

Aml-based control of ventilation and air conditioning systems and exemplary application to the phenomenon of "dry air"

W. Kozak, D. Stein, C. Felsmann, B. Hensel, K. Kabitzsch, M. Rösler

**Research
Project F 2299**

W. Kozak
D. Stein
C. Felsmann
B. Hensel
K. Kabitzsch
M. Rösler

**Aml-based control of ventilation and air
conditioning systems and exemplary
application to the phenomenon of “dry air”**

Dortmund/Berlin/Dresden 2015

This publication is an interim report of the project 'Chances and limitations of Aml-based control of ventilation and air conditioning systems and exemplary application to the phenomenon of "dry air"' – Project F 2299 – on behalf of the Federal Institute for Occupational Safety and Health.

The responsibility for the contents of this publication lies with the authors.

Authors: Dipl.-Ing. Wojciech Kozak
Prof. Dr.-Ing. Clemens Felsmann
Dr.-Ing. Markus Rösler
Technische Universität Dresden, Institut für Energietechnik
01062 Dresden, Germany

Dipl.-Inf. Denis Stein
Dipl.-Ing. Burkhard Hensel
Prof. Dr.-Ing. habil. Klaus Kabitzsch
Technische Universität Dresden, Institut für Angewandte Informatik
01062 Dresden, Germany

Project monitoring: Dr.-Ing. Kersten Bux
Federal Institute for Occupational Safety and Health

Cover picture: Dr.-Ing. Ralf Gritzki
Technische Universität Dresden

Cover design: Susanne Graul
Federal Institute for Occupational Safety and Health

Publisher: Federal Institute for Occupational Safety and Health
Friedrich-Henkel-Weg 1-25, 44149 Dortmund, Germany
Telephone +49 231 9071-0
Fax +49 231 9071-2454
poststelle@baua.bund.de
www.baua.de

Berlin:
Nöldnerstr. 40-42, 10317 Berlin, Germany
Telephone +49 30 51548-0
Fax +49 30 51548-4170

Dresden:
Fabricestr. 8, 01099 Dresden, Germany
Telephone +49 351 5639-50
Fax +49 351 5639-5210



All rights reserved, including photomechanical reproduction and the reprinting of extracts.

www.baua.de/dok/5756256

Contents

	Page
Abstract	5
Kurzreferat	6
1 Introductory remarks	7
2 Control engineering relationships and development of an Aml-platform concept	8
3 The limits of the conventional climate control	10
4 Modelling of human body and dummy measurements of the evaporation rate of human skin	12
5 Detailed building and air flow simulation	16
6 Concluding remarks	19
References	20

Aml-based control of ventilation and air conditioning systems and exemplary application to the phenomenon of “dry air”

Abstract

This interim report covers all activities of the research project: Chances and limitations of Aml-based control of ventilation and air conditioning systems and exemplary application to the phenomenon of “dry air”. At first, an analysis of the kind of the contributions necessary to achieve a representative picture of the research topic at hand had been carried out. For this purpose, the measurable properties of the skin have been discussed and the state of the art of Aml (Ambient Intelligence) specified. The control of HVAC systems and visions of Aml control have also been thoroughly analyzed.

In addition to the requirements of an Aml-based humidity control the report specifically focuses on measurements of evaporation from the skin, that have been conducted on the specially designed test specimen in a dedicated test facility. These experiments were necessary because the data found during the comprehensive literature review did not account for the variation of the room air parameters. The measurements produced the matrix of the evaporation rates as a function of the local climatic conditions.

Furthermore, a building simulation program has been extended to take the human skin evaporation into account and used to carry out the needed calculations. Preliminary results have shown the indoor air quality and humidity calculated with the single node model. In the next stage this simplified model has been coupled with a detailed field model for flow simulation in order to account the air flow influence. The resulting virtual office has combined detailed air flow analysis with the thermal and hygrical simulation and the results of the evaporation experiments. This set up been able to show that the flow in the room significantly affects the evaporation from the skin. The high expense of such calculations, however, significantly limits the number of calculations that can be carried out for the purpose of this study. The presented results offer valuable insights into the relationships between the heating and ventilation system and local climate in the vicinity of persons and provide important stimuli for the further development of Aml for HAVC systems but cannot and do not claim to represent the complete picture of the researched topic.

Key words:

Aml-based control, HVAC systems, dry air, relative humidity, moisture skin, eye blink frequency, humans, building simulation, localization, identification, indoor air flow, computational fluid dynamics (CFD)

Aml-basierte Regelung von Klimaanlage und Anwendung auf das Phänomen der „Trockenen Luft“

Kurzreferat

Dieser Zwischenbericht fasst die Aktivitäten im Forschungsprojekt »Möglichkeiten und Grenzen einer Aml-basierten Regelung raumluftechnischer Anlagen und beispielhafte Anwendung auf das Phänomen „Trockene Luft“« zusammen. Zu Beginn stellt der Bericht verschiedene Aspekte gegenüber, um Beiträge zu ermitteln, die notwendig sind, um das Forschungsthema repräsentativ darzustellen. Vor diesem Hintergrund werden die messbaren Eigenschaften der Haut diskutiert und der Entwicklungsstand im Bereich Aml (Ambient Intelligence) aufgezeigt. Betrachtungen zur Regelung von RLT-Anlagen und Visionen einer Aml-Regelung schließen daran an.

Messungen zur Verdunstung an der Haut, nachempfunden durch speziell entworfene Probekörper und eine zugehörige Versuchseinrichtung, bilden einen weiteren Schwerpunkt des Berichtes. Diese Versuche waren notwendig, da die international recherchierte Datenlage keine gesicherten Erkenntnisse und Abhängigkeiten von raumluftechnischen Parametern zuließ. Als Ergebnis liegt eine Matrix zur Verdunstungsrate in Abhängigkeit der raumklimatischen Bedingungen vor.

Die Wirkungen von Lüftungssystemen wurden mit einem gezielt für die Aufgabenstellung weiterentwickelten Programm zur Gebäude- und Anlagensimulation berechnet. Die gewonnenen Daten zur raumklimatischen Situation wurden zunächst mit Hilfe eines Knoten- oder auch Zonenmodells dargestellt und dann mit einem detaillierten Feldmodell zur Strömungssimulation gekoppelt. Hier fließen Mess- und Berechnungsergebnisse in einem virtuellen Büro zusammen, die zeigen, dass die Strömung im Raum die Verdunstung an der Haut deutlich beeinflusst. Der Aufwand derartiger Berechnungen schränkt allerdings die wünschenswerte Variantenvielfalt deutlich ein. Die im Ergebnis aufgezeigten Zusammenhänge zwischen Heizungs- und Lüftungssystem und lokalem Klima im Nahbereich von Personen geben daher weitere wichtige Anregungen zum Einsatz von Aml in der Klimatechnik, ohne jedoch einen Anspruch auf Vollständigkeit zu erheben.

Schlagwörter:

Aml-basierte Regelung, RLT-Anlagen, trockene Luft, relative Luftfeuchte, Hautfeuchtigkeit, Lidschlagfrequenz, Personenmodelle, Gebäudesimulation, Lokalisierung, Identifizierung, Raumlufströmung, Strömungssimulation (CFD)

1 Introductory remarks

There is a huge body of scientific evidence and a great deal of experience concerning the optimization of the indoor climate. Its aim is to make the indoor climate comfortable and beneficial for the health of room's occupants. This has to happen without any adverse effects for the security and health of the users. The ventilation and air conditioning appliances running in a suboptimal manner can potentially result not only in dissatisfied users but sometimes even erode their health. Both the satisfaction and healthy use must be secured by the HVAC system. If only the complex relationship between the way of operation of the HVAC system, the resulting indoor climate and the possible adverse effects for the health of the occupants for example these caused by the "dry air" are known, the control system using the ambient intelligence will actively prevent the health damage. Ambient Intelligence (Aml) embodies the „intelligent ambience“ that reacts in a sensitive und adaptive manner to the presence of people and objects and simultaneously serves the needs of the users. Its application is a possible and feasible solution for people in almost all daily routines of life.

In the winter the employees are often complaining about the too dry air and the health complaints related to it such as skin problems, eye irritation and electrostatic discharges. The blame for those problems is often attributed to poorly functioning HVAC systems. The dry air and its influence on the comfort and health is a controversial topic among the experts. Numerous studies speak out for and against the possible consequences of the low relative air humidity (Hahn 2007). This is to be expected as not only the relative humidity but also other physical factors such as temperature, velocity and turbulence intensity of the air acting in concert are responsible for the rate of water evaporation from the human skin. The interconnection of these parameters in their influence on the evaporation together with the subjective character of the evaluation of their influence on the test subjects may make the studies that analyze only one physical parameter, i. e. relative humidity extremely prone to the erroneous interpretations of the results. Various studies reaffirm the need for the joint examination of the above mentioned physical parameters (Zeidler et al. 1999, Reske 2002). If results of such an analysis were available to the Aml based control system, it could act appropriately in order to minimize the negative effects of dry air on human beings or to eliminate them altogether. The current situation in the field of the office ventilation can be characterized by the two opposing tendencies. On the one hand there are the HVAC systems that are capable of providing every desired thermal environment that sometimes fall short of the expectations because of the operation mode focused on the commercial considerations or because of the problems with the air distribution in the system. On the other hand there are offices furnished only with the hydronic heating systems that during the wintertime are ventilated with the outside air, mostly delivered by tilting the windows. The latter systems by definition generate very low air humidities in the office rooms and remain the unsolved problem in the field of ventilation that is being vigorously discussed in the HVAC community. The above considerations make it obvious that the conditions in the offices could be locally improved by means of the Aml controlled systems. In order to attain this goal the intertwining influences of the air temperature, velocity and turbulence on the evaporation from the human skin have to be elucidated and the possibility that the velocity and turbulence of air may affect evaporation to a similar extent as its temperature and relative humidity has to be examined in detail.

2 Control engineering relationships and development of an Aml-platform concept

The use of personalized Aml control system takes for granted that the system has the means to localize and recognize the user and to match to him his saved preferences of the ventilation air. In the offices it is sufficient to recognize the presence of the user at his fixed workplace, i. e. the desk for the Aml system to work. The user's reaction to the indoor air can be determined with the help of the skin humidity sensors or through the measurement of user's blink rate by the dedicated measurement system. The contemporary technology provides the ambient sensors that carry out the measurements of skin humidity and blink frequency. The application of the ambient personalized system, that would shape the indoor climate at the workplace and by that reduce the health risk, requires the following elements:

1. sensors for
 - a. acquisition of the parameters of the indoor climate (amongst others temperature and relative humidity)
 - b. localisation of the user
 - c. identification of the user
 - d. ascertaining the well-being of the user (optional)
2. actors for the local manipulation of the climate
3. flexible processing platform for control purposes.

Aml-system requires significantly more sensors than usual in the conventionally out-fitted office. They are needed to make the localised and personalized indoor climate shaping possible. Working with many only temporarily available sensors such as temperature sensors in the smartphones poses high requirements on the dynamical processing platform. In order to use it to shape the indoor climate according to the needs of the users and save them from complicated analysis of their environment, better control strategies are needed. This leaves the developer with no other choice but model based predictive control that has the following advantages over conventional solutions:

1. reduction of the number of sensors
2. improvement of the control quality
3. problem free dealing with multidimensional systems
4. flexible reaction to the failure of sensors and actors

The approach to the localisation of people in the buildings is a good example of the demands made on the platform. Tracking of people in time and space is not necessary to provide personalized climate at the workplace. The knowledge of the localisation of the fixed workplace, for example the desk is sufficient. The use of mobile devices besides the sensors that are already present in the building seems very promising. The proliferation and acceptance of smartphones are growing. Their use incurs almost no further costs. They are also applicable in the "undeveloped" buildings with scarce Aml-infrastructure. However, the data won from these appliances are not of the highest quality and the appliance is only temporarily available as a sensor. The

localisation and identification of the user is still possible when using such poor quality and partly redundant data as long as appropriate software is being used.

An overview of the possible architecture of the generic Aml-platform that fulfils the desired criteria is given in the Figure 2.1.

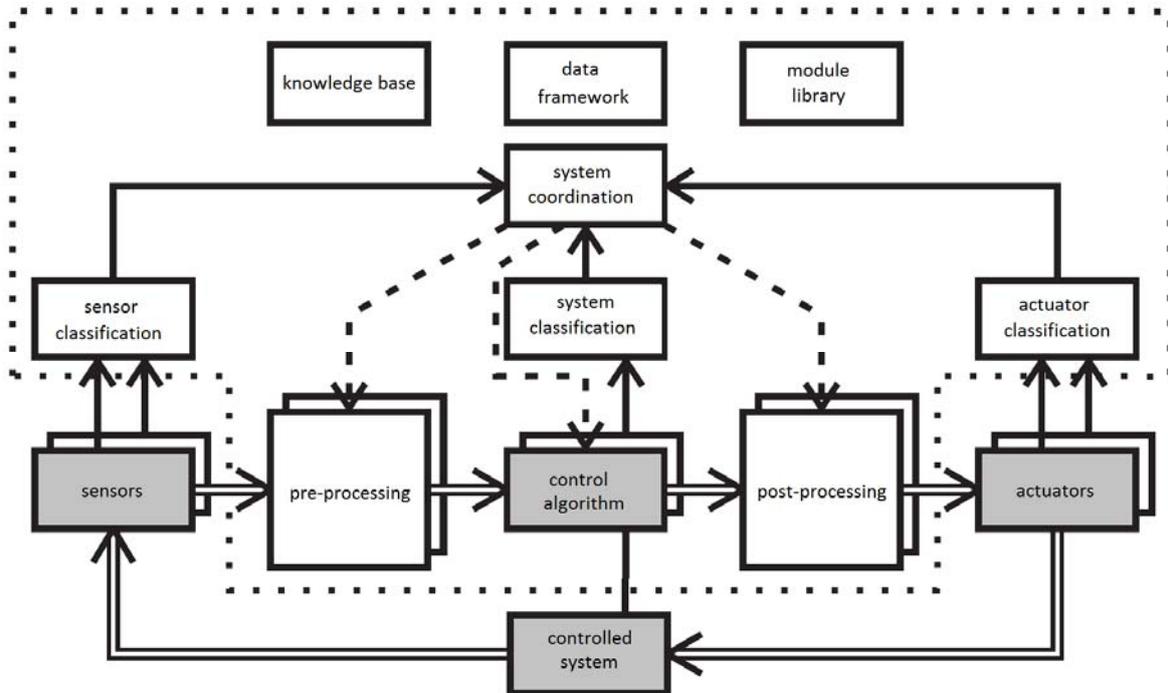


Fig. 2.1 Main components of visionary, modular Aml-platform concept
(Source: STEIN et al. 2012)

Unlike the conventional control systems, it uses the available sensors and actors by dynamically integrating them in real time. The selection of the applicable elements can be conducted by the model coordinator (box “system coordination” in Fig. 2.1) during runtime. Even the best personalized climate control strategy is futile if there is no adequate information from sensors on presence and identity of the user or when the actor in an open plan office is a lone radiator instead of the series of individual air inlets. The coordinator processes the outputs of the sensors’, controllers’ and actuators’ classifiers (“classification” boxes). The used classification that is based upon an ontological model (BASont (PLOENNIGS et al. 2012); box “knowledge base”) is being applied to sensors as an example. Other possible components are a data framework that saves current and historical data in order to pre- and postprocess them, and a module repository (box “module library”) that contains default control algorithms.

3 The limits of the conventional climate control

The phenomenon of the dry air occurs in the heating period with various intensity depending on the boundary conditions of the ventilated space and the mode of operation of the HVAC system. In order to estimate its severity extensive model calculations by a one node model have been carried out. The exemplary room with length, breadth and height of 6,0 m x 5,0 m x 3,0 m without possibility of air humidification has been modelled using various air exchange rates recommended in DIN EN 13779 Table A.11, that is for 5, 10 und 20 l/(s · person) under assumption that two people are present in the room. These values result in air changes of 0,4/h, 0,8/h and 1,6/h respectively. The results have been presented in Fig. 3.1 and 3.2. Fig. 3.1 shows, that the relative air humidity decreases with rising rate of the ambient air volume per person and no air humidification in the HVAC-installation. In this context, the aggregated frequency read for the volume rate of 20 l / (s · person) and 30 % of relative humidity is 38 %. That means that for the 38 % of the time that people are present the relative humidity in the room ventilated with 20 l / (s · person) is equal or lower than 30 % r. h. Keeping relative humidity above the recommended threshold of 30 % requires the reduction of the air flow rate. When the ventilation rate is 5 l / (s · person) the relative humidity never falls below the 30 % r. h. threshold. The Fig. 3.2 reveals on the other hand, that keeping the relative air humidity above the threshold of 30 % in such a room by reducing the ventilation rate results in a degradation of the indoor air quality. The systems with ambient air flow rate of 20 l/(s · person) boast of the highest class of the indoor air quality (IDA 1 according to DIN EN 13779, see Fig. 3.2) during whole usage time while these with flow rate of 5 l / (s · person) attain that standard only for the 12 % of the usage time and so always land in the poor air quality categories IDA 2 and IDA 3. In the wintertime one has either to install some humidification device or choose between a good air quality (i. e. low CO₂ concentration) combined with low relative humidity (below 30 % r. h.) and poor air quality combined with beneficial, higher relative humidity (above 30 % r. h.).

This assessment is based, as the underlying calculations, on the model of ideal mixing, that means, there is only a single set of air condition parameters for the whole room. Because of this approximation the situation is investigated step by step in more detail in the following sections.

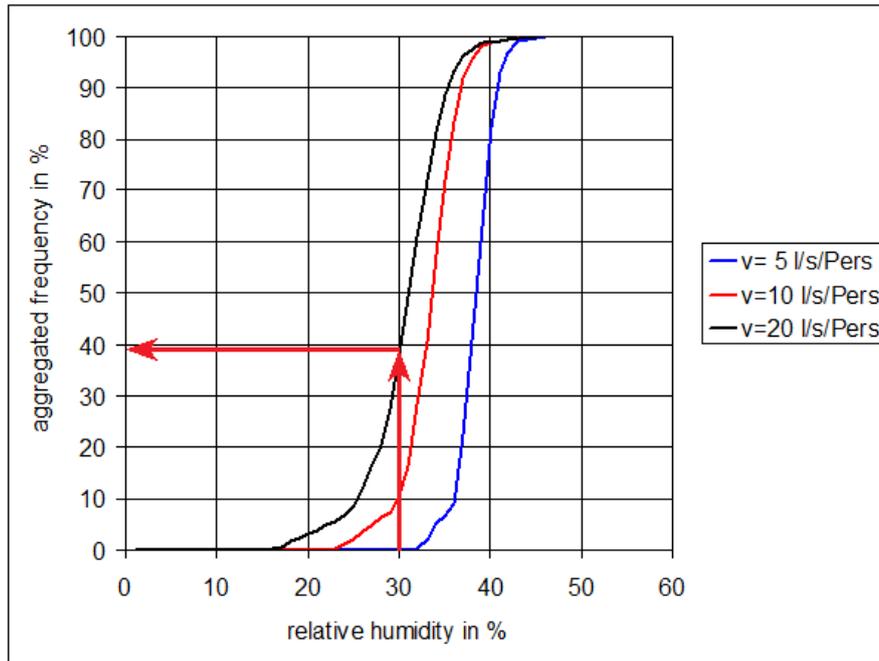


Fig. 3.1 Aggregated frequency of occurrence of the relative humidity in the investigated room in the heating period during occupation for various rates of ambient air flow per person and two people in the room

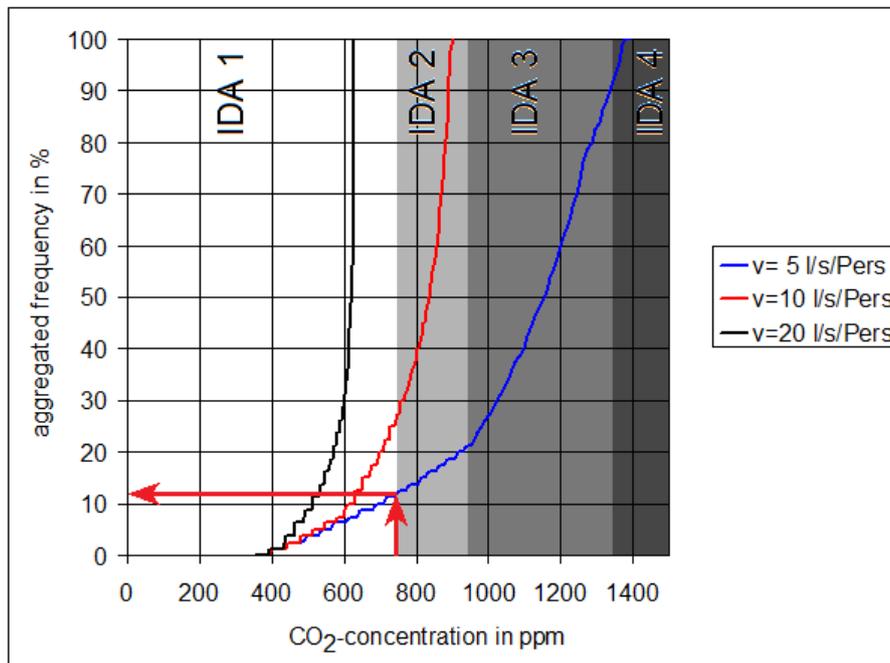


Fig. 3.2 Aggregated frequency of occurrence of the CO₂-concentration in the investigated room in the heating period during occupation for various rates of ambient air flow per person and two people in the room as well as their classification in air quality categories according to DIN EN 13779

4 Modelling of human body and dummy measurements of the evaporation rate of human skin

The ways in which the dry air influences the human body are so various and intertwining that their analysis is only possible by using a computational model comprising of validated part models. In that particular case the temperatures of the surfaces of the human body have been calculated as a mean value of the data measured on 7 subjects (see Fig. 4.1). The model of the human body is then coupled to the building simulation and computational fluid dynamics programs. Such coupling allows to find out the interdependence of the HVAC concept with the conditions at the close proximity of people occupying the room, that in turn are decisive for their thermal and hygroscopic comfort.

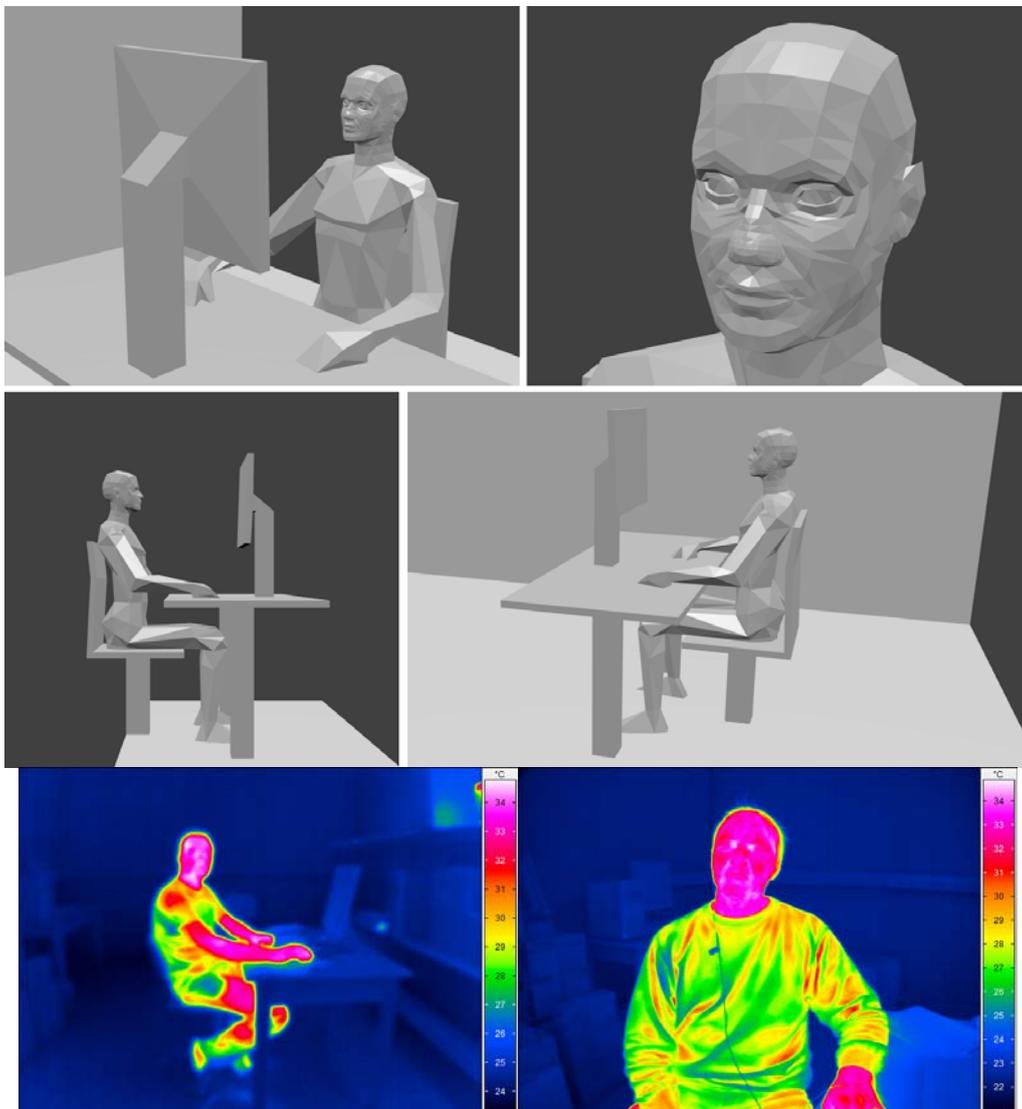


Fig. 4.1 Detailed model of the human body and the temperatures of the body surfaces recorded by means of an infrared camera on one of the subjects

The anticipated evaporation rates at the parts of the human body are not fully known. The data found in the literature have not taken the influence of the state of the air surrounding the subjects into account. Such correlation had to be found by two months long experiments that have been conducted in the ventilation laboratory of BAuA in Dortmund, see Fig. 4.2. The results are given in the Fig. 4.3. They show a clear and strong correlation between the evaporation rate and the temperature, relative humidity, velocity and turbulence intensity of the air surrounding the probe.



Fig. 4.2 Tested specimen and the instrumentation for measurement of the evaporation rate and its dependence on the air parameters in the climate test chamber

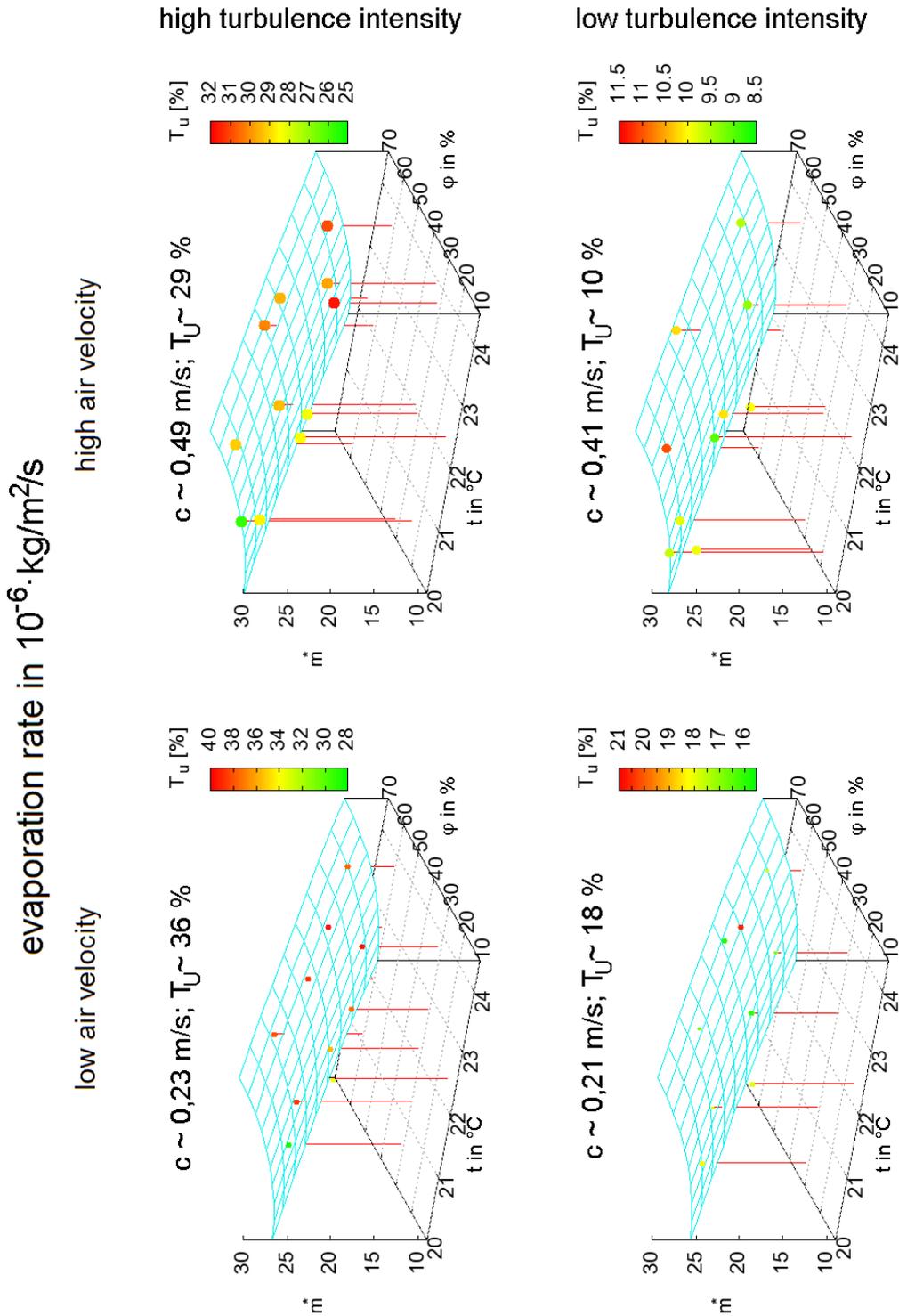


Fig. 4.3 Measured evaporation rate and its approximation with the function defined by equation 4.1. The size of the data points reflects the velocity of the air surrounding the probe. The four diagrams cover four zones of various velocities and turbulence intensities of the air. The values of velocity and turbulence intensity of air reflect the average values calculated for each of the given diagrams.

This correlation could also be expressed in form of the approximation function

$$\dot{m} = b_0 + b_1 \cdot t + b_2 \cdot \varphi + b_3 \cdot c + b_4 \cdot T_u + b_5 \cdot t^2 + b_6 \cdot \varphi^2 \quad (4.1)$$

that has been applied to further calculations.

The main conclusion to be drawn from the measurement data are the influences of the temperature and relative humidity on the one side and of the velocity and turbulence of the air on the other side on the total evaporation rate. The results make it clear that the influence of relative humidity is almost three times higher than the one of velocity and turbulence intensity. In other words, the influence of the room air flow on the evaporation rate constitutes within the investigated range around 30 % of the evaporation caused by the temperature and relative humidity gradients. The absolute values are higher than in studies with human subjects. The study of Mayrovitz et al. conducted on human subjects has yielded evaporation rates around $4 \cdot 10^{-6} \cdot \text{kg/m}^2/\text{s}$ whereas the probe measurements carried out with dummies in comparable ambient conditions have given a value of $16 \cdot 10^{-6} \cdot \text{kg/m}^2/\text{s}$, i.e. a four times higher evaporation rate.

5 Detailed building and air flow simulation

The numeric simulation allows an examination of various ventilation regimes and the analysis of their influence on the human comfort. For the aim of such simulations a representative office room has been chosen and the calculations have been carried out.

The simulations using a simple one node model (unable to take the room air flow and its temporal variance into account) have shown that achieving the high air quality and maintaining a relative humidity in the room above 30 % are not sustainable during the heating period (also see [chapter 3](#)). These results refer to a case of ideal mixing in the investigated room. In order to conduct calculations with the more realistic assumptions concerning the air flow in the room a CFD (Computational Fluid Dynamics) model has been developed that makes it possible to predict the local conditions and therefore the thermal comfort at the workplace. The last missing pieces of information needed for the model to work were the unknown evaporation rates of the skin and eyes of the people present in the room. They have been determined during the above mentioned experiments. In order to validate and classify the results of the experiments, surveys of literature on the transepidermal water loss in absence of sweating and on ocular evaporation have been carried out. The found data have been integrated into the simulation program. As expected, the ocular evaporation turned out to be insignificant for the whole water balance of a person and has no tangible effect on the predicted air flow and comfort.

A detailed analysis of indoor air conditions is possible by means of the coupling of a building simulation program with a CFD code and geometrical and physical models of a person staying in the room. Together they form a coherent and consistent model of heat and mass transfer between the person and its environment that allows a detailed examination of the interaction between the person and its office environment. Eventually the conducted calculations have focused on the comparison of two rooms with the same thermal and moisture loads that are conditioned by means of two different ventilation concepts that should reflect the conditions found in mixing and displacement ventilation regimes:

1. with floor heating and the fresh air being delivered by an air inlet slit in the outside wall located under the window (see Fig. 5.1 left)
2. with an air heating system delivering both reheated exhaust air and fresh one through the swirl diffuser located in the ceiling (see Fig. 5.1 right).

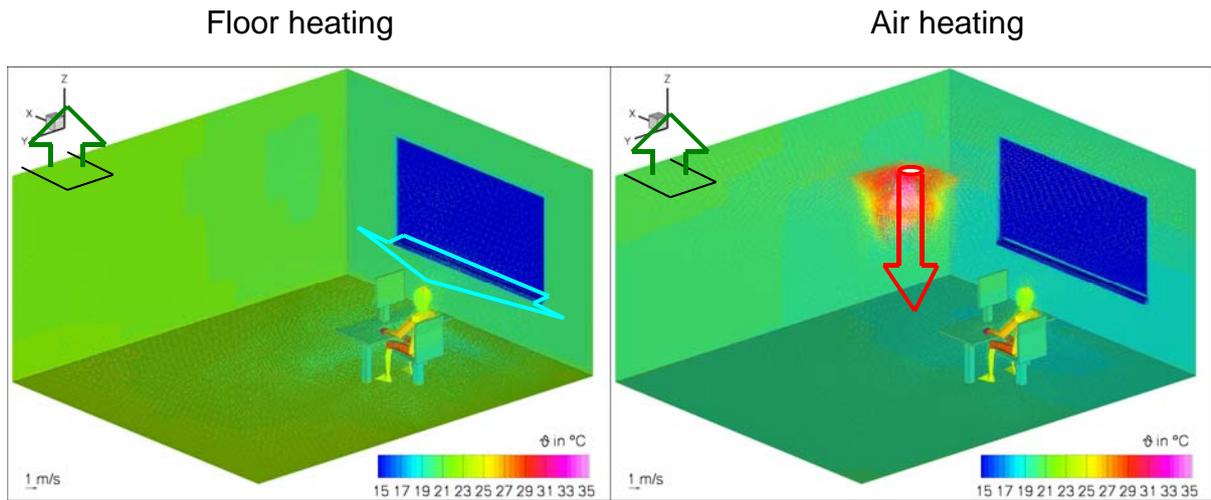


Fig. 5.1 The view of air flow and surface temperatures in the two analysed heating and ventilation systems. To the left: the floor heating with an outside air inlet located below the window; to the right: air heating with a swirl diffuser located in the ceiling.

The results of analysis have shown that provided the portability of the dummy experiments on the evaporation behaviour on the human skin, the different regimes of ventilation will result in differing properties of the air at the parts of the body of investigated person (see Fig. 5.2).

The results confirm the conclusions of earlier studies although the stated differences are smaller than in the literature. The earlier works of ZEIDLER et al. (1999) and RESKE (2002) indicate that the differences between mixing and displacement ventilation can lead to much higher differences of velocity and turbulence at the human body than it has been shown in the two calculated examples. That can result in bigger differences of the evaporation rate and different perception of the dryness of the air. The smaller magnitude with which this phenomenon is reflected in the simulation can be partially explained by the fact that in the wintertime conditions, the investigated HVAC systems do not fully represent the typical mixing and displacement ventilation systems. In addition, there are relative small thermal loads in the room.

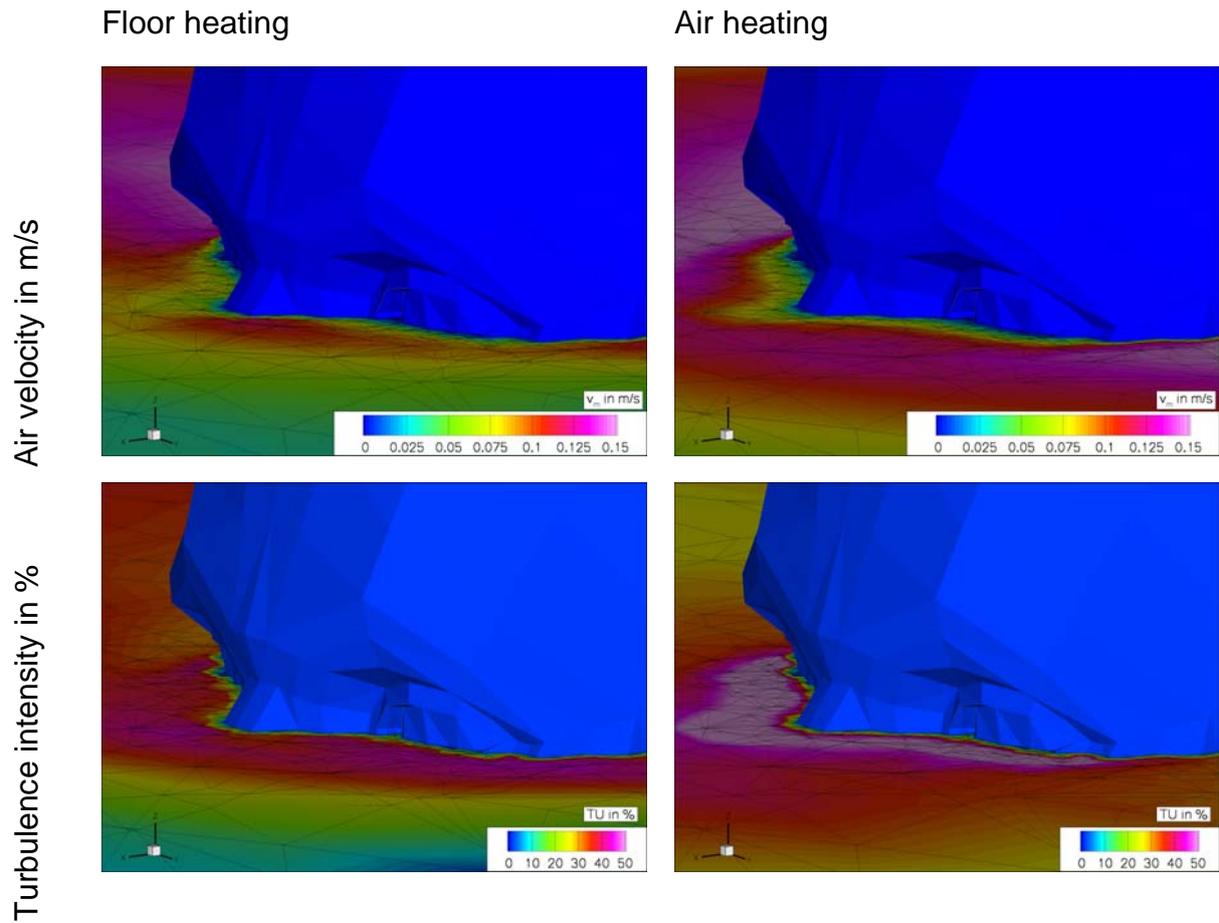


Fig. 5.2 Slices of velocity and turbulence intensity of the indoor air close to the head of the investigated person in the two analysed heating and ventilation systems on a cold winter day

6 Concluding remarks

The following statements can be used to summarize the findings of the study:

1. There is no complete Aml-based solution for control of the HVAC-systems.
2. There are sensors and components needed for construction of an Aml-based control system of a HVAC-facility. A proposal for architecture of such a system has been developed and presented. This proposal represents an innovative and visionary solution, commissioning of which would require further development work.
3. The evaporation rate of skin depends not only on temperature and relative humidity of the surrounding air but also on its velocity and turbulence intensity. This correlation has been established experimentally and quantified.
4. The exemplary calculations have shown that the air flow regime and ventilation type result in differing air parameters close to the surfaces of the investigated human body. It confirms the results of the earlier works and establishes the significant influence of the room air flow on the occurrence of the dry air phenomenon.
5. The validity of the probe measurements has to be verified by experiments involving human subjects.
6. In order to give practical recommendations concerning the elimination of the dry air phenomenon further calculations using the fine models of the person and possibly more differing configurations of heating and ventilation systems are needed.

References

von Hahn, N.: „Trockene Luft“ und ihre Auswirkungen auf die Gesundheit – Ergebnisse einer Literaturstudie, Gefahrstoffe – Reinhaltung der Luft, 67 (2007) Nr. 3 – März, S. 103 ff

Mayrovitz, Harvey N.; Bernal, Maria; Brlit, Frances; Desfor, Rebecca: Biophysical measures of skin tissue water: variations within and among anatomical sites and correlations between measures, Skin Research and Technology 2013, **19**: pp. 47–54f.

Ploennigs, J.; Hensel, B.; Dibowski, H; Kabitzsch, K.: BASont - A modular, adaptive Building Automation System Ontology, in Proceedings of the 38th Annual Conference of the IEEE Industrial Electronics Society (IECON 2012), Montréal, Canada, October 2012

Reske, M.: Einfluss der Raumströmung auf die lokale Feuchtigkeitsabgabe am Auge, Konferenzband Hermann-Rietschel-Colloquium 2002, S.179-188, Buderus-Heiztechnik 2002.

Stein, D.; Lehmann, M.; Ploennigs, J.; Kabitzsch, K.: Sensors, models and platform for ambient control, in IECON - 38th Annual Conference of the IEEE Industrial Electronics Society, 2012

Zeidler, O.; Kriegel, K.; Fitzner, K.: Unterschiede der Feuchtigkeitsübertragung einer Person in Quell- und Mischlüftung, KI Luft- und Kältetechnik, Jun 1999; No.6, pp.319-323

DIN EN 13779: DIN Deutsches Institut für Normung e.V. Lüftung von Nichtwohngebäuden – Allgemeine Grundlagen und Anforderungen für Lüftungs- und Klimaanlage und Raumkühlsysteme, September 2007