International Journal of Thermal Sciences 86 (2014) 189–197

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

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

Thermal radiation heat transfer: Including wavelength dependence into modelling

Ron Zevenhoven [a, *], Martin Fält [a, 1], Luis Pedro Gomes [a, b]

[a] Åbo Akademi University, Thermal and Flow Engineering Laboratory, Piispankatu 8, 20500 Turku, Finland
[b] Visiting from University of Coimbra, Department of Mechanical Engineering, Coimbra, Portugal

ARTICLE INFO

Article history:
Received 10 August 2013
Received in revised form
5 July 2014
Accepted 7 July 2014
Available online 8 August 2014

Keywords:
Thermal radiation
Wavelength dependence
Radiative cooling

ABSTRACT

Thermal radiation heat transfer is receiving increased attention from the field of energy-efficient building. Well known is the enhanced greenhouse effect that results from an imbalance between incoming short-wave (SW) solar radiation and outgoing long-wave (LW) radiation from earth. Likewise, passive cooling can be achieved if outgoing radiation is not balanced by incoming radiation through another wavelength band. This paper reports on simulating thermal radiation from a building space using a double-glazed window with the option of having a participating gas like CO_2 filling the inter-glazing space. The infrared spectrum is sectioned into four bands: SW < 4 μm, and three LW bands 4–8 μm, 8–14 μm (the atmospheric window) and >14 μm, respectively, and the relative importance of thermal radiation in the various bandwidths is assessed. The effect of changing the transmittance of the double-glazed gas-filled window on heat transfer is analysed for both day-time and night-time for air, CO_2 and HFC-125. For distinguishing SW and LW thermal radiation through the atmosphere measurement data obtained with a pyranometer and a pyrgeometer is used. The results demonstrate that the calculation tool allows for designing double-glass window systems towards the minimisation of energy requirements for cooling or heating. It is found that expanding the wavelength range for window material transmittance increases heat fluxes through the system while using participating gases gives an insulation effect. For HFC-125 the effect is significant while for CO_2 it is much smaller.

1. Introduction

The cooling and air conditioning of residential and office space is very energy intensive and represents a significant part of the electricity use worldwide. Thermal radiation in a passive system may be considered if a suitable driving force for that exists and windows materials are used that have a suitable transmittance. In that case a net energy input (typically as electricity) can be avoided and significant savings can be achieved. Thermal radiation heat transfer is therefore receiving increased attention from the field of energy-efficient building, with air conditioning and cooling being equally important as heating or electricity production using thermal or photovoltaic solar energy systems [1].

One feature that can be made use of is that an imbalance between thermal radiation in short-wave (SW, <4 μm) and long-wave (LW, >4 μm) bands leads to a net heating or cooling effect. Well known is the enhanced greenhouse effect that results from an influx of short-wave thermal radiation from the sun that nowadays is not balanced by long-wave outgoing radiation. Likewise, passive cooling can be achieved if outgoing radiation in certain wavelength bands cannot be balanced by incoming thermal radiation through another wavelength band.

In our earlier work, we have reported on using LW thermal radiation with the main focus on cooling [2–5]. Double glass (where "glass" may be materials like plastics) with a participating gas like CO_2 filling the space between the windows may give increased heat fluxes and/or lower temperatures of the spaces involved. More recently, we have suggested a special design for a skylight (roof window) [6,7] that gives increased heat flow from a room to the sky above by inducing a natural convection flow that, again, is enhanced by the presence of greenhouse gas CO_2 – see Fig. 1 as simulated with Comsol 4.1 software. Important features made use of are the temperature difference that exists between the (ground level) surroundings and the sky, and as shown here, the so-called atmospheric window 8–14 μm for which the atmosphere is transparent for thermal radiation.

---

* Corresponding author. Tel.: +358 2 215 3223; fax: +358 2 215 4792.
E-mail address: ron.zevenhoven@abo.fi (R. Zevenhoven).
[1] Currently at Elomatic Oy, Vantaa, Finland.

http://dx.doi.org/10.1016/j.ijthermalsci.2014.07.003

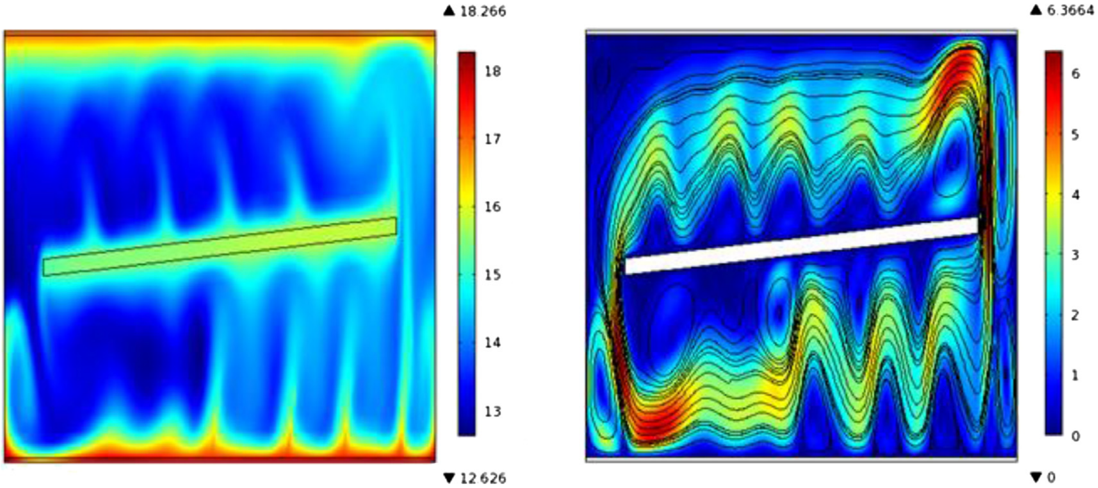

Fig. 1. Temperature (°C, left) and velocity (m/s, right) profiles for a skylight (width 0.5 m, height 0.1 m, not to scale) containing CO_2 with absorptivity = emissivity = 0.19, during summer (Helsinki, Finland). Heat flux with CO_2 117 W/m^2, with air 15 W/m^2. Simulated with Comsol 4.1 [7].

For more accurate modelling calculations but also for simulations using commercial software it is important that the wavelength dependence on the optical properties of materials is taken into account.

Unfortunately, this makes calculations much more complicated while commercial software codes have not comprehensively included the option to consider this in the calculations. Especially in situations where also convective and conductive heat transfer must be considered the situation becomes problematic and one may be forced to produce in-house software code.

In this paper, we will report on simulating heat transfer, primarily as SW and LW thermal radiation, from a building space using an optimized double-glazed window with the option of having a participating gas like CO_2 filling the inter-glazing space. For this purpose the infrared spectrum is sectioned into four sections or wavelength "bands": SW < 4 μm, and three LW bands 4–8 μm, 8–14 μm (the atmospheric window) and >14 μm respectively, and the relative importance of the thermal radiation in the various bandwidths is assessed. The motivation for dividing the LW bands into three sections is that the atmosphere is opaque to LW radiation outside the atmospheric window (see below for more detail).

Thermal radiation is addressed here as one-dimensional (diffuse radiation) heat transfer from a building space ("room") through a horizontal double-glazed window (skylight) and the atmosphere towards the sky. Radiation is assumed diffuse, no reflectance or scattering are considered here, thus emissivities, ε, absorptivities, α, and transmittances, τ, here considered wavelength-dependent, are related as $\varepsilon_i = \alpha_i = 1 - \tau_i$ for material i. In earlier work [8] reflectance $\rho = 0$ and $\rho = 0.1$, giving slightly different absorptivities $\alpha = \varepsilon = 1 - \tau - \rho$ were considered for a gray model. No significant temperature differences were found although heat fluxes were up to 10% reduced. (The absorptivity by multiple reflections $(1 - \rho)\cdot(1 - \tau)/(1 - \rho\tau)$ for high values $\tau >> \rho$ gives $\alpha \approx (1 - \rho)\cdot(1 - \tau)\cdot(1 + \rho\tau) \approx 1 - \tau - \rho$.)

The approach followed is similar but a simplification of the line-by-line approaches used for atmospheric radiative transfer and outgoing (earth to sky) LW radiation [9,10], where transfer equations are used that are independently valid for each frequency. Typical data for the earth/sun system are 342 W/m^2 incoming solar radiation (SW) of which 107 W/m^2 is reflected by the atmosphere, while the remaining 235 W/m^2 is re-emitted as outgoing longwave (LW) radiation (data from [11]). This gives a system that here is simplified by five temperatures $T_{\text{sun}} > T_{\text{earth}} > T_{\text{atmosphere}} > T_{\text{sky}} > T_{\text{universe}}$, with SW incoming radiation driven by $T_{\text{sun}} > T_{\text{earth}}$ and outgoing radiation driven by $T_{\text{earth}} > T_{\text{atmosphere}} > T_{\text{sky}} > T_{\text{universe}}$. Each of the radiative transfer processes is governed by wavelength-dependent emissivities, absorptivities, transmittances (and reflectances), here lumped into four bands for each of which Kirchhoff's law holds. The approach followed here is similar to what is used in [12] for climate modelling, improving a "semi-gray" gas model for two-stream (from earth and towards earth, respectively) thermal radiation through the atmosphere by adding the transparent atmospheric window. At the same time it is less computationally heavy than line-by-line methods with ~10^6 lines [10].

Simulating the effect of changing the transmittance of the double-glazed gas-filled window, and the use of CO_2 or HFC-125 instead of air, the radiative heat transfer for both day- and night-time is analysed. For discriminating between ground-level surroundings and upper sky temperatures data from a pyrgeometer was used. (Although a Kipp & Zonen pyrgeometer CNR1, measurement range 5.4–42 μm, is available at our laboratory, data earlier obtained from the Finnish Meteorological Institute was used for the work reported here.)

The first (main) part of the paper excludes heat convection and conduction from the assessment. At the end of this reporting the relative importance of these modes of heat transfer through the double-glazed window is analysed. Implementation in or combination with commercial software (Comsol, ANSYS Workbench Platform) in order to make these more versatile is briefly addressed as well.

2. System description and radiation network

2.1. The double-glazed window

For the purpose of this study, we revisit a system addressed in earlier work [3,8] where gray-body radiation was considered. The geometry of the set-up to be considered is given in Fig. 2, showing a double glass window that separates a building space ("room") from the outside atmosphere. In this paper, however, the two glazing materials are taken to be identical. Furthermore, Fig. 2 shows the equivalent radiation network for this system where nodes J_3 and J_4 represent the left-hand and right-hand side window at temperatures T_{G1} and T_{G2}, and Eb_G gives the blackbody radiation