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Modelling floor heating systems using a validated two-dimensional ground-coupled numerical model

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Abstract

This paper presents a two-dimensional simulation model of the heat losses and temperatures in a slab on grade floor with floor heating which is able to dynamically model the floor heating system. The aim of this work is to be able to model, in detail, the influence from the floor construction and foundation on the performance of the floor heating system. The ground-coupled floor heating model is validated against measurements from a single-family house. The simulation model is coupled to a whole-building energy simulation model with inclusion of heat losses and heat supply to the room above the floor. This model can be used to design energy efficient houses with floor heating focusing on the heat loss through the floor construction and foundation. It is found that it is important to model the dynamics of the floor heating system to find the correct heat loss to the ground, and further, that the foundation has a large impact on the energy consumption of buildings heated by floor heating. Consequently, this detail should be in focus when designing houses with floor heating.

Keywords: Floor heating; Numerical modelling; Ground coupling; Energy consumption; Model validation

1. Introduction

The dynamical behaviour of the ground heat loss is not very well known for single-family houses with floor heating. Especially the influence of the foundation must be better investigated. This is of interest since the heat loss to the ground is larger when floor heating is used and since the ground heat loss is becoming increasingly more important, as the parts of the building above ground are getting still better insulated [1].

1.1. Hydronic floor heating

Simulation models of floor heating focusing mainly on the heat transfer from pipe to room can be found in the literature as basis for characterisation and dimensioning. Different types of floor heating systems have been investigated using finite element models with respect to thermal properties [2], and dynamical behaviour [3]. A classification of the thermal output to the room for floor heating systems has been established with the purpose of being able to design and dimension such systems in EN1264 [4]. Different control strategies are investigated in [5], concluding that they have a large impact on the energy consumption. Different floor covering materials have been found to impact temperatures, reaction time and energy consumption [6]. Dynamical models of hydronic floor heating combined with a room model in building energy simulation have been elaborated [7–9]. These models have the advantage of realistic dynamic properties of hydronic floor heating. However, the simple ground geometry omits the influence from foundation and ground volume.

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1.2. Heat loss from floors without floor heating

Another field of interest for this work is the so-called ground coupling between floor and ground volume. Analyses have been carried out to account for the floor construction and foundation, focusing on especially boundary conditions, multidimensional analysis and level of detail including material properties for the ground volume conditions [10–14].

The outside boundary condition between air and ground surface depends, among others, on the incident radiation, snow, wind and rain. In the simulations, different boundary conditions can be applied ranging from simple convective conditions to more detailed ones including short- and long-wave radiation, evaporation and rain. In a theoretical investigation on a basement structure [14], a comparison of different level of detail in the boundary condition shows that while a simple convective heat transfer gives the same average temperature at the ground surface as a formulation including radiation, evaporation and rain, the temperature amplitude on the ground surface is much smaller, which means that the heat loss during the winter period will be underestimated. In this case, the simplification leads to about 10% lower predicted heat loss.

In Janssen et al. [15], moisture conditions have been included in a fully coupled model of heat and moisture transport. Here, it is found that material properties depend on a long list of factors, which cannot be taken into account when constant values are applied; i.e. the heat-transfer coefficient of soil varies by a factor 10 depending on moisture levels and composition of the soil material. It is concluded that for a poorly insulated basement, a model without coupling with simple convective boundary conditions underestimates the heat loss of 10–15% compared to the detailed coupled model. However, this underestimation becomes smaller with better insulation level and when floor slabs are considered instead of basements. In total, these simplifications leads to an underestimation of the heat loss, which cannot, however be predicted based on the literature available.

In addition, it is acknowledged that considering the uncertainties in especially ground volume material properties, the use of coupled heat and moisture modelling cannot be defended because of the relatively small difference in the results [14,15]. This is also the case for simplified boundary conditions compared to more detailed ones.

The importance of using multidimensional ground coupling for poorly insulated constructions is well illustrated in [11]. Here, analyses are carried out on the consequences of using one-dimensional rather than two- or three-dimensional modelling of temperature and heat flow, reporting discrepancies of up to 22% between two- and three-dimensional simulations and up to 41% between one- and three-dimensional simulations. In other studies the difference between one-, two-, and three-dimensional analysis [10–13] generally finds through both measurements and theoretical considerations that ground heat loss is a three-dimensional process. Anderson [12] introduces a characteristic dimension of the floor defined as the floor area divided by half the exposed perimeter. If this dimension is used in the two-dimensional simulation model instead of half the width of the building, the three-dimensional problem can be simplified to a two-dimensional one. This is shown in Eq. (1).

$$B' = \frac{A}{\frac{1}{2}P}. \tag{1}$$

Here B' is the characteristic dimension, while A is the area and P is the perimeter.

Another investigation [10] has found that large floors can be considered two dimensional. However, a three-dimensional calculation is needed to accurately account for the heat flows in the corner regions and for assessing risk of condensation due to the lower temperatures in the corners.

A standard for calculating heat loss to the ground has been established in EN ISO13370 [16], where the width of the floor construction is required to be at least as large as the characteristic dimension defined in [12]. The basis for calculating heat losses through building components has been described in EN ISO10211.1 [17] and EN ISO10211.2 [18]. Here the total heat loss can be summed from one-, two- and three-dimensional contributions. For a floor construction this corresponds to the slab, the foundation and the corners of the building. In [13,19] it is found that the heat loss through the slab and foundation must be found by transient analysis while the heat loss through the corners can be found from steady-state analysis.

1.3. Modelling ground coupling

Different approaches can be used to model the heat flow from buildings. The most detailed (and time consuming) are achieved by numerical models based on finite element, finite difference or finite control volume methods. Once the method is implemented, it is straight-forward to create accurate geometrical models with detailed boundary conditions. Other methods uses are (semi)-analytical models [20–24] to reduce the simulation time considerably compared to numerical implementations. The reduction in simulation time is achieved through simplifications by finding eigenvalues or response factors, typically using numerical pre-processing. This approach requires simplifications of the geometry, but once they have been established, fast and numerous analyses can be carried out.