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A cellular automaton based model simulating HVAC fluid and heat transport in a building. Modeling approach and comparison with experimental results

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ABSTRACT

A discrete model characterizing heat and fluid flow in connection with thermal fluxes in a building is described and tested against experiment in this contribution. The model, based on a cellular automaton approach, relies on a set of a few quite simple rules and parameters in order to simulate the dynamic evolution of temperatures and energy flows in any water or brine based thermal energy distribution network in a building or system. Using an easy-to-record input, such as the instantaneous electrical power demand of the heating or cooling system, our model predicts time varying temperatures in characteristic spots and the related enthalpy flows whose simulation usually requires heavy computational tools and detailed knowledge of the network elements. As a particular example, we have applied our model to simulate an existing fan coil based hydronic heating system driven by a geothermal heat pump. When compared to the experimental temperature and thermal energy records, the outcome of the model coincides.

1. Introduction

A third or more of the energy consumption of industrialized countries is expended on creating acceptable thermal and lighting conditions in buildings. As a result, the design of buildings and models of thermal behaviour of those buildings tends to be very important. See [1] for a review.

Air conditioning (AC) systems are elements in charge of creating comfortable thermal conditions in buildings. For these elements several simulations tools have been developed over the years. Among them, the TRNSYS software is a well respected simulation tool.

In recent years, ground source heat pumps (GSHP) have been recognized as a good choice for residential and commercial buildings [2,3,4]. A GSHP system consists of a conventional heat pump coupled with a ground heat exchanger. The efficiency of this kind of system is inherently higher than that of air-source heat pumps because the ground temperature is higher than the average air temperature in winter, when heating is required, and lower in summer, when cooling is required. This is the kind of system we are working with in this paper.

Obviously, heat transfer from the fluid of an AC system to a building is an important matter. Nowadays performances of a wide range of fluids used in heat transfer are under analysis. Some examples are: anomalous thermal behaviour of nanofluids (suspended nanoparticles in conventional fluids), see [5] for a review, and heat transfer problems involving non-Newtonian fluids (the relation connecting the shear stress and the shear rate is nonlinear), see [6] as an example.

Fluids of an AC flow by pipes. The physics involved in this process of transportation are well known. Navier-Stokes equation, Fourier's Law and Newton's Law are a common physical background. Numerical methods for the resolution of resulting differential equations are widely used. The market is full of CFD (Computational Fluid Dynamics) software, where these methods are implemented in order to simulate transportation processes.

Nevertheless, obtaining mathematical models for complex systems or systems with complex boundary conditions is a difficult matter. Thermic inertia, diffusivity, technical characteristics of systems and climate conditions, amongst others, are factors that contribute towards making a mathematical model complicated for a complex building-AC system.

The aim of this paper is to characterize the global energy behaviour of a building-AC system. In order to achieve this aim we propose a model for heat and mass flow based on some representative elements of systems. Thus, by using a few parameters, the energy behaviour of the building related to the AC in winter

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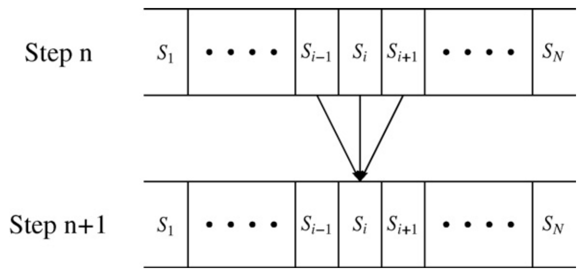

Fig. 1. In this figure arrows relate states of time step n that collaborate to generate state S_i at next time step $n+1$.

season, must be reproduced. This model must simplify the internal behaviour of a system, without detailed knowledge of that internal behaviour. Finally, that model must be independent of a specific layout.

In Section 2 we present this model and we adapt it to a building-AC system. In Section 3 some simulations of this building-AC system are presented and compared with experimental temperature data.

2. Model

We look for a discrete model of heat and fluid flow. This discrete model must reproduce relevant processes of heat and mass flow, and fulfill some interesting characteristics. An essential characteristic must be the ability to reproduce global behaviour as a result of local interactions. Also, another interesting property should be the independence in respect to a specific layout. Layout or boundary conditions should be reduced to some representative parameters, that should be attached in a subsequent modelling process of the system.

Unlike models based on differential equations, we are looking for a discrete model from its conception. Thus, we will consider a dynamical system evolving in discrete steps. For this kind of system J. Von Newmann [7] proposed a mathematical model: *cellular automaton* (CA). A definition of this model should be "an ordered set of objects characterized by":

1. An infinitely extended grid formed by cells of any dimension.
2. Each cell has a finite number of states.
3. Each cell has a finite number of neighbors.
4. Transition function between states are rules that take into account the value of a cell and its neighbours to construct the next state.

A more simplified definition could be found in [8]. Nevertheless, a large part of applications of cellular automaton is in a non-standard way by altering some of the previous conditions.

In this kind of system cells change their states synchronously at discrete time steps, depending on the states of some nearby cells, the neighbours, as determined by a local update rule. All cells use the same update rule, so that the system is homogeneous, like many physical and biological systems [11].

In Fig. 1 we represent state of cell i, S_i, and states of its neighbors, S_{i-1} and S_{i+1}, at time step n. They are related to state S_i at time step $n+1$. Rules are in charge of update states S_i at time step n+1 from state of cells S_{i-1}, S_i and S_{i+1} at time step n.

The previous case is a typical one-dimensional (1D) automaton. A cell i from a 2D automaton has more neighbours than in the case set out.

Discrete simulation of fluid flows using CA is a field of its own in which CA models are called lattice gases, see [12,13] for two fundamental lattice gas models. Other classic CA simulation of physical systems include Ising spin models [14] and diffusion phenomena [15].

Inspired by these ideas, we will act in the same way in order to construct our flow model. Thus, in any system which we need to simulate, we must identify a grid of cells modelling a zone of space. We also need to identify the relevant physics in interactions amongst cells and identify rules of transition responsible for the system's evolution. Some examples could be found in [18,19].

The ability of cellular automaton to generate complex behaviour with simple transition rules is well known. [9,10].

As a first implementation of that model we propose the study of a building-AC system. We are only interested in a reduced configuration that could reproduce important aspects of that AC. Hence, this model includes simple nearest-neighbour evolution rules with terms for continuous heat loss to the environment and two source terms for heating and cooling zones. In the next section we proceed to identify elements of that system.

2.1. *The air conditioning system (ground source heat pump system (GSHP))*

In order to test performances of the discrete flow model in a real system, the AC system of an academic building at the Polytechnic University of Valencia (Valencia, Spain) is studied. The experimental implementation of our Ground Source Heat Pump system was developed within the framework of the 5th Framework Program project GEOCOOL and was intended to perform a quantitative assessment of savings, from the energy efficiency point of view, with respect to a conventional air-source heat pump-based system. The system is thoroughly described in reference [16].

The ground-coupled heat pump system consists of six ground heat exchangers of 50 m depth distributed in a rectangular (2×3) configuration, see Fig. 2. The heat pump unit is a development of a reversible water to water heat pump of CIATESA (model IZE-70) with nominal values 15.9 kW and 19.3 kW of cooling and heating capacity respectively. The ground-coupled heat pump was placed on the ground floor of the building next to the internal hydraulic group.

Both GSHP and air-source based systems have been installed inside an academic building at the Polytechnic University of Valencia. (Valencia, Spain) The total AC area is comprised of 250 m^2 and is distributed by way of a corridor, nine offices, a computer room, a room with photocopiers and a coffee dispenser. All rooms are equipped with one or two fan-coils except for the corridor.

The data acquisition system was designed to characterize the system performance. To this purpose, different system parameters like water temperature, mass flow and power consumption were measured. A network of forty four probes was set up to allow for the monitoring of the most relevant thermal and flow parameters of the internal hydraulic group, the external hydraulic group, both heat pumps and the ground. This flow parameter included: temperatures inside the borehole, temperatures in the main connection pipes of the system, water mass flow in the internal and external water circuits and power consumption of all the electrical elements of the system, see Fig. 2. All measurements were taken over 1 min intervals. As well as this, a stand alone meteorological station placed on the roof of the building records meteorological data as temperature and humidity over 5 min intervals.

To treat the considerable amount of data generated by the whole acquisition system, specific software was written to automatically perform the necessary database-matching and statistical analysis.

Following that we model the fluid and heat transport and test it in a realistic scenario as the air conditioning system of the aforementioned building.