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Validation of a lumped RC model for thermal simulation of a double skin natural and mechanical ventilated test cell

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ABSTRACT

Most current building thermal codes impose upper limits to the predicted annual building energy demand for heating, ventilation and air conditioning. In the building design phase these predictions are obtained using thermal simulations with variable complexity. The simplest approach uses a single lumped thermal capacitance to model the high thermal mass building elements, combined with five thermal resistances (known as the 5R1C model proposed in EN ISO 13790 standard). This model is used by many European countries as the reference simplified methodology to assess overheating risk and calculate yearly building energy demand. This paper presents a successful extension of this model that allows for its application to the prediction of the internal air temperature of free-running buildings with double skin façades. The extension consists in an increased number of thermal resistances used to model the double skin façade zone. The extended model is validated using a set of detailed thermal measurements obtained in a free-running double skin test cell. For the case analysed the simplifications used in the RC model do not reduce the overall accuracy: the mean absolute error for room air temperature is approximately 1 °C, the same order of magnitude of more detailed EnergyPlus simulations (1.2 °C).

1. Introduction

The last two decades have seen an increased public awareness of the environmental and operational costs of building energy consumption. As a result, most current building thermal codes impose upper limits to the predicted annual energy demand for heating, ventilation and air conditioning systems (HVAC). In the building design phase these predictions are obtained using thermal simulation models with variable levels of detail and approximations. The most complex buildings require models with several thermal zones and, in some cases, tri-dimensional computational fluid dynamics simulations (CFD). For small buildings with simple indoor climate control systems, such as single-family homes and apartments, there is an increase in use of single thermal zone simulation models. In response to this increased use, the research community is continuously working on improved models with all levels of complexity.

The main challenges of building thermal simulation are in modelling of room airflow and heat transfer in building elements with high thermal mass (floor, walls, etc.). In the majority of simple thermal models room air is considered perfectly mixed and represented as a single thermal node that is connected to all room internal surfaces via thermal resistances [1]. Heat transfer in building elements with high thermal mass can be modelled using variable levels of detail, ranging from detailed finite difference methods to conduction transfer functions (CTF) [2] or, in the simplest approach thermal resistances connected to a thermal capacitance. The thermal resistance and capacitance used in the models have physical meaning and can be calculated approximately from the thermal properties of the building elements. Fig. 1 shows the combination of a perfectly mixed room air approach with a resistance capacitance model for the high thermal mass elements, this approach is known as an RC model. These models are typically labeled according to the number of resistances and thermal capacities used. EN ISO 13790 standard [3], adopted by many European countries as the reference methodology to assess overheating in buildings during summer and calculate building energy demand, uses a single capacitance that represents all high thermal mass elements and five thermal resistances (making it a 5R1C model).

The widespread use of the 5R1C model makes it a preferred target for further development. This paper presents an extension of this model for application to double skin façade (DSF) buildings.

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Nomenclature

A_v	vents opening area [m^2]
A_t	total surfaces area [m^2]
A_f	floor area [m^2]
A_m	mass surfaces area [m^2]
c_a	air specific heat [J/(kg K)]
c_d	discharge coefficient
C_m	effective mass heat capacitance [J/K]
f	fraction of heat absorbed that is released to air
g	gravity acceleration [m/s^2]
g_c	solar heat gain coefficient at sunspace
g_{rm}	solar heat gain coefficient at room
h	height difference between inlet and outlet [m]
H_{ei}	heat conductance between e and i temperatures nodes [W/K]
H_{em}	heat conductance between e and m temperatures nodes [W/K]
H_{is}	heat conductance between i and s temperatures nodes [W/K]
H_{ms}	heat conductance between m and s temperatures nodes [W/K]
H_{cs}	heat conductance between mc/nc and s temperatures nodes [W/K]
H_{ce}	heat conductance between mc/nc and e temperatures nodes [W/K]
H_{cc}	heat conductance between mc_i/nc_i and mc_o/nc_o temperatures nodes [W/K]
H_{ve}	heat conductance between sunspace and external air by ventilation [W/K]
H_{tr}	heat conductance between sunspace and external air by transmission [W/K]
$\dot{v}$	volumetric air flow [m^3/s]
α	glazing absorptance
β	volumetric expansion coefficient [K^{-1}]
ρ	glazing reflectance
ρ_a	air density [kg/m^3]
τ	glazing transmittance
θ_e	external air temperature (temperature source) [°C]
θ_i	room air temperature [°C]
θ_m	mass temperature [°C]
θ_s	'star' temperature [°C]
θ_{mc}	air temperature at mechanically ventilated sunspace [°C]
θ_{nc}	air temperature at naturally ventilated sunspace [°C]
Δt	time iteration [s]
Φ_m	heat flow at m temperature node [W]
Φ_s	heat flow at s temperature node [W]
Φ_{mc}	heat flow at mc temperature node [W]
Φ_{nc}	heat flow at nc temperature node [W]

subscripts

b	blinds
c	sunspace air cavity
i	glass pane of inner double glazing that is close to the sunspace
ic	inner sunspace air cavity
o	outer single glazing
oc	outer sunspace air cavity
r	glass pane of inner double glazing that is close to the room
rm	room space

The proposed model is validated using a set of detailed thermal measurements obtained in a free-running double skin test cell [4]. The next section presents a review of existing RC models and model validation studies. The following section presents the model methodology followed by the presentation of free-running test cell measurements. The final section presents the results of the model validation.

2. Literature review

One category of RC models – the *lumped parameter construction element models* – approximates each building element with high thermal mass (e.g. walls, roofs, floors) by one or more capacitances (Fig. 2). A first-order representation refers to a single capacitance by each building element, a second-order refers to two capacitances. Therefore, the whole room model can have several capacitances and their number increases for higher order representations. It is noteworthy that thermal capacitances are always an approximation of the transient effects and, therefore, their number strongly defines the complexity of the RC model.

One of the first published works used a lumped parameter construction elements model [5] with a second-order representation for external walls and the floor above a crawl space, while all other elements (windows, external roof and partitions) are modelled by first-order representations. A very good agreement between measurements and model results is obtained for two houses, very different on thermal mass, with wood and concrete structures, respectively. A first-order representation of buildings elements is later assumed [6] and implemented in Matlab Simulink. The model results have also a good agreement with measurements. A comparison between second-order and first-order representations has revealed that there is no increased accuracy in using higher-order representations. More recently, a computational study of 45 types of building elements from four categories (external walls, internal partitions, floors and roofs) [7] evidenced that a second-order modelling could be sufficiently accurate to model buildings elements in simplified RC networks. However, third-order representation of mass building elements is used in [8,9] and forth-order in [10]. There are applications where RC parameters are statistically obtained, rather than calculated by the elements thermal properties. To that end, different optimisation algorithms are applied such as least squares method [11], Sequential Quadratic Programming [12] or Genetic Algorithms [13,14].

However, a parallel research is being also conducted on a much more simplified models: the *lumped parameter whole room models*. The research issue is to find the minimum number of capacitances that accurately model a single-thermal zone, lumping the whole zone instead of each building element (Fig. 3). A lumped parameter whole room model with only two capacitances and three resistances (3R2C) was applied by Crabb et al. [15]. Dewson et al. [11] tried to model a single-thermal zone using the same five parameters, but the parameter were statistically obtained by fitting the model results to the measurements. A three capacitance model, but still a lumped parameter whole room model, was further suggested [16] in order to solve some of the inaccuracies found in the previous models. Subsequent studies used a 2R2C network to model single-thermal zones [17,18]. More recently, Kampf and Robinson [19] extended the two capacitances model of [18] to model multiple thermal zones and found relative differences in the heating energy needs below 13%. The aforementioned models, despite the fact of having one, two or three capacitances representing the thermal zone, were the embryo of the 5R1C model of EN ISO 13790 [3]. Therefore, the 5R1C model belongs to the *lumped parameter whole room models* category, since it considers a capacitance that lumps all high thermal mass building elements. Further details on its parametrisation are found in Section 3.