Energy and Buildings 82 (2014) 330–340

Contents lists available at ScienceDirect

Energy and Buildings

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

Establishment and experimental validation of a dynamic heat transfer model for concrete radiant cooling slab based on reaction coefficient method

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ARTICLE INFO

Article history:
Received 26 March 2014
Received in revised form 13 July 2014
Accepted 14 July 2014
Available online 22 July 2014

Keywords:
Concrete radiation cooling
Reaction coefficient method
Dynamic heat transfer

ABSTRACT

To study the dynamic thermal response performance of concrete radiant cooling slab, this paper introduces the concept of core temperature layer. Heat transfer process in the concrete slab is divided into three sub-processes, correspondingly, and three heat transfer models are built by reaction coefficient method. Two-dimensional unsteady heat transfer model of concrete cooling slab is established ultimately. Experiments are conducted to test the slab thermal performance in steady and unsteady conditions. Error analysis and consistency verification are presented between the experimental value and calculated results of the model. The relative error between calculation and experimental value is within 2% in steady conditions and within 7% in unsteady conditions. The application scope of the heat transfer model for practical engineering is defined in this paper.

1. Introduction

Unlike other radiant cooling technologies, in concrete radiant cooling system, building itself with a large heat capacity acts as a part of air conditioning terminal, which is directly involved in the cooling process of air conditioning system. Active intervention of building regenerator not only causes the cooling transfer process of the terminal trend to be complex, but also changes the coupling process between heat transfer within the building and cooling by air conditioning system. In order to ensure the realization of energy saving effect of concrete radiant cooling technology and form a complete design and operation technology system, clear understandings need to be got about the coupling relationships of the two processes. One of the problems is how to find out the dynamic response of the thermal properties of concrete radiant cooling system.

It is the dynamic changes of cooling load that determines that the concrete radiant cooling technology research must be built on the basis of unsteady heat transfer process. Therefore, studies on heat transfer process in the concrete slab have been the major research directions in this field. Numerical simulations and simplified heat transfer models become two main technology roadmaps as a result of the difficulty to obtain analytical solutions. Finite difference method (FDM) and finite element method (FEM) are typically used in numerical methods. Fort establishes a numerical model of heat transfer process within concrete radiant cooling terminal by using FDM method. This method has high accuracy. However, it is not well balanced with circular pipe geometry in the slab for the use of square meshes. It also causes shocks in calculation and requires high quality grids as well as strong performance computers [1]. Holopainen et al. establish an uneven nodal network model with finite difference heat balance method, by which show the benefits of placing the densest gridding in steepest curvature of the temperature gradient [2]. FEM method is also used in calculation, but it is not widely used in engineering for the complexity in modeling and long time spent in computing. Babiak studies the dynamic response of 24-h-period sine wave signals on several concrete radiant cooling terminals. The author believes that when the load or cooling capacity changes, not the whole slab but 10–15 cm thick slab is involved in regenerative regulation. Due to the complexity in modeling and long time spent in computing of the FEM method, the author ignores the coupling of passive thermal storage of other building envelopes. Further analysis on how other forms of fluctuation influences the regenerative regulation is not carried out in the article [3]. Simplified heat transfer models are relatively simple to build, and they take little computational effort but can

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http://dx.doi.org/10.1016/j.enbuild.2014.07.031
0378-7788/

Nomenclature

L	spacing between adjacent pipes (mm)
l	pipe length (mm)
d	diameter of pipes (mm)
T	temperature (°C)
T_k	constant temperature = 273.15 °C
λ	thermal conductivity [W/(m K)]
Re	Reynolds number
Pr	Prandtl number
y_1	spacing between pipes and the upper floor surface (mm)
y_2	spacing between pipes and the underside floor surface (mm)
q	heat flux (W/m^2)
t	time
s	complex number of Laplace transform
a	thermal diffusivity in the concrete slab (m^2/s)
Δ	duration of unit triangular wave function
n	reaction coefficient number
$\bar{T}$	temperature of the Laplace transform
$\bar{q}$	heat flux of the Laplace transform
h	heat transfer coefficient [W/(m^2 K)]
$T(t)$	temperature disturbance (°C)
$AUST$	average unheated surface temperature (°C)

Subscript

0	chilled water
1	upper slab surface
2	underside slab surface
air	air in the test room
c	core temperature layer
u	air boundary upon upper concrete slab surface
w	air boundary below lower concrete slab surface
tot	total
cov	convention
rad	radiation
wc	from air boundary upon upper concrete slab surface to core temperature layer
cw	from core temperature layer to air boundary upon upper concrete slab surface
uc	from air boundary below lower concrete slab surface to core temperature layer
cu	from core temperature layer to air boundary below lower concrete slab surface
0*c*	from chilled water to core temperature layer
*c*0	from core temperature layer to chilled water

ensure high accuracy. Therefore, many of the current studies focus on them. Thermal resistance and heat capacity network method (TRHC) and heat conduction transfer function method (HCTF) are two representative practices and they have already been used in Trnsys and Energy Plus current version, respectively. TRHC method is based on the similarity between heat transfer in building materials and electrical circuit. Methods of electrical circuit calculation are introduced to convert unsteady heat transfer in time domain to frequency domain, greatly reducing model complexity and computational workload. HCTF method is based on transfer function method, which is the basic analysis method of control theory. Transfer function is typically used in single-input and single-output analog circuit, which is mainly applied in signal processing, communication theory and control theory. For simple continuous-time input and output signals, the linear mapping between Laplace transform of the input signal and the output signal under conditions of zero state is reflected by transfer function. Stephonson et al. apply transfer function to calculate air conditioning load of the building envelope, which is its beginning of the application in heat transfer problems [4]. Koschenz and Lehmann employ HCTF model to calculate heat transfer from water pipe node to core temperature layer and use TRHC algorithm to compute heat transfer of other part, thus forming a joint TRHC-HCTF model. This simplified model is adopted by the radiant cooling module in Trnsys Ver.16 and subsequent Ver.17 [5–7]. As a result of large calculation errors, this model is only suitable for lightweight construction and relatively constant temperature conditions, it is less applicable for simulation conditions with thin concrete radiant cooling terminals and temperature fluctuation period less than 10 h [8,9]. Weber develops a numerical model to obtain equivalent thermal resistance and heat capacity of nodes and then uses star TRHC method to compute. Although this approach expands the scope of the model, it complicates computing process at the same time [8]. Strand builds a concrete cooling heat transfer model based on the HCTF method, which is used in EnergyPlus energy simulation software to calculate heat transfer through building envelope, the author adds heat source and heat convergence in HCTR method and then solves the model via Laplace transform or state space method. This algorithm was adopted by EnergyPlus software in its radiant cooling module and has been used till now [10,11]. Compared with TRHC method, HCTF method can only handle linear equations because it can't associate with nonlinear processes such as changes in water flow. When calculating heat transfer between pipes and concrete slab, HCTF method can only assume that fluid is still and its temperature does not change along pipe length. Consequently, HCTF model may not do very well in simulating unsteady heat transfer process in concrete slab under variable flow conditions [8]. Rijksen believes that regenerative effect is bound to reduce the peak load of concrete radiant cooling system. For the sake of achieving universal design guidelines, the maximum room heat gain handled by concrete radiant cooling system in Netherlands is simulated, and the value is about 60 w/m^2 [12]. Zhang et al. found a two-dimension simplified calculation model for concrete cooling slab. They put forward a simplified method to calculate the cooling capacity of the concrete slab and temperature distribution of floor surface, pointing out that thickness and heat transfer coefficient of materials have great impact on cooling performance [13]. Liu et al. use the result of TRHC method to establish a simplified TRHC model for unsteady heat transfer process in concrete radiant cooling system. The authors define the equivalent heat capacity and thermal resistance of core temperature layer according to the geometrical and thermal parameters, making modeling process be separated from numerical simulation. The model further simplifies calculation process but brings big error since Fourier decomposition is introduced to deal with step changes of input variables [14].

Previous models have their own limitations in handling heat transfer process of concrete radiant cooling system, further studies are still necessary to improve and develop concrete radiation heat transfer models. This paper establishes a heat transfer model which takes unsteady heat transfer process in flat wall as theoretical foundation and processes input disturbance using response coefficient method (RC). Compared with simplified calculation methods proposed in Refs. [2,13,14], the model in this paper has better applicability for actual slab heat transfer process.

2. Heat transfer model

2.1. Heat transfer in the concrete slab

In order to make it easy to study and analyze heat transfer process in concrete slab, core temperature layer concept is introduced