# SIMULATION-BASED METHOD TO ASSESS BUILDING ENERGY CONSUMPTION LEVEL AT OPERATION STAGE

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## ABSTRACT

Energy conservation at building's operation stage is very important for the national economy. Building up reasonable methods to assess building operational energy consumption is critical and necessary.

Japanese researchers use CEC (Coefficient of Energy Consumption), which is the ratio of actual energy consumption to ideal energy consumption, to assess building system's operation level. In this paper, a concept of SCEC is proposed, which is calculated from building thermal simulation.

Firstly, in order to build up a building thermal model whose input parameters are all from on-site measurement, the unmeasured parameters are obtained by backcalculation. Then, a building thermal model reflecting the reality accurately is built. Secondly, ideal energy consumption is simulated by the revised model with ideal indoor parameter replacement. Finally, SCEC is calculated.

The method is applied to assess the operation level of the VAV system in Beijing Fortune Building. According to the case study, the feasibility of the simulation-based assessment method is validated.

## KEYWORDS

operation stage, building simulation, assessment method, SCEC (Simulation-based Coefficient of Energy Consumption),

## INTRODUCTION

Broadly speaking, the assessment of building energy consumption level can be divided into four stages, namely, planning, design, construction and operation stage. As a continuous entity, building is bound to be accompanied with much energy consumption, of which only the part of building's operation stage takes over 25% of the total national energy consumption. Therefore, energy utilization assessment, and management at the building's operation stage are of great importance to the national economy and people's livelihood.

But unfortunately, the development of energy consumption assessment at this stage is still in its infancy , though that at the other three stages has all been well-researched and extensively applied. Therefore, it is necessary to validate the feasibility of this assessment and take some methods to make it not only accurate but simple.

Benchmarks should be firstly established when we assess the operational energy consumption level. Japanese researchers propose to use "Coefficient of Energy Consumption" (CEC) to assess operational energy consumption level. CEC is the ratio of a building's actual annual operational energy consumption ($E_{\text{actual}}$, denoted by electricity consumption) to the building's ideal annual operational energy consumption ($E_{ideal}$), which is expressed as:

$$CEC = \frac{E_{actual}}{E_{ideal}} \tag{1}$$

CEC is smaller , the operational energy consupmtion is lower, and the operation level is higher.

## SCEC: SIMULATION-BASED CEC

The method of CEC assessment proposed by Japanese researchers is similar with the "Reference building method", but with no simulation. The denominator of CEC, i.e., a certain kind of building's ideal annual operational energy consumption, is calculated in some simple equations by standard forms, which determine the limited values and correction coefficients of each aspect affecting the energy consumption.

Separated from simulation, the denominator can not be properly reckoned due to predigestion of calculation, and some alterative, irresistable and functional factors, such as occupancy rate, weather outside and comfort-degree demand, will not be taken into account. Thus, this paper proposes a new concept of SCEC, in which the denominator of CEC is calculated by simulation with the factors mentioned above all considered.

However, in order to obtain a precise SCEC, large numbers of measured data should be used, so a more precise SCEC is needed, a heavier workload is taken. Meanwhile, the denominator of SCEC is difficult to define because we are difficult to decide under what operational conditions and system efficiencies we can announce that the energy consumed in the building this year is "ideal". Due to the two reasons, a simplified SCEC method is applied in the following contents and a SCEC of a practical case of Beijing Fortune Building, a high-rise commercial office building, is calculated by DeST (A building thermal simulation software developed by Tsinghua University). Figure 1 shows the procedure of gaining the SCEC in this case study.

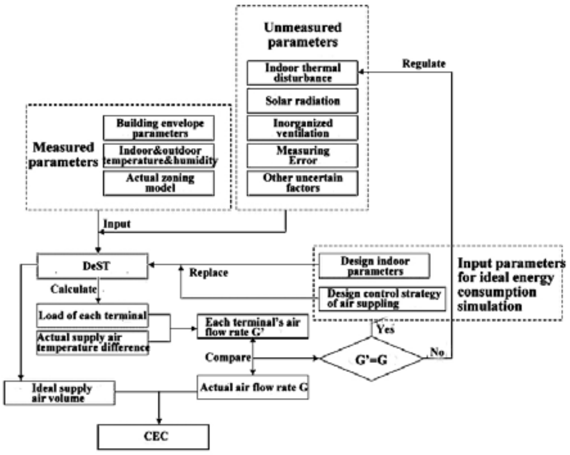

*Figure 1 Procedure of the SCEC solving*

## EXPERIMENT PRINCIPLE AND PROCEDURE

### Model Setup and Data Usage

The experiment is aimed at the 12th floor, which is a standard floor of Beijing Fortune Building. This floor is divided into 6 VAV system zones which are respectively conditioned by 6 AHUs. As seen in Figure 2, VAV14 and VAV 15 in the southeast exterior zone (A), as well as VAV1, VAV2, VAV3 and VAV5 in the interior zone (A) are focused upon in the experiment. Figure 3 shows the particial building thermal model displayed in DeST.

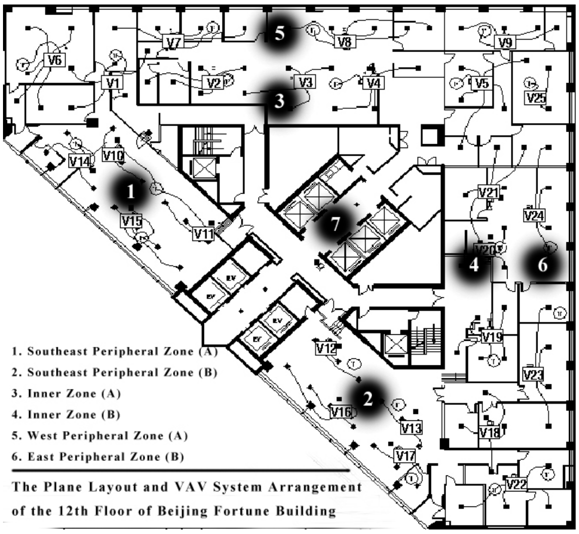

*Figure 2 The plane layout and the VAV system arrangement of the 12th floor*

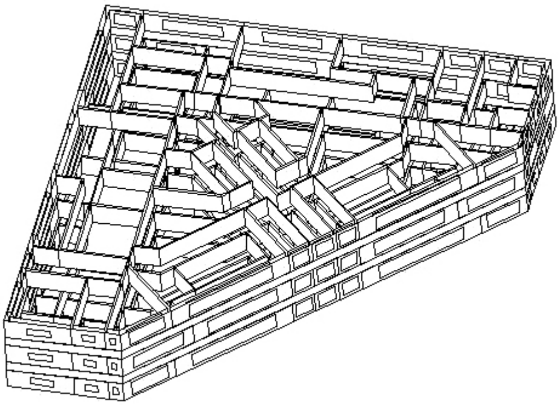

*Figure 3 The building thermal simulation model in DeST*

Besides the shape and dimension parameters of the building, there are three different types of input data in the model. The first type are the measured data including the outdoor temperature and humidity obtained from local weather stations, the indoor temperature and relative humidity, the supply air temperature recorded, the setpoint of the supply air temperature of every VAV terminal, the supply air volume and the on-and-off signal of the air conditioning system, etc. All these data are obtained hourly during the year of 2005. The second type of data are the fixed data such as the building enclosure thermal parameters which are calculated by the structure and composition of walls and windows; the third type of data are the unknown input parameters which are difficult to measure, including the indoor heat source, hourly solar radiation, inorganized ventilation rate, outdoor wind direction and velocity, etc. For the third type of data, all the unkown parameters are represented as an assumptive indoor heat source, which is back-calcualted by an initial simulation discussed below.

### The Simplification Methods and the Simulation Process

To obtain an integrated SCEC is still very difficult or even impossible though simulation method is used, because, on the one hand, SCEC is a ratio concerning all types of A/C system energy consumption (converted to electricity consumption) of an entire building in a whole year, so the measurement, collection and management of data are very demanding and time-consuming; on the other hand, all the parameters affecting energy consumption, even the personnel movement and equipment using rate should be recorded. Therefore, some appropriate simplification is necessary. In this experiment, only part of the VAV terminals of the 12th floor, rather than the entire building, only the cooling load and supply air flow rate, which respectively reflect the energy consumption of refrigerators and fans indirectly, rather than electricity consumption, and only a week in July, rather than the whole year, are studied to obtain a series of narrowly sensed SCECs corresponding to different VAV terminals. Table 1 shows the simplification terms of the simulation.

*Table 1 Simplification terms of the simulation*

| | **PERIOD** | **AREA** | **EQUIP TYPE** | **AIM AT** |
|---|---|---|---|---|
| **INTEGRATED SCEC** | All-year | The entire building | A/C system | Electricity consumption |
| **SCEC IN THE EXPERIMENT** | A week in July | Some VAV terminals | Heat/cold sources and fans | Air volume and A/C load |

Since DeST is generally used to calculate design A/C load, in order to obtain A/C energy consumption, the sequences of input parameters, which are sequences of design values such as design indoor air temperature in general DeST usage, should be changed to the sequences of measured parameters. As mentioned above, many needed parameters are unknown such as the indoor heat source and solar radiation. In order to get these parameters, initial values of them should be assumed before the first simulation, for example, set all the unknown thermal disturbance levels and air change rates at DeST's default values. Then, A/C load result of the initial simulation is converted to supply air flow rate and compared with the actual value so that the unknown parameters can be regulated to make simulation result access the actual result. At last, the ideal A/C energy consumption level is calculated by setting the indoor air temperature and relative humidity at their design values so that the supply air flow rate can be also obtained with the temperature difference determined by the design AHU control strategy. Comparing the actual and ideal A/C energy consumption level and supply air flow rate, two types of SCECs, one for the heat/cold sources and one for the fans, can be calculated. The procedure is shown in Figure 1.

## SIMULATION INITIALIZATION AND MODEL CALIBRATION

Based on the initial model, which uses the DeST's default setting for the unknown parameters, energy consumption of the VAV terminals of the 12th floor, especially VAV1, VAV2, VAV3 and VAV5 in the interior zones and VAV14 and VAV15 in the exterior zones, are calculated by simulation. The result is converted to air flow rate by the actual supply air temperature difference. Figure 4 is the contrasting result between the calculated and measured supply air flow rate of terminal VAV5 dating from July 11 to July 16, 2005 (all weekdays). It can be concluded from the figure that the calculated air flow rates are basically consistent with the actual values, so there isn't much difference between the actual unknown input parameters and the default values of DeST. Because VAV5 is located in the interior zone, the indoor heat productions constitutes an essential part of the A/C load, thus it is probable that the actual number and schedule of occupants, office equipment and lights are close to the DeST's default setting. However, the calculated air flow rates are smaller than the actual values on Thursday and Friday, by inquiring the building's staff, the researchers find that part of the region served by VAV1 are meeting rooms, in which there's usually nobody, but two regular meetings will be held on Thursday and Friday, that's why the calculated air flow rate goes smaller on these two days.

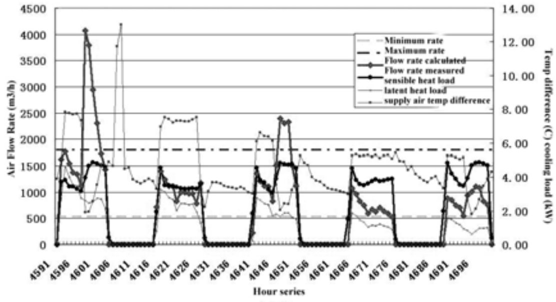

*Figure 4 Comparison between the simulated and measured supply air flow rate (VAV5, f12, July 11-July 16, 2005)*

Figure 5 is the result of another terminal VAV15, which is located in the exterior zone and serves the outer part of a big-span room. Being different from what is shown in Figure 4, the calculated air flow rates are much smaller than the actual values all the time. There are two possible reasons: firstly, the model uses DeST's default solar radiation but the reality is those testing days were all sunny, so the actual A/C load is higher; secondly, as VAV15 and VAV11 serve the outer and the interior part of the same big-span room respectively, existence of two different systems may lead to a larger air change rate between the two room parts, makeing the A/C load higher.

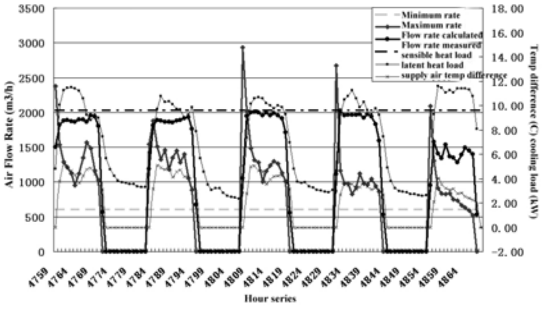

*Figure 5 Comparison between the simulated and measured supply air flow rate (VAV15, f12, July 11-July 16, 2005)*

After simulation initialization, according to the contrasting result of the initial simulation, the hourly indoor heat production should be regulated to make the model match the actual conditions. An accurate model is a prerequisite for the next step of calculating the ideal energy consumption.

Standards to judge whether the model has been calibrated are whether the sums of the calculated and actual supply air volume approximately equals, and whether the hourly average difference between the actual and the calculated is the smallest. In order to regulate the indoor heat production effectively, suppose an hourly indoor heat production regulating coefficient $K_i$ by some certain hypothesizes and approximations, the former indoor heat production numbers can be replaced by a new one which is the product of $K_i$ and itself, repeatedly. The steps to get $K_i$ are as follows:

Suppose a load change coefficient $S_i$, which refers to the ratio of the actual A/C load to the calculated load at time $i$, as:

$$S_i = \frac{Q_{\mathrm{act,i}}}{Q_{cal,i}} \tag{2}$$

Suppose an indoor thermal disturbance proportional coefficient $b$, which denotes the indoor heat production's proportion of the entire A/C load.

Then, $K_i$ can be denoted as:

$$K_i = 1 + \frac{S_i - 1}{b} \tag{3}$$

However, perhaps no matter how $b$ changes, there may not be good results due to the existence of the measuring error of the supply air temperature difference, so suppose $d$ as the fixed system measuring error of the supply air temperature difference and $e_i$ as an air flow correction coefficient about $d$, so the actual air flow rate can be denoted as:

$$G + \Delta G = \left(\frac{a}{u} + \frac{ad}{u^2}\right)Q = \left(1 - \frac{d}{u}\right)a\frac{Q}{u} \tag{4}$$

Where: $G$ is the flow rate; $u$ is the supply air temperature difference; $Q$ is the heating or cooling load; $\Delta G$ is the error of $G$; $a$ is a constant.

In equation (4), $aQ/u$ is the supply air flow rate ignoring the error of temperature difference, thus:

$$e_i = 1 - d/u \tag{5}$$

Then, $K_i$ can be denoted as:

$$K_i = e_i\left(1 + \frac{S_i - 1}{b}\right) \tag{6}$$

To calibrate the model, $b$ and $d$ are supposed, by the calculated $S_i$, $K_i$ can be derived and a new sequence of indoor heat production is determined. If $b$ and $d$ are valued properly, the new simulation results will match the actual. The procedure of model calibration is shown in Figure 6.

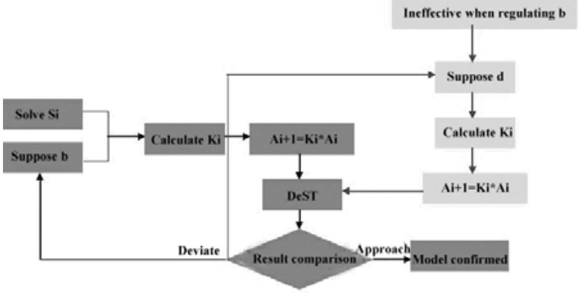

*Figure 6 Procedure of model calibration*

Because the initial simulation has made a good result, indoor heat source of terminal VAV5 is regulated only once at $b = 1$ and $d = 0$ (Figure 7). The simulation result becomes more consistent with the actual after the regulation. However, the value $b$ or $d$ is regulated twice on terminal VAV15 belonging to an exterior zone (Figure 8), once $b = 0.3$, $d = 0$, once $b = 0.5$, $d = 0$. The result of the latter is better than that of the former, which illustrates that the indoor heat productions take about 50% ($b = 0.5$) of the entire A/C load.

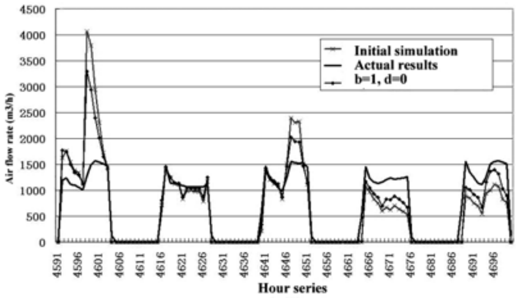

*Figure 7 Model Calibration of VAV5 (July 11-July 16, 2005)*

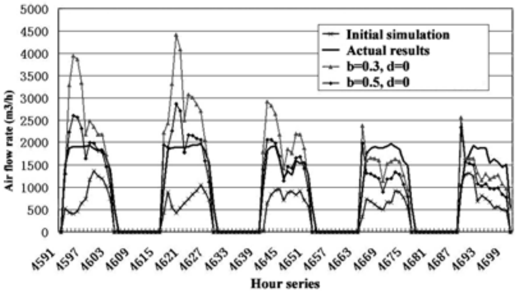

*Figure 8 Model Calibration of VAV15 (July 11-July 16, 2005)*

## RESULT ANALYSIS

After model calibration, the ideal supply air volume (or flow rate) and A/C load can be calculated by means of:

- Replacing the hourly indoor air temperature and humidity by their design values in the model;
- Using the supply air temperature calculated by the design air supply control strategy (for example, supply air at the highest temperature difference unless the supply air volume reaches the minimum required quantity) rather than the actual values in calculating the ideal supply air volume manually after simulation.

Defining and calculating the ideal supply air volume in this way reflects such aspects of how the actual energy consumption deviates from its ideal quantity as follows:

- Whether the control of indoor air temperature meets with the design requirement.
- Whether the control strategy of AHUs is appropriate and how much energy conservation potential can be achieved.

However, many influencing factors can not be reflected such as energy conservation consciousness of the staff, whether the unnecessary air changes are avoided, whether there's intended nonstandard control of the A/C system to reduce A/C load (for example, save energy by sacrificing comfort) and so on.

### Results of the Ideal Cooling Load/Flow Rate

Take VAV5 for example (Figure 9), for the regions served by this terminal, indoor air temperature is kept close to the design value in the daytime, so the actual load is also close to the ideal result, leading to a small SCEC and high capacity of energy conservation on heat/cold sources.

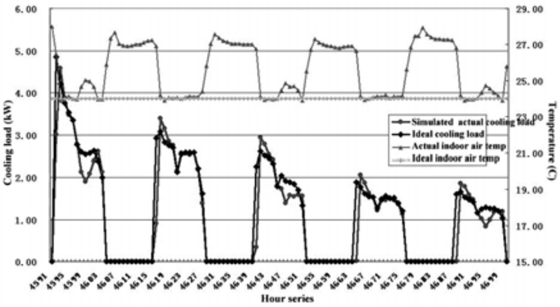

*Figure 9 Comparison between the actual and the ideal cooling load (VAV5, July 11 to July 16)*

As for supply air volume, Figure 10 shows the curves of the actual, ideal and design supply air temperature difference as well as the actual and ideal supply air flow rate. It is found that the actual supply air temperature differences are basically close to the ideal values, which illustrates a high control accuracy. As cooling load has been proved equal approximately, the actual and ideal supply air flow rates are also equal approximately. However, differences still exist somewhere, for example, the actual supply air temperature differences are 3-4℃ lower than the ideal values on Wednesday averagely, making the actual air flow rates higher than their ideal values. In the addition, it is found from Figure 10 that the ideal temperature difference curve has three falls on the latter three days, that's because cooling load of the interior zones is small but the equipment capacity is big so that some terminals of the AHU may run at the minimum required fresh air volume and raise the supply air temperature, making other terminals of the AHU forced to follow.

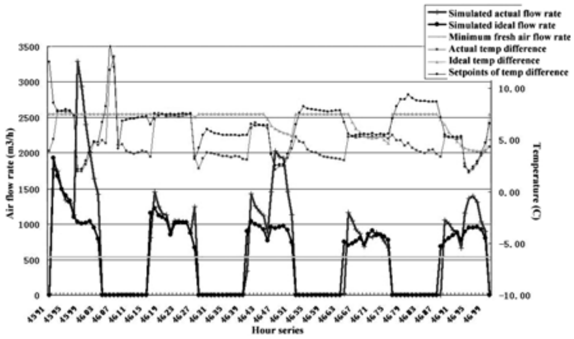

*Figure 10 Comparison between the actual and the ideal supply air flow rate (VAV5, July 11 to July 16)*

Figure 11 is the contrasting result of terminal VAV14 serving peripheral offices. It is obvious that the actual temperature differences are lower than their setpoints, while the setpoints are basically consistent with the ideal values at the start-up stage of the equipment. It illustrates that there may be a lack of the water system capacity.

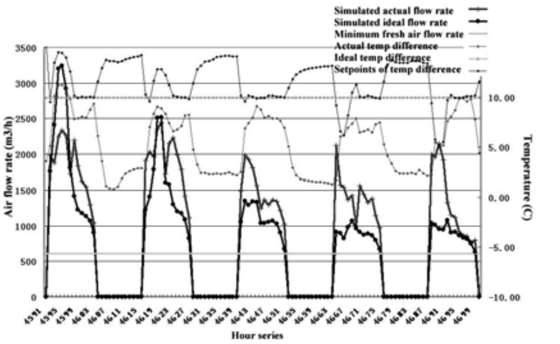

*Figure 11 Comparison between the actual and the ideal supply air flow rate (VAV14, July 11 to July 16)*

## Derivation of SCEC

Suppose $SCEC_Q$ and $SCEC_G$ as:

$$SCEC_Q = \frac{Q_{actual}}{Q_{ideal}} \tag{7}$$

$$SCEC_G = \frac{G_{actual}}{G_{ideal}} \tag{8}$$

Where: $Q_{actual}$ is the actual cooling load (calculated by the calibrated model rather than true values, so is $G_{actual}$); $Q_{ideal}$ is the ideal cooling load; $G_{actual}$ is the actual air flow rate; $G_{ideal}$ is the ideal air flow rate. $SCEC_Q$ and $SCEC_G$ of each terminal are listed in Table 2. All data are sums of July.

*Table 2 SCEC of each terminal*

| TMNL NO. | ACTL G(M3) | ACTL Q(KW) | IDL G(M3) | IDL Q(KW) | $SCEC_G$ | $SCEC_Q$ |
|---|---|---|---|---|---|---|
| VAV1 | 265218 | 357.5 | 214988 | 498.7 | 1.23 | 0.72 |
| VAV2 | 373263 | 568.9 | 244108 | 558.9 | 1.53 | 1.02 |
| VAV3 | 225591 | 352.6 | 157751 | 365.4 | 1.43 | 0.96 |
| VAV5 | 282003 | 488.9 | 233003 | 535.7 | 1.21 | 0.91 |
| VAV14 | 373040 | 986 | 317474 | 1070 | 1.18 | 0.92 |
| VAV15 | 355947 | 1187.5 | 320058 | 1296.7 | 1.11 | 0.92 |

Table 2 shows that $SCEC_Q$ are basically less than 1. It means that indoor air temperature is higher than its setpoint and energy consumption is less than its ideal quantity most of the time though quality declines. Thus, a problem is brought up that if SCEC should eliminate the influence of raising energy conservation capacity by sacrificing environment or control quality. If yes, how to realize?

Otherwise, $SCEC_G$ are all greater than 1. It can be inferred that there are problems in the A/C system or the control strategy is improper.

## Sensitivity Analysis of SCEC

According to the simulation results of the ideal cooling load, $SCEC_Q$ and $SCEC_G$ are greatly influenced by the design indoor air temperature. In the analysis below, changes of SCEC, when design indoor air temperature is raised by 1 ℃, will be discussed.

Take VAV5 for example, when indoor air tempearture is raised by 1 ℃, the ideal cooling load and supply air flow rate are changed as shown in Figure 12.

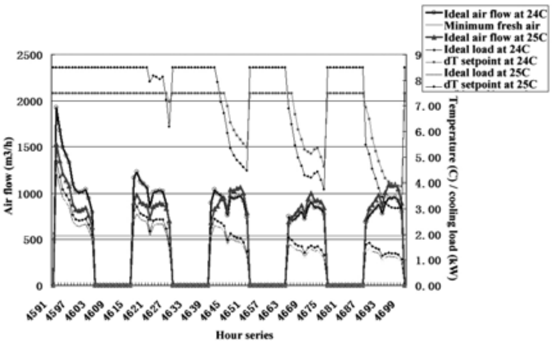

*Figure 12 Sensitivity analysis on ideal cooling load/air flow (VAV5, July 11-July 16)*

Cooling load decreases by 10% in an approximate constant amplitude. The supply air temperature difference is raised by 1℃ due to the indoor air temperature rise, so supply air flow should have a sharper decline than cooling load, but, on the latter three days, decline of air flow is slighter than that of cooling load, that is because air flow reaches its minimum required value due to an insufficiency of cooling load, making temperature difference decrease on the contrary. In other words, from a 1℃ indoor air temperature rise sensitivity of $SCEC_G$ is weaker than that of $SCEC_Q$ in this case. However, as for the peripheral terminals like VAV14 and VAV15, cooling load is relatively higher, the minimum required air volume won't be reached, so the decline of the ideal supply air flow is more notable than that of the ideal cooling load.

Table 3 shows the changes in cooling load, air flow rate, $SCEC_Q$ and $SCEC_G$ of each terminal. Obviously, $SCEC_G$ of interior zone terminals are all lesser than $SCEC_Q$, instead, $SCEC_G$ of exterior zone terminals are all greater than $SCEC_Q$, the conclusion is verified.

*Table 3 Sensitivity analysis of indoor air temperature rise by 1 ℃*

| TMNL NO. | 25℃ ECL (KW) | 24℃ ECL (KW) | 25℃ FLOW $M^3$/H | 25℃ FLOW $M^3$/H | $SCEC_G$ CHG RATE | $SCEC_Q$ CHG RATE |
|---|---|---|---|---|---|---|
| VAV1 | 431.4 | 498.7 | 187404 | 214988 | 15.6% | 14.7% |
| VAV2 | 502.5 | 558.9 | 225703 | 244108 | 11.2% | 8.2% |
| VAV3 | 322.1 | 365.4 | 141229 | 157751 | 13.4% | 11.7% |

| | | | | | | |
|---|---|---|---|---|---|---|
| **VAV5** | 486.6 | 535.7 | 216943 | 233003 | 10.1% | 7.4% |
| **VAV14** | 1015.9 | 1070 | 278236 | 317474 | 5.3% | 14.1% |
| **VAV15** | 1227.4 | 1296 | 282779 | 322570 | 5.6% | 14.1% |

## CONCLUSION

Several conclusions can be drawn from the research as follows:

1. Simulation-based method to assess energy consumption of building operation stage is feasible though many simplification methods should be taken. Therefore, finding the optimal balance between the model accuracy and simplification extent is a key point of the work.
2. SCEC-based method is an effective and feasible way to achieve comprehensive assessment; it can be a foundation to instruct energy consumption assessment of building operation stage. The system operation status, the control ability and effect, the energy conservation extent and capacity can be denoted by SCECs. However, this index can’t reflect the system control quality, so further study is needed.
3. By simulation, index comparison and sensitivity analysis, building’s operation can be directed, so it is of great significance for the building energy conservation.

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