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Are the relative variation rates (RVRs) of energy consumption approximate in different cities for the same increase of ventilation rate?

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Abstract

This paper makes simulations on the annual heating and cooling energy consumption of four kinds of buildings under the climatic conditions of 19 background cities in China, USA and Europe when ventilation rates increase from 0 to 1.5 vol/h, respectively by, CTM, DOE-2 and DeST-h. The simulation results by CTM show that the increments of annual heating and cooling may differ up to 10s of times or even more than 100 times in different cities for the same building with the same increase of ventilation rates, while the annual heating and cooling RVRs are both approximate in different cities. For the same building with the same increase of ventilation rate in the same city, its annual heating RVRs are far higher than its annual cooling RVRs. The above conclusion can be reached for any building whether with various envelopes or with different shape coefficients.

Keywords: Ventilation rate; Relative variation rates (RVRs) of energy consumption; Cooling; Heating; Envelope

1. Introduction

Air ventilation is an important design index of the indoor thermal environment. In order to ensure sanitation conditions in the room and personnel's health, outdoor fresh air must be sent into the room to release the concentration of pollutants emitted by people or polluter during cooling and heating time either in summer or winter. Especially, the profound lessons from SARS (Severe Acute Respiratory Syndrome) that erupted in China and spread rapidly throughout the world in year 2003 made people more aware of the importance and necessity of strengthening indoor air ventilation. A large amount of cases have proved that the imperfect circulation of indoor air is an important way of cross-infection and spread. Thus reinforcing air circulation of residential or working circumstances is the most effective measure to prevent SARS from spreading.

However, the increase of ventilation rates can increase design load of air conditioning system and annual energy consumption, so air changes or ventilation rates are prescribed in design standard for energy efficiency of each country. For example, 0.5 vol/h is provided for design ventilation rates in Design Standard for Energy Efficiency of Residential Buildings in China (for new heating residential buildings) while ventilation rate is defined as 1.0 vol/h in Design Standard for Energy Efficiency of Residential Buildings in Hot Summer And Cold Winter Zone. The standard of ASHRE (USA)(62-1989) recommends that the ventilation rate of residential buildings is 45.5 m³ per person in an hour. If it is assumed that each person occupies an area of 15 m² and the net height of each floor is 2.5 m, then it amounts to about 1.5 vol/h of ventilation rates.

In a word, when laying down the energy efficiency standard, each country around the world will define or recommend the limitation to ventilation rates or air
changes. The above definition is on the premise that the 
relative increase rates (RVRs) of energy consumption 
are roughly approximate in various cities for the same 
building when the ventilating rate increases from 0 to 
the defined value. Otherwise, if there were great 
discrepancy in all locations involved in a standard, it 
would not be necessary at all to give a unified limitation 
to the ventilation rate. It seems to be more reasonable 
that larger ventilation rate should be adopted in the 
cities where the RVRs are small, because the increase of 
ventilation rates is invariably beneficial to both the 
health of dwellers and the improvement of indoor air 
quality.

The proposition to be studied in this paper is ‘Are the 
annual RVRs of energy consumption approximate in 
different cities or districts concerned with a standard for 
the same increase of ventilation rate?’ And it will be 
studied within a larger range in this paper. We will study 
the annual heating and cooling energy consumption of 
four kinds of buildings under the climatic conditions 
of 19 background cities (located in north latitude 
22.82–52°) in China, USA and Europe when ventilation 
rates increase from 0 to 1.5 vol/h and explore whether 
the above proposition is tenable under different weather 
conditions of the above 19 cities.

The annual RVRs of energy consumption are the 
percentages calculated by the ratio of increment of 
annual cooling or heating need when ventilation rates 
increase from 0 to 1.5 vol/h to the annual cooling and 
heating need when the ventilating rate is 0 for the same 
kind of building. The RVRs of annual heating or 
cooling energy need are compared with one another 
laterally in the 19 cities so as to find the common rule. 
According to the above introduction, if the model 
buildings with an area of 960 m² and 2304 m² were built, 
respectively, with traditional and improved envelope, 
then there would be four kinds of buildings with various 
shape coefficients and envelopes. Therefore the common 
conclusions revealed by the research would be more 
representative.

The research method to the problem is still CTM 
proposed by the author. As mentioned above, indoor air 
humidity is not controlled strictly and thus only the 
sensible heat of outside air is taken into account. The 
starting and stopping mode of heating and cooling 
equipment is mainly controlled according to the indoor 
air temperature, which is called temperature control 
mode (in brief, TC). For instance, heating equipment 
will stop if indoor characteristic temperature exceeds 
setting value in winter (here 16°C), and cooling 
equipment will do so if the temperature in summer is 
below setting value (here 26°C). Firstly, let us have a 
look at the answers to this question by DOE-2 and 
DeST-h public in China. Here, we just provide some 
typical results so as to reduce the length of the paper.

2. The answer of DOE-2

It is well known that the higher the ventilation rates 
are, the more outside air supplied into the building in 
unit time. Fig. 1 shows the comparison of annual 
heating and cooling RVRs of 960 m² model building 
with a traditional envelope simulated by DOE-2 under 
the climatic conditions of 14 background cities in China 
when the ventilation rate increases from 0 to 1.5 vol/h. 
The comparative basis is the energy consumption when 
the ventilation rate is 0. The coordinate represents the 
animal heating or cooling RVRs, %; the horizontal 
coordinate represents various Chinese cities, and the 
different values in the chart represent the corresponding 
variation rates. In the figure, the abbreviation ‘RVR-H’ 
and ‘RVR-C’ stand for the annual heating and cooling 
RVRs, respectively. It can be concluded from this figure 
that (1) the annual heating RVRs range from 56.3% to 
131.9% for the same increase of ventilation rate in all

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Fig. 1. Comparison of annual RVRs with the same increase of $n_k$ in various cities (960 m$^2$ tradi.).
cities concerned. Obviously, there is great discrepancy in
the annual heating RVRs for a few cities and (2) the
annual cooling RVRs range from \(-36.3\%\) to \(91.6\%\) for
the same building with the same increase of ventilation
rate in all cities concerned. Two of them (Haerbin and
Wulumuqi) are minus, which means that the annual
cooling energy consumption does not increase but decease
with the increase of ventilating rate and the difference of
annual cooling RVRs is very significant in various cities.

Fig. 2 shows the comparison of annual heating and
cooling RVRs of 2304 m\(^2\) model building with an
improved envelope simulated by DOE-2 under the
climatic conditions of 14 background cities in China
when ventilation rate increases from 0 to 1.5 vol/h. The
comparative benchmark is the energy consumption
when the ventilating rate is 0. The coordinate system is
similar to the former chart. It can be concluded from
this figure that (1) the distribution laws of the annual
RVRs of energy consumption of the two kinds of
buildings with different shape coefficients and envelopes
are very similar in different cities, i.e., the figure is similar
to Fig. 1; (2) the annual cooling RVRs of the 2304 m\(^2\)
building with a smaller shape coefficient are higher than
those of 960 m\(^2\) building with a larger shape coefficient
when taking the same increase of ventilation rate to the
same building in various cities. And the variation range of
annual cooling RVRs is also larger (\(-87.5\%–220.8\%)\); (3)
the variation range of annual heating RVRs is larger too,
which varies from 103.0% to 264.5%. Evidently, the basic
energy consumption for the 2304 m\(^2\) building with
improved envelope may be smaller, and thus the RVRs
of energy consumption may be higher.

3. The answer of DeST-h

Figs. 3 and 4 show the comparisons of annual heating
and cooling RVRs of 2304 m\(^2\) model building, respec-

tively, with traditional and improved envelope simulated
by DeST-h under the climatic conditions of 12 back-
ground cities in China when ventilation rate increases
from 0 to 1.0 vol/h. Similar to the above, the compara-
tive benchmark is also the energy consumption when the
ventilating rate is 0. The coordinate system is similar
to the former charts. It can be concluded from the two
figures that (1) the annual heating RVRs predicted by
DeST-h have little discrepancy between two buildings
with different kinds of envelope in the same city when
the increase of ventilating rate is the same. However,
they are significantly different in various cities even for
the same building, roughly between \(39\%\) and \(480\%\)
while the difference is insignificant for most cities; (2) the
annual cooling RVRs are much lower than those of
heating in the same city whether for a building with
traditional or improved envelope, and the discrepancy in
annual cooling RVRs is relatively great in different
cities. The RVRs of annual cooling needs are minus in 7
cities (\(-1.5\% to \(-0.25\%\)) and plus in five cities
(1.1–42.9%) for the same building with traditional
envelope while for the same building with improved
envelope, the annual cooling RVRs are minus (\(-8.24\% to
\(-0.26\%\)) in 4 cities and plus in 8 cities (0.1–42.3%).
Why did these results happen? The authors have not
found out the reasons.

The total tendency that the energy consumption
increases with the increase of ventilation rate is reason-
able for most simulation results of DOE-2 and DeST-h.
Furthermore, it can be seen from the above figures that
the relative variation rates (RVRs) of annual cooling or
heating needs with the same increase of ventilating rate
predicted by DOE-2 and DeST-h are roughly approxi-
mate in most of the cities concerned. However, there
exists a great difference in the annual heating or cooling
RVRs in some of the cities concerned for the same
building with the same increase of ventilation rate.
Under the condition that the latent heat of outside air is
should the difference of annual cooling and heating RVRs be so great for the same building with the same increase of ventilating rate in some cities? This phenomenon needs further research. Obviously, the above conclusions that there exists great difference or even are beneficial to energy efficiency for the same increase of ventilation rate in some cities may cause disputation on whether the limitation to ventilating rate should be modified and whether increasing ventilation rate could be considered as an energy-efficient measure in these cities when energy-efficient standards were carried out.

4. The answer of CTM

4.1. The comparison of variation of building energy consumption

In order to analyze and compare the annual variation law of building energy consumption when the ventilating rate increases, Table 1 shows the simulation results of annual cooling and heating need by CTM for the same 960 m² model building with traditional envelopes in 19 cities of China, USA and Europe when ventilation rates are 0 and 1.5 vol/h respectively. We can see from Table 1 that (1) the absolute increment of annual heating need is different in various cities with different climate conditions for the same building with the same increase of ventilation rate, and the maximum discrepancy in annual heating need and its absolute increment can reach as high as about 20 times among different cities; (2) the absolute increment of annual cooling energy consumption is also obviously different. The biggest difference in annual cooling needs among 19 various cities can reach as high as about 70 times, and that in its absolute increment can reach as high as about 250 times in 19 various cities for the same increase of ventilation rate; (3) it can be concluded that the annual cooling or heating energy consumption and its absolute increment are closely relevant to the weather conditions of 19 cities concerned for the same increase of
ventilation rates to the identical building. Once the building, its operation conditions and the measures are determined, the annual heating or cooling energy consumption and its absolute variation amount are mainly dependent on the meteorological conditions of different locations where the building is located.

4.2. Are the RVRs approximate in different cities for the same increase of ventilation rate?

Fig. 5 shows the comparison of annual heating and cooling RVRs of 960 m² model building with a traditional envelope simulated by CTM under the climatic conditions of 19 background cities in China, USA and Europe when ventilation rate increases from 0 to 1.5 vol/h. The comparative basis is the energy consumption when the ventilating rate is 0. The coordinate system is similar to the former charts. In fact, this figure is calculated and plotted according to the data in Table 1. The horizontal coordinate represents various cities, which corresponds to Table 1. It can be concluded from this figure that (1) the annual heating RVRs are very approximate (42.2–48.1%) in 19 cities concerned with totally different weather conditions for the same building with the same increase of ventilating rate; (2) the discrepancy in the annual cooling RVRs is not obvious in different cities (2.0–6.7%) for the same building with the same increase of ventilating rate; (3) the annual RVRs of heating are much higher than those of cooling under the same conditions; (4) the difference in the annual heating or cooling RVRs among various cities may be relevant to the proportion of classified energy consumption when there is no solar radiation (at night) in the annual total energy needs.

Fig. 6 shows the comparison of annual heating and cooling RVRs of 960 m² model building with improved envelope simulated by CTM under the climatic conditions of 19 background cities, respectively, in China, USA and Europe when ventilation rate increases from 0 to 1.5 vol/h. It can be seen from this figure that the annual heating and cooling RVRs of the building with improved envelope are both higher than those with traditional envelope because the comparative basis of energy consumption of the former (when ventilating rate is 0) is lower than that of the latter. In addition, the annual heating RVRs are also approximate for the same increase of ventilation rate to the same building with an improved envelope, and there is only a little distinction in the annual cooling RVRs among different cities. The fundamental law with improved envelope is very similar to that with traditional envelope.

Figs. 7 and 8 show the comparisons of annual heating and cooling RVRs of 2304 m² model building, respectively, with a traditional and improved envelope simulated by CTM under the climatic conditions of 14 background cities, respectively, in China, USA and Europe when ventilation rate increases from 0 to 1.5 vol/h. We can see from the above two figures that the common rule of annual heating and cooling RVRs of 2304 m² model building in various cities for the same
building with the same increase of ventilation rate is very similar to that of 960 m² building presented before (shown in Figs. 5 and 6).

In summary, the answer of CTM to the proposition in this paper is that for the same building with the same increase of ventilating rate, the annual heating RVRs are approximate in different cities, the discrepancy in the annual cooling RVRs among various cities is not obvious and the annual heating RVRs are far higher than the annual cooling RVRs in the same city; for different kinds of buildings (such as with various envelopes or different shape coefficients), although the annual heating and cooling RVRs are different, the above proposition can still hold water because the premise to the proposition is aimed at the same building.

It needs to be pointed out that the conditions adopted by CTM are the same as those adopted by DOE-2 when annual heating and cooling energy consumption is simulated (Figs. 1 with 5, Figs. 2 with 8). That is to say, the buildings, the increase of ventilating rate, the hourly climatic data in each city and other assumptions are completely the same except for the load simulation methods. By contrasting the above four figures, we can find that the simulation results by CTM and DOE-2 have great discrepancy qualitatively and quantitatively.

Comparing Figs. 5–8, there are two considerable questions: (1) why are the annual heating RVRs always far higher than the annual cooling RVRs for different buildings with the same increase of ventilation rate? According to the experience of the authors, it is true. For example, in the same room, when the air conditioner is working on, we can feel more bracing with windows or doors open slightly in summer while in winter, we cannot feel warmer under the same condition with the above. Unless all doors and windows are closed, the room temperature will rise obviously. Whether this conclusion is the proof that people living in the cold district are accustomed to closing all the doors and windows tightly in winter will be discussed in detail later. It is interesting that the results predicted by

Fig. 5. Comparison of annual RVRs with the same increase of $n_k$ in various cities (960 m² tradi.).

Fig. 6. Comparison of annual RVRs with the same increase of $n_k$ in various cities (960 m² impr.).
DeST-h is also that the annual RVRs of heating are far higher than those of cooling for different buildings with the same increase of ventilation rate. (2) Why do the annual cooling RVRs have some difference in various cities? Although the discrepancy is only several percent, the relative difference is larger for the base is very small. Just as mentioned above, the discrepancy in the annual assorted cooling need without solar radiation in the totality is significantly different among various cities and maybe it is one of the reasons for the phenomena (it will be discussed in the following paper). Another reason is perhaps the difference of annual average of outdoor velocity, of which the preliminary analysis will be made.

5. The influence of annual average velocity of outdoor wind

Figs. 9 and 10 show the variation laws of annual cooling RVRs with the annual mean outdoor velocity corresponding to each city when the ventilating rate increases from 0 to 1.5 vol/h for the 960 m² building with traditional envelope and the 2304 m² building with improved envelope, respectively. In Fig. 9, 19 data points are corresponding to 19 cities, respectively, and in the Fig. 10, 14 data points are corresponding to the 14 cities, respectively. It can be seen from the above two figures that there exists some internal relationship between the annual mean outdoor wind velocity and the difference of annual cooling RVRs among various cities. The total tendency is that the bigger the annual mean wind speed is, the lower annual cooling RVRs are. The reason is that on the assumption that other conditions are all the same: the bigger the annual mean wind speed is, the higher the basic cooling need \( (n_k = 0) \) is, and thus the annual cooling RVRs are lower. But the data points in the figure are quite dispersed. The reason for this phenomenon is very complicated, and yet part of the reason may be that the annual average outdoor velocity cannot represent the average of all the hours in need of.
cooling. Because of too much statistics and calculation load, the authors could not make further analysis.

Fig. 11 shows the variation law of annual total heating and cooling RVRs with the annual mean outdoor velocity corresponding to each city when the ventilating rate increases from 0 to 1.5 vol/h for the 960 m² building with an improved envelope. In Fig. 11, the 19 data points are corresponding to the 19 cities, respectively. It can be found from this figure that the correlation between the annual total RVRs of energy consumption and annual mean outdoor wind speed is better than that in Figs. 9 and 10; the annual total RVRs of energy consumption decrease wholly with the increase of annual average wind velocity.

6. Conclusions

(1) For the same building with the same increase of ventilating rate, the absolute increments of annual heating and cooling energy consumption are totally different in various cities and the maximum discrepancy may reach as high as 10s of times or even more than 100 times, which illustrates that climatic conditions are the key determining factor of the increment of energy consumption.

(2) The annual heating RVRs are approximate in different cities for the same building with the same increase of ventilation rate.

(3) The discrepancy in the annual cooling RVRs is not obvious in different cities for the same building with the same increase of ventilating rate.

(4) The annual heating RVRs are far higher than the annual cooling RVRs in the same city for the same building with the same increase of ventilating rate.

(5) For the same building with the same increase of ventilating rate, the annual RVRs of energy consumption are approximate as a whole in various cities and the slight discrepancy among different cities is partly caused by outdoor wind velocity. In general, the bigger the annual average wind velocity is, the lower the annual RVRs of energy consumption are.