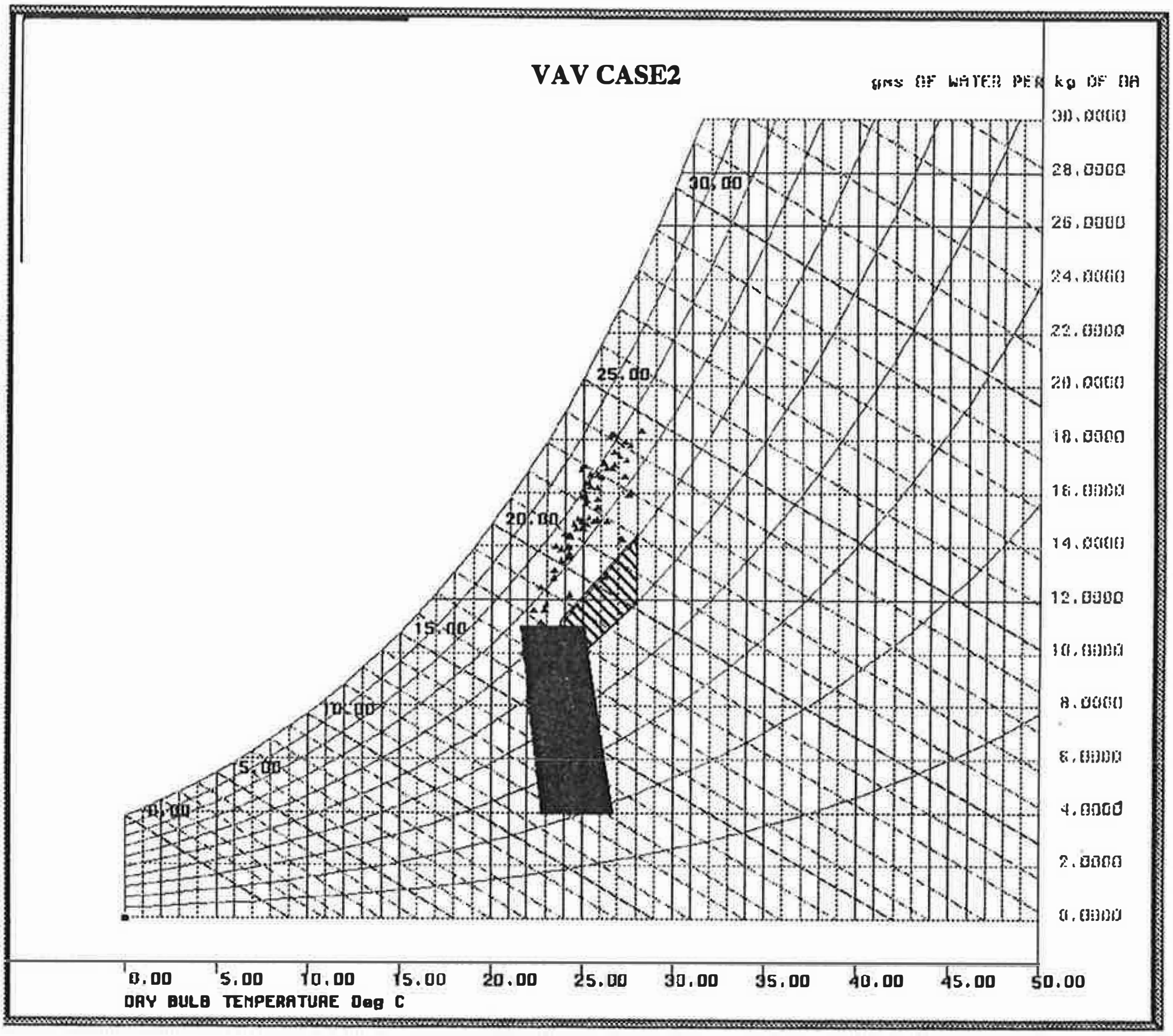


Fig. 3. Experimental results of the controlled indoor environment of the VAV system.

form, or:

$$f(x) = b_0 + b_1 x + b_2 x^2 \tag{5}$$

Therefore, through plain calculations:

$$X_c = \frac{\int_0^1 f(x)\,dx}{\int_0^1 dx} = \int_0^1 f(x)\,dx \tag{6}$$

which closes the problem. That is, the integration of the $f(x)$ curve across the entire operation range gives the results for X_c.

4. Full-scale experiment

In order to provide a detailed quantitative analysis of the energy savings effect of a typical VAV system under local weather conditions, a full-scale experiment has been performed in the NSYSU test building. This test building has a size of $17 \times 12 \times 10$ m, and comprises two identical rooms facing west and supplied with separate HVAC systems, one room with CAV and the other with VAV. These two rooms, with a size of $3 \times 4 \times 5$ m, simulate typical offices in the Taiwan area. The layout of the experiment is shown in Fig. 2.

The indoor environment was set at $26°C \pm 2°C$ with uncontrolled relative humidity. The indoor climate and power consumption of each system was monitored at 10 min intervals each. The VAV system is a typical air-duct type with a VAV control box and by-pass duct leading to ambient conditions.

When the VAV box reduces the air supply volume to the indoor conditioned space, the by-pass air volume is recorded and converted into power savings accordingly.

A successful experimental result was obtained. Fig. 3

Table 1
Normalized power consumption of the VAV system in various load fractions

Load fraction X	Power consumption P_x/P_n
0.110	0.11
0.151	0.15
0.211	0.21
0.218	0.22
0.231	0.23
0.240	0.24
0.249	0.25
0.289	0.30
0.273	0.28
0.303	0.31
0.305	0.31
0.316	0.32
0.378	0.35
0.389	0.38
0.466	0.45
0.566	0.56
0.589	0.57
0.611	0.61
0.656	0.64
0.672	0.65
0.675	0.68
0.696	0.68
0.716	0.69
0.729	0.71
0.744	0.75
0.780	0.77
0.806	0.81
0.834	0.83
0.843	0.84
0.86	0.83
0.866	0.86
0.938	0.92
1.000	1.00

shows the controlled indoor climate drawn as dots on a psychrometric chart with ASHRAE thermal comfort zone plotted for reference. The indoor temperatures were controlled accurately as expected, yet the relative humidity was a bit higher due to the slightly inadequate dehumidification capacity when the VAV system supplies less air. This leads to an important point when designing a VAV system in hot and humid areas such as Taiwan and Southeast Asia, in that enhancing dehumidification is an important design consideration.

5. Results and discussion

5.1. Finding the $f(x)$

The VAV system was experimented under various partial load conditions X, with power consumption P_x measured. The results were normalized as listed in Table 1, and further curve-fitted as:

$$f(x) = 0.0204X^2 + 0.9676X + 0.0087 \tag{7}$$

The $f(x)$ curve has good accuracy as shown in Fig. 4.

5.2. Finding X_c

It was noticed the VAV system maintains a lower limit for the air supply volume so that the indoor air quality is maintained without causing a 'stuffy' feeling. In our case (see Table 1), that lower limit was 11% of the total which also means that for 0–11% of the minimum power consumption was kept constant and can be calculated as:

$$f(\min) = 0.0204 \times 0.112 + 0.9676 \times 0.11 + 0.0087$$

$$= 0.1154 \tag{8}$$

$$X_c = \int_{x=0}^{x=0.11} (0.1154)\mathrm{d}x + \int_{x=0.11}^{1} (0.0204x^2 + 0.9676x + 0.0087)\mathrm{d}x$$

$$= 0.5052 \tag{9}$$

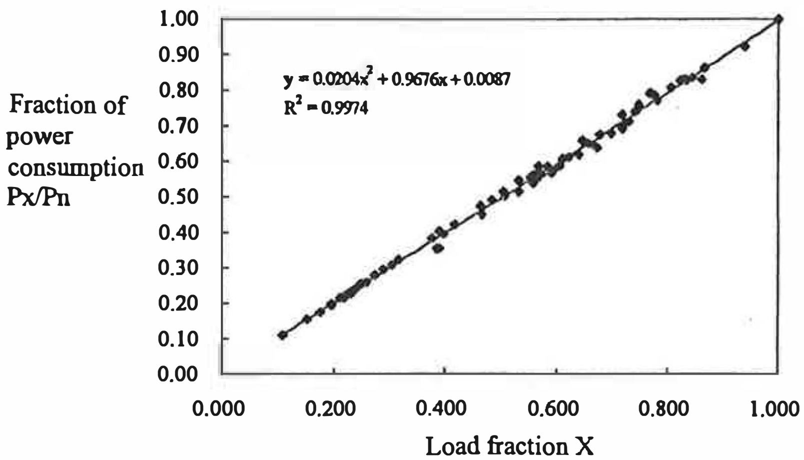


Fig. 4. The correlation $f(x)$ curve in this experiment.

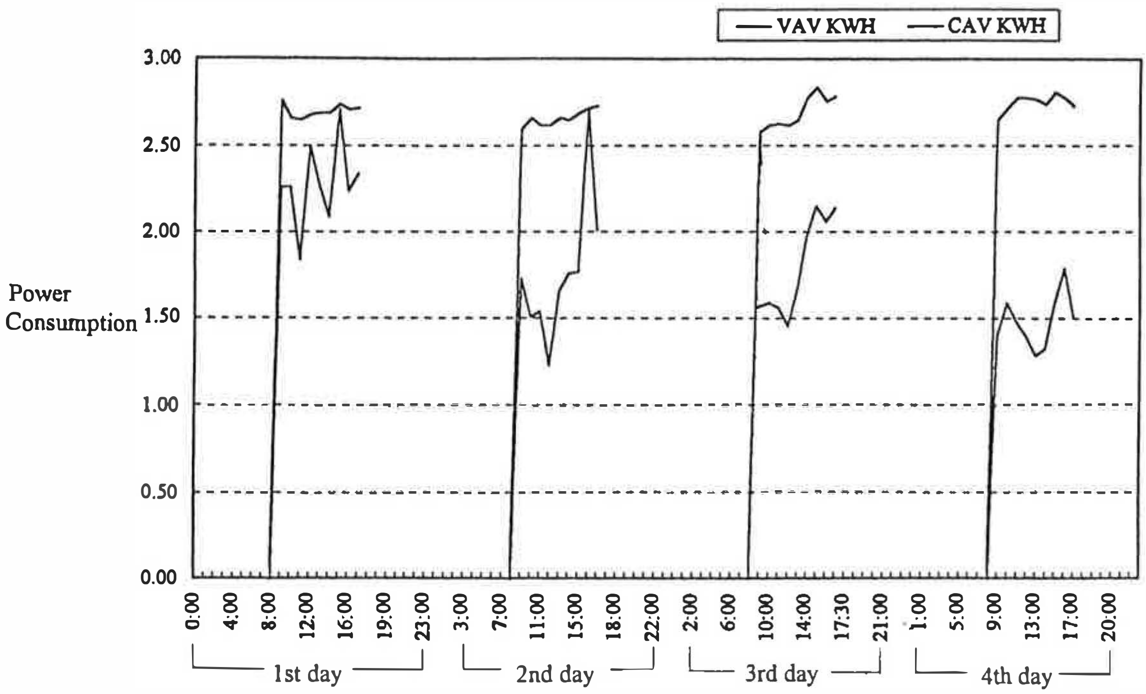


Fig. 5. VAV vs CAV power consumption comparisons.

It was then estimated that the energy savings potential, or $1-f(x)$, in this VAV system is as high as 49.7%.

5.3. Energy savings effect

It is interesting to note, in Fig. 5, the typical VAV vs CAV power consumption comparison in this experiment for four different days implying different types of weather. The first day was rather hot, so the VAV system saved around 20–25% of the energy when the load factor shifted from 20 to 50%, and approached the CAV figures at 16:00, where the VAV system was operating at full capacity and had essentially become a CAV system. The second day had milder weather. The VAV system saved 35–40% of the energy and again approached the peak at 16:00. The third day was hazy. The VAV system saved up to 40–45% of the energy. On the fourth day, another hazy day with indoor occupancy cut in half, the power savings were as great as 45–50%, as expected.

This was a successful validation of the calculated results using the innovative method developed in this study. In addition, the normalized power consumption curve as derived from experiment, is generally applicable to all VAV systems with the same performance characteristics, and has great potential for engineering aplications.

6. Conclusion

The VAV system is an efficient and widely adapted air-conditioning system. In this study, an innovative methodology for estimating the energy savings effect was developed. A full-scale experiment was performed to validate this calculation procedure by finding the characteristic curve $f(x)$, and X_c which implied that the energy savings effect could be as high as 49.7%.

The experiment was conducted for a year where four typical weather types were tested. The results indicated that the energy savings range from 30 to 50% as expected in hot and humid areas such as Taiwan, and with wide engineering application potentials.