Sustainable Cities and Society 52 (2020) 101812

Contents lists available at ScienceDirect

Sustainable Cities and Society

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

Transient simulation of coupled heat and moisture transfer through multi-layer walls exposed to future climate in the hot and humid southern China area

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ARTICLE INFO

Keywords:
Porous media
Coupled heat and moisture transfer
Climate warming
Hygrothermal
Cooling load transmitted through the wall

ABSTRACT

As climate warming trends have been observed with certainty, the existing weather data may inappropriate to the building's performance calculation. Projected climate changes have been developed in the representative city of Guangzhou based on the IPCC RCP4.5 scenario. A model of coupled heat and moisture (CHM) transfer is established, it has continuous driving potentials of capillary pressure and temperature that allow hygrothermal simulation within porous media. The results obtained with the proposed model are in good agreement with the HAMSTAD project. Then, dynamic simulation of the hygrothermal behavior for external insulation walls are performed during summer months under future climate. The results show that moisture accumulation risk is great at the interface between insulation and mortar. Cooling load transmitted through the brick (concrete) wall calculated with CHM model is predicted to increase by 11.3% (15.6%) compared with that done with transient heat conduction (TH) model in the period between 2072 and 2089. The sum of latent load accounts for 10.1% (13.5%) of the total cooling load transmitted through the brick (concrete) wall by 2089. Results point to an increment of coupled heat and moisture transfer trends in the walls if the climate change happens.

1. Introduction

Continuous exposure to an excessively hot and humid environment greatly affects the thermal performance of building materials, particularly thermal insulation, and has a negative impact on building energy consumption. The materials used in constructions are mainly characterized by porous and hygroscopic properties that make them sensitive to the water vapor contained in the surrounding air. A "dry" porous medium can provide good insulation due to its low thermal conductivity, but the presence of water vapor may pose a strong degradation of thermal performance and have a negative impact on its durability (Khoukhi, 2018; Vrán, 2007). With regard to moisture, the design of building envelope must prevent the prolonged and significant presence of water in liquid form, which could affect the durability of the materials especially on the outside, or promote the appearance of mould on the inside. Recently, the Intergovernmental Panel on Climate Change (IPCC) has released its 5th conclusive report on the very certain responsibility for human activity in greenhouse gas (GHG) emissions (IPCC Working Group 1, 2013). According to different study scenarios, an increase of 1.5°Cto 6°C of the average temperature of the atmosphere is expected by 2100. To limit this and ensure the sustainable development of society, it is now accepted that global GHG emissions will have to be halved by 2050. Only rapid and significant reductions in emissions would keep the rise in temperatures below 2°C. The work of the IPCC establishes, on a sound and independent scientific basis, the need for countries to continue to pursue policies to reduce their GHG emissions. For recent three years (2011–2013), the life-cycle energy consumption of buildings is close to 43% of China's total energy consumption. Energy consumption in buildings' operation phase has been salient, accounting for over 20% of China's total energy consumption (Zhang, He, & Tang, 2015). The constraint of reducing CO_2 emissions, but also to guarantee China's energy security and addressing problems caused by climate change, make it necessary to reduce building energy consumption. This pressure on the energy performance targets of the buildings has led to a change in construction habits, primarily by increasing the insulation of the envelope and improving the airtightness. In China, energy-saving policies and thermal regulations have led to the introduction of thermal insulation to reduce the heating or cooling

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https://doi.org/10.1016/j.scs.2019.101812
Received 24 February 2019; Received in revised form 23 June 2019; Accepted 26 August 2019
Available online 30 August 2019

transmission load (Ministry of Housing & Urban-Rural Development of the People's Republic of China, 2016, 2012). However, the installation of insulation in new buildings or renovation of existing buildings can create confined living spaces with very tight walls, fine air-tightness and little renewal of indoor air. These changes to the envelope can cause phenomena that related to moisture: mould growth, degradation of air quality, condensation in the walls, which can lead to decrease in the durability of the materials and their thermal performance.

The attention of the scientific community is particularly focused on the study of hygrothermal transfer issues in buildings. The theoretical bases for modeling the coupled phenomena of heat and mass transport in a porous medium have been developed since 1957 by Philip and De Vries (1957) and later by Luikov (1975); Whitaker (1977) and Künzel (1995). However, the physical parameters or coefficients in the governing equations proposed by Philip and de Vries, Luikov and Whitaker are difficult to obtain, and the solution is very complicated. The Philip and de Vries's model underestimates the flow of moisture by approximately five orders of magnitude (Bouddour, Auriault, & Mhamdialaoui, 1998). The disadvantage of Luikov's model is the presence of phase change factor in energy balance equation which is not derived from a physical law and the empirical determination of this factor is difficult. Furthermore, thermo-migration of the liquid phase is neglected in Künzel model. In recent years, many studies have been launched in many countries to better understand the phenomena associated with hygrothermal transfer and to adapt or correlate models of hygrothermal coupling calculations. Odgaard, Bjarlv, and Rode (2018) evaluated the influence of hygrothermal phenomena on envelope characteristics and durability. The impact of combined heat and mass transport on the real thermal conductivity behavior of polystyrene insulation material was reported in a recent published study (Khoukhi, 2018). Tariku, Kumaran, and Fazio, 2010; Tariku, Kumaran, & Fazio, 2010) conducted a study aimed at characterizing and modeling the thermo-hydric behavior of porous materials, showing their particular behavior having an influence on the indoor hygrothermal comfort and the energy performance of building. Some studies estimated the effect of "water inertia" known as the "water buffer" capacity and the ability of hygroscopic materials to store and destock water vapor (Woods & Winkler, 2016; Zhang et al., 2017). For many years, the scientific community has been interested in coupled heat and mass transfers in buildings at different scales (material (Tariku et al., 2010a; Tariku et al., 2010b), wall elements (Hansen, Bjarløv, & Peuhkuri, 2018) and whole building (Woloszyn & Rode, 2008). To date many models are available and applied to particular situations of materials and problems. Several tools are in advanced stages of development, usable by the architecture designers. One of the best known for modeling hygrothermal transfer in hygroscopic materials is the WUFI software developed by the Fraunhofer Institute for Building Physics (Ge & Baba, 2015), it is the result of a remarkable work carried out by Künzel during his doctoral dissertation at the University of Stuttgart (Künzel, 1995). Künzel simplifies the moisture transfer to a pure diffusive model: vapor transport and surface liquid diffusion are described with Fick's diffusion law, with water vapor partial pressure as driving potential for vapor flow and relative humidity for the surface diffusion (Guizzardi, 2014). The HAMLab tool can be used for heat and moisture transport modeling at the building scale (Kelly, Walter, & Rowland, 2014). Most of hygrothermal studies were conducted as part of the international projects of the International Energy Agency (IEA) and its program Energy Conservation in Buildings and Community Systems.

Proper moisture predication is an essential prerequisite to ensure no moisture risk related to the sustainability of building materials. However, it is not possible to establish general rules, because of the number of parameters involved in humidity control (local climatic conditions, types of construction) that vary according to the country. This is why a major scientific effort has been made to develop hygrothermal models to predict the temperature and humidity conditions in the walls, the roof et al. Historically, the Glaser method makes it possible to evaluate the vapor pressure profile in a multi-layer wall in a steady state (Glaser, 1958; Tadeu, Simões, & Branco, 2003). Likewise, the saturation vapor pressure profile can be obtained from the temperature profile determined by the thermal conductivity formulas. It is then possible to verify in the wall the existence of points whose vapor pressure is greater than the saturation vapor pressure: condensation phenomena will occur at these points. The main limitation of this method is that it is restricted to cases of steady-state profiles. However, a building wall is subject to daily and seasonal variations in indoor and outdoor temperature and relative humidity. Therefore, the analysis of the hygrothermal behavior of a building wall requires a model capable of evaluating the humidity and temperature variations in dynamic mode, what is commonly called a HMT (Heat and Moisture Transfer) model (Künzel, 1995; Tariku et al., 2010a; Tariku et al., 2010b). In spite of these numerous developments, several scientific obstacles remain to be raised to better apprehend the phenomena. On the one hand, discrepancies between physical measurements and numerical simulations have been observed in many projects. On the other hand, there are trade-offs and uncertainties, while insulation renovation is popular and beneficial in many ways e.g. reduce heating or cooling load transmitted through a wall, it may also be detrimental in other respects, such as moisture accumulation and degradation of thermal performance depending on the location of the building, the climate, and even the season as benefits and drawbacks change over the year.

The presence of water vapor in the wall may reduce its thermal insulation effectiveness. Moisture migration through the building envelope can promote the appearance of mold on the inner surface of building wall, induce poor indoor air quality, these affecting the health of the occupants. The sustainable design, construction and retrofitting of buildings demands a long-term view of their performance. Climate change can affect buildings in different ways, i.e. it can change the hygrothermal behavior or the energy demand of buildings in the future. Warming trends currently occurring have been observed with certainty. As a result, historical weather data may not be the best source for the calculation of heating/cooling load and hygrothermal behavior of building walls. Studying the sustainability of the built environment can be done by hygrothermal calculation of building envelope towards future climate. With increasing concerns about effects of the climate change on buildings, it is essential to perform impact analysis using the available future climate. This was the initiation of the present work. In recent years, the threat of climate change and increased comfort expectations have further increased the demands on the energy and environment of buildings. That is why architects and engineers are called upon to better understand and take into account the building physics processes in building components now and in the future. In the literature there are few prospective studies on the impact of climate change on building performance in the hot and humid southern China area in the context of climate warming. This article describes the evaluation of the hygrothermal performance of multi-layer walls based on IPCC RCP4.5 scenario for the representative city of Guangzhou located at the hot and humid southern China area. The impact studies of the climate change were done by looking into the relative humidity at the interface between mortar layer and insulation layer and also cooling load transmitted through the wall.

2. Climatic characterization of the study area

Climate is the primary factor affecting the response of the building envelope. A preliminary climate study can contribute to the problems of heat and mass transfer within the hygroscopic envelope. In this study, the IWEC-version weather data of Guangzhou is chosen as the baseline climate for the generation of future climate, and it is downloaded from EnergyPlus website with the file name of CHN_Guangdong.Guangzhou.592870_IWEC.epw (https,//energyplus.net/weather-location/asia_wmo_region_2/CHN//CHN_Guangdong.Guangzhou.592870_IWEC). Guangzhou, the representative and largest city in the hot summer and warm winter region of China is selected