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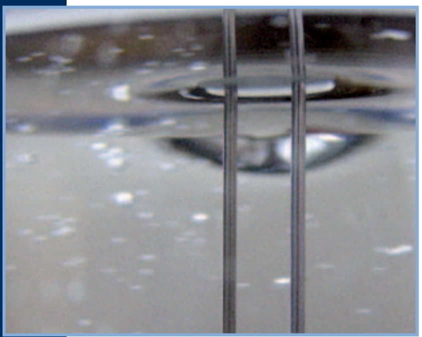

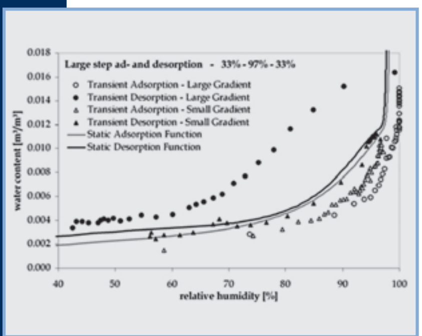

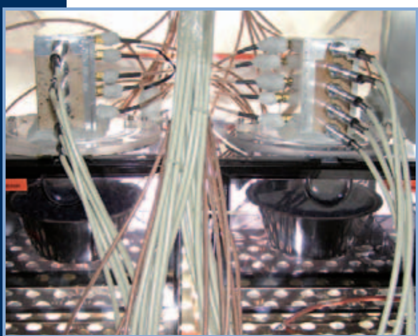

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VALIDATION OF HYGROTHERMAL MATERIAL MODELLING UNDER CONSIDERATION OF THE HYSTERESIS OF MOISTURE STORAGE

VALIDIERUNG HYGROTHERMISCHER MATERIALMODELLIERUNG UNTER BERÜCKSICHTIGUNG DER HYSTERESE DER FEUCHTESPEICHERUNG

For achievement of the academic degree

Doctor of Engineering (Dr.-Ing.)
at the Faculty of Civil Engineering
at Dresden University of Technology

accepted thesis submitted by

Dipl.-Ing. Gregor Albrecht Scheffler

born at May 11th 1978 in Dresden, Germany

Supervisors: Prof. Dr.-Ing. habil. Peter Häupl
Prof. Dr. habil. Henryk Sobczuk
Prof. Dr. Carsten Rode

Date of defence: February 12th 2008

This thesis has been supported by the National German Foundation CUSANUSWERK.

πάντα ῥεῖ

Heraklit of Ephesos (ca. 540 - 475 BC)

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for Rudi and Katharina

PREFACE & ACKNOWLEDGEMENT

The work reported in this thesis has been accomplished during my research studies at the Institute of Building Climatology, Dresden University of Technology in the years of 2003 to 2007. Once introduced to hygrothermal building component simulation, it became one of my main objectives to connect the two powerful research fields of material investigation and hygrothermal transport modelling. I am convinced that here, sophisticated and sustainable research is only possible when it is based on a fundamental understanding of both, experimental material investigation and hygrothermal transport modelling.

The actual connection between these fields is the material modelling. Limited by both, the available input data as well as the current state of transport modelling, the material model is frequently blamed to be responsible for insufficient precision of simulation results. It is often difficult to clearly assign an observed effect to its actual cause. Therefore, the presented study aims on a fundamental material model validation combining experimental material investigation with hygrothermal transport as well as material modelling. The access to it requires though a broad review on each of these fields. The presented thesis starts therefore on a broad theory as well as experimental basis from which the accomplished developments and investigations are conducted.

The achievements of this broad study finally justify both, the chosen approach and the particular procedure. It is hence with both, pride and satisfaction to be able to submit this thesis now and present it to the interested scientific public. However, such a work is hardly achievable without mentors, promoters and friends. I have had the pleasure of having several of them whom I would like to express my gratitude for their various support. Moreover, I received financial support from different bodies which I want to be gratefully acknowledged, too.

In the years 2004 to 2006, I was awarded with a Ph.D. scholarship by the Cusanuswerk, the German national foundation for gifted catholic students. Besides the financial support of my research, I am very grateful for the various opportunities to participate in graduate seminars, symposia and other educational events I have been offered. The encouragement and motivation I gained during encountering so many open minded, enthusiastic and talented people contributed significantly to the success of my work.

Out of the people who supported and promoted me, I wish to thank Prof. Peter Häupl first for leaving the field of material model validation to me as the subject of my research. Almost ten years ago, it was he who sparked my interest in Building Physics, and especially in modelling and understanding heat and moisture transport. With his supportive frankness, the many lively discussions and his appreciation of scientific tenacity, he benefited both, my conducted research and my own development, for which I am very grateful.

Prof. Henryk Sobczuk and Prof. Carsten Rode were unreservedly willing to be the other supervisors of my thesis. I would like to thank them for their advises and comments concerning my work as well as their encouragement during the last year of completion.

The person who encouraged me most and who was probably most closely involved in the whole growing process of my work is Dr. Rudolf Plagge, the laboratory chief at the Institute of Building Climatology. I am both, proud and grateful of having him as a teacher, a mentor and a friend. There are many ways in which he shaped me and my work, and which I am grateful for. For instance our conversations and our plenty discussions, the nights we spent in the laboratory installing and calibrating the TDR technology, the different perspectives on our field of research he opened, the frankness in which he introduced me to the scientific community and, last but not least, the kind and friendly atmosphere in the laboratory.

The laboratory would though have been rather empty without another person who I wish to thank for his continuous and smooth support. Frank Meißner accompanied most of the conducted experiments, helped during the sensor calibration and installation, and contributed sustainably to the laboratory spirit.

For their aid in the laboratory, I also wish to thank Irene Heuchler and Peter Schmieder who made many devices to become brilliant reality which I had never dared to dream of. Moreover, I thank Sören Klose and Markus Beug for their steady assistance.

My fellow Ph.D. students Andreas Nicolai and Max Funk I want to thank for the many illuminative discussions on the theory of heat and mass transfer and for the time they spent with me during my stays in Zurich and Syracuse. Moreover, I wish to acknowledge the generous financial support I received from Prof. Jianshun Zhang and the Department of Mechanical, Aerospace, and Manufacturing Engineering at Syracuse University (NY) which enabled my research stay in Syracuse. Furthermore, I wish to thank Andreas Nicolai for the well structured introduction into C++ programming which provided the basis for my own program developments.

At the Institute of Building Climatology, I want to thank Heiko Fechner for answering many programming questions, supporting me with his own software developments and being a constant and authentic dialogue partner. Furthermore I thank Prof. John Grunewald for allowing me to participate in the national salt project and for supporting my studies in many discussions. Ultimately, my gratitude may be acknowledged to all the other colleagues at the Institute of Building Climatology for the warm and welcome atmosphere there.

Besides this wide and distinct financial and professional support, my research as well as my thesis could not have developed the way they did without my family and my friends. Most important was and is my wife Katharina who helped me carrying the load of set backs, consistently encouraged me and patiently read and reviewed the whole thesis. My parents and my sister and brother gave me support whenever I needed it and ensured me being part of a great family.

There are many more people I am grateful for, as Claudia Nikol who significantly helped to improve my English, Daniel Münch who has drawn the future in the brightest colours for me whenever I was down and Kornél Magvas, Jakob Polak, Janek Neubauer and Hans Janssen who encouraged me in many long conversations.

Gregor A. Scheffler,

Dresden & Meißen, 12th of February 2008.

Abstract

The achievable accuracy of hygrothermal building component simulation is significantly dependent on the applied material functions. These functions are determined by the material modelling marking the connection between the basic storage and transport parameters which are obtained from basic measurements, and the storage and transport coefficients which are defined within the balance and flow equations. It is the aim of the present study to develop a flexible and widely applicable material model which is not restricted to the current level of the transport theory. Furthermore, limits and options of this model are to be validated by means of four building materials on the basis of special transient moisture profile measurements.

The study's starting point is a comprehensive investigation of both, the different existing modelling approaches and the available experimental methods to determine basic hygrothermal material parameters. On this basis, the material modelling is set into the context of the heat and moisture transport theory derived from thermodynamics. The involved limits and restrictions are highlighted and options as well as requirements for further developments are pointed out. The developments this study focuses on comprise three fields: experiments for basic property determination, material modelling, and experiments for material model validation.

The set of basic material investigation methods has been extended by the drying experiment under defined conditions. The different influences on the drying as well as its application to hygrothermal material model calibration are pointed out and appraised. On this basis, a drying apparatus is designed, built and applied. Ultimately, standardisation criteria and the derivation of a single-value drying coefficient are evaluated. Appropriate extensions are indicated.

Based on the bundle of tubes approach, an own material model is developed. It is coupled with a mechanistical approach accounting for serial and parallel structured moisture transport phenomena. The derived liquid water conductivity is adjusted by the help of measured conductivity data close to saturation as well as within the hygroscopic moisture range. Subsequently, two internal modelling parameters are calibrated which is done by numerical simulation of the water uptake and the drying experiment under consideration of the hysteresis of moisture storage.

Facilitating its application to the obtained laboratory data, the material model has been implemented into a computer program. It is applied to the four building materials brick, lime-sand brick, aerated concrete and calcium silicate. The adjusted material functions are shown and discussed. In all four cases, the calibration provides an excellent agreement between measured and calculated material behaviour.

As experimental basis of the material model validation, the instantaneous profile measurement technique (IPM) has been extended to be applied in Building Physics. Special equipment is developed and measurement procedures are designed. Different models to derive the water content from dielectric data obtained by Time Domain Reflectometry (TDR) measurements are evaluated and implemented. Ultimately, an extensive program of transient moisture profile measurements within the hygroscopic and the overhygroscopic moisture content range is conducted and evaluated.

Within the frame of validation, the developments on the experimental as well as on the modelling fields are combined. The IPM experiments are recalculated on the basis of the measured initial and boundary conditions applying the adjusted and calibrated material functions. The comparison of measured and calculated data reveals the power of the developed material modelling just as the consequences of the simplifications made on the transport theory level. The distinct influences of the hysteresis of moisture storage consisting of effects depending on the process history and effects depending on the process dynamics, are proven.

By the presented study, the material modelling has been decisively further developed, the set of basic measurement methods has been extended by a substantial experiment and the instantaneous profile measurement technique has been made applicable to Building Physics. Moreover, the influences of the process history and the process dynamics on the moisture transport and the resulting moisture profiles could be shown and proven. By that, not only a material model is now available which perfectly applies to the requirements of flexibility, applicability and extendability. The obtained data provides also a powerful basis for further research and development.

KURZFASSUNG

Die Genauigkeit hygrothermischer Bauteilsimulation hängt maßgeblich von den verwendeten Materialfunktionen ab. Sie werden durch die Materialmodellierung bestimmt, welche die Verbindung zwischen den aus Basisexperimenten gewonnenen Speicher- und Transportparametern sowie den innerhalb der Bilanz- und Flussgleichungen definierten Speicher- und Transportkoeffizienten herstellt. Ziel der vorliegenden Arbeit ist zum einen die Entwicklung eines flexiblen, breit anwendbaren und gleichzeitig nicht auf den gegenwärtigen Stand der Transporttheorie beschränkten Materialmodells. Dessen Grenzen und Möglichkeiten sollen zum anderen auf der Grundlage spezieller instationärer Feuchteprofilmessungen anhand von vier Baustoffen untersucht und aufgezeigt werden.

Ausgangspunkt der Arbeit ist eine ausführliche Beleuchtung sowohl der vorhandenen Modellansätze als auch der zur Verfügung stehenden experimentellen Methoden zur Bestimmung hygrothermischer Basisparameter. Auf dieser Grundlage wird die Materialmodellierung in den Kontext der aus der Thermodynamik abgeleiteten Wärme- und Feuchtetransporttheorie eingeordnet. Die damit verbundenen Grenzen und Einschränkungen werden hervorgehoben und Entwicklungsmöglichkeiten sowie weiterer Entwicklungsbedarf aufgezeigt. Dieser umfasst drei Bereiche: die Experimente zur Bestimmung von Basisparametern, die Materialmodellierung, sowie Experimente zur Modellvalidierung.

Die Reihe der Basisexperimente wird um den Trocknungsversuch unter definierten Bedingungen erweitert. Die verschiedenen Einflüsse auf die Trocknung und deren Anwendung in der Kalibrierung hygrothermischer Materialmodellierung werden herausgestellt und bewertet. Darauf aufbauend wird eine Apparatur entworfen, gebaut und angewendet. Schließlich werden Kriterien zur Standardisierung und Ableitung eines Einzahlenkennwertes evaluiert. Sinnvolle Erweiterungen werden aufgezeigt.

Es wird ein eigenes Materialmodell auf der Grundlage eines Porenbündelansatzes hergeleitet, welches mit einem mechanistischen Ansatz gekoppelt wird, der den Feuchtetransport in seriell und parallel strukturierte Bereiche untergliedert. Die abgeleitete Flüssigwasserleitfähigkeit wird anhand von Leitfähigkeitsmessdaten im nahe gesättigten sowie im hygroskopischen Feuchtebereich justiert. Zwei interne Modellparameter werden anschließend unter Berücksichtigung der Hysterese der Feuchtespeicherung anhand des Aufsaug- und des Trocknungsversuches kalibriert.

Das Materialmodell ist zur Erleichterung der Anwendung in ein Computerprogramm zur Anpassung an die Labordaten implementiert worden. Das Programm wird auf die vier Baustoffe Ziegel, Kalksandstein, Porenbeton und Calciumsilikat angewendet. Die entsprechend angepassten Materialfunktionen werden gezeigt und diskutiert. Im Rahmen der Kalibrierung wird eine hervorragende Übereinstimmung zwischen gemessenem und berechnetem Materialverhalten erreicht.

Zur Modellvalidierung wird die Augenblicksprofilmethode (IPM) für die bauphysikalische Anwendung erweitert. Spezielle Apparaturen werden entwickelt und Versuchsabläufe entworfen. Modelle zur Ableitung des Wassergehaltes aus mit Hilfe der Time Domain Reflectometry (TDR) gewonnenen Dielektrizitätsmessdaten werden evaluiert und implementiert. Schließlich wird ein umfangreiches Programm an Feuchteprofilmessungen im hygroskopischen und überhygroskopischen Feuchtebereich umgesetzt und ausgewertet.

Im Rahmen der Validierung werden die Entwicklungen auf experimenteller sowie auf Modellierungsebene zusammengeführt. Die IPM Experimente werden anhand der gemessenen Anfangs- und Randbedingungen und auf der Grundlage der angepassten und kalibrierten Materialfunktionen nachgerechnet. Der Vergleich zwischen Messung und Rechnung offenbart die Stärke der entwickelten Materialmodellierung ebenso, wie den Einfluss der auf Ebene der Transporttheorie getroffenen Vereinfachungen. Ein deutlicher Einfluss der sich aus der Prozessgeschichte sowie der Prozessdynamik zusammensetzenden Hysterese der Feuchtespeicherung kann nachgewiesen werden.

Mit der vorliegenden Arbeit ist somit nicht nur die Materialmodellierung entscheidend weiterentwickelt, die Reihe der einfachen Basisexperimente um einen wesentlichen Versuch erweitert und die Augenblicksprofilmethode für bauphysikalische Belange anwendbar gemacht worden, es wurden auch die Einflüsse der Prozessgeschichte, und erstmals auch der Prozessdynamik, auf den Feuchtetransport sowie die sich einstellenden Feuchteprofile deutlich aufgezeigt und nachgewiesen. Es ist demnach nicht nur ein Materialmodell, welches den gestellten Anforderungen an Flexibilität, breite Anwendbarkeit und Erweiterbarkeit genügt, entwickelt worden, es wird mit den gewonnenen Messdaten auch die Grundlage weiterer Forschung zur Verfügung gestellt.

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