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COMPUTATIONAL APPROACHES TO THE DESIGN OF LOW-ENERGY BUILDINGS

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Abstract

European and Czech directives and technical standards, approved in several last years, force substantial changes in thermal behaviour of all buildings, including new and reconstructed one- or more-family houses, block of flats, etc., especially radical decrease of their energy requirements. This stimulates the development of advanced materials, structures and technologies. Since no reliable experience with their design is available, robust and non-expensive computational simulation approaches, compatible with principles of classical thermodynamics, are needed. This paper demonstrates the impact of such requirements on the development of relevant computational algorithms, with the accent on the conception of a building as a thermal system, at various generality levels of analysis of its particular elements and subsystems.

1. Introduction

Phrases like "solar houses", "low-energy houses", "passive houses", with increasing frequency of exploitation in last years, reflect the tendencies to reduce, with help of various non-traditional energy sources, all energy demands of buildings, to their heating and air-conditioning, operation of household equipments, etc. Although i) some ideas of studious utilization of solar radiation can be observed even in the ancient literature and ii) the modern experiments with low-energy houses have their own interesting history, dating back to the first experimental house of the Massachusetts Institute of Technology (1939), most designers of building structures know just iii) the final result of discussion (about 1989) between B. Adamson (Lund University, Sweden) and W. Feist (Institut für Wohnen und Umwelt in Darmstadt, Germany), well-known as the "passive house standard". This result becames 2 decades later, after a lot of practical implementations in various countries, under different climatic conditions, reflected in [6], a part of the European directive [13], as well as of national technical standards, e. g. [15] in the Czech Republic.

Under the Central European conditions, the following requirements follow from [6]: a) the building must be designed to have an annual heating and cooling demand not higher than 15 kWh/m^2 per year, b) the total primary energy consumption (for

Figure 1: Illustrative photos from the Czech Republic, from the left: a) Block of family houses in Židlochovice (2006). b) One-family house "Vějíř" ("Punka") in Brno - Bystrc (2009). c) Cooling towers of the nuclear power plant Dukovany, view from the national nature reserve of xerophilous herbs near the township village Mohelno.

heating, hot water, electricity, etc.) cannot exceed 120 kWh/m^2 per year, c) the building with the total volume V must not leak more air than 0.6 V per hour at pressure 50 Pa, as tested by the blower door, d) as an non-obligatory (unlike a), b) and c)) additional condition: the power requirement for heating under the lowest considerable environmental temperature (typically $-12\,^\circ$C) should not exceed 10 W/m^2. By [6], i) passive solar building design and energy-efficient landscaping, ii) superinsulation and elimination of line and surface "thermal bridges" (locations of massive thermal losses), iii) advanced window technology, iv) airtightness, v) heat recovery ventilation systems, vi) space heating utilizing solar energy and heat pumps and vii) passive and active daylighting techniques and electrical appliances with eco-label certification marks are needed to reach a), b), c), d). Two examples of such houses of various types are shown on Fig. 1 a), b).

More advanced thermal considerations can be found in the literature in the last decade: e. g. [9] takes even the solar radiation absorbed by bodies of inhabitants into account. However, some critical comments cannot be neglected: installing and maintaining a passive solar energy system is rather expensive, its performance depends strongly on the climate, etc. Even the total economical and ecological benefits may be not clear, namely in comparison with other projects: e. g. the heat pipeline from the nuclear power plant in Dukovany to Brno, designed 1985 (for the urban area with 500 000 inhabitants, 41 km long, working with water and water vapour at the temperature between 56 and 142 $^\circ$C), has never been brought into effect – the waste vapour emits into the surroundings, including the national nature reserve, cf. Fig. 1 c).

2. Modelling of thermal transfer in buildings

From the pragmatical point of view, building designers, respecting [13] and [15] (which do not contain any computational formulae) need not to discuss advantages and drawbacks of the "passive house standard", applied to all new and reconstructed buildings, but must be interested in its practical implementation. Evidently, the strict requirements of [13] and [15] stimulate the development of advanced materials, structures and technologies. Since no reliable experience with their design is available, reliable and non-expensive computational simulation approaches are needed.

A rather general and transparent approach can be based on the principles of classical thermodynamics, namely on the conservation of scalar quantities $u(x,t)$ on a domain Ω in the Euclidean space R^3 and in the time interval I (t here denotes the non-negative time, $x = (x_1, x_3, x_3)$ the Cartesian coordinate system in R^3, $\partial\Omega$ means the boundary of Ω in R^3, supplied by the unit local formally outward normal $n(x) = (n_1(x), n_2(x), n_3(x))$, dot symbols are reserved for partial time derivatives) with internal volume sources f on $\Omega \times I$ and external surface sources g on $\Gamma \times I$ where $\Gamma \subseteq \partial\Omega$, later also $\Theta = \partial\Omega \setminus \Gamma$, i. e.

$$\begin{aligned} \dot{\varepsilon}(u) - \nabla\eta(u) &= f && \text{on } \Omega \times I \\ \eta(u)\cdot n &= g && \text{on } \Gamma \times I \\ \eta(u)\cdot n &= \psi(u,u_*) && \text{on } \Theta \times I\,; \end{aligned} \tag{1}$$

here all values u_* must be prescribed on $\Theta \times I$, together with an appropriate transfer function ψ. For simplicity, let us assume the initial condition $u(.,0) = 0$; a simple transform makes it possible to get such initial problem from anyone corresponding to the initial equilibrium. Moreover, (1) contains evolutionary (enthalpic) terms $\varepsilon(u)$ and fluxes $\eta(u)$ (3 components), whose evaluation relies on some reasonable (usually empirical) constitutive relations of the Fourier, Fick, Newton, etc. types, both corresponding to scalar quantities u. In particular, under the assumption of (at least macroscopic) material homogeneity and isotropy, it is possible to write the linearized relations

$$\begin{aligned} \eta(u) &= -\nabla\beta(u) && \text{on } \Omega \times I\,, \\ \beta(u) &= \lambda u && \text{on } \Omega \times I\,, \\ \varepsilon(u) &= \kappa u && \text{on } \Omega \times I\,, \\ \psi(u,u_*) &= \gamma(u-u_*) && \text{on } \Theta \times I\,, \end{aligned} \tag{2}$$

with certain constants κ, λ and γ. For instance, in the case of (thermal) energy balance u is usually considered as the (absolute) temperature. Moreover, in (2) κ refers to the thermal capacity (related to the unit volume), λ to the thermal conductivity and γ to some interface heat transfer coefficient; all values u_* should be known from the environment, from the adjacent building component, etc. Let us notice that the first relation of (2), respected in this paper everywhere, forces the potential problem, with zero rotation of $\eta(u)$; this needs to be generalized namely in the analysis of air or moisture flow in rooms and structures, as sketched in [7]. Most computational approaches make use of the weak formulation for some appropriate function space V, typically the Sobolev space $W^{1,2}(\Omega)$ or its subspace: to find such abstract function u, mapping I to V, that

$$(\dot{\varepsilon}(u), v) + (\nabla\beta(u), \nabla v) = (f, v) + \langle g, v\rangle_\Gamma + \langle\psi(u,u_*), v\rangle_\Theta \quad \text{on } I\,; \tag{3}$$

here $(.,.)$ in the simplest case refer to scalar products in $L^2(I, L^2(\Omega))$ or $L^2(I, L^2(\Omega)^3)$,

Figure 2: Photos of crucial details for deterioration of thermal properties of buildings, from the left: a), b) Imperfect connections of particular components. c), d) Moisture condensation on exterior surfaces.

$\langle .,. \rangle_\Theta$ and $\langle .,. \rangle_\Gamma$ to those in $L^2(I, L^2(\Theta))$ and $L^2(I, L^2(\Gamma))$, which can be modified in the sense of dualities in more general spaces.

The usual choices of u in (1), (2) and (3) are: i) the temperature, ii) the (air, material, …) density, iii) the components of velocity of the motion (related to some appropriate reference configuration); these choices correspond to the conservation of i) energy, ii) mass and iii) (linear and angular) momentum from classical thermodynamics by [1]; f and g from (1) are allowed to be applied to coupling of these approaches, e. g. for the study of simultaneous heat and moisture transfer (i. e. energy and mass balance). An interesting generalization can be found in [5]: in addition to the first thermodynamical principle it takes into account also the second one, involving some entropy considerations, working with so-called "exergy"; however, many users of this term understand "exergy" not in a transparent physical sense, but as certain trinity of i) energy, ii) environment and iii) sustainable development. Moreover, some authors, like [3], advert to the priority of the comfort of individual users (just on the example from Fig. 1 a)), as well as to the quality of the architecture of particular buildings and of the whole urban area, which can be frequently in contradiction with any economical optimization.

3. Practical evaluation of energy consumption

The evaluation of energy consumption of a building from (3) (more precisely: from its finite-dimensional discrete version in practice) seems to be easy now (any thermal flux can be evaluated from the complete information on the temperature development), but hides some difficulties: i) (3) describes one domain (as a constructive or insulation layer, a room, etc., in a building) formally, but the whole building is composed from a high number of such domains, whose mutual interaction relies on the last additive term in (3), ii) advanced building design, from the mathematical point of view, is a complicated optimization problem, seeking for the minimal energy consumption, under a rather large number of conditions coming from technical standards, as those of obligatory temperature levels and temperature stability in rooms – cf. [12]. The list of building energy software [14] contains 417 items now; nevertheless, all of them work with strong (often non-transparent) simplifications – cf. [2].

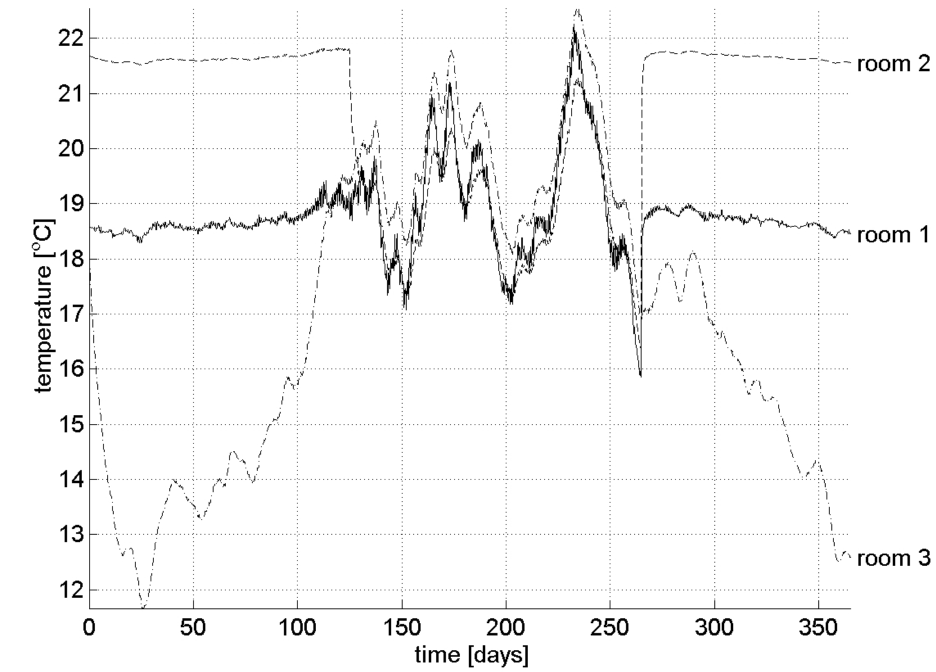

Figure 3: Computational evaluation of the annual energy demand of a low-energy family house during a typical climatic year: temperature development in selected rooms (room 1: full line, room 2: dashed line, room 3: dash-dotted line).

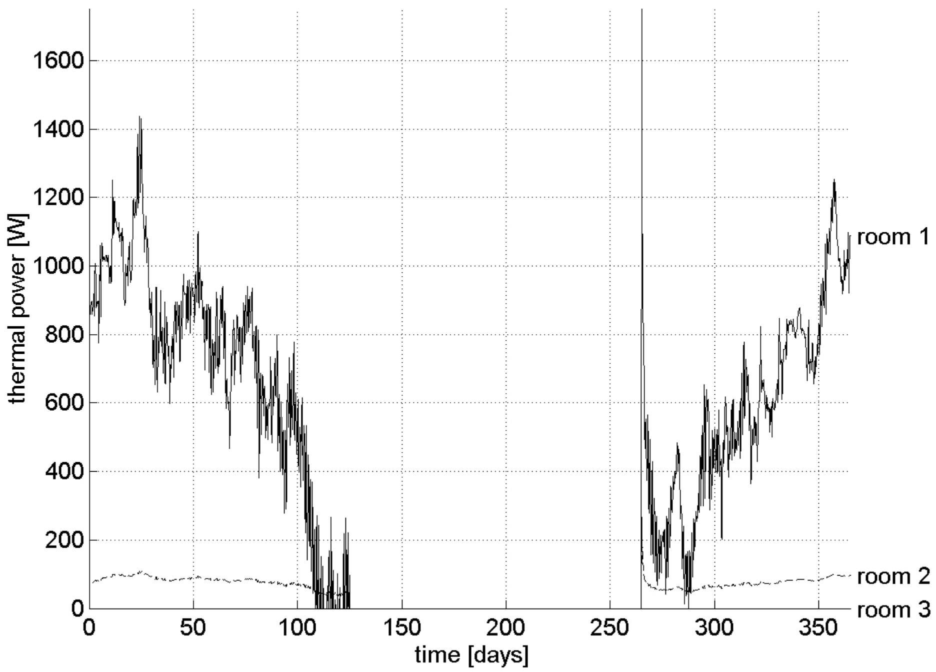

Figure 4: Requirements to artificial heating, corresponding to Fig. 3

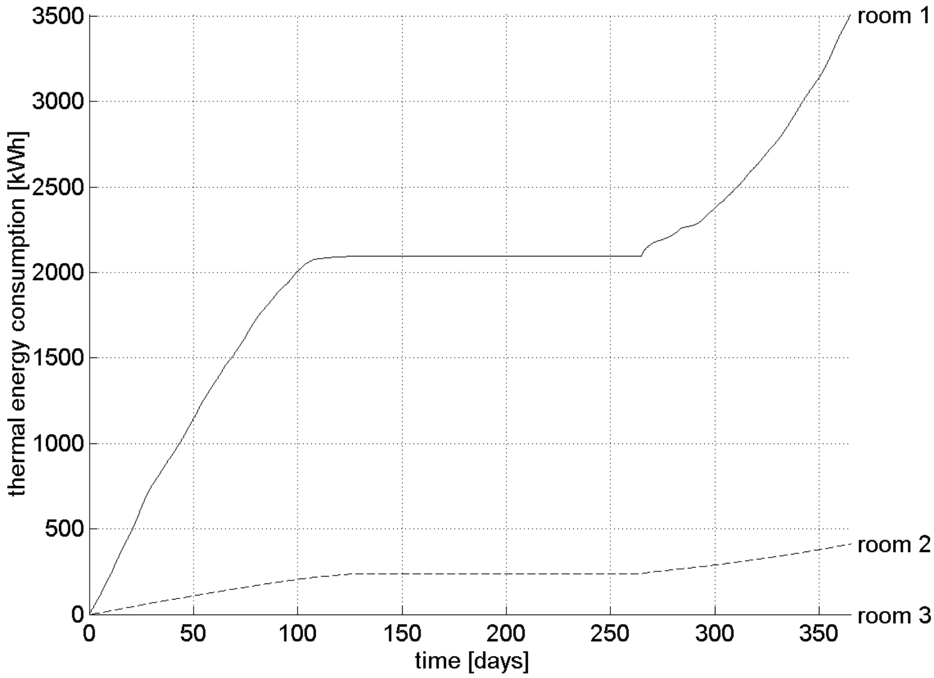

Figure 5: Cumulative energy consumption, related to Fig. 4

The non-commercial software package *Therm Stabil*, developed at the Institute of Technology of Building Materials and Components of Brno University of Technology, Faculty of Civil Engineering (not included in [14]), in the programing language Pascal in the Delphi environment, applies the system approach, taking rooms, walls, roofs, etc., as building elements and subsystems, connected by thermal (and some other physical) fluxes, analyzing (3) using the finite element, volume and difference techniques together with the Rothe sequences (for time discretization). This package is still in progress; its development is a part of research of advanced building materials and their utilization in structures and technologies, as presented at *http://www.fce.vutbr.cz/thd*. Interested reader may request more detailed information from the author of this paper or from the principal author of *Therm Stabil*, Prof. Stanislav Šťastník (e-mail *stastnik.s@fce.vutbr.cz*).

All numerical results presented in this paper have been obtained from this software, except the post-processing for Fig. 3,4,5, prepared in the MATLAB environment. The principal heat fluxes to particular rooms considered in *Therm Stabil* come i) from adjacent building components, ii) through windows, doors, etc., including solar radiation, iii) thanks to the air exchange, iv) from artificial sources of heating and / or air conditioning. Moreover, Fig. 2 demonstrates other effects observed in real building structures, namely so-called potential "thermal bridges" on connections of different building components (photos a), b)), as well as moisture condensation on exterior surfaces with unpleasant consequences of algae population, as discussed in [10] and [11] (photos c), d)).

Fig. 3 shows some results of the computational simulation of thermal fluxes in a new low-energy family house (not passive by the definition of [6], in a village close to Brno), based on the proper description of its location, orientation and composition and on the detailed knowledge of annual climatic data for Brno. Averaged temperatures in 3 typical rooms (from 8 in total: rooms 1 and 2 contain heating equipments of different type, room 3 is heated indirectly) are modulated in the (rather long) winter period by the artificial heating; no air conditioning is applied. Such requirements to artificial heating by Fig. 4 generate the cumulative thermal energy consumption for the whole building, as evident from Fig. 5; no other energy demands (as those from other electrical appliances) are taken into considerations. The measured energy consumption in several first years of existence of this building (and 3 other tested ones) is slightly higher – however, this depends also on the user habits and priorities in heating, ventilation, etc.

The same software package has been applied, inspired by [4], to the simulation of energy consumption in an existing freezing plant in Central Moravia. One could expect much more significant energy reduction, in such an industrial building (containing the freezing space at –24 °C, several offices, etc.), thanks to its sophisticated design, than in a family house. Unfortunately, in this case, described in [8], all available energy consumption data are higher than those predicted by simulation. The a posteriori analysis in situ showed some imperfect connections of building components and the presence of moisture in polyurethane insulation layers (theoretically dry, following the technical standard), as the probable immediate cause of deterioration of their thermal properties.

4. Conclusion

Energy reduction in building structures is a challenge of last two decades, seen by various authors from ecological, engineering, physical, mathematical and computational points of view. As a reasonable compromise between the traditional stationary evaluations of thermal resistances, improper in advanced structures, and complicated models referring to large systems of partial differential equations of evolution, this paper offers an alternative system approach namely to the computational evaluation of energy for heating and air-conditioning; the system complexity can be reduced here thanks to transparent simplifications, compatible with classical thermodynamics. More advanced models (e. g. those containing involving air and moisture flow, driven by Navier - Stokes equations), up to now, suffer from expensive computations and bad correlation between the results of deterministic calculations and available experimental data. However, due to its social significance, the further research is very desirable.

Acknowledgements

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