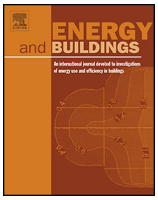
Energy and Buildings 75 (2014) 472–482

Contents lists available at ScienceDirect

Energy and Buildings

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



Simulating external longwave radiation exchange for buildings

Ralph Evins [a,b,*], Viktor Dorer [a], Jan Carmeliet [a,b]

[a] Empa, Swiss Federal Laboratories for Materials Science and Technology, Überlandstrasse 129, 8600 Dübendorf, Switzerland
[b] Chair of Building Physics, ETH Zürich, Stefano-Franscini-Platz 5, 8093 Zürich, Switzerland

ARTICLE INFO

Article history:
Received 5 August 2013
Received in revised form 3 February 2014
Accepted 8 February 2014

Keywords:
External
Longwave
Radiation
Energy balance
Simulation

ABSTRACT

Longwave (infrared) radiation is exchanged between exterior building surfaces, the ground and the sky. This process affects exterior surface temperatures and hence building energy consumption. Current approaches to modelling this exchange in building and microclimate analysis tools are discussed. There are various shortcomings, the most significant concerning radiation exchange between building surfaces at different temperatures.

This work implements improvements to the longwave exchange processes in the EnergyPlus simulation engine, allowing improved calculation of surface temperatures and thus of heating and cooling loads. The improvements cover ground temperature assumptions and the coupling of other building surfaces. The coupling of radiative transfer was achieved by means of a timelag; it is shown that for small timesteps this approach is adequate.

The new approaches are compared to the existing implementation in EnergyPlus for arrangements including a street canyon and shading devices. The combined impact gave an increase in surface temperature of up to 6 °C, with an average change of 2 °C. This caused a decrease in annual heating load of 18% and an increase in cooling load of 19%. This confirms the importance of accurate longwave radiation modelling both for buildings in dense urban areas and for buildings with external shading devices.

1. Introduction

1.1. Longwave radiation exchange

Longwave (infrared) radiation is emitted and absorbed by surfaces of objects. The net heat exchange between two surfaces is dependent predominantly on their surface temperatures, relative areas and positions, and surface properties. The two important surface properties are transmittance (here taken to be zero for opaque surfaces), and emittance, which gives the ratio of its emissivity to that of a perfect 'black body' emitter.

There are several standard assumptions regarding longwave radiation modelling for engineering purposes [1]. The 'grey body' assumption takes emittance to be independent of wavelength. The impact of the medium between the surfaces is usually neglected, as for dry air over short distances this is very small. It is also usually assumed that longwave radiation is emitted and reflected diffusely rather than specularly. The above assumptions allow the net radiant exchange between two surfaces to be written as:

$$q_{lw} = \varepsilon_1 F_{1-2} \sigma (T_1^4 - T_2^4) \tag{1}$$

where ε_1 is the emittance of surface 1, F_{1-2} is the view factor from surface 1 to surface 2, σ is the Stefan–Boltzmann constant ($5.67 \times 10^{-8}\,\mathrm{kg\,s^{-3}\,K^{-4}}$) and T_1 and T_2 are the surface temperatures in Kelvin. The view factor depends only on geometry, and gives the fraction of the view from a base surface obstructed by a given other surface. These can be calculated numerically or analytically [2].

1.2. Longwave radiation and building energy use

Determining the energy demand of a building is often based on heat balances at the outside surface, inside surface (linked via conduction) and zone air (linked via convection) [3]. In this way the exterior conditions (from weather data) are used to drive the calculation of the energy needed to maintain a given inside air temperature range, based on the properties of the buildings.

The exterior surface heat balance for a building can be written as follows [4], since the heat fluxes for shortwave, longwave, convection and conduction must sum to zero:

$$q_{sw} + q_{lw} + q_{conv} + q_{cond} = 0 \tag{2}$$

---

* Corresponding author at: Empa, Swiss Federal Laboratories for Materials Science and Technology, Überlandstrasse 129, 8600 Dübendorf, Switzerland.
Tel.: +41 58 765 6511.
E-mail address: ralph.evins@empa.ch (R. Evins).

http://dx.doi.org/10.1016/j.enbuild.2014.02.030

Nomenclature

r_{sw}	incident longwave radiation (W/m^2)
q_{sw}	net shortwave radiation (W/m^2)
q_{lw}	net longwave radiation (W/m^2)
q_{cond}	conductive heat flux (W/m^2)
q_{conv}	convective heat flux (W/m^2)
F_{i-j}	view factor from surface i to surface j
σ	Stefan–Boltzmann constant (5.67×10^{-8} kg s^{-3} K^{-4})
$T_{\{i,gnd,sky,air,obs\}}$	temperature of surface (K) for surface i, ground, sky, air and obstructions
$\Theta_{\{i,gnd,sky,air,obs,in\}}$	temperature of surface (°C) for surface i, ground, sky, air, obstructions and inner glass pane
ε_i	longwave emittance of surface i
Θ_{soil_av}	annual average soil surface temperature (°C)
A_s	amplitude of soil surface temperature (°C)
t_0	phase constant of soil surface temperature (days)
$F_{\{gnd,sky,air,obs\}}$	view factors from building surface to ground, sky, air and obstructions
$h_{r\{gnd,sky,air,obs\}}$	radiative heat transfer coefficients for ground, sky, air and obstructions
h_c	convective heat transfer coefficient
k	conductance of glass layer
S	short and longwave radiation absorbed by glass pane (W/m^2)
T_i'	assumed temperature (K)
δ	error in temperature (K)
γ	error in longwave flux (W/m^2)

The exterior and interior conduction fluxes are linked via an equation which describes conduction through the surface. The interior surface heat balance equation links the interior conduction flux and the interior convection flux, which allows the zone air balance to be formulated. This then determines the zone temperature (if uncontrolled) or the heating or cooling required to maintain a fixed temperature. It is necessary to simultaneously solve these linked equations for each zone surface to accurately predict the building energy demand. For the exterior surface, the longwave radiation, convection and conduction terms all depend on surface temperature, so this variable is critical.

Longwave radiative exchange occurs between the exterior building surface and the following elements (as shown in Fig. 1):

- The sky, which has a very low effective temperature, particularly at night, leading to significant heat loss through longwave radiation.
- The ground, where the temperature changes more slowly than the air so can have a buffering effect.
- Other surfaces, including other buildings and exterior surfaces like shading devices as well as more distant objects like mountain slopes. Vegetation cover also affects the influence of other surfaces.

Because longwave exchange is a two-way process that depends on the temperature of both surfaces, it is necessary to simultaneously calculate the full set of surface heat balances to determine the overall temperatures and energy fluxes. This requires an iterative predictor–corrector approach or similar due to the T^4 relationship. It also makes it challenging to discern the impact of longwave radiation on building energy use, since any change requires the full set of temperatures to be recalculated. There is also a spatial dependence: every small area experiences a different radiation balance, so the granularity of the model used is important.

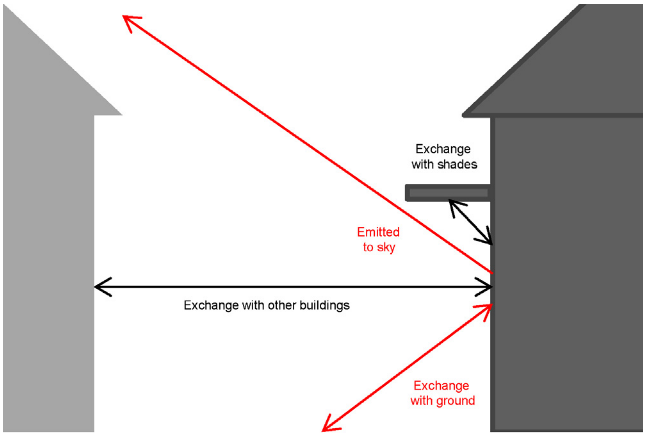


Fig. 1. Longwave radiation exchange processes at an exterior building surface. Those to other buildings and shades are modelled here with bi-directional dependence: longwave radiation exchange affects the temperatures of both surfaces. Those to ground and sky are modelled without bi-directional dependence: the temperature of the other surface does not depend on the longwave radiation exchanged with the building.

1.3. *This work*

This paper begins by discussing the treatment of external longwave radiation exchange in common building energy simulation programs. It is concluded that none offer sufficient capability to model both detailed building energy use and the complex external conditions found in dense urban areas. Previous research in this area is also covered. Next, errors arising from decoupling the radiation equations by introducing a lag of one timestep are analysed, and it is shown that for small timesteps this error can be kept to a minimum. Several modifications to the program EnergyPlus are proposed that allow much greater detail in simulating exterior longwave radiation, including ground temperatures and other surfaces at different temperatures. These are then applied to a series of cases for an example building, covering street canyon arrangements and external shading. Results are presented giving the changes in heating and cooling loads due to these improvements, as well as surface temperatures and radiation fluxes for typical days.

2. Background

2.1. *Existing analysis approaches*

This section presents a discussion of the treatment of external longwave radiation exchange in various building energy and urban microclimate simulation packages. There are many different options, none of which offer a comprehensive solution.

EnergyPlus [5] is a building energy simulation tool which is widely used, particularly in research. Exterior longwave exchange accounts for the sky, air and ground, however the ground is assumed to be at the same temperature as the air. Exterior obstructions block the view to the sky (assessed for 144 points on the sky dome), but are assumed to be at the same temperature as the air (and ground). An isotropic distribution across the sky is assumed. Linearised radiative heat transfer coefficients are used. The details of the calculation are discussed further in the following section, where improvements are implemented.

There is the option of an 'exterior naturally ventilated cavity' for which longwave radiation is exchanged with both the sky, air and ground and with the underlying building surface. This allows heat exchange with a hotter surface to be simulated, but the model is only valid for an opaque surface, so precludes any solar gains or