Applied Energy 128 (2014) 217–229

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Heating and cooling building energy demand evaluation; a simplified model and a modified degree days approach

Mattia De Rosa, Vincenzo Bianco, Federico Scarpa *, Luca A. Tagliafico

University of Genoa, DIME/TEC, Division of Thermal Energy and Environmental Conditioning, Via All'Opera Pia 15 A, 16145 Genoa, Italy

HIGHLIGHTS

- A dynamic model to estimate the energy performance of buildings is presented.
- The model is validated against leading software packages, TRNSYS and Energy Plus.
- Modified degree days are introduced to account for solar irradiation effects.

ARTICLE INFO

Article history:
Received 27 December 2013
Received in revised form 21 April 2014
Accepted 22 April 2014
Available online 15 May 2014

Keywords:
Dynamic models
Building
Energy demand
Modified degree days

ABSTRACT

Degree days represent a versatile climatic indicator which is commonly used in building energy performance analysis.

In this context, the present paper proposes a simple dynamic model to simulate heating/cooling energy consumption in buildings. The model consists of several transient energy balance equations for external walls and internal air according to a lumped-capacitance approach and it has been implemented utilizing the Matlab/Simulink® platform. Results are validated by comparison to the outcomes of leading software packages, TRNSYS and Energy Plus.

By using the above mentioned model, energy consumption for heating/cooling is analyzed in different locations, showing that for low degree days the inertia effect assumes a paramount importance, affecting the common linear behavior of the building consumption against the standard degree days, especially for cooling energy demand.

Cooling energy demand at low cooling degree days (CDDs) is deeply analyzed, highlighting that in this situation other factors, such as solar irradiation, have an important role. To take into account these effects, a correction to CDD is proposed, demonstrating that by considering all the contributions the linear relationship between energy consumption and degree days is maintained.

1. Introduction

Energy consumption of buildings has become a relevant international issue and different policy measures for energy saving are under discussion in many countries. In the European Union (EU), buildings account for about the 40% of the total energy consumption and they represent the largest sector in all end-users area, followed by transport with the 33% [1]; whereas in terms of CO_2 emission, buildings are responsible for about 36% of it. It is estimated that the residential sector alone represents about 25% (in 2011) of the final energy consumption in EU [2]. Energy in household is consumed for different purposes, such as hot water, cooking and appliances, but the dominant energy end-use in Europe (responsible for around 70% of total consumption in households) is space heating [1]. Moreover, trend in energy demand, both for heating and cooling purpose, assumes a relevant issue on the development of energy systems and energy policies. Isaac and van Vuuren [3] highlight that energy demand for heating and cooling purposes tends to rise in the 21th century, especially due to the increasing income in developing countries and to the climate change. In particular, the climate change has a double effect: (i) it decreases the global heating energy demand by over a 30% and, on the other hand, (ii) it increases cooling energy demand by about 70% [3]. An extended review on the impact of climate change on energy use in building for different world locations was performed by Li et al. [4].

In order to achieve relevant saving of primary energy, several potential mitigation measures can be implemented involving the

* Corresponding author. Tel.: +39 0103532312; fax: +39 010311870.
E-mail address: fscarpa@ditec.unige.it (F. Scarpa).

http://dx.doi.org/10.1016/j.apenergy.2014.04.067
0306-2619/

Nomenclature

Roman letters

a, b	forced convection coefficient
C	thermal capacitance or heat capacity (J K^{-1})
C_t	natural convection coefficient (W m^{-2} $K^{-4/3}$)
CDD	cooling degree-days (°C)
CDD^*	modified cooling degree-days (°C)
D_m	number of days in a month
E	energy demand (kW m^{-2})
E^*	cooling energy demand calculated using CDD^* (kW m^{-2})
f	shadowing factor
F_1, F_2	brightening coefficient
h	heat transfer coefficient (W m^{-2} K^{-1})
H	building global heat transfer coefficient (W K^{-1})
HDD	heating degree-days (°C)
$I_{b,n}$	normal direct solar radiation (W m^{-2})
$I_{d,h}$	horizontal diffuse solar radiation (W m^{-2})
$I_{d,n}$	diffuse solar radiation on surface (W m^{-2})
$I_{j,n}$	Global solar radiation on surface j (W m^{-2})
$I_{t0,y}$	total horizontal solar radiation in the year computed by CDD^* model (W m^{-2})
j	index of wall layers
n	number of external walls
$\dot{q}$	heat flux (W)
R	thermal resistance (K W^{-1})
S	surface (m^2)
t	time (s, h)
T	temperature (°C)
$\overline{T}_{e,d}$	daily mean temperature (°C)
U	transmittance (W m^{-2} K^{-1})
V	wind velocity (m s^{-1})

Greek letters

α	solar height angle/absorbance coefficient
β	surface tilt angle (°)
γ	surface azimuth (°)
δ	declination angle (°)
ε	emissivity
ζ, χ	parameters for CDD^* calculation
θ	incidence angle between solar radiation and surface normal axis (°)
ξ_r	tilt solar redirected radiation factor
ρ	ground solar reflection factor
σ	Stefan Boltzmann's constant (W m^{-2} K^{-4})
τ	solar transmission coefficient
ϕ	latitude (°)
ω	hour angle (°)

Subscripts

b	base temperature
c	cooled
cs	cooling system
d	days
e	external
E	east
f	floor
h	hour
hs	heating system
ht	heated
i	internal
is	internal sources
j	wall index for vertical walls and roof
m	month
N	north
r	roof
s	solar
S	south
sg	solar gain
tot	convective plus irradiative
v	ventilation
w	wall
W	west
win	windows
y	year

building envelope, internal condition, heating/cooling systems, etc., as reported in Wan et al. [5].

In this context, the 91/2002 "Energy Performance of Buildings Directive" (EPBD) [6] has been emanated to introduce several requirements for new and existent buildings within EU. Accordingly, designers and researchers must optimize all the possible aspects (building envelope, shadowing, heating and cooling system components, regulation criteria, etc.), starting from the earliest design phase with an optimization perspective, in order to respect the prescriptions of the current directive and, at the same time, ensuring the thermal comfort for occupants [7,8].

In this context, software able to predict the thermal energy demand for heating and cooling can contribute to find the best solution to increase energy efficiency and this is the reason why several numerical models for buildings simulation have been developed over the years.

Different basic approach can be adopted for building energy analysis tools, depending on the different level of building description which could be useful for each different purpose. Generally, long term calculation with steady-state models, without considering the inertia effect (or considering some correction factors), are commonly used for preliminary building design and for scenario analyses. The degree-days method represents the simple way to obtain an idea of the building energy consumption, performing very simple and fast calculations. Their base assumption is that for long term calculation, the energy consumption is proportional to the difference between external and internal temperature. Therefore, assuming a global building transmission coefficient H in W/K, the monthly energy consumption $E_{h,m}$ can be calculated as follows [9]:

$$E_m = \frac{H \cdot DD_m \cdot t_h}{\eta_{hs/cs}} \tag{1}$$

where t_h is the heating time in a day (which can be assumed equal to 24 h if a continuously heating/cooling is provided), $\eta_{hs/cs}$ is the efficiency of the equipment, and DD_m is the total heating or cooling degree days of a month m. A simple method to calculate the degree days is reported in Eqs. (2) and (3) for heating (HDD) and cooling (CDD) calculation respectively:

$$\text{Heating}: \quad DD_m = \text{HDD}_m = \sum_{d=1}^{D_m} (T_{b,hs} - \overline{T}_{e,d})^+ \tag{2}$$

$$\text{Cooling}: \quad DD_m = \text{CDD}_m = \sum_{d=1}^{D_m} (\overline{T}_{e,d} - T_{b,cs})^+ \tag{3}$$