Energy and Buildings 77 (2014) 48–57

Contents lists available at ScienceDirect

Energy and Buildings

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

Study of hygrothermal behaviour of a hemp concrete building envelope under summer conditions in France

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ARTICLE INFO

Article history:
Received 17 November 2013
Received in revised form 18 February 2014
Accepted 19 March 2014

Keywords:
Hemp concrete
Moisture transfer
Thermal inertia
SPARK
Simulation

ABSTRACT

This paper presents some preliminary investigations about the transient hygrothermal behaviour of a hemp concrete envelope under summer conditions in France. The first part compares the thermophysical properties of hemp concrete to those of other materials used in construction. Then in order to investigate the material hygrothermal behaviour in a building envelope, a coupled heat and mass transfer model is implemented into the simulation environment SPARK and validated with experimental data available from the current literature. Simulations for a room made of hemp concrete are run under summer conditions for three French cities. Our results suggest that in South France the use of hemp concrete in buildings can lead to an indoor superheating for more than 70% of occupation period. These conditions can be improved significantly by using the combined effect of external solar shading, night ventilation technique and high energy storage capacity materials.

1. Introduction

Human reliance on energy, particularly fossil fuel, has led to serious environmental concerns with unsustainable levels of carbon emissions causing global warming. Thus if buildings were constructed using sustainable materials, with reduced energy usage, this could have a major impact on curbing emissions. Vegetal fiber materials are an interesting solution as they are eco materials and have low embodied energy. Hemp concrete is one of these materials which is more and more recommended by the eco-builders for its low environmental impact [1].

Previous research has presented the material physical properties [2–7]. They highlighted that the material presents high moisture buffering capacity and a good balance between low mass and storage capacity when compared to classical insulation materials. Few works studied material hygrothermal behaviour on wall or building level [8–16]. They showed that hemp concrete can attenuate the oscillations of external environment and reduce energy consumption in winter when compared to cellular concrete. However these efforts of reducing heating energy input, should not cause thermal discomfort to occupants in summer over sustained periods which can lead to pressure for the installation of mechanical cooling. Such systems will lead to an increase in overall building energy use.

This paper presents some preliminary investigations about the transient hygrothermal behaviour of a hemp concrete building envelope in summer in France. First we describe the material, its thermophysical properties and the mathematical model for coupled heat and moisture transfer into porous materials. The mathematical model is based on Philip and de Vries model [17] which uses as driving potentials the temperature and moisture content gradient. It is validated using recent experimental results on a hemp concrete wall [12]. Sensitivity analysis is also done in order to identify the most important parameters affecting temperature and relative humidity profiles.

Finally a nodal model is integrated with the presented coupled heat and moisture transfer model and is applied to a room made of hemp concrete. Simulations are run for three French cities. Several cases are investigated such as the use of solar shadings, white roof painting and night ventilation. The effect of adding mortar layers is studied and hemp concrete behaviour is compared to normal concrete.

2. Hemp concrete thermal inertia

Depending on the nature of the thermal action on a wall, there are mainly two types of thermal inertia:

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http://dx.doi.org/10.1016/j.enbuild.2014.03.040
0378-7788/

Nomenclature

Cp	specific heat at constant pressure (J kg^{-1} K^{-1})
Cp_0	specific heat of dry material at constant pressure (J kg^{-1} K^{-1})
D_T	mass transport coefficient associated to a temperature gradient (m^2 s^{-1} K^{-1})
$D_{T,v}$	vapour transport coefficient associated to a temperature gradient (m^2 s^{-1} K^{-1})
D_θ	mass transport coefficient associated to a moisture content gradient (m^2 s^{-1})
$D_{\theta v}$	vapour transport coefficient associated to a moisture content gradient (m^2 s^{-1})
g	gravity acceleration (m s^{-2})
h_r	radiative heat transfer coefficient (W m^{-2} K^{-1})
h_M	convective mass transfer coefficient (m s^{-1})
h_T	convective heat transfer coefficient (W m^{-2} K^{-1})
j	total flow density (kg m^{-2} s^{-1})
j_v	vapour flow density (kg m^{-2} s^{-1})
L_v	heat of vaporization (J kg^{-1})
P_v	vapour pressure (Pa)
Q_m	air flow rate (kg s^{-1})
S	surface area (m^2)
T	temperature (K)
T_m	mean radiant temperature (K)
t	time (s)
V	volume (m^3)
x	abscissa (m)
θ	moisture volumetric content (m^3 m^{-3})
θ_s	moisture volumetric content at saturation (m^3 m^{-3})
λ	thermal conductivity (W m^{-1} K^{-1})
ρ_0	mass density of dry material (kg m^{-3})
ρ_i	air density (kg m^{-3})
ρ_l	mass density of water (kg m^{-3})
ρ_v	mass density of vapour water (kg m^{-3})
ϕ	relative humidity (%)
σ_0	Stefan-Boltzmann constant (W m^{-2} K^{-4})
δ	water vapour permeability (kg m^{-1} s^{-1} Pa^{-1})
ε	wall emissivity (long wave)
φ	heat flow density (W m^{-2})
Φ	heat flux (W)
Φ_{ray}	radiation heat flux (W)
Φ_{source}	heat source power (W)
ξ	specific hygric capacity (–)
μ	vapour diffusion resistance factor (–)
δ_a	air vapour permeability (kg m^{-1} s^{-1} Pa^{-1})

Subscript

i	Inside
LW	Long wave radiation
M	Mass
o	Outside
ray	radiation
T	Thermal

- Thermal inertia under outdoor varying conditions: It considers envelope behaviour under periodical time varying meteorological conditions. Its importance is due to the fact that the larger part of the building shell mainly consists of the outer walls which act as the main barriers for the protection of the building's interior from the outside weather conditions such as cold in the winter, heat in the summer, humidity, rain, wind and noise. This inertia causes amplitude reduction of the indoor temperature and its time-lag in relation to the outdoor temperature [18–20]. It is characterized by material thermal diffusivity ($a = \lambda/(\rho\, C_p)$), ρ, C_p and λ are respectively material density, specific heat and thermal conductivity. The lower the thermal diffusivity is, the higher time lag and amplitude reduction are. Table 1 compares the thermal diffusivity and time lag of some materials used in building construction. The latter was determined by simulation for a wall of 20 cm thickness under a daily outdoor periodical temperature variation [11]. It is seen that hemp concrete has the lowest thermal diffusivity and the highest time lag which means that it can reduce the propagation of outdoor weather conditions through building envelope.
- Thermal inertia under indoor thermal actions: these actions are regarded as permanent (indoor space heating) or random due to solar radiation. In this case, thermal inertia consists of storing heat energy through building envelope and releasing it later by radiation [21–23]. It is characterized by the thermal effusivity ($b = \sqrt{\lambda\rho C_p}$) which indicates the aptitude of a material to absorb and to restore energy. The higher the thermal effusivity is, the higher the stored heat energy within the material would be. This means that the material can help in reducing indoor superheating in summer (or decreasing heating energy input in winter by releasing stored energy to indoor space). Table 1 compares the thermal effusivity of hemp concrete to other materials. It is noticed that it is lower than other materials which means that it can store less energy and thus superheating problems in summer can occur [10].

In the next section we present the mathematical model that is used on wall and building level in order to study envelope behaviour under summer conditions.

3. Mathematical model

In the literature, there are several works about modelling the hygrothermal transfer through porous materials. Most of the research is still carried out by using phenomenological macroscopic models, introducing heuristic laws relating thermodynamic forces to fluxes through moisture and temperature dependent transport coefficient. In this way, one of the most used and accepted macroscopic models for studying heat and moisture transfer through porous material is the Philip and de Vries model [17] which uses as driving potentials the temperature and moisture content gradient. While most studies on heat transport processes largely agree, no consensus in the choice of driving potentials for describing moisture transport phenomena exists at present and some authors modified the Philip and de Vries model by using other driving potentials instead of the moisture content. We should cite Perdesen [24] who used the capillary pressure, but in practice it is difficult to be directly measured. Künzel [25] used the relative humidity as a potential. The calculation methodology employed by them is correct since it takes into account the discontinuity phenomenon at the interface.

In the present paper, the Umidus model [26] in which the moisture in porous material can be transported under liquid and vapour phases is used. The governing partial differential equations to model heat and mass transfer through the wall are given by equations (1) and (2). They were derived from conservation of mass and energy in a 1-D elemental volume of the porous material. The energy conservation equation is written as

$$\rho_0\, c_m(T,\theta)\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda(T,\theta)\frac{\partial T}{\partial x}\right) - L_v\frac{\partial}{\partial x}(j_v) \qquad (1)$$

while the mass conservation equation as

$$\frac{\partial \theta}{\partial t} = -\frac{\partial}{\partial x}\left(\frac{j}{\rho_l}\right) \qquad (2)$$