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TRANSIENT ANALYSIS OF THE THERMAL AND MOISTURE CONDITIONS IN WALL CONSTRUCTIONS WITH ADDITIONAL THERMAL INSULATION

Abstract

In the present paper a transient simulation method TRATMO with applications to the analysis of the hygrothermal behaviour of timber frame constructions with additional thermal insulation will be discussed. The present simulation method makes it possible to evaluate the hygrothermal behaviour with respect to risks of mouldering since it gives the simultaneous knowledge of moisture content and temperature at certain sections of the construction. Based on the computer simulations and experiments a number of practical aspects to be applied in additional thermal insulation of timber frame constructions will be introduced.

Le présent article traitera d'une méthode de simulation instantanée, appelée TRATMO, et de son application à l'étude du comportement hygrothermique des structures portantes en bois dotées d'une isolation thermique. Cette méthode permet d'évaluer le comportement hygrothermique dans la perspective des risques d'effritement, fournissant la connaissance simultanée de leur teneur en humidité et de leur température en certains endroits. A partir de simulations et d'expériences conduites avec l'aide de l'ordinateur, il sera présenté un certain nombre de points practiques à observer lors de l'isolation thermique additionnelle des structures portantes en bois.

1 INTRODUCTION

A significant part of damages of building components are evaluated to be due to internal and external thermal and moisture loads not considered to a sufficient extent in the design and dimensioning of constructions. Traditionally building components and constructions were developed via experience during periods of generations. Nowadays new materials and constructions are introduced for use without thorough analysis of the durability, for which the knowledge of the thermal and moisture physical behaviour, first of all, has to be available. Especially in timber frame constructions after retrofitting there has appeared serious moisture problems. The analysis of durability with respect to hygrothermal loads may be done by laboratory or field experiments or by simulations. The simulations of the hygrothermal behaviour of constructions provides an approach, which enables studies on transient transport phenomena, because boundary conditions vary as a function of time and because most building materials have a natural property to charge and discharge heat and moisture.

The moisture physical behaviour of constructions has traditionally been estimated with respect to the condensation conditions. That approach is, however, too simplified. Relevant arguments for the critical hygrothermal conditions of materials and constructions are chemical or mechanical destruction (mouldering or frost damages, respectively), loss of thermal resistivity or strength, corrosion of metallic components etc. It has to be emphasized that the critical moisture content of each material or construction has to be determined experimentally, but the knowledge of where and when with given environmental conditions the critical conditions will be reached, can be obtained by simulations. For examples, wood begins to decay at about 85 % relative humidity when the temperature is over the freezing point.

The numerical simulations of the hygrothermal conditions in wall constructions with additional thermal insulation, to be introduced in the present paper, are carried out with computer code TRATMO (Transient Analysis Code for Thermal and Moisture Physical Behaviour of Constructions) [1]. A number of the results obtained by TRATMO - simulations have been verified with laboratory or field experiments, too.

2 SIMULATION OF COUPLED HEAT AND MOISTURE TRANSFER IN MULTILAYER CONSTRUCTIONS

Due to its essential role in the studies on the durability of wall constructions with respect to hygrothermal loads, the outlines of the simulation method TRATMO will be discussed

When heat and mass transfer in capillary-porous bodies is discussed, the total mass flux $\Sigma\vec{q}_{M,i}$ includes diffusion, surface diffusion, capillary flow and viscous flows of humid air and liquid water. Model equations for $q_{M,i}$:s are obtained with analyses of momentum equation. It can be shown that diffusion and capillary flows can be related to moisture content and temperature and the viscous flows to the gradient of static pressure. Consequently, the transient moisture balance equation becomes [1,2]

$$\langle\rho_0\rangle \frac{\partial\langle u\rangle}{\partial t} = \sum_{k=1}^{3} \nabla\cdot(\underline{a}_{m,k}^{(u)}\cdot\nabla\langle u\rangle + \underline{a}_{m,k}^{(T)}\cdot\nabla\langle T\rangle + \nabla\cdot(\frac{\underline{K}_{v,14}}{\nu_{14}}\cdot\nabla\langle p_{14}\rangle^{(14)} + \frac{\underline{K}_{v,2}}{\nu_2}\cdot\nabla\langle p_{2,0}\rangle^{(2)}) . \quad (1)$$

Correspondingly, the transient energy balance equation becomes [1,2]

$$\frac{\partial}{\partial t}(C'''_{eff}\langle T\rangle = \nabla\cdot(\underline{K}_q\cdot\nabla\langle T\rangle) + \sum_j l_{ij}\langle\dot{q}_{ij}\rangle - \sum_{i=2,14}\nabla\cdot\langle h_i q_{m,i}\rangle . \quad (2)$$

The following transport properties have to be known to simulate simultaneous coupled heat and mass transfer in porous bodies

(i) moisture and thermal moisture diffusivities, $a_{m,k}^{(u)}$ and $a_{m,k}^{(T)}$

(ii) permeabilities for humid air and liquid water flows, $K_{v,14}$ and $K_{v,2}$

(iii) thermal capacity and conductivity, C'''_{eff} and K_q.

Methods for the determination of these transport properties are introduced in [2] as well as the detailed derivation of Eqs (1) and (2).

The constitutive equations for the boundary conditions are obtained from Eqs (1) and (2) assuming quasi-steady-state transport processes across boundary layers.

In building physical applications the following fluxes have to be taken into account

(i) thermal radiation fluxes
(ii) conduction heat flux
(iii) convection heat flux
(iv) conduction moisture flux
(v) convection water vapour flux
(vi) convection liquious water flux (driving rain)
(vii) filtration (viscous) flux of water or humid air.

The interface of adjacent layers may be considered in the cases, where there is

(i) perfect hydraulic content
(ii) no hydraulic contact
(iii) non-capacitive layer e.g. the so-called surface resistance
(iv) air gap (ventilation of constructions)

between the adjacent layers.

When the hydraulic contact is perfect and accumulation of heat and moisture is not allowed at the interface, the following conditions of continuity are valid

(i) temperature distribution and heat flux are continuous
(ii) moisture transfer potentials (temperature and water vapour pressure and pressure of capillary condensate) are continuous.

A. Air-solid interface
B. Perfect hygrothermal contact between adjacent layers
C. Surface resistance between adjacent layers
D. Viscous flow in the air gap between layers

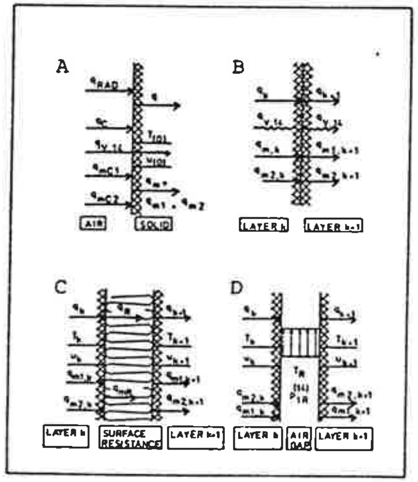

Fig. 1. Fluxes and transport potentials at different kinds of boundary conditions in building physical applications.

For the numerical analyses of hygrothermal conditions in building constructions computer code TRATMO has been compiled. TRATMO is written in FORTRAN-4 language for CDC Cyber 173 and it utilizes IMSL and NAG library subroutines.

The environment conditions for transient simulations are evaluated by temperature, vapour pressure or humidity ratio of air, solar radiation and wind velocity. The environmental data can be read from a special weather file including the quantities listed above and the time step, which may vary due to Crank-Nicholson method, from step to step (commonly 4 - 6 hours). Furthermore, artificial weather files involving in the simulations of laboratory experiments can be used.

Material and transport properties are stored in library subprograms. MATER subprogram includes density (function of u), thermal conductivity and capacity (functions of u and T), moisture and thermal moisture diffusivities (functions of u and T) of materials. Subprogram VAPOR includes the vapour pressure table of adsorbed moisture used in calculation of boundary conditions. Two independent output files can be formed, one for the line printer and one for the CALCOMP drum plotter. The following items can be stored into the files

(i) environment conditions
(ii) temperatures and moisture contents at grid points
(iii) heat and moisture fluxes at surfaces
(iv) water vapour pressures (⇒ relative humidity) at surfaces
(v) cumulative heat and moisture fluxes at the external surface of construction.

3 TRANSIENT ANALYSIS OF THE HYGROTHERMAL CONDITIONS IN WALL CONSTRUCTIONS WITH ADDITIONAL THERMAL INSULATION

Hygrothermal conditions in typical wall constructions involving in renovations of existing buildings have been studied [3]. The purpose of the work was to find out, if it is necessary to install a new water vapour barrier or not due to additional thermal insulation. If necessary, where to locate it and what to do with the original water vapour barrier or with impermeable (painted) wall papers.

In Finland, the most typical wall construction in small houses up to the fourties was the log wall. During the fourties and fifties small houses had timber frame with 100 mm sawdust enclosed with tar paper as thermal insulation. After that mineral wool was introduced for use as thermal insulation material. Typical thickness of the insulation layer was 100 mm. In the sixties houses with massive aerated concrete walls were built, too. At the moment those existing houses are under renovation and thermal insulation is often added in order to lower the U-values of walls to the level required from the new buildings.

The simulations have been executed using hourly weather data typical for middle Finland, (this kind of weather files are commonly used in programs for the energy analyses of buildings). The interior temperature was assumed to be +20 °C during heating period and equal to outside temperature at other times. The interior humidity ratio was assumed to be $x_{in} = x_{out} + 0{,}003$. Figure 2 shows the temperature and moisture distributions in a sawdust wall with 100 mm mineral wool insulation. As the curves show, the construction does not work without water vapour barrier, since the moisture content in certain sections exceeds 18 per cent by weight when the temperature

is above +5 °C. Furthermore, net accumulation of moisture takes place at annual periods. Corresponding simulations have been executed with log wall, mineral wool and aerated concrete wall. These computations as well as the laboratory and field experiments are the basis of the discussion of the durability presented later in this paper.

4 LABORATORY AND FIELD EXPERIMENTS

In order to verify the validity of TRATMO simulations of the hygrothermal conditions in wall constructions a number of laboratory and field experiments have been carried out [3]. The laboratory experiments were performed in a weathering chamber, where the exterior and interior climate can be controlled automatically. The dimensions of test walls are approximatelly 2 x 2 m^2. The hygrothermal loads were chosen to correspond typical climate in southern Finland during the winter months, e.g. during the so-called wetting period. The experiments lasted about from two to four months. For the moisture detection it was used Vaisala Humicap capacitive sensors and samples from the test walls. Figure 3 illustrates computed and measured results of the laboratory test with a timber frame wall with additional 100 mm mineral wool insulation inside the original construction having 100 mm sawdust insulation. There was no water vapour barrier inside the mineral wool layer. The results show that although no surface condensation occurs, the hygrothermal behaviour of the wall construction is not acceptable, since the moisture content reaches values critical to wood already during a short wetting period. In addition, it may be seen that the computed and measured values of moisture contents are in a rather good agreement, which verifies the validity of TRATMO for longterm simulations, too. Corresponding experiments varing insulating material have been carried out with a log wall, mineral wool wall, aerated concrete and 1½ stones masonry walls.

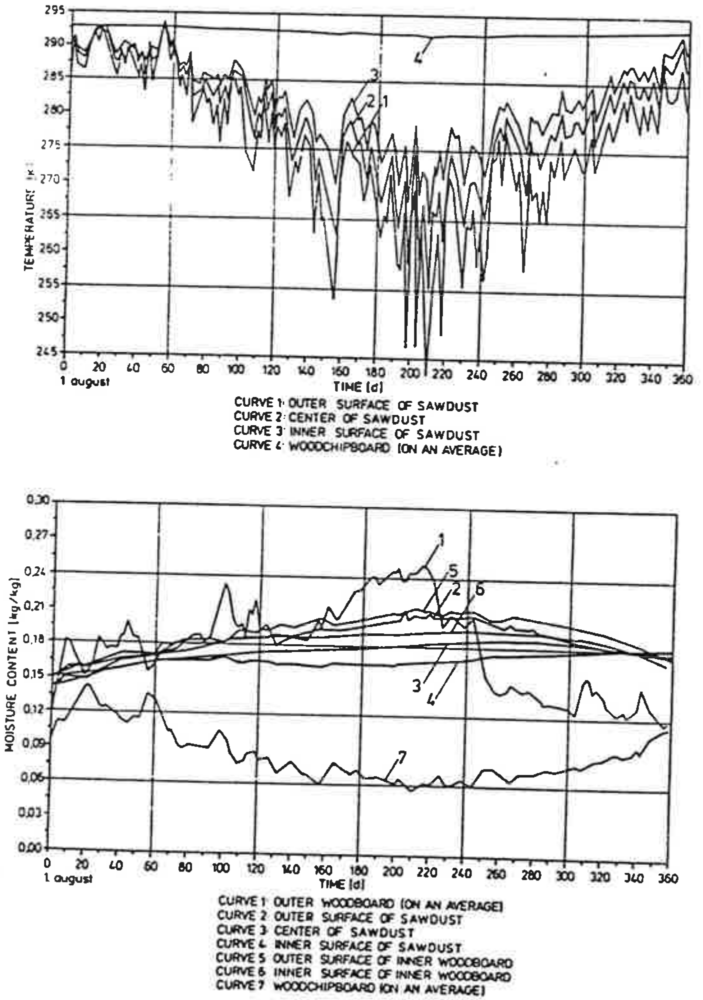

Figure 2. Temperature and moisture content distributions in a sawdust wall with internal additional thermal insulation.

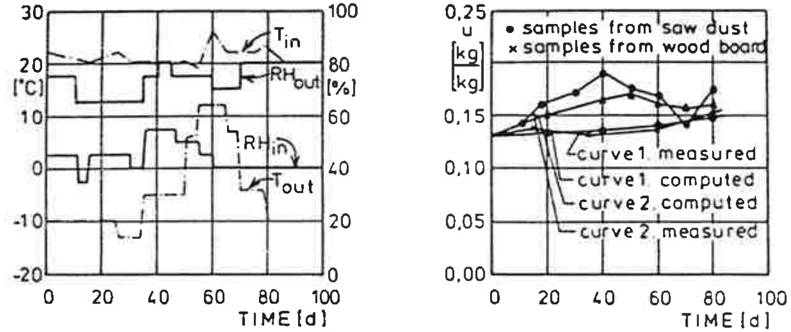

Figure 3. Computed and measured moisture contents in a sawdust wall with 100 mm internal mineral wool insulation.

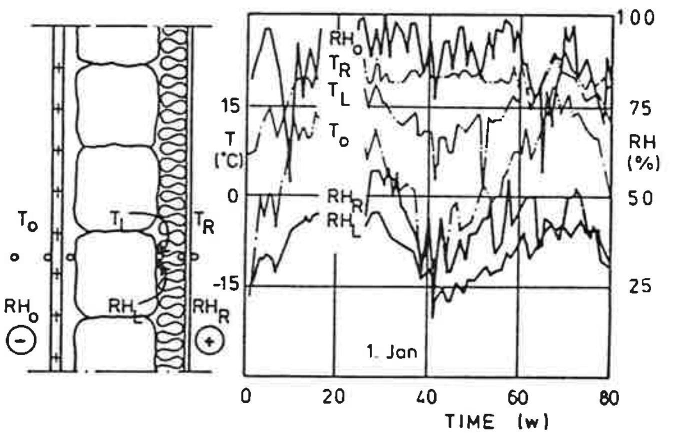

Figure 4. Measured temperatures and relative humidities in a 6 " log wall with 100 mm internal mineral wool insulation.

The field experiments of the referred study were carried out by Partek Ltd. The test houses were existing and occupied. In each experiment house there were three four separate "measuring lines", where the temperatures and relative humidities at internal and external and interfacial surfaces of the layers of the exterior walls were recorded.

Figure 4 illustrates results of a field experiment carried out in a small house with log walls. The results show that there is no need of water vapour barrier due to the internal moisture transfer.

5 DISCUSSION

A number of practical aspects concerning additional thermal insulation of wall constructions have been established with computer simulations and field and laboratory experiments. The essential question in additional thermal insulating is, if new water vapour barrier has to be installed or not. However, it is to be emphasized that water vapour barrier has a function with respect to air leakages, too. Owing to the advanced simulation method TRATMO it has been possible to analyze the hygrothermal behaviour of wall constructions with respect to relevant criteria, e.g. with respect to the temperature and moisture content in wall constructions.

Under Finnish natural climate the following principles in additional thermal insulating of existing constructions should be applied :

1. External insulation is preferable to internal, since it brings less risks to moisture damages than internal insulation. When closed-cell foam insulating materials are used the minimum thickness of external insulation is about 25 mm.

2. New water vapour barrier on the inner surface of insulating material is not necessary in internal additional insulating of 6 " log walls, when the thickness of permeable insulating material (mineral wool, expanded polystyrene) is less than 100 mm and when relative impermeable materials, for example woodchipboard, are used as interior covering. When polyurethane or extruded polystyrene are used as insulation, it is obvious that there are no limitations to the thickness of insulation layer or internal covering. Again, we have to note that air leakages from inside to outside may cause serious accumulation of moisture.

3. The internal thermal additional insulation of the so-called sawdust walls provides new water vapour barrier inside the insulating layer, except when impermeable insulating materials as polyurethane or extruded polystyrene are used. When using rigid sheets it has to be ensured that the joints of the sheets are well sealed.

4. The hygrothermal conditions in the so-called mineral wool walls depend on the ratios of the thermal and water vapour resistivities of original and reconstructed wall construction. The analysis of the hygrothermal conditions may be done, in this case, by the traditional dewpoint considerations, since the thermal and moisture capacities of the layers involved are not dominating in heat and mass transfer processes, e.g. heat and moisture fluxes can be considered as quasi-stationary fluxes.

5. Critical hygrothermal conditions for aerated concrete and masonry walls equal conditions, where mechanical destruction, e.g. frost damages take place. Furthermore, the moisture contents corresponding the

possibility of frost damages are due to external moisture transfer, e.g. due to driving rain. Consequently, any general rules or recommendations can not be established.

It is, however, obvious that since internal additional thermal insulation lowers the temperature of the outer layers of walls, risks of frost damages increase. Also for these constructions the external thermal insulation seems to be preferable to internal.

In the present paper only the changes in the hygrothermal conditions of wall constructions due to additional thermal insulating have been discussed. Other effects of the measure are first of all, reduction in heat losses (which is the primary purpose of the measure), decreasing of the seasonal efficiency of the heating boiler (which does not, however, mean increasing of losses in boiler), need of readjustment of the radiator network. These questions, among others, are discussed in [4].

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