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A novel building energy efficiency evaluation index: Establishment of calculation model and application

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ABSTRACT

In current system of building energy efficiency, the building energy saving rate is calculated based on energy consumption per unit area on a certain past stage. The approach is restricted by the development of economy, progress of energy-saving technologies and climate change. In present work, a novel building energy efficiency evaluation index is developed to represent building energy saving performance. A building model can be first established according to architectural design scheme, current standards and operating conditions. Then, average daily indoor air temperature would be obtained using hourly outdoor air temperature as input conditions, with the one-dimensional unsteady heat transfer model. Finally, the calculation equations of energy saving of envelopes (ΔS) and building energy saving rate (BESR) are derived. In application, a building envelopes trade-off option is proposed and a target building in Western China is employed for case study. The results indicate that, about 19.3% of whole energy achieving indoor human thermal comfort is provided by building envelopes for the target building. The parametric analyses indicate that, BESRs of the standard building model in cold climate zone (2A) are much higher than those in cold climate zone (2B) in China. It is found that, the trade-off option can also be employed to select and optimize insulation materials and layer thicknesses. The approach can provide new thoughts for evaluation of energy saving performance of building envelopes in the design phase.

1. Introduction

With quick progress of economic development of developing countries, world energy consumption indicates a rapid growth trend in recent years. Building energy conservation started from the first world energy crisis in 1973 and has been developed rapidly for past forty years. In China, the building industry achieved high-speed development and the total construction area had been exceeded 56.1 billion m^2 in 2014 [1]. Energy consumption of building sector increased from 0.289 to 0.677 billion tons of standard coal, from 2000 to 2010. According to related predictions with life cycle approach, energy consumption in building sector would account for more than 43% of the overall energy consumption in China in recent years [2].

The factors that affect building energy consumption are mainly climate conditions [3], climate change [4], thermal performance of building envelopes (walls, floors, doors, windows, etc, which can hold indoor space and generate thermal environment) [5,6], indoor human thermal comfort demand [7], operating efficiency of heating, ventilation and air conditioning (HVAC) systems [8], operating mode of buildings [9] and occupant behaviours [10]. Therefore, to reduce energy consumption in building sector, there are mainly two kinds of approaches. The one is in the design phase, to adjust building envelopes to adapt local climate conditions [11]. The other is to improve operating efficiency of HVAC systems, operating mode of buildings and occupant behaviours during operating period [12]. It has been recognized that the former one is the foundation for energy conservation in buildings [13].

To reduce building energy consumption and guide building energy efficiency design, different design strategies of energy saving have been proposed. The major countries in the world have developed corresponding standards and codes. National standards from most European countries limited energy demand for new buildings [14]. There were generally two ways, one was to set minimum insulation requirements for building components. The other was to set maximum energy demand for the whole buildings. ASHRAE Standard 90.1 [15] also established specific indicators for thermal performance of envelopes. Additionally, mandatory requirements of lightning and HVAC systems were proposed. It can be obtained that mandatory requirements of basic parameters of buildings and energy use systems were key ways to reduce building energy consumption. With the development of building

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Nomenclature

a	beginning date of counting building energy efficiency, dimensionless
b	ending date of counting building energy efficiency, dimensionless
c	specific heat, $J\cdot kg^{-1}\cdot°C^{-1}$
$f_{comf}(x)$	annual average comfortable temperature curve, dimensionless
$f_{in}(x)$	annual indoor air temperature curve, dimensionless
$f_{out}(x)$	annual outdoor air temperature curve, dimensionless
F	area of walls and roofs, m^2
F_c	area of external windows, m^2
$H_{d,h}$	direct solar radiation on the horizontal plane (hourly values), $kJ\cdot m^{-2}\cdot h^{-1}$
$H_{s,h}$	scattering radiation on the horizontal plane (hourly values), $kJ\cdot m^{-2}\cdot h^{-1}$
$H_{t,h}$	total solar radiation on the horizontal plane (hourly values), $kJ\cdot m^{-2}\cdot h^{-1}$
$H_{t,v}$	total solar radiation on the vertical plane (hourly values), $kJ\cdot m^{-2}\cdot h^{-1}$
I	solar radiation intensity (hourly values), $W\cdot m^{-2}$
J	building energy saving rate, %
J_a	energy saving rate of actual building model, %
J_s	energy saving rate of standard building model, %
$J_{w\tau}$	cooling load intensity due to heat gain of windows without shading device, $W\cdot m^{-2}$
k	heat transfer coefficient, $W\cdot m^{-2}\cdot°C^{-1}$
k_c	heat transfer coefficient of external windows, $W\cdot m^{-2}\cdot°C^{-1}$
l	counting days of building energy efficiency, dimensionless
N	ventilation rate, h^{-1}
N_0	number of days, dimensionless
Q_c	indoor cooling load due to heat gain of windows (hourly values), W
R_d	ratio of direct solar radiation on the vertical and horizontal plane (hourly values), dimensionless
S	baseline of building energy consumption, °C·d
S'	design building energy consumption, °C·d
t	temperature, °C
t_{sa}	outdoor sol–air temperature (hourly values), °C
$\bar{t}_{D,in}$	average indoor air temperature (daily values), °C
$\bar{t}_{D,out}$	average outdoor air temperature (daily values), °C
V	volume of room, m^3
w_s	sunset angle on the horizontal plane, dimensionless
w_s'	sunset angle on the south plane, dimensionless
X_d	site correction factor, dimensionless
X_g	construction correction factor of the window, dimensionless
$y_{D,out}$	deviation between $\bar{t}_{D,out}$ and $f_{comf}(x)$, °C

Greek letters

α_1	convective heat transfer coefficient between indoor air and the first layer of external walls (or roofs), $W\cdot m^{-2}\cdot°C^{-1}$
α_2	convective heat transfer coefficient between outdoor air and the nth layer of external walls (or the mth layer of roofs), $W\cdot m^{-2}\cdot°C^{-1}$
γ	declination of sun, °
δ	thickness, m
ΔS	energy saving of building envelopes, °C·d
$\Delta\tau$	time step, s
η_1	transmission efficiency of heat-supply network,%
η_2	boiler operating efficiency,%
λ	thermal conductivity, $W\cdot m^{-1}\cdot°C^{-1}$
ρ_{gr}	reflection coefficient of the ground against solar radiation, dimensionless
ρ_{in}	density of indoor air, $kg\cdot m^{-3}$
ρ_{out}	density of outdoor air, $kg\cdot m^{-3}$
ρ_s	absorption coefficient of solar radiation, dimensionless
τ	time, s
φ	local geographic latitude, °

Subscripts

1	1st layer of external walls or roofs
a	actual
D	Dth day
e	east
i	ith hour
in	indoor
m	mth layer of roofs
n	nth layer of external walls, north
out	outdoor
r	roofs
s	standard, south
w	external walls, west
x	xth layer of external walls
y	yth layer of roofs
z	values at $\tau = z\cdot\Delta\tau$
z + 1	values at $\tau = (z+1)\cdot\Delta\tau$

Abbreviations

BESR	building energy saving rate
CHTC	convective heat transfer coefficient
HTC	heat transfer coefficient
HVAC	heating, ventilation and air conditioning
TMY	typical meteorological year

energy conservation, energy efficiency index could be increased continuously, especially for the thermal parameters of building envelopes (see Table 1 [16]). Taking UK for an example, heat transfer coefficient (HTC) of external walls, roofs, floors and windows reduced by 22%, 36%, 44% and 33% from 1995 to 2000.

Energy saving rate in buildings was first proposed in Europe since 1973. For European countries with a large proportion of heating load, energy consumption per unit area at one certain stage is employed as a base, to calculate building energy saving rate. For instance, energy consumption of residential buildings before the energy crisis is treated as a base in France. In the beginning, energy saving rate was set 25%. After that, the energy saving rate was advanced by 25% twice, respectively. Recently, the index was improved by 25% and 40% based on the previous basis (for different types of buildings), respectively. By taking both advanced experience of building energy conservation from Europe and America, also considering development phase of China, the Chinese Government published the first design standard on residential

Table 1
Development process of HTC in Building Regulations in UK [16]

Element	HTC ($W\cdot m^{-2}\cdot°C^{-1}$)		Percentage reduction (%)
	1995 standard	2000 standard	
Walls	0.45	0.35	22
Roofs	0.25	0.16	36
Floors	0.45	0.25	44
Windows	3.30	2.20	33