INFLUENCE OF SENSOR POSITION IN BUILDING THERMAL CONTROL: DEVELOPMENT AND VALIDATION OF AN ADAPTED ZONE MODEL

P. Riederer*, D. Marchio**, J. C. Visier*, A. Husaunndee*, R. Lahrech*

* Centre Scientifique et Technique du Bâtiment, 84, Avenue Jean Jaurès, 77421 Marne la Vallée Cedex 2, France
** Ecole des Mines de Paris – Centre Energétique, 60, Boulevard St. Michel, 75272 Paris Cedex 06, France

ABSTRACT

This paper presents the development of a zone model adapted to the study of the influence of the sensor position in building thermal control.

The temperature measured by the sensor of a room temperature controller depends on its position in the zone. The measured sensor temperature depends of the convective coupling of the zone and its emitter and can differ from the "mean air temperature". Models, currently used for control studies, are either too simplified (well-mixed models) or are not generic enough to provide a flexible and usable testing tool for room controllers.

The important phenomena, to be represented in the model, are analysed experimentally and by detailed simulation. From this analysis, a detailed list of criteria for the development of zone models is obtained. The criteria are used to develop a new model.

The proposed model is able to distinguish between air temperature and sensor temperature with time variation depending on air movements. An application for a zone conditioned by a fan coil unit illustrates the model. Validations of the model are carried out in a real test room.

INTRODUCTION

The aim of this study is the development of zone models that shall be implemented in a toolbox of dynamic models of HVAC components ([Hus97]).

Zone models exist with different levels of complexity: from simple "well mixed" models with one air node representing the whole air volume in the room to complex computational fluid dynamic (CFD) models solving the equations of conservation of mass, momentum and energy. The aim is to find a model that is adapted to the problems studied. The model should unite simplicity on the parameter level and a correct description of the internal zone conditions that are important for control studies. The model must be valid for different room sizes and room types (e.g. heavy/light inertia).

Controllers are tested either by simulation or by emulation (real controller). On the test bench, the link between room temperature(s) and controller as well as the data used for the assessment of controller performance is not clearly defined (Figure 1).

Either the occupant or the sensor can be at different positions in the zone. Depending on the emitter used and the position of the sensor, there can be important temperature differences between the air in the occupant area and the air at the sensor of a controller.

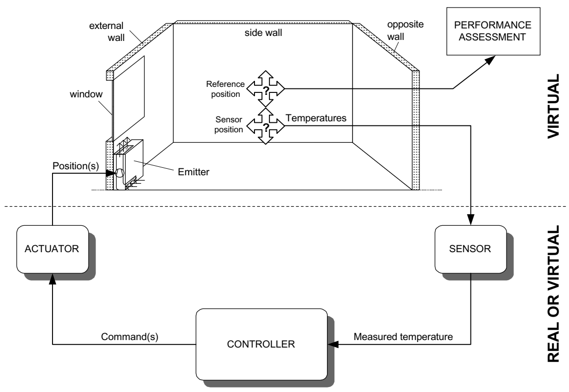

Figure 1: Scheme of a test bench for terminal controllers (simulation / emulation)

Three main aspects have thus to be considered for the model development [Rie01]. The zone model has:

- to be adapted to the test of controllers (modularity, flexibility, parametering, simplicity)
- to provide the necessary data for the assessment of the conditions in the zone
- to provide the necessary data for the link with the sensor of a controller

In [Rie00], simple zone models have been tested for the use in control applications. These models were a well-mixed model and a second model with only two air sub volumes. The applicability of these models for controller tests has been shown. However three main problems appeared while using these models:

- the difference between centre and sensor temperature
- the validity of the models in cases with varying emitter loads
- the sensor characterisation

In this paper, a more detailed model is presented taking into account the mentioned criteria.

PHENOMENA IN A ROOM AND AROUND THE SENSOR OF A CONTROLLER

The phenomena important for controller studies can be divided into two parts, sensor phenomena and zone phenomena.

- **Sensor phenomena**

A zone model adapted to the study of control systems has to provide all necessary information for the model of controller (including sensor). It is thus important to have a clear understanding of the physical quantities measured by the controller sensor in order to model all phenomena necessary for the controller.

The measurement depends on the heat exchanged by convection, conduction and radiation between the sensor and its environment. The partition of the heat exchanges depends on the position of the sensor box, the type of sensor or the position of the sensor in the sensor box. The importance of a correct modelling of convective phenomena in the room can thus not be neglected.

The conductive and the radiative parts depend mainly on the modelling of the wall structure of the zone (which depends again on the modelling of the convective phenomena). The convective phenomena rely mainly on the modelling of the room air.

- **General zone phenomena**

The error while modelling radiative and conductive phenomena is reduced by increasing the grid number in the wall. Nevertheless the precision of the wall modelling must be comparable to that of the internal air volume. The modelling of convective phenomena (zone air) depends on the convective coupling of the emitter and the room air. These phenomena can vary strongly from one emitter to another and even for different emitter loads. The main concern in the following study of zone phenomena will thus be the convective phenomena.

Convective phenomena are mainly:

- Plumes (free plumes and wall plumes)
- Wall jets (free or mixed convection)
- Jets (horizontal and vertical, iso- and anisotherm)

In a separate study, the convective phenomena in a zone, equipped with different heating or cooling systems, were analysed ([Rie01], [Rie00]) for the following systems:

- Radiator and convector
- Fan coil unit (heating and cooling)
- Ceiling (heating and cooling)
- VAV system (heating and cooling)

The study was divided into two parts: observation of characteristic airflow patterns in the room and measurements of the internal room temperatures. Figure 2 and Figure 3 show as an example the airflow pattern for heating systems and for a fan coil unit (cooling mode).

The main attention in the observation of airflow pattern was paid to the airflow at the internal walls, where the controller sensor is placed.

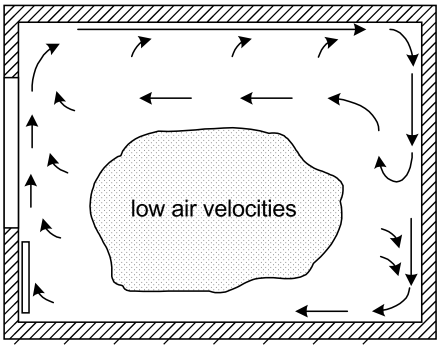

Figure 2: Observed airflow pattern in a room equipped with radiator, convector or fan coil unit (cooling case)

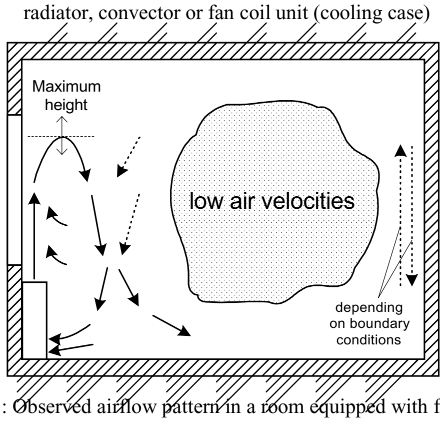

Figure 3: Observed airflow pattern in a room equipped with fan coil unit (heating case)

- **Convective phenomena at the internal walls**

The airflow near the internal walls is observed to be either a phenomenon of free or of mixed convection. There exist two principal cases:

Case 1: Heated or cooled air arrives at ceiling or floor of the zone and is, at the internal walls, pushed upwards/downwards as a negatively buoyant wall jet. This wall jet reaches a point where the flow inverses due to the negative buoyant forces. This phenomenon is observed for all kind of systems emitting convective heat. The temperature profile in these cases is qualitatively shown in Figure 4 :

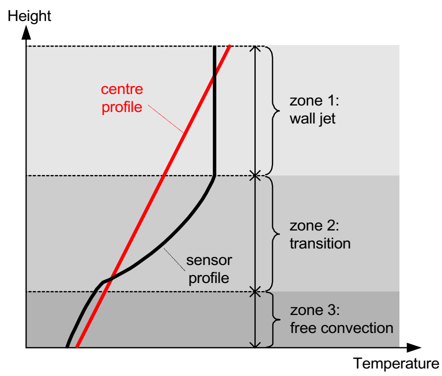

Figure 4: Qualitative temperature profiles at centre and near walls for the example of a heating system

Three typical zones of the vertical temperature profile near walls (sensor profile) are observed ([Rie01]):

- Isothermal zone of wall jet
- Transition zone – end of wall jet
- Boundary layer zone – free convection

In standard rooms the sensor is generally placed in zones 1 or 2, in high rooms or halls in zone 3. This has an important effect on the temperature response of the air around a sensor and thus on the control performance.

For cooling systems, the same phenomenon is observed in the case where the direction of the airflow in the boundary layer of free convection at the internal walls is not opposed to the wall jet.

Case 2: When the emitter is turned off and that the temperature differences between internal surfaces and the room air are small, boundary layers dominated by free convection are observed at the internal walls. This case is important as well since the models have to guarantee good results in dynamic conditions (e.g. ON/OFF controller).

The effects of the observed phenomena can have a major impact on the assessment of the performance of a controller. The development of a model taking into account the observed phenomena shall give more information about their importance on thermal room control.

STATE OF THE ART OF ZONE MODELS

To date, mostly "well mixed" models are used for control studies ([Klin99], [Rou97], [Lar80], [Hav98], [Os96], [Kast98]). They are not able to provide detailed information about the room conditions. [Rie00a] showed problems that appeared while using these models.

In some cases, zonal models or, rarely, CFD models are used ([Peng96], [Rat98]). However, these models are not generic and can hardly be reused for other zones or emitters.

The simple models on the one hand are commonly used to study the energy consumption in buildings ([TRN96], [DO89]).

CFD models, on the other hand ([PHO91]), are used for comfort studies and the prediction of airflow in rooms as they provide detailed conditions in the room. Since CFD calculations are very time consuming, they are mostly used for static problems. To date, transient phenomena are rarely studied ([Rat98]).

Different authors have integrated convective phenomena in their modelling. [Peng96] developed a zone model for a fan coil application based on pre-simulations using CFD calculations. Since the sensor was, in his case, placed at the air extraction of the fan coil unit, it was not necessary to model convective phenomena around the sensor (wall jet). The main assumption in his modelling was that the airflow in the zone is a function of the fan speed of the fan coil only, even for different boundary conditions. This type of model cannot be generalised.

[Ina88], [Dur94] or for example [Bou93] developed zonal models for different emitter systems. However, no phenomena of mixed convection at the internal walls are considered in these models since the main concern was the assessment of comfort in rooms.

In this study, simple but generic models shall be developed including the main phenomena in the room. The user shall be able to simulate similar cases simply by changing the parameters of the model (e.g. slightly different room geometry).

The chosen model type is the zonal model approach. This permits the representation of the important phenomena while keeping a minimum level of complexity. Starting with a general structuring of the zonal model in the Matlab-Simulink environment, the implementation of all phenomena is shown.

THE ZONAL MODEL AND ITS IMPLEMENTATION IN MATLAB-SIMULINK ENVIRONMENT

In a zonal model, the internal zone air volume is divided in several sub-volumes ([Bou93], [Wur95], [Pen96]). Contrarily to CFD models only the equations of conservation of mass and of energy are solved. The Navier-Stokes equations are not considered. The airflow between the sub-volumes has to be calculated by correlation or other simplified method (pressure calculation). Figure 5 represents the different types of heat and mass exchange for a general case.

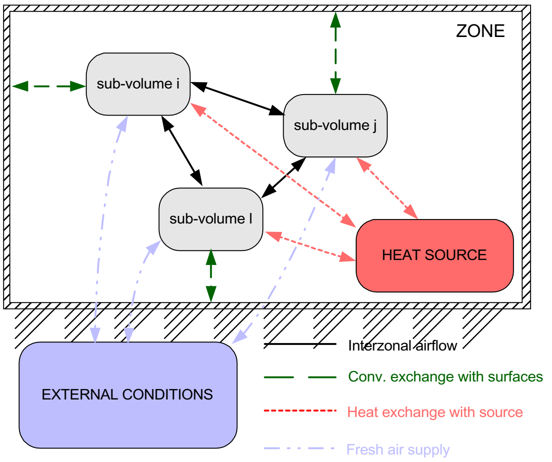

Figure 5: Heat and mass transfer in a zonal model

The following energy transfers appear in a zonal model:

- Airflow between sub-volume i and sub-volume j
- Convective heat exchange of sub-volume i with adjacent surface A_k
- Airflow between sub-volume i and external conditions (fresh air supply or ventilation)
- Heat source in sub-volume i

The inter-zonal air flow rates are obtained by the use of one or both of the following principles:

- pressure laws ([Bou93],[Wur95])
- Correlations for convective phenomena (Laret [Lar80], During [Dur94], Horwarth [Hor83])

- **Structuring of the model by the state space approach**

The energy balance for a sub-volume i can be written as:

$$\begin{aligned} m_i\, c_p \frac{d\vartheta_i}{dt} &= \sum_{j=1}^{l} \dot m_{j,i}\, c_p\, \vartheta_j - \sum_{j=1}^{l} \dot m_{i,j}\, c_p\, \vartheta_i \\ &+ \sum_{k=1}^{m} h_{i,k}\, A_{i,k}\, (\vartheta_{A,k} - \vartheta_i) \\ &+ \sum_{r=1}^{s} \dot m_{ext;r,i}\, c_p\, \vartheta_{ext,r} - \sum_{r=1}^{s} \dot m_{ext;i,r}\, c_p\, \vartheta_i \\ &+ \sum_{p=1}^{q} \Phi_p \end{aligned} \tag{1}$$

with:

l : number of sub-volumes
m : number of internal surfaces
s : number of ventilations or extractions
q : number of convective heat sources

Equation (1) can easily be represented by the state space equation (2).

$$\begin{aligned} \dot X &= A X + B U \\ Y &= D X \end{aligned} \tag{2}$$

The corresponding state vector and the disturbance vector in equation (2) are:

$$X = [\vartheta_1 : \vartheta_i : \vartheta_l]^T \tag{3}$$

$$U = [\vartheta_{A-1} : \vartheta_{A-k} : \vartheta_{A-m}, \vartheta_{ext-1} : \vartheta_{ext-r} : \vartheta_{ext-s}, \Phi_1 : \Phi_p : \Phi_q]^T \tag{4}$$

The matrix A is a *variable* and is given by:

$$A = C^{-1}\,(A_1 - A_2 - A_3 - A_4) \tag{5}$$

with the matrices:

- A_1 is the transposed matrix of the airflow matrix
- A_2 is the diagonal matrix of airflow leaving sub-volumes i
- A_3 is the diagonal matrix of heat exchange coefficients between the sub-volume i and surfaces in contact with the sub-volumes i
- A_4 is the diagonal matrix of airflow leaving the sub-volumes i to the outside

The matrix C is the diagonal matrix with the thermal mass of the sub-volume i.

The matrix B is also *variable* given by:

$$B = \left\| [C^{-1} B_1] [C^{-1} B_2] [C^{-1} B_3] \right\| \tag{6}$$

with the matrices:

B_1: matrix of heat exchange coefficients at m surfaces
B_2: matrix of fresh air supply into sub-volumes i
B_3: matrix of heat sources in each sub-volume i

The matrix D in equation (2), diagonal in this case, is a matrix defining the outputs of the system,.

- **Implementation of convective phenomena into the model**

In the first chapter the principal convective phenomena in a room are shown by experiment. They have to be implemented in the developed structure. As seen in Figure 1, the interesting points are the temperature profile at the centre as well as the temperature profile near the walls. The latter can be either a wall jet or a boundary layer of natural convection. Figure 6 shows the convective phenomena to be implemented in the zonal model.

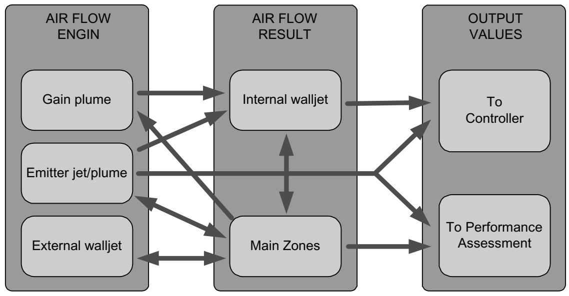

Figure 6: Convective phenomena in a zone

The "engines" of the airflow in the room are the plume/jet of internal gains and emitters as well as the boundary layer at the external walls/windows. These engines can cause a wall jet at the internal walls and influence the conditions at the main zones (zones with low air velocities) of the room.

Corresponding to Figure 1 the conditions around the controller sensor as well as the conditions at the main zones are used for the link to the controller as well as for the performance assessment of the controller.

The general main structure of the model is developed. This permits to implement all kind of emitters or ventilation systems into the general basis. In this general basis the phenomena modules corresponding to Figure 6 are implemented:

- Module 1: Main air sub-volumes: Horizontal air layers at centre part of the room
- Module 2: This is an air distribution volume either at floor or at ceiling and represents the distribution of warm air at ceiling or cold air at floor
- Module 3: Emitter plume/jet sub-volumes: Sub-volumes of plumes or jets (horizontal or vertical)
- Module 4: Gain plume sub-volumes: Sub-volumes representing plumes from occupants or equipment
- Module 5: External wall jet sub-volumes: Sub-volumes representing free convection boundary layer at external surfaces
- Module 6: Internal wall jet sub-volumes: Sub-volumes representing free or/and mixed convection boundary layer at internal surfaces

Module 2, one of the sub-volumes at floor or ceiling, is integrated in order to reduce the necessary number of air layers while representing the important phenomena.

Module 1 and 2 represent the basis of the zonal model. The other modules are integrated the rules imposed by this basis.
Figure 7 demonstrates the division into zones for the example of three horizontal air layers. The number of air layers is a parameter of the model so that the model can be adapted to each emitter system (after comparison with other data).

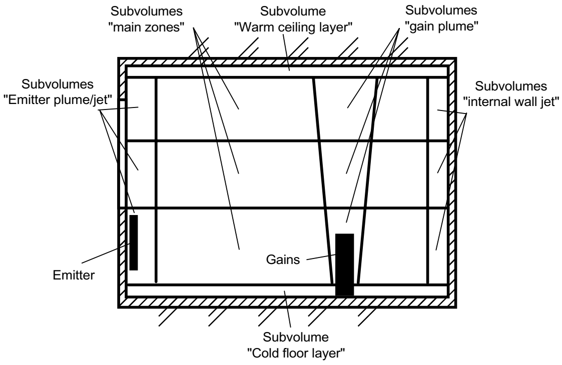

Figure 7: Example for a division into zones in the zonal air model

Since the model is only divided into horizontal air layers the calculation of the air flow rates is simple and as follows:
The airflow in all engine zones is determined by correlations ([All87], [Ina88], [Bou93], [Mus99]) describing the flow rate in the convective phenomenon. Then, from these known flow rates the other flow rates are obtained by simple mass balances. The advantage of this principle is, that no iteration has to be carried out for pressure calculations ([Fau85]). However, the model is structured to have the possibility, if this is wished, to implement higher zone discretisation and calculation of flow rates by pressure laws.
The separation of the diverse convective phenomena has the advantage of a complete modularity. The model can be used from a very simple form to a more detailed form by adding or removing the modules of phenomena.
Attention is paid in this model on the determination of the zone conditions near the internal walls.

- **Modelling of the module "internal wall jet"**

The airflow in the sub-volumes of the internal wall jet is strongly dependent on the airflow engines in the room. Depending on these engines, either correlations for mixed convection (with engine) or natural convection (no engine) are used. In Figure 8 their use is shown for the example of zone heating and a model of three air layers. The two cases (mixed or natural convection) are explained in the following.

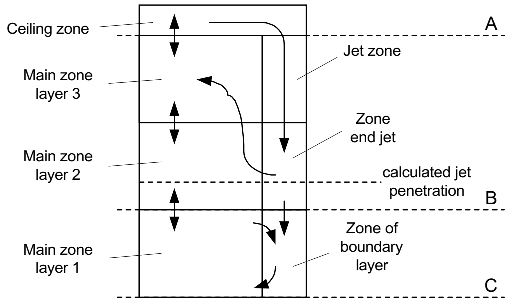

Figure 8: Modelling of the internal wall jet zones (3 air layers)

Case of mixed convection (A-B):

A correlation, developed for the study of fires in buildings, can be used for the model ([Gold86]):

$$\frac{\delta_p}{D} = 4.5\left(\frac{Gr}{Re^2}\right)^{-0.402} \qquad (7)$$

This correlation describes the maximum penetration δ_p of a negatively buoyant wall jet in a room as a function of the initial jet thickness D and the Archimedes number, defined as Gr/Re^2. The penetration δ_p is used to define the point where the flow inverses. From the air sub-volume of the wall jet corresponding to this height, all airflow of the jet is injected to the main air sub-volumes at the centre of the room that is at a similar temperature as the air in the jet (in general the upper air layer).
The boundary conditions in the experiments where the correlations have been established are characterised by higher temperature differences as well as higher air velocities as in the case of room heating. A parametric study has thus been carried out in order to prove the adaptability and sensibility of this correlation for the case of room heating or cooling [Rie00b]. The parameters studied were the initial jet thickness D, the initial jet flow rate, the initial temperature difference between jet and room air, the estimated length of the wall jet (around the internal walls) and the summation of all possible errors. The result is that the correlation is well adapted for a heated/cooled room with a restriction in the minimum height of a horizontal air layer.
Using the obtained flow rates, the temperature of the jet volumes is calculated.

Case of natural convection / boundary layer (B-C):

The wall jet is, in this case, a classic boundary layer. A correlation for turbulent flow is used after comparison with other correlations [All87]. The correlation calculates the airflow in the boundary layer. A thermal balance on the volume gives the temperature in the boundary element.

VALIDATION OF THE DEVELOPED ZONE MODEL

The validation of the model is carried out for he example of an electric convector. The developed convective zone model is coupled with an adapted and validated model of the envelope [Rie00c] and the model of an electric convector. The results shall be compared for two cases of heat emissions (700W and 1700W) of the convector. A step is carried out in each test from 0 to 100% of the indicated value of heat emission. The test cell is described in [Rie01].

For the comparison, the number of air layers is chosen to 3. Figure 9 visualises the division in sub-volumes of the air model used for the validation:

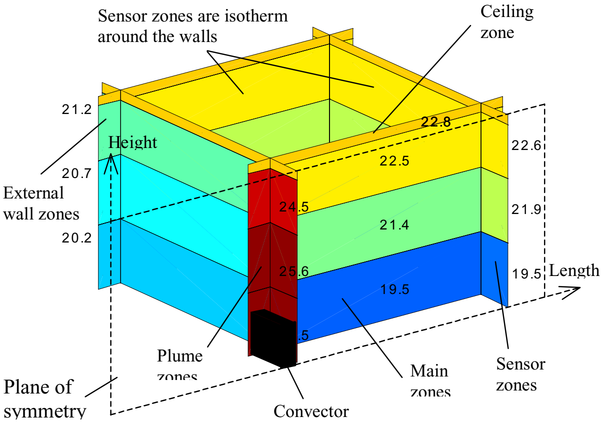

Figure 9: Temperature slices through the air volume of the room (convector -1700W) – zone is cut at symmetry plane

The model shall be able to represent the stratification in the room for the assessment of the controller performance. Then, considering that the sensor is placed at one of the internal walls, the difference between the centre and sensor air temperature profiles shall be in agree with the measurements. The validation is thus divided into two parts that are treated as follows.

- **Comparison of centre air temperature profile**

The comparison is carried out for two heat emissions, 700W and 1700W. Since the number of air layers is three, the temperature in the three main air layers shall be compared with the measurement results. Therefore the measurement data is interpolated in order to get the measurement temperature at the corresponding height.

The temperatures are validated for the first 60 minutes of the test since they are of high importance for control problems. The temperatures agree well for the upper zone (height = 2m) in the two test cases, the high heat emission and the low emission (Figure 10 and Figure 11). For the mean height and for the low height differences are observed. The model responds faster than the measurements (diff. 2-3 minutes). The temperature response shows some slight differences as well (2-4 minutes difference). However the results are in good agreement with the measurements.

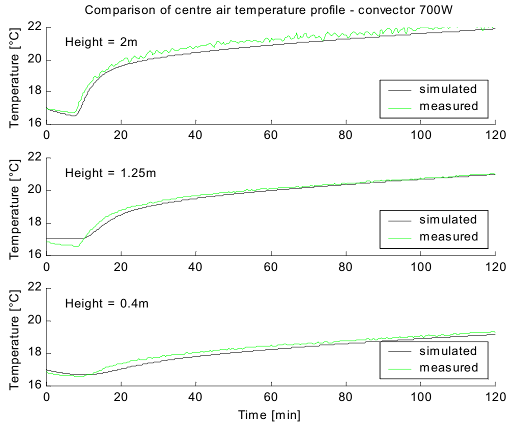

Figure 10: Temperature evolution at the main sub-volumes (convector 700W)

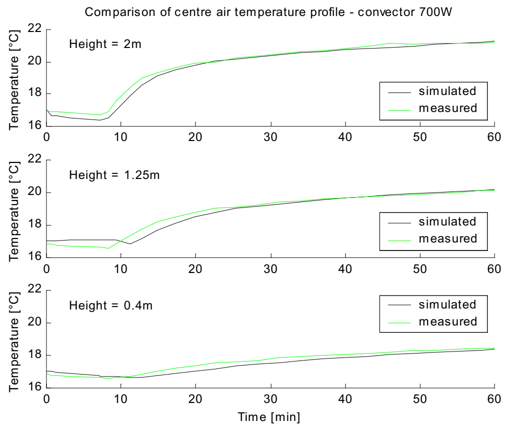

Figure 11: Temperature evolution at the main sub-volumes (convector 1700W)

- **Comparison of the difference between centre and sensor temperature profile**

The aim of this part is not the validation of the sensor air temperature. This would not make sense since there is already a difference between the measured and simulated centre temperatures. The important thing for controller studies is the difference that exists between the temperature of the air near the walls and the air at the centre. This difference is thus compared as follows for the two test cases. Figure 12 and Figure 13 show this temperature difference at a time of 20 minutes after the step in the heat emission of the convector. The three different zones (jet zone, transition zone and boundary layer zone) should be well represented by the model.

The profile is in good agreement with the measurements. In the upper zone the difference is quite small for the measurement as well for the simulation case. In the mean zone the effect of the wall jet is well represented by the model. Theoretically, the result could be improved by increasing the number of horizontal air layers, but at the same time the height of one air layer should not be reduced to values smaller than the incertitude of the wall jet correlation ([Rie00b]).

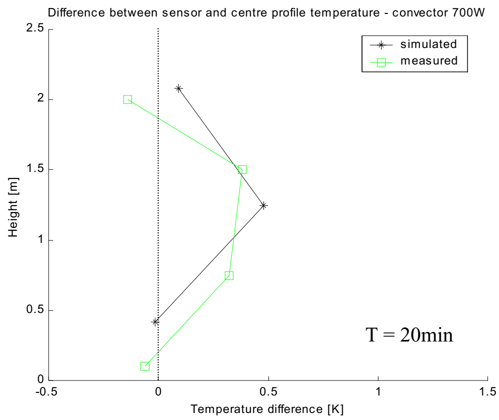

Figure 12: Temperature difference between sensor (wall) and centre profile for the convector at 700W

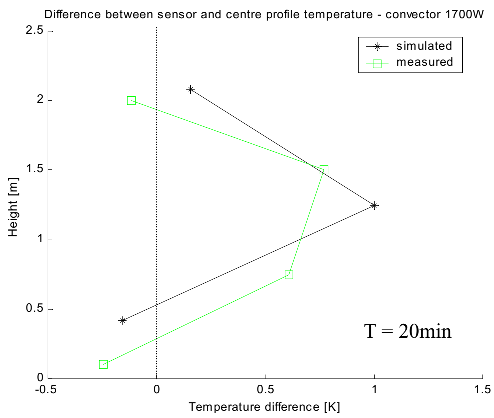

Figure 13: Temperature difference between sensor (wall) and centre profile for the convector at 1700W

CONCLUSION

The air temperature at the position of a controller sensor and at the centre of a room can differ in its static as well as in its transient behaviour.

Differences have been observed regarding height and position in the room. For the development of controllers it is important to know where the sensor of a controller is placed. At the same time the assessment of controller performance has to be obtained at a reference position in the room.

An adapted model for controller studies should thus represent well the stratification as well as the difference between the centre temperature and the temperature near the walls, where the controller is placed. The dynamic behaviour of the model is of major importance.

The zonal model approach is chosen to model these phenomena, since the model is easy to parameter and the simulation times is short compared to detailed CFD models (that are, to date, rarely used for dynamic cases).

A general representation in a graphical programming environment has been developed. A general basis as well as separated modules modelling the governing convective phenomena permits the easy addition of different emitter types.

The model is able to distinguish between sensor and centre air temperature as a function of height in the room and time. It is thus well adapted for the analysis of the position of a controller sensor in a room regarding height and position (wall – centre).

The simplicity concerning their parametering and their use makes them interesting for manufacturers of controllers as well as for research laboratories carrying out studies in the control field.

BIBLIOGRAPHY

[All87] Allard, Contribution à l'étude des transferts de chaleur dans les cavités thermiquement entrainées à grand nombre de Rayleigh, PhD Thesis, INSA Lyon, 1987

[Bou93] Bouia, Modélisation simplifié d'écoulements de convection mixte interne: Application aux échanges thermo-aérauliques dans les locaux, PhD Thesis, University of Poitiers, 1993

[Doe89] Overview of the DOE-2 program, Version 2.1D. Simulation Research Group, Lawrence Berkeley Laboratory, LBL-19735, 1989

[Dur94] During, Consommations énergétiques et confort thermique des locaux chauffés: approche par les modèles zonaux, PhD thesis, INSA Lyon, 1994

[Fau85] Fauconnier et al., Simulation thermique détaillé des bâtiments: Présentation du modèle BILGA, Rapport de recherche UTI/CEBTP E51.84, january 1985

[Gol86] Goldman et al., Effect of opposing buoyancy on the flow in free and wall jets, J. Fluid Mech., vol 166, pp. 41-56, 1986

[Hav98] Haves, A standard simulation test bed for the evaluation of control algorithms and strategies, ASHRAE Transactions, 1998, Vol. 104, Part 1

[Hor83] Horwarth, Temperature distributions and air movements in rooms with a convective heat source, PhD thesis, University of Manchester, 1983

[Hus97] Husaunndee, SIMBAD : A simulation toolbox for the design and test of HVAC control systems. Proceedings of the 5th international IBPSA conference, Prague, CZECH REPUBLIC, 2 : 269-276

[Ina88] Inard, Contribution à l'étude du couplage thermique entre un émetteur de chaleur et un local, PhD thesis, INSA Lyon, 1988

[Kast98] Kast, Dynamischer Anlagensimulator für Heiz- und RLT-Anlagen, Gesundheitsingenieur, 119, 1998

[Klin99] Klinger, Bedarfsgerechte Regelung des Raumluftzustandes in Wohngebäuden – Teil 1-2, HLH, Bd. 50, 1999

[Lar80] Laret, Contribution au développement de modèles mathematiques du comportement thermique transitoire de structures d'habitation, PhD thesis, University of Liège, 1980

[Mus99] Musy, Génération automatique de modèles zonaux pour l'étude du comportement thermo-aéraulique des bâtiments, PhD Thesis, Université La Rochelle, 1999

[Os96] Osman, Model- based control of laboratory HVAC systems, PhD thesis, University of Wisconsin, 1996

[Peng96] Peng, Modelling of indoor thermal conditions for comfort control in buildings, PhD thesis, Delft, University of Technology, 1996

[PHO91] PHOENICS, Reference manuals, CHAM Company, UK 1991

[Rat98] Ratnam, Advanced feedback control of indoor air quality using real-time computational fluid dynamics, ASHRAE transactions, 1998, Vol. 104, Part 1

[Rie00a] Riederer et al., Building zone modelling adapted to the study of temperature control systems, ASHRAE/CIBSE conference 2000, Dublin, Ireland

[Rie00b] Riederer, Modelling of the internal wall jet, internal report, CSTB, unpublished, 2000

[Rie00c] Riederer, Comparaison de différents modèles d'enveloppe, internal report, CSTB, unpublished, 2000

[Rie01] Riederer et al., Influence of sensor position in building thermal control: Criteria for zone models, Clima2000, Naples, Italy, 2001

[Rou97] Rouvel, Ein regelungstechnisches Modell zur Beschreibung des thermisch dynamischen Raumverhaltens, Teil 1-3, HLH, Bd. 48, 1997

[Sim98] SIMULINK dynamic System Simulation for Matlab. Version 2.1 Mathworks Inc., Ma., USA, 1998

[TRN96] TRNSYS, A transient Simulation Program. Solar Energy laboratory of the University of Wisconsin; Madison, USA, 1996

[Wur95] Wurtz, Modélisation tridimensionelle des transferts thermiques et aérauliques dans le bâtiment en environnement orienté objet, PhD thesis, Ecole Nationale des Ponts et Chaussées, Paris, 1995

NOMENCLATURE

English letter symbols:

$\dot{m}$	Flow rate	[kg/s]
A	surface	[m²]
Ar	Archimedes number (Gr/Re)	[-]
c_p	Thermal heat capacity of air	[J/(kg*K)]
D	Thickness	[m]
Gr	Grashof number	[-]
h	Convective heat transfer coefficient	[W/m²/K]
Re	Reynolds number	[-]
t	Time	[s]

Greek letter symbols:

δ_p	Penetration of jet	[-]
Φ	Heat flux	[W]
ϑ	Temperature	[°C]

Matrices

A	Matrix of heat loss of sub-volumes by heat and mass flow ($A_1 – A_4$)
B	Matrix of heat gain of sub-volumes by heat and mass flow ($B_1 – B_3$)
C	Matrix of thermal masses of the sub-volumes
D	Matrix defining the outputs of the system
X	State vector
Y	Output vector

Subscripts:

conv	convective
ext	external
i	current air sub-volume number
j	sub-volume adjacent to sub-volume i
surf	surface