Building and Environment 46 (2011) 556–569

Contents lists available at ScienceDirect

Building and Environment

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

Application of model based predictive control for water-based floor heating in low energy residential buildings

Henrik Karlsson*, Carl-Eric Hagentoft

Department of Building and Environmental Engineering, Chalmers University of Technology, SE-412 96 Göteborg, Sweden

A R T I C L E I N F O

Article history:
Received 16 April 2010
Received in revised form
19 August 2010
Accepted 23 August 2010

Keywords:
Floor heating
Predictive control
Low temperature heating
Optimisation

A B S T R A C T

A model based predictive control method is applied in order to determine the optimal supply fluid temperature in the case of concrete embedded water-based floor heating in low energy residential buildings. The aim of the control is to keep the indoor temperature within a defined comfort interval. The forthcoming supply fluid temperature is obtained through a numerical optimisation based on a prediction of the upcoming heat demand. The elementary response function, which is the basis for the method, is obtained from a numerical control volume model, and as an alternative, from a simplified 2-node lumped model. The accuracy of the results obtained from the simplified model is surprisingly good in comparison to the detailed numerical model. The control method is applied for a single room for which a perfect prognosis of the heat demand exists. The results show a fairly steady optimised supply fluid temperature.

1. Introduction

The control of water-based floor heating systems is usually divided into two parts; a central control, which considers the external conditions and an individual room control [1]. Commonly in Scandinavian countries, the supply temperature is feed-forward controlled based on the outdoor temperature while a thermostatic on/off control operates on the room level in order to avoid over temperature due to heat gains with unexpected intensity.

A concrete floor slab, which embeds a hydronic pipe circuit, comprises a significant thermal mass that leads to a delay time between the heat supply and the response in indoor temperature. A drawback with conventional control techniques is their inability to compensate for the delay time and to adapt to changing dynamics [2]. Moreover, a careful tuning of PI controller parameters is required for systems with long delay times.

The major benefit of predictive control is that the heat supply can be adjusted in advance due to a prediction of the future heat demand. Hence, predictive control methods counteract the long response time of the embedded floor heating system. Lee et al. (1999) and Cho et al. (2003) [3,4] studied typical on/off control methods for floor heating in Korea (i.e. *Ondol* heating). Lee et al. (1999) [3] developed a predictive control scheme that determines the proper circulation pump on/off time for a floor heating circuit that supplies heat to an apartment room. The thermal characteristics of the studied room are determined in a learning process through the use of artificial neural network technique. Cho et al. (2003) [4] developed a predictive control, which determines the on/off time based on a weather forecast for the next day. Both Lee et al. (1999) and Cho et al. (2003) [3,4] concluded that predictive control is better than the current 2-position on/off control in terms of energy consumption.

Model based predictive control has found wide acceptance in industrial applications [5]. A model based predictive control in our floor heating application would iteratively find, through the use of a model which describes the system, the forthcoming constrained supply heat flux which optimises a certain objective function. The optimal objective function is preferably the minimal indoor temperature deviation. The historical supply heat flux and a prognosis of the forthcoming heat demand are the inputs for the optimisation procedure. Model based predictive control can explicitly take into account constraints on the signals in the system, which is an advantage in comparison to other control techniques (i.e. constraining the supply heat flux within practical limits).

Chen (1997 and 2001) and Pyeongchan (2003) [6,2,7] have applied model based predictive control in floor heating applications. Pyeongchan (2003) [7] considers a water-based system while Chen (1997 and 2001) [6,2] considers an electrical floor heating system. The aim is to improve the utilisation of free heat gains (e.g. solar gains) and to stabilise the indoor temperature within a given comfort interval. Pyeongchan (2003) [7] applies Strand's (1995) [8] heat source/sink conduction transfer function model, which is implemented in the EnergyPlus software in order to iteratively find

* Corresponding author.
E-mail address: henrik.600@me.com (H. Karlsson).

0360-1323/$ – see front matter © 2010 Published by Elsevier Ltd.
doi:10.1016/j.buildenv.2010.08.014

Nomenclature

Symbols

a	matrix element $\boldsymbol{A}$
b	reduction parameter [−]
C	heat capacity [J/K]
h	surface heat transfer coefficient [W/m^2/K]
G	net objective function [−]
g	momentary value of G [−]
H	Heaviside's unit step-function [−]
K	thermal conductance [W/K]
T	temperature [K]
t	time [s]
t_p	period time [s]
u	non-dimensional step-response temperature [−]
Q	heat flux [W]
q	heat flux amplitude [W]
β	penalty constant [−]
η	insulation efficiency [−]
τ	preceding time [s]

Matrix and vectors

$\boldsymbol{A}$	elementary pulse-response matrix
$\boldsymbol{T}^+$	temperature increase vector
$\boldsymbol{Q}$	heat supply vector

Indices

S	steady state
i	interior (operative temperature)
e	exterior (air temperature)
t	transient
s	supply of the embedded pipe circuit
p	pulse
op	optimised
m	index for present time
M	index for prognosis horizon
n	index for pulse excitation
fh	floor heating element
+	indicating the temperature increase
free	free-running
setpoint	set point
conv	convection
rad	radiation
upper	indicating upper constrain
lower	indication lower constrain

the optimal solution. In the work of Chen (1997 and 2001) [6,2] a generalized thermal network model is applied. Different formulations of the objective functions are also possible which both Chen (1997) [6] and Pyeongchan (2003) [7] explore; for instance minimising the operating cost or the accumulated supply heat flux in conjunction with the indoor temperature target interval.

This study is aimed at model based optimal control of energy efficient residential buildings without temperature control at room level. The aim is to determine the optimal supply fluid temperature. The combination of floor heating and low energy building yields a relatively low supply fluid temperature, only a few degrees above a comfortable room temperature. Hence, the possibility to utilise energy of low quality in space heating applications is hereby facilitated.

A response factor method that describes the transient relation between a piecewise constant supply heat flux and the succeeding shift in indoor temperature is applied. The elementary response which constitutes the model, which describes the relation between heat supply and the indoor temperature response is generated by a detailed numerical control volume model [9]. As an alternative to the detailed numerical model, the elementary response is explicitly given by a simplified lumped 2-node. The advantage of the suggested response factor method is that the elementary response is based on an underlying physical model in contrast to the artificial neural network method [3] or the generalized thermal network method [6,2]. In these references, the transient properties are determined by means of a learning process or by parameter fitting based on experiments.

Furthermore, the control of the supply fluid temperature is also of major importance since the self-regulation effect is active only if the supply temperature is the controlled parameter [10]. Self-regulation operates as a negative feedback process that counteracts unknown thermal perturbances [11]. Any error in the prognosis, which is the foundation of the applied control method, constitutes a thermal perturbance. Thus, control of the supply fluid temperature yields a more robust control than a supply heat flux control since no active feedback is applied at room level. Therefore, the optimised supply heat flux is transformed into the corresponding supply fluid temperature in the final step of the proposed method. The current research of predictive controlled floor heating (Chen, 1997 and 2001 [6,2]; Lee et al., 1999 [3]; Cho et al., 2003 [4] and

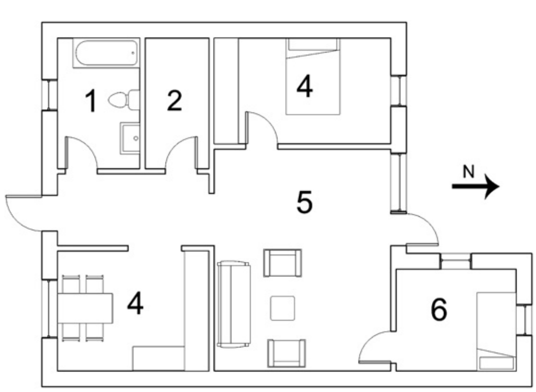

Fig. 1. Plan of the studied building.

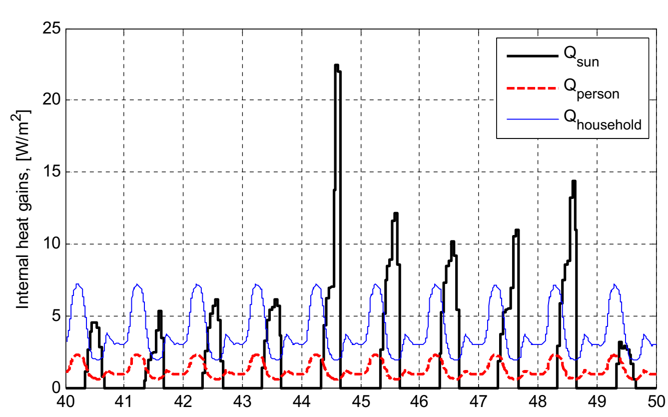

Fig. 2. Transmitted solar heat Q_{sun}, heat gains from persons Q_{person} and the utilised heat fraction from household electricity $Q_{household}$ for room 7 (reference room).