Moisture Research in the Field of Architecture, Japan

Shuichi Hokoi

Professor Emeritus Kyoto University, Yoshida-Honmachi, Sakyo-ku, Kyoto 606-8501, Japan
E-mail: hokoi@maia.eonet.ne.jp

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Abstract

There are many moisture-related problems and topics in the field of buildings. In this review, the past research trend in the field of moisture in Japan is first overviewed by examining the activities reported in the AIJ symposium on thermal environment. The theme of the symposium held every 10 years indicates the research trend, i.e., the research until the year 1990 established the theoretical basis of heat and moisture transfer; then, until the year 2000, the established theory was developed to be applied in practice, and until the year 2010 the results obtained so far were presented to a wide range of occupants and end users.

The indoor humidity and the accompanying problems are closely related to the fact that most of the materials constituting the building are porous, and thus absorb water vapor. Therefore, the important topics of moisture research emphasizing the heat and moisture transfer in porous building materials are described, i.e., heat and moisture transfer in porous material and method of analysis, condensation and mitigation of humidity change, freezing-thawing, mold and wood-rotting fungi, health and comfort, conservation of cultural properties, etc.

Finally, the challenges and prospects are presented.

Keywords: building physics, porous material, heat and mass transfer, moisture damage, health

1. INTRODUCTION

There are many moisture-related problems and topics in the field of buildings, including damages due to moisture such as condensation, mold growth, rot, and rust formation, and the development of various energy saving techniques such as ground thermal storage and evaporative cooling. The growth of mold caused by condensation and the accompanying breeding of mites are related to atopic dermatitis, which is critical for the health of infants and elderly people. On the contrary, the spread of heating devices that do not generate moisture, such as heat-pump air conditioner or floor heating panel, lowers the indoor humidity of residential buildings during winter and spring, which tends to cause allergic or respiratory diseases, and electrostatic shocks. Thus, suitable indoor humidity should be provided, since both moist and dry environments cause health problems. The humidity of the environment must be properly controlled for the maintenance of artifacts in museums, and the proper management and control of food or industrial products in factories.

The indoor humidity and the accompanying problems are closely related to the fact that most of the materials constituting the building elements, furniture, etc. are porous, and thus absorb/desorb water vapor and absorb liquid water. Therefore, an overview of the past research trend in the field of moisture in Japan is presented, followed by a description of the important topics of moisture research, emphasizing the heat and moisture transfer in porous building materials. Finally, the challenges and prospects are presented.

2. RESEARCH TREND IN THE FIELD OF MOISTURE (Hokoi 2014a)

2.1 Symposium on thermal environment of Architectural Institute of Japan (AIJ)

The trend in the field of moisture-related research in Japan can be understood by examining the activities reported in the AIJ symposium on thermal environment held every four or five years under the auspices of AIJ. Table 1 lists the titles and topics of the symposium in the past three decades, for every ten years, focusing on the field of moisture.

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moisture transfer; further, until the year 2000, the established theory was developed to be applied in practice, and until the year 2010 the results obtained so far were presented to a wide range of occupants and end users, followed by further development.

2.2 Until the year 1990

As shown by the subtitle of the symposium in 1991, ‘Analysis of phenomena and design’, the fundamental theoretical basis for describing physical phenomena related moisture transfer was mostly accomplished before 1990, and subsequently a comprehensive review was first presented in the symposium. Accordingly, the simultaneous equations of heat and moisture transfer proposed by late Professor Emeritus, Mamoru Matsumoto, were validated, along with the provisions of the minimum physical properties necessary for design. The measured results of indoor humidity and the method of calculation were examined, and practical simple methods of calculation were also developed. Along with the theoretical analysis, the actual situations of crawl spaces, attic, and air layers in ventilated walls, and severe climatic conditions such as cold snowy regions, which had not been fully understood, were reported and discussed. This period was a research stage during which the research flow aiming at establishing a design method was accelerated by integrating basic theory and field survey. As the title ‘New development in moisture research’ illustrates. Therefore, session 2 ‘Fundamentals of heat and moisture transfer’, included studies on Lewis relation, freeze-thaw processes, local equilibrium, moisture properties etc., complemented the fundamental theory, and developed an elaborate description of the phenomena.

The main objectives of the symposium in 2000 were to discuss buildings with a long life required by the global environment, and the definition of and measures to alleviate moisture damage from a viewpoint that practitioners and occupants should understand and utilize the research results. These reports were subject to the results obtained so far based on theoretical research, experimental research, and in situ survey (Iwamae 2000) on durability, moisture damage, effect and evaluation of hygroscopic materials, etc.

Session 5 ‘Effect and evaluation of hygroscopic materials’ illustrated examples of utilizing the hygroscopic behavior of porous building materials in order to solve moisture-related problems, because this feature had been gradually adopted. At session 6, ‘New development’, the studies on health problems, urban environment issues, condensation in underground space connected to the ground, clothing and thermal physiology, evaporative cooling by lawn, etc. were presented. At this stage, the health problem was already regarded as one of the moisture-related issues.

2.4 Until the year 2010

The title of the symposium in 2010 was ‘Moisture for humans, things, and buildings’; further, the symposium in 2014, whose title was ‘Useful moisture research’, had almost the same contents as the former symposium, except that the research related to cultural heritage formed an independent session.

At the session ‘Humans and moisture’, indoor
floating fungus, transport and growth of bio-aerosol in indoor environment (Ito 2014), allergy, dryness, etc. were discussed in relation to moisture, and the relationship between insulation and health was also reported. The studies on the influence of moisture on health, and the studies on human physiology had already become important topics in the field of moisture research. The session ‘Things and moisture’ was concerned with the relationship between cultural properties and moisture, wherein salt weathering, environment in exhibition space, Takamatsuzuka tumulus, influence of algae, etc. were reported. These researches investigated the influence of moisture on cultural properties and the ways to preserve them - a new application field of moisture research. At the session ‘New building systems - new energy and moisture’, desiccant air conditioning (by separation of sensible and latent heats) and fuel cell were introduced as equipments that utilize porous material. These equipments can be regarded as a more active utilization of porous hygroscopic materials than the use by a mud wall (Yokobayashi 2008) or total heat exchanger.

One of the signs of maturity of the field of moisture research is the study of moisture damage. Classification of moisture damage, consciousness of residences to moisture damage, and typifying moisture accidents were discussed, and an AIJ standard regarding moisture damage was developed. Another sign of maturity is that creating a reference problem to evaluate hygroscopic material was initiated.

3. BASIC AND APPLIED RESEARCHES CHARACTERIZING MOISTURE RESEARCH IN JAPAN

This section provides an outline of the studies on (1) heat and moisture transfer in porous building material and method of analysis, (2) condensation and mitigation of humidity change (hygroscopic behavior), (3) freezing-thawing, (4) multi-component systems with salt, (5) mold and wood-rotting fungi, (6) health and comfort, (7) plants and microorganisms, (8) conservation of cultural properties, and (9) indoor and outdoor conditions, in order to characterize moisture research in Japan.

3.1 Basic Equations of Heat, Air and Moisture (H2AM) Transfer

(1) Heat and moisture transfer in porous material and basic equations expressing their movement

By applying the theory of non-equilibrium thermodynamics to heat and moisture transport, Matsumoto (1984a) derived the diffusion equations of heat, air, and moisture (in gaseous and liquid phases), by regarding a porous material with moisture as a mixture of air, moisture, and solid material. By assuming local equilibrium, i.e., the temperature and water chemical potential of water vapor in the pore are equal to those of liquid water in contact with it (Ohsawa 1996), the balance equations of moisture and heat are expressed, respectively, as follows (Matsumoto 1984a).

Moisture balance

\[ \frac{\partial w}{\partial t} + \frac{\partial \mu}{\partial t} = \nabla \cdot \left( \lambda \nabla T + \lambda' \nabla \mu \right) \]

Eq. 1

Heat balance

\[ C \rho \frac{\partial T}{\partial t} + c_v \rho \nabla \cdot \nabla T = \nabla \cdot \left( \lambda \nabla T + \lambda' \nabla \mu \right) + j_v \cdot \nabla \lambda' \nabla \mu \]

Eq. 2

where,

- \( \rho_o \) : density of water [kg/m³],
- \( w \) : volumetric moisture content [m³/m³],
- \( t \) : time [s],
- \( \mu \) : water chemical potential [J/kg],
- \( T \) : temperature [K],
- \( \lambda \) : thermal conductivity of material [W/mK],
- \( \lambda' \) : heat capacity of water [J/kgK],
- \( j_v \) : liquid water flux [kg/m²s],
- \( c_v \) : heat capacity of water [J/kgK],
- \( r_e \) : heat of evaporation [J/kg],
- \( \lambda' \) : vapor diffusivity owing to temperature gradient [kg/m²sK],
- \( \lambda' \) : vapor diffusivity owing to water chemical potential gradient [kg/m²s(J/kg)].

The first and second terms on the right hand side of Eq. 1 represent the moisture transfer owing to temperature \( T \) and water chemical potential \( \mu \) gradients, respectively, and moisture diffusivities \( \lambda' \) and \( \lambda' \) are the sum of gaseous and liquid components. The first, second, and third terms on the right hand side of heat balance equation, Eq. 2, represent the heat conduction, and the latent heat transfer caused by vapor transfer owing to temperature \( T \) and water chemical potential \( \mu \) gradients, respectively. The second term on the left hand side represents the sensible heat transfer caused by liquid transfer. Various models of heat and moisture transfer used in foreign countries (IEA 2007) can be regarded as equivalent to Eq. 1 and Eq. 2.

(2) Validation of basic equations and analysis of condensation

The above described basic equations were validated with respect to the condensation process (Matsumoto 1984a). Similar examinations were carried out using soft wood fiber board (Ikeda 1985), glass
fiber board (Hokoi 1993), clothing (Takada 2007), etc., and they resulted in the validation of the aforementioned equations. The basic equations enabled the calculation of non-steady state heat and moisture transfer both for theoretical research and practical use.

(3) **Hygrothermal properties**

In order to use the basic equations of heat and moisture transfer described in Section (1), the equilibrium moisture content, thermal conductivity, and several moisture (vapor and liquid) diffusivities are necessary as explained below. The basic equations based on the empirical flux – potential gradient relationship are effective only when coupled with these hygrothermal properties.

**Equilibrium moisture content** (Matsumoto 1984a)

The equilibrium moisture content has been measured for many materials (Kumaran 1996, 2002). Equilibrium moisture content, which represents the moisture capacity, can be also used for separating moisture diffusivities into vapor and liquid components (Matsumoto 1984a, Hokoi 1985). Many building materials exhibit hysteretic behavior in their equilibrium moisture content. Although hysteretic phenomena have long been recognized, they have not been properly dealt with, because it is very tedious and difficult to treat them theoretically. However, a theoretical analysis was developed by Matsumoto and Matsushita in 1981 based on the independent domain theory (Everett 1952).

**Moisture diffusivity**

Although the vapor permeability of building materials has long been measured for many materials based on the Cup method prescribed by Japanese Industrial Standards JIS A 1324 (JIS 1995), the measurements of the moisture diffusivity with liquid components are very limited in Japan. The database of ASHRAE (Kumaran 2002) is the most complete and satisfying database at present.

Figure 1 shows the measured \( \lambda' \) of Autoclaved Lightweight Concrete (ALC) (Ogura 2009). Hysteretic behavior (difference between absorbing and desorbing processes) can also be observed in diffusivity. Figure 2 (a)(b) shows the calculated results of the evaporation process in both cases without and with the consideration of hysteresis of equilibrium moisture content and \( \lambda' \) based on the independent domain theory. It can be understood that the consistency with the measured results can be improved by considering hysteresis (Ogura 2009, Matsushita 2016).

**Thermal conductivity \( \lambda \)**

The measurement of the thermal conductivity of moist porous material is more difficult than that of dry material, since the moisture distribution in the material becomes non-uniform owing to moisture movement caused by a temperature gradient, which must be imposed to measure the thermal conductivity. Furthermore, the heat transport accompanying the vapor transfer also complicates the situation. ISO 16957 (ISO 2016) prescribes the measurement method considering these aspects.

Figure 3 shows the thermal conductivity of a soft fiber board as a function of the moisture content and temperature (Hokoi 1985). The thermal conductivity increases by approximately four times from 0.06 to 0.23 W/mK as the moisture content increases from 0 to 200 weight percent. The thermal conductivity significantly differs depending on the mean temperature, because the latent heat transfer caused by the vapor movement depends on the mean temperature.

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**Figure 1. Diffusivity \( \lambda' \) of ALC.**

**Figure 2. Moisture content distribution in evaporation process: (a) without hysteresis, (b) with hysteresis.**
3.2 Condensation and mitigation of humidity change by hygroscopicity
(1) Interstitial condensation: moisture accumulation in porous material
Interstitial condensation has long been one of the most important issues attempted to be addressed in the field of moisture research, and one of the main topics related to the moisture movement inside building materials. However, it can be predicted with sufficient accuracy using analytical methods as Figure 4 (moisture distribution) and Figure 5 (temperature distribution) show (Matsumoto 1984a).

(2) Mitigation of indoor humidity change by use of hygroscopic materials
Figure 6(a) shows the calculated indoor humidity in a non-heated room (adjacent to a heated room) of reinforced concrete (RC) dwelling unit of an apartment house, which is heated by an open-type oil furnace during winter (Matsumoto 1984b). Surface condensation occurs on the window glass during the heating period in the morning and evening. The humidity of the external wall is also high and the possibility of condensation is very high. Contrary to the high humidity during daytime, the indoor air humidity drops down to 10% from midnight to early morning, indicating excessive dryness. By changing the heating device from an open type furnace to a heat-pump air conditioner or floor heating to avoid condensation, the indoor dryness becomes much more severe and may cause health problems.

In such a situation, most of the porous materials, such as wood or paper, exhibit hygroscopicity and can be used effectively to mitigate the change of humidity of the indoor air. Figure 6(b) shows the calculated indoor humidity when a hygroscopic surface finishing is used. In this case, the humidity in the non-heated room can be maintained at moderate values, and neither condensation nor excessive dryness occurs. Contrary to the humidity control by an air conditioner, this is a passive method of humidity control. It can maintain a healthy indoor condition and contribute to energy saving.

With respect to the use of hygroscopic materials, Imanaka and Ikeda (2010) propose to solve both excessive dryness and condensation simultaneously by using a proper open-close control of the openings between the rooms and the moisture generated inside the house. Mukai et al. (2008), Umeno et al. (2016), Matsuoka et al. (2016) examined the influence of hygroscopic materials on the humidity inside walls or attic space, and Matsuo et al. (1987) examined absorption by books and clothing.

3.3 Freeze-thaw processes
Freezing is one of the factors that seriously deteriorate walls of a building. In addition to cold regions, freezing may occur even in relatively mild climatic regions such as Kanto or Kinki, if rain water penetrates or water vapor infiltrates accompanied by cooling down owing to nocturnal radiation. In many cases, the degradation of roof tiles occurs when freezing and thawing are repeated (Figure 7, Iba 2016).
The heat and moisture transfer including freeze-thaw processes can be analyzed as a three phase system consisting of water vapor, liquid water, and ice, by combining the relationship between the freezing temperature and water chemical potential with the basic equations of heat and moisture transfer described in Section 3.1 (1) (Matsumoto 1993).

Figure 8 shows the calculated results of the freezing process in a mud wall, where the water vapor flowing from the inside (from the right side of the figure) freezes, concentrating at one point on the wall (Iba 2000). A comparison of the calculated and measured results using ALC or a glass fiber board has been carried out (Hokoi 2000).

3.4 Moisture transfer when salt is included: multi-component system

(1) Salt

Salt crystallization can often be observed in RC or brick walls. Abuku et al. (2007) investigated the change of equilibrium relationship caused by salt, and the influence of salt on transport properties, in the case of salt crystallization on clothing owing to sweating. Furthermore, they proposed a moisture and salt transport model in porous material, and measured the equilibrium relationship and liquid water diffusivity. Particularly they clarified the influence of crystallized salt on them (Abuku 2014) (Figure 9). On the other hand, a study of enhancement of hygroscopicity by using salt was also proposed (Tanimoto 1994).

(2) CO2 concentration change owing to micro-organism activity in the ground

The concentration of CO2 in the ground is higher than that in the atmosphere. This is caused by the activity of micro-organisms; thus, the state of the ground water, which is essential for their existence, determines the concentration CO2 in the ground. A theoretical model considering the moisture is proposed to predict the concentration change of CO2 and O2 caused by micro-organisms in the ground, which is used to predict the concentration in the tumulus (Ogura 2011).

3.5 Degradation owing to mold and wood-rotting fungi

From the perspective of global environment, a long life of buildings is strongly required, for which the durability of material, building elements, and whole building must be improved. Hukka et al. (1999) proposed a criterion evaluating the level of damage to wood caused by fungi growth using a damage function. Nagai, Suzuki et al. (2009) carried out steady state and cyclic change experiments to express the influence of rottin on the mechanical strength of wood as a function of moisture content, amount of humidification, and
elapsed time, and showed that wood will rot if a moisture content between 30% and 70% is maintained for a certain period. A system for evaluating the durability of wood is proposed (Nofal 2001) in which a structural analysis and HAM model is incorporated with the aforementioned damage function. Similarly, Saito et al. (2014) proposed a moisture balance equation considering the moisture generated owing to the decomposition of wood, identified the reaction rate constants and moisture generation rate based on rotting experiments, and showed that the influence of moisture generation is significant inside the wood.

3.6 Health and comfort

For disease prevention in an indoor environment, Aoki and Mizutani (2014) summarized the relationship among indoor temperature, humidity, and diseases, such as circulatory, allergic, and infectious diseases. For designing an indoor environment without excessive dryness, Kaihara et al. (2012) examined the non-steady state response of moisture content of skin to the change of indoor temperature and humidity based on laboratory experiments, and proposed a prediction model using heat and moisture transfer equations. They clarified that the correlation between moisture content of skin and indoor absolute humidity is high (Figure 10), and the distribution of moisture content can be predicted by considering the non-uniformity of vapor transfer resistance inside the skin layer (Figure 11).

An excessively dry state is serious, particularly in elderly people, and the relationship between indoor humidity and the growth and death of the influenza virus have been investigated (Shaman 2009).

Indoor humidity is closely related to thermal comfort. Figure 12 compares the measured and calculated physiological responses during sleep considering the mutual interaction among human physiological responses, bedding, and the indoor thermal environment (Hibino 2012).

3.7 Plants, microorganisms (moss, fungi, and mold), insects, and animals

Buildings and living beings have contact with each other in many aspects; for example, plants used as foliage or wall greening, microorganisms such as moss, fungi, and mold, insects and animals living inside or
outside the building. Since moisture is essential for the existence of living beings, these issues have to be considered.

(1) Plants and greening
The studies on the measurement of evapotranspiration from plants, control of temperature and moisture content of the ground for growing plants in a greenhouse (Matsumoto 1988), and greening of external walls or roof (Todo 2008, Onmura 2001) have been carried out.

(2) Microorganism
In order to control the growth of fungi on the external walls of buildings (Tsujimoto 1992), an examination of the relationship between fungi growth and the ambient air temperature and humidity, and a proposal for the growth model have been implemented (Miyauchi 2008, Nakajima 2015).

3.8 Preservation of cultural properties
Much of the deterioration of cultural properties is related to moisture. The preservation of cultural properties has been carried out so far in related fields such as the history of art or archaeology. However, quantitative evaluation of the influence of the environment, particularly the influence of the moisture, has not been performed. However, research from the point of view of building environmental engineering has been actively carried out. In this regard, Ogura (2014a) reviewed and explained that cultural properties have been affected by various factors such as condensation, salt weathering, fungi growth, insect damage (Uno 2014), color appearance (Ogura 2014b), microorganism activity in ground and concentration of O2, CO2 (Ogura 2011), and oxidation of Fe (Wakiya 2016), rust (Yanagida 2015), water repellent (Yoshioka 2015), etc. It should be noted that the influence of condensate on the visual appearance of mural paintings in Kamao tumulus (Ogura 2014b) can be clarified only by conducting moisture research, although solar radiation or temperature are generally the main factors influencing the deterioration of paintings.

3.9 Influence of rain
In order to determine the influence of rain on buildings, Saito (2014) examined the relationship between the rainfall intensity and the penetration rate through the interstice between the roof materials based on the wind-driven water spray experiment. In the case of the wind-driven rain incident on the building, Abuku (2012) carried out detailed experiments and analysis,

Figure 12. Skin and core temperatures.

Figure 13. Numerically determined (a,b) impact angle θ, (c,d) impact speed v, and (e,f) specific catch ratio σd of raindrops at center on the facade of the tower. The reference wind direction is perpendicular to the facade.
and clarified the characteristics (Figure 13).

4. FUTURE CHALLENGES AND PROSPECTS

The future challenges are hereby listed, in no particular order.

(1) HAM model considering micro structure of porous building material

Carmeliet (1999) proposed a model based on multiscale network. Considering the progress of computing speed and memory capacity of computers, it is desirable to perform research on the direct computation of material properties and HAM transfer, which considers the micro structure of the porous material (Derome 2012), and avoid simplifications as far as possible.

(2) Scatter of material property and randomness of input parameters

Most of the external climatic conditions and occupant activities are not deterministic, and change randomly depending on the situation. Consequently, the temperature and humidity on the walls or in the rooms fluctuate stochastically. Furthermore, the physical properties of building materials exhibit a general scatter as shown in Figure 14 (moisture diffusivity) (Kumaran 1996), and the building as a whole may exhibit a random nature owing to the difference in craftsmanship. Although the randomness should be suitably considered for a reasonable building design, research in this direction is insufficient (Hokoi 1997).

Recently, research has been carried out, wherein many samples have been measured to clarify the scatter of the physical property (super cooling temperature). It shows a probabilistic distribution of the measured results, and attempts to explain the results using an analytical model (Figure 15) (Takahashi 2016).

(3) Toward design

One of the final goals of architectural environmental engineering and moisture research is design; for example, the design problem of an exhibition hall of cultural properties, intended for both preservation and display to the public (Wakiya 2014). In such cases, indoor humidity conditions to be realized must be prescribed for design.

As an example of such criteria, AIJ issued AIJES-H003-2013, which defines and classifies moisture damages (AIJ 2013), as AIJ academic standard. Furthermore, a standard for the evaluation of the ability to mitigate change of humidity (JIS A 1470-1 (JIS 2014)) is prescribed by JIS. Regarding international standards, JIS A 1470-1 has been transformed to ISO (ISO 24353 (ISO 2008)), and AIJES-H003-2013 has been discussed for conversion into an ISO, under convener Prof. Takada (NP22185 (ISO 2016)).

For an optimal design of building elements and buildings that satisfies the required performance and is consistent with related standards, it is necessary to simulate multiple times with various combinations of related parameter values, and to continue the designing process by confirming the moisture performance. Accordingly, software for HAM analysis is required. Each researcher usually develops software for his/her own use, and there are several commercially available software. By using simple and typical wall structures or buildings, the validity of software must be verified (based on mutual correspondence). For that purpose, several reference problems have been proposed (Kishimoto 2014).

(4) Regional, urban, and global environment

As a Column of member’s opinion (Hokoi 2014b) of Society of Heating, Air-conditioning and Sanitary Engineers of Japan (SHASE) in 2014, the following question was asked. ‘Considering that the relative humidity of 40% during heating, which is recommended by the regulation of maintaining buildings, is not usually observed, although dryness in winter makes latent heat load (humidification) increase, should this recommendation be reexamined?’ So far, studies on urban climate focus only on the thermal problem. In order to create healthy and comfortable indoor and outdoor hygric environments for human beings, attention should be paid to urban climate from a hygrothermal point of view to improve present ‘dry island’. Contrary to the situation in summer, the temperature increase in winter (this is the original heat island) lowers the relative (not absolute) humidity and worsen

![Figure 14](image1.png) Scattering of moisture diffusivity.

![Figure 15](image2.png) Distribution of super-cooling temperature.
the dry state, although it is desirable for the temperature and energy consumption; further, the increase in absolute humidity may suppress the growth of the influenza virus. Countermeasures such as the recovery of naked land or water surface and greening, which supply moisture, should be adopted.

(5) Contribution of water for supplying energy, which determines our living standard

A building wall with reducing cooling/heating loads (hygroscopic materials), desiccant air conditioner (Momoi 2014), etc. have been proposed and utilized to reduce the energy consumption as contributions from the field of moisture research. A porous material is used in the fuel cell, and the generated water vapor owing to the burning of hydrogen gas may be effectively utilized. Use of underground water (Nakamura 2001) or well water (Hagihara 2016), photosynthesis, and fixing of solar energy by fungi (from energy saving to creating energy) are other contributions.

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References
Abuku M., Hokoi S., Takada S., Hashikata M. (2007) Heat and Moisture Transfer in Cloth Considering Salt Influences, Part 1 - Experiment of Salt Water Uptake and Absorption Isotherm of Cloth Considering Salt Influences, Transactions of the Society of Heating, Air-Conditioning and Sanitary Engineers of Japan, 119: 17-22. (in Japanese)
Abuku M., Roels S., Janssen H., Poesen J. (2012) Towards a reliable prediction of moisture response of walls to wind-driven rain, IBPC 2012: 921-928.
Abuku M., Ogura D., Hokoi S. (2014) Measurement and Modeling of Water Sorption Isotherm of Autoclaved Aerated Concrete with Salt, Journal of Environmental Engineering (Transactions of AIJ), 79(700): 499-506. (in Japanese)
AIJ (2013) Standards for Diagnosing Moisture Damage in Buildings and Implementing Countermeasure, AIJES (Architectural Institute of Japan, Environmental Standards), AIJES-H0003-2013. (in Japanese)
Aoki T., Mizutani A. (2014) Classification and Organization of Temperature and Humidity Conditions and Various Diseases Prevention, 44th Symposium on Thermal Environment, AIJ: 81-86. (in Japanese)
Carmeliet J. (1999) A Multiscale Network Model for Simulating Moisture Transfer Properties of Porous Media, Transport in Porous Media, 35: 67-88.
Derome D., Rafsanjani A., Patera A., Sedighi-Gilani M., Dressler M., Carmeliet J. (2012) The role of Water in the Behavior of Wood, Proceedings of the 5th IBPC, Kyoto, Japan.
Everett D.H., et al. (1952) “A general approach to hysteresis”, Trans. Faraday Soc., part I, 48: 749-757.
Hagihara K., Iba C., Hokoi S. (2016) Effective use of a ground-source heat-pump system in traditional Japanese “Kyo-machiya” residences during winter, Energy and Buildings, 128: 262-269.
Hibino Y., Hokoi H., Yoshida K., Takada S., Nakajima M., Yamate M. (2012) Thermal physiological response to local heating and cooling during sleep, Frontiers of Architectural Research, 1(1): 51-57.
Hokoi S., Ikeda T., Horie G. (1985) Classification and Organization of Temperature and Humidity Conditions and Various Diseases Prevention, 44th Symposium on Thermal Environment, AIJ: 81-86.
Hokoi S., Ikeda T., Horie G. (2014a) Trend in the Past 20 Years and Future of Moisture-Related Research Field, Special articles in honor of the 50th anniversary of Kinki Branch, SHASE Monthly Journal, 88(4): 369-370. (in Japanese)
Hokoi S. (2014b) What is a suitable value for set-point humidity? in column of personal opinions, SHASE Monthly Journal, 88(4). (in Japanese)
Hukka A., Viitanen H. (1999) A Mathematical Model of Mold Growth on Wooden Material, Wood Science and Technology, 33(6): 475-485.
Iba C., Hokoi S. (2000) Freezing-Thawing Processes in a Wall Made of Soil in Relatively Warm Area in Japan, Part 2 Influence of external and indoor climatic conditions, Proceedings of Cold Climate HVAC 2000, Sapporo, Japan: 93-98.
Iba C., Ueda A., Hokoi S. (2016) Field survey on frost damage to roof tiles under climatic conditions, Structural Survey, 34(2): 135-139.
IEA (2007) IEA Annex 41, Subtask1 - Modelling Principles and Common Exercises.
Ikeda T., Hokoi S., Horie G. (1985) Studies of Simultaneous Heat and Moisture Transfer in Porous
Materials under Conditions of Condensation: Part 1
Simultaneous heat and moisture transfer equation and determination of transfer coefficients contained in the equation, Journal of architecture, planning and environmental engineering, 355: 1-11. (in Japanese)
Imanaka M., Ikeda T. (2010) Effect on Prevention of Over Dry and Vapor Condensation on Window by Using a Hygroscopic Material in Multiple-rooms, 40th Symposium on Thermal Environment, AIJ: 149-156. (in Japanese)
ISO (2008) ISO 24353 Hygrothermal performance of building materials and products - Determination of moisture adsorption/desorption properties in response to humidity variation.
ISO (2016) ISO 16957 Measurement of apparent thermal conductivity of wet porous building materials by a periodic method.
ISO (2016) NP22185 Design of building components and built environment for avoiding moisture damages.
Ito K. (2014) Numerical Prediction of Spore Dispersion and Fungal Growth in Indoor Environment, 44th Symposium on Thermal Environment, AIJ: 7-11. (in Japanese)
Iwamae A., Matsumoto M., Chikada T., Matsushita T., Matsumura O. (2000) A Study on Hygrothermal Behavior in Crawl Space Dampproofed at Soil Surface, J. Archit. Plann. Environ. Eng., AIJ, 528: 29-36. (in Japanese)
JIS (1995) JIS A 1324: Measuring method of water vapor permeance for building materials. (in Japanese)
JIS (2014) JIS A 1470-1 Determination of water vapor adsorption/desorption properties for building materials-Part 1: Response to humidity variation. (in Japanese)
Kaihara N., Takada S., Matsushita T. (2012) Transient response of skin surface moisture content to change in indoor humidity, Measurement and modeling of moisture transfer in skin surface, Proceedings of the 5th International Building Physics Conference (IBPC), Kyoto, Japan: 939-944.
Kishimoto Y. (2014) Various Effective Utilization of Hygroscopic Materials and Evaluation Method, 44th Symposium on Thermal Environment, AIJ: 3-6. (in Japanese)
Kumaran M.K. (1996) Material Properties, IEA ANNEX 24, Task 3.
Kumaran M.K. (2002) ASHRAE Research Project 1018-RP, "Thermal and Moisture Transport Property Database for Common Building and Insulating Materials", 04.
Matsumoto M., Matsushita T. (1981) Simultaneous Heat and Moisture Transfer into and out of Inorganic Porous Body in Hygroscopic Range: Part 2 Effect of ad/de-sorption Hysteresis on Transient Moisture Transfer, Journal of architecture, planning and environmental engineering, 306: 65-72. (in Japanese)
Matsumoto M. (1984a) New Series of Architecture, Vol. 10 Chapter 3 Moisture, Shokokusha Co.Ltd. (in Japanese)
Matsumoto M., Itani S. (1984b) A simultaneous analysis of temperature and humidity variations in the coupled room during the intermittent heating: 1. Method of analysis, 2. Characteristics of humidity and temperature, Summary of AIJ Annual Meeting, Planning: 767-768, 769-770. (in Japanese)
Matsumoto M., Hokoi S., Narita Y. (1988) An Analysis of Heat and Moisture Load in Greenhouse – Heating by pipes buried in the ground -, Summary of AIJ Annual Meeting, D: 609-610. (in Japanese)
Matsumoto M., Gao Y., Hokoi S. (1993) Simultaneous Heat and Moisture Transfer during Freezing-Melting in Building Materials, Proceedings of the CIB W40 Meeting in Budapest.
Matsu Y., Inoue T., Kin S., Nishioka M. (1987) A Study on Moisture Characteristics of Paper, Part 1 Estimation of hygroscopic coefficients, Part 2 Prediction of vapor permeability, Summary of AIJ Annual Meeting, Planning: 945-946, 947-948. (in Japanese)
Matsuoka D., Hokoi S. (2016) Analysis of Hygrothermal Conditions in Attic Space with Eaves Ventilation During Winter Season, Journal of Environmental Engineering (Transactions of AIJ), 81(725): 581-588. (in Japanese)
Matsushita T. (2016) Study on Gas-Liquid Separation Model of Moisture Conductivity and Temperature Gradient Moisture Conductivity – Separation of “Void connection” and “Gas-Liquid Series Connection” of Moisture Conductivity and Temperature Gradient Factor-, Summary of AIJ Kinki Chapter Research Meeting, Environmental Engineering, 56: 201-204. (in Japanese)
Miyauchi M., Hokoi S., Uno T., Ogura D. (2008) Effects of Algae on Monuments in Hot and Humid Climates, Journal of Environmental Engineering (Transactions of AIJ), 73 (623): 9-15. (in Japanese)
Momoi Y., Yoshie R., Yamaguchi F., Hoshino K. (2014) Numerical Model of Heat and Water Vapor Transfer for Desiccant Cooling System, 44th Symposium on Thermal Environment, AIJ: 25-30. (in Japanese)
Mukai K., Hokoi S., Kominami K., Abuku M., Suzuki H., Iba C. (2008) Thermal and Moisture Characteristics in Insulated Wall of Conventional Wooden House-Simulation of full-scale insulated wall experiment with airflow in porous building elements-, Journal of Environmental Engineering (Transactions of AIJ), 73(623): 17-22. (in Japanese)
Nagai H., Suzuki H., Kitadani Y., Iwamae A., Kominami K., Sakamoto Y. (2009) The Relationship between
Water Content and Decay of Various Woods Under Hygrothermal; Studies on the quantification of decay phenomenon in wood-base building material and its mathematical prediction mode (Part 1), Journal of Environmental Engineering (Transactions of AIJ), 74(638): 457-463. (in Japanese)

Nakajima M., Hokoi S., Ogura D., Iba C. (2015) Modeling of Algal Growth and Death on Exterior Walls of Buildings, Journal of Environmental Engineering (Transactions of AIJ), 80(718): 1125-1131. (in Japanese)

Nakamura M., Shimizu T., Hokoi S. (2001) System Concept and Confirmation of Thermal Performance; Study on thermal energy storage system utilizing finite aquifer Part 1, J. Archit. Plann. Environ. Eng., AJ: 546: 69-74. (in Japanese)

Nofal M., Kumaran M.K. (2001) On Implementing Experimental Biological Damage-Functions Models in Durability Assessment Systems, Proceedings of CIB W40 Meeting, Wellington: 111-124.

Ogura D., Hokoi S., Shimizu T., Noguchi H. (2009) Influence of Hysteresis in Sorption Isotherm and Moisture Conductivity on Condensation and Evaporation Processes, Journal of Environmental Engineering (Transactions of AIJ), 74(643): 1065-1074. (in Japanese)

Ogura D., Hokoi S., Takahashi K., Kimura N. (2011) Study on the Method of Controlling Air Conditioning in the Stone Chamber during the Excavation of Tsugeyama Tumulus, Conservation Science, 50: 23-33. (in Japanese)

Ogura D. (2014a) Challenges and Prospects on Conservation and Exhibition of Indoor and Outdoor Cultural Properties, 44th Symposium on Thermal Environment, AJ: 87-89. (in Japanese)

Ogura D., Morita N., Hara N., Hokoi S. (2014b) Study on the appearance of mural painting due to moisture content Part 3: Prediction model on change of the appearance of the wetted pigment, Summary of AIJ Annual Meeting, D-2, Environmental Engineering: 485-486. (in Japanese)

Ohsawa T., Mizutani A., Tsuchikawa T., Ono K. (1996) Measurement of Local Moisture Transfer Coefficient for a Wood Board: Nonequilibrium moisture transfer in porous building materials Part 1, Journal of Architecture, Planning and Environmental Engineering, 488: 9-15. (in Japanese)

Omura S., Matsumoto M., Hokoi S. (2001) Study on Evaporative Cooling Effect of Roof Lawn Gardens, Energy and Buildings, 33: 653-666.

Saito H. (2014) Prediction of Hygrothermal Performance for Roof Construction in Consideration of Rain Penetration and Damage Analysis for Actual Damaged House, 44th Symposium on Thermal Environment, AJ: 61-68. (in Japanese)

Shaman J., Kohn M. (2009) Absolute humidity modulates influenza survival, transmission, and seasonality, PNAS, 106(9): 3243-3248.

Takada S., Hokoi S., Kumaran M.K. (2007) Experimental and Analytical Investigation of Moisture Movement in Clothing, Journal of Building Physics, 31(2): 125-142.

Takahashi K., Yamagishi H., Kishimoto Y., Hama Y. (2016) Establishment of the Thermodynamic Non-Equilibrium Freezing Probability Prediction Model Based on the Probability Distribution Taking into Account the Supercooling Phenomenon in Mortar Part 2: Influence of Independent Variables on Probability Distributions of Freezing Point and Instantaneous Increment of Ice Content due to Supercooling, Summary of AIJ Annual Meeting, Environmental Engineering: 515-516. (in Japanese)

Tanimoto J., Kimura K., Harimoto K. (1994) Development of Non-Organic Porous Materials Impregnated with Lithium Chloride for Efficient Humidity Regulation in Buildings, J. Archit. Plann. Environ. Eng., AJ: 466: 17-22. (in Japanese)

Todo K., Ogura D., Hokoi S., Kotani H. (2008) Reduction of Thermal Impacts on Indoor and Outdoor Environment by Greening Walls, Journal of Environmental Engineering (Transactions of AIJ), 73(631): 1109-1116. (in Japanese)

Tsujimoto Y., Ohba N., Sudho T. (1992) Identification of Fresh-water Algae of External Building Walls and Study on an Evaluation Method for the Soiling by Fresh-water Algae; Study on the soiling by fresh-water algae of external building walls, Journal of Struct. Constr. Eng. AJ, 433: 11-17. (in Japanese)

Umeno T., Hokoi S., Saito H., Honma Y. (2016) Field Survey of Hygro-thermal Characteristics in an Experimental House, A study of anti-condensation performance in the vented air space of exterior walls Part 2, Journal of Environmental Engineering (Transactions of AIJ), 81(729): 951-959. (in Japanese)

Uno T., Shimadzu Y., Iba C. (2014) Conservation State of the Wall Paintings in the Ajanta Caves Influenced by Inside Temperature and Humidity Changes and Surface Coating, 44th Symposium on Thermal Environment, AJ: 113-118. (in Japanese)

Wakiya S., Kuwabara N., Hokoi S., Ogura D. (2014) Examination on environmental control inside the shelter for the preservation of openly exhibited soil site, 44th Symposium on Thermal Environment, AJ: 97-102. (in Japanese)

Wakiya S., Kuwabara N., Hokoi S., Ogura D., Kouzuma H. (2016) Disfiguring Caused by Iron Hydroxide on the Remains Exhibited in the Excavation Site Exhibition Hall, Nara Palace Site, Archaeology and Natural Science, 72: 1-14. (in Japanese)
Yanagida A., Wakiya S., Yasui H., Ogura D., Hokoi S. (2015) Study on preservation of buried cultural properties in the stone chamber by means of the simulated tumulus Part3: Effect of environment on corrosion of metal artifacts in the stone chamber, Summary of AIJ Annual Meeting, Environmental Engineering: 275-276. (in Japanese)

Yokobayashi S., Sato M. (2008) A Study on Heat and Moisture Properties of Material Used by Traditional Skill – Evaluation of plaster material (Nakanuritsuchi) made of substances in Hyogo-, J. Environ. Eng., AIJ, 73(630): 965-969. (in Japanese)

Yoshioka M., Iba C., Hokoi S. (2015) Prevention against frost damage using surface finishing to Rock-hewn churches in Cappadocia; Effects of surface-finishing material on the ice content distribution in outer walls, Summary of AIJ Annual Meeting, Environmental Engineering: 271-272. (in Japanese)