CO_2 CONTROL ALTERNATIVE FOR HEALTHY RESIDENTIAL SPACES

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Abstract

Most common thermal comfort models include in some form air change rate for the sake of thermal evaluation of indoor environment. The lowest rate is set by hygienic standards and primarily should act as prime information for any on-line indoor environment controls. The work demonstrates the way of using mostly measured indoor air temperature for an estimate of air density, i.e. water vapor content, and finally the air chemical content (CO_2). The relationship between the chemical and water vapor produced by human body predeterminates the method may be applied within common occupied spaces without additional (non-human) CO_2 production.

1 Principles of Chemical Factors Sensation

Ensuring an optimal thermal environment means keeping a quite wide set of indoor thermal environment quantities in certain range favoured by human body through its sensation receptors. They act independently, however, their outcomes are often expressed through parameters containing two or more quantities. The most known are PMV or PS (PV) indices introduced to several recommendations and even standards dealing with indoor environmental phenomena [1]. These parameters facilitate measurements, recommendations and building up mathematical and simulation models, which are useful in planning, predicting or improving real occupied spaces. Natural part of these parameters includes chemical factors given the side production on human lungs activity. The process of human activity always means exchange of oxygen for carbon dioxide and water vapor. In order to supply into the occupied space fresh air means keeping the percentual part of the gases mentioned remains in acceptable range for human body. Any deviation would immediately influence the whole chemical chains of reactions on blood circuits within as well as out the lungs. The process transformed ultimately affects physical and psychical condition of the body according to principle known as Weber-Fechner principle relating the degree of response or sensation of a sense organ and the intensity of the stimulus:

$$\log(\Delta I) = \log I + \log K_W \tag{1}$$

Where ΔI is known as discrimination threshold and K_W is Weber's fraction, which does not change for different values of I. Effectively, it transforms the human body response less dramatically to the stimulus as indicates the logarithm in Eq. (1). In other words, for multiplications in stimulus strength, the strength of perception would only add. Applied on time-varying CO_2-level in less concentrations of carbon dioxide, its increase (decrease) would be noticed for example on physical activity more obviously, than if the same changes would occur on room with CO_2 load.

Secondly, the human physical body activity produces proportionally adequate amount of water vapor directly via breathing and through skin, depending on indoor climate factors, clothing and the physical as well as psychical activity. Therefore the presumption made by Weber-Fechner law would apply for the late phenomenon too. In that point it is possible to 'switch' the CO_2-sensoring for water vapor content in surrounding indoor air. Thus, the quantity of absolute or relative humidity preserves the proportionality in the thermal state equation, too. Any contribution to the water vapor content above the outdoors rel. humidity level would also obey the Dalton law in similar manner as it does for other contamination components.

2 Indoor Air Thermal State Evaluation

The occupied space in any case should be checked for the air change rate (*ACH*) through the well-known means [2], [3] and compared with the rate recommended. In quite wide types of spaces it may vary from ACH=1 to 20, depending on the room purpose. In our space were kept conditions according to Table 1:

Table 1: REQUIRED THERMAL STATES IN WINTER PERIOD FOR INTERIORS WITH ACCEPTABLE RANGE OF 80% (90%) [2], [4]

Relative Humidity Range	*Operative Temperature*
50 % *RH* for 80 %*	20,5 … 24,5 ºC
50 % *RH* for 90 %*	21,3 … 23,7 ºC

* percentage level of acceptability

The acceptable range of operative temperatures and humidity for the heating season are often drawn on a psychrometric chart. In Table 1 are extracted values required to be anywhere within the defined occupied zone *OZ* for the winter period if 80 %, resp. 90 % of the acceptability level will be reached, otherwise thermal comfort criteria within the occupied zone would not be met.

2.1 Temperature-Variable in Standards

From the physics of heat exchange between the human body and the environment is known the result of comfort temperature as an influence of average surface temperature of surrounding things and the walls beside the indoor air temperature. The thermal physiology depends through it on the way of heating the room. In the investigated space the main heat energy disseminator used was a steam convector placed under a window, thus necessary creating non-uniform and non-isothermal conditions throughout the space. However, the reference room disposition featured one-spatial symmetry (along the main cross-sectional cut - meridian), thus halving the space into two with thermal environments mirroring each other.

Standard ASHRAE 55-1992 [2] approaches *effective temperature* (*ET*) and *operative temperature* (*Top*) as arbitrary indices that combine into a single number the effects of the dry-bulb temperature, humidity and air motion on the sensation of warmth or cold felt by the human body. Since under the presumption of a fixed moisture value the effective temperature almost equals the operative temperature defined by Eq. (2):

$$t_{op}(\tau)=\frac{h_{cv}(\tau)t_a(\tau)+h_r(\tau)t_{MRT}(\tau)}{h_{cv}(\tau)+h_r(\tau)} \tag{2}$$

where h_c - convective heat transfer coefficient (W.m^{-2}.K^{-1})
h_r - radiant heat transfer coefficient (W.m^{-2}.K^{-1})
t_{MRT} - mean radiant temperature (°C)
τ - time (s)

Where the Biot number was expected Bi > 0,1 on surrounding wall, the Laplace equation on heat conduction through the slab (wall) was applied on an isotropic homogenous part, with different surface temperatures and boundary conditions, respectively. This part was modeled with Simulink toolbox of MATLAB environment, Fig. 1:

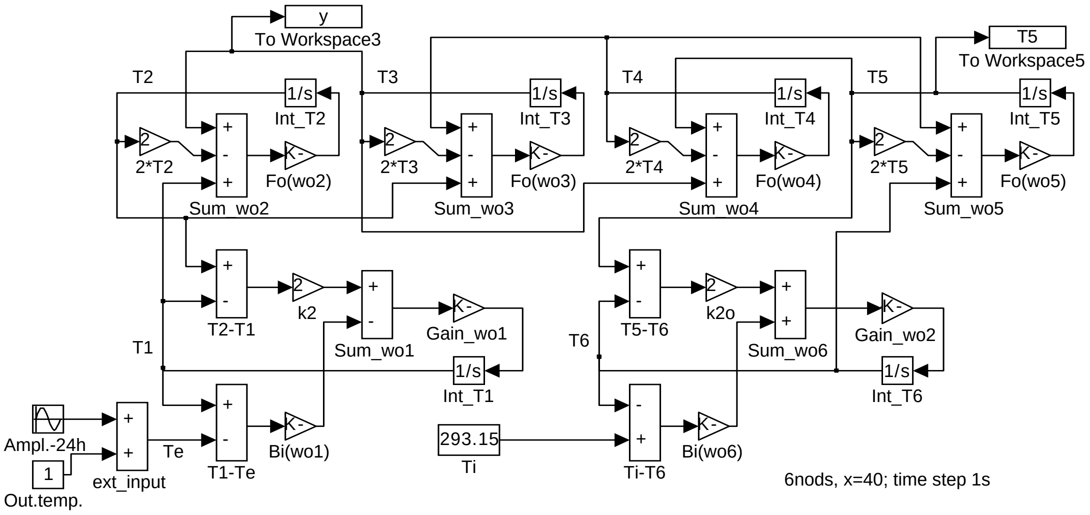


Figure 1: Analog of exterior wall temperature distribution with convective boundary conditions (Matlab/Simulink environment).

2.2 Temperature and Velocity Profiles. Governing Formulation of 2D-model

The airflow within an enclosure was investigated [5] in order to map the thermal state in a cross-section of the space. An explicit, two-step, forward-time scheme applied to the Navier-Stokes equations (NSE) was solved [6]. Second order accurate discretization was applied both in space and time. The pressure is solved using a pre-conditioned state equation of the air in the conjugate gradient method and the indoor air was treated as ideal gas (with Poisson const. 1,4 as usual). The conventional Eqs. (3-1), (3-2) and (3-3):

$$\frac{\partial u_j}{\partial x_j} = 0 \tag{3-1}$$

$$u_j \frac{\partial u_i}{\partial x_j} = -\frac{\partial p}{\partial x_j} + Pr \frac{\partial^2 u_i}{\partial x_j \partial x_j} + Ra_i \cdot Pr \cdot T \tag{3-2}$$

$$u_j \frac{\partial T}{\partial x_j} = \frac{\partial^2 T}{\partial x_j \partial x_j} \tag{3-3}$$

were implemented as the standard dynamic model [7], in which air properties are assumed to be constant within the computational grid, both spatial as well as time step. Sufficient spatial and time gridding were chosen in order to secure numerical stability. The spatial grid of the 2-dimensional flow field was set into ordinary rectangular elements within the reference space inner surfaces set as boundaries and adequately marked. The ventilation system was turned off leaving natural infiltration alone driving the flow to reach a stable state. Digital Fortran software tool was used to calculate the NS equations and images were acquired of velocity and temperature distributions throughout the meridian cross-cut area. A graphical program (Stanford Graphic) was used to plot and convert the 2D-velocity field images, temperature (Fig. 2) within the meridian cut into a color (gray) scale image.

The governing equations were made dimensionless using *L*, *H*, *h*, *k* (space length and height, convection and conduction heat transfer coefficients) and density ρ as reference quantities. The velocities are zero at both opposite walls. They were treated as adiabatic and had about similar surface temperatures. Uniformly staggered grids of 25 x 25 and 26 x 15 nodes were set on the meridian cross-cut plane, Fig. 2, 3.

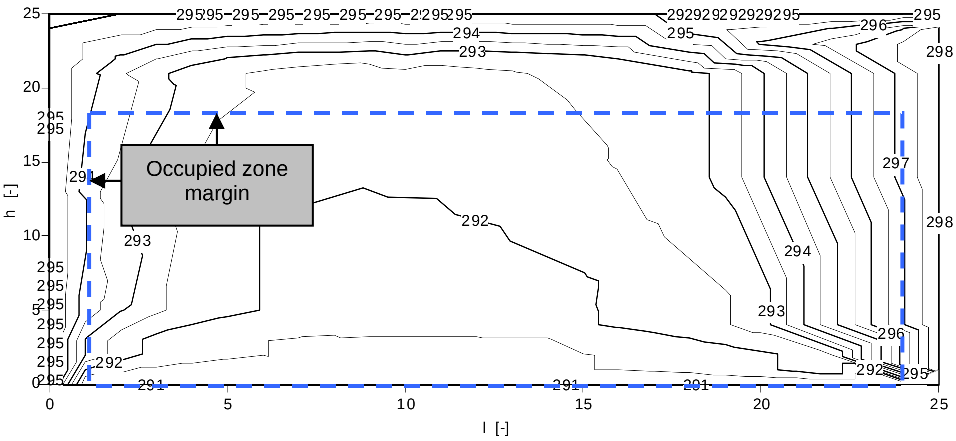


Figure 2: Isotherms of ambient air temperature field with asymmetrically cooled external wall (*ACH*=1). Maximal difference in vertical direction was 2K.

3 Indoor Air CO_2 Evaluation and Its Control

The temperature field along with 2-dimensional velocity map on the same cross-cut assessed in previous paragraph is the main outcome of solving NS equations (3-1), (3-2) and (3-3). The pressure and moisture data over the grid area were also available as complementary calculation quantities which are bound through state equation for air ($p/\rho T$ = const.). From this yields the meridian air density profile, Fig. 3:

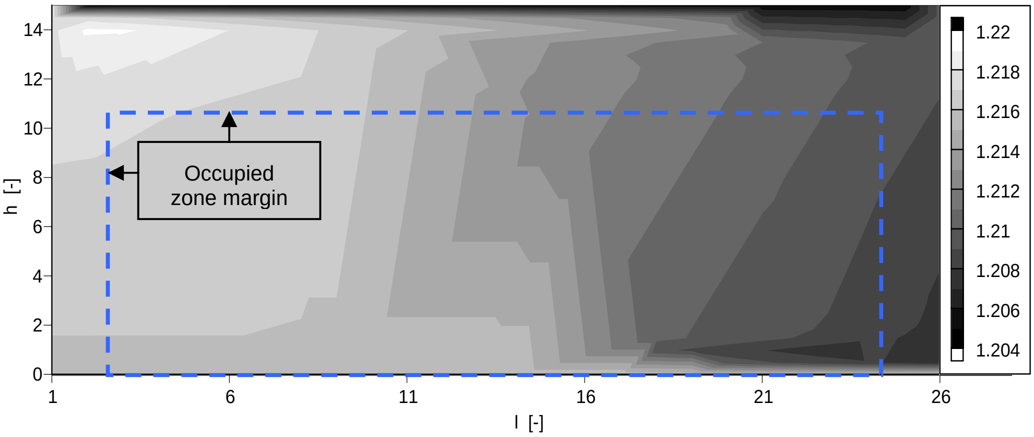


Figure 3: Air density profile with 1,1 % in maximal variation (~0,013 kg.m^{-3}) within the occupied zone; air change rate *ACH* = 1 h^{-1}; scale on the left in kg.m^{-3}.

The indoor air density field represents on-line screening map of maximal values of moisture exceeding the guarded space, Figure 3, blue dashed line. It replaces any additional measuring within the occupied zone, in fact the sensors are often placed on its margins. The values are being saved into a matrix and continuously updated in MATLAB environment, therefore giving the data about the CO_2 content in the monitored space over the time. There is needed only once to check the unique CO_2-value elsewhere within the space for the particular case with relatively inexpensive real-time digital air monitoring equipment (e.g. fy Protronix). Then the CO_2 level over the space represents a moisture matrix multiplied with the constant multiplier. If the highest carbon dioxide value exceeds permitted limit, a controller would evaluate the amount of fresh air needed and switch on air ventilation system upon which outdoor 'fresh' air can dilute carbon dioxide along with other contaminants that are produced in the indoor environment, such as odors released from people and contaminants released from the building, equipment, furnishings, and people's activities. Effectively, the CO_2 level will drop into an acceptable range: depending on the type of facility and room these rates of ventilation should keep carbon dioxide concentrations below 1000 ppm (parts per million) creating indoor air quality conditions acceptable to most individuals.

The Time-Dependent MATLAB CO_2-Matrix

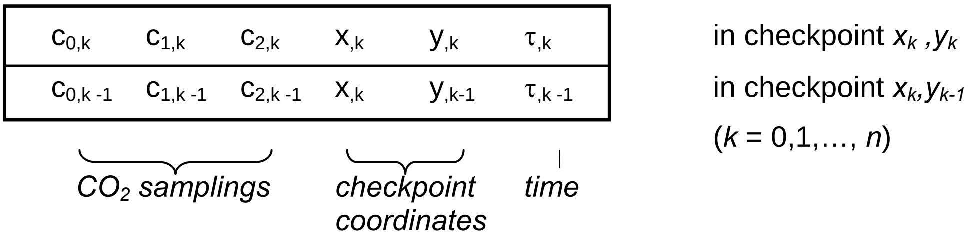
The major advantage of updating the CO_2 concentration with the MATLAB matrix reflects the fact that human body reaction (and to the certain level its adaptation) to the CO_2 exposition is time-dependent. Widely accepted standards [9] have set workplace safety standards of 10 000 ppm for an 8-hour period and 30 000 ppm of carbon dioxide for a 15 minute period. This means the average concentration over an 8-hour period should not exceed 10 000 ppm and similarly, the average concentration over a 15 minute period should not exceed 30 000 ppm of CO_2 (these levels were assessed for healthy working adults and may not be appropriate for sensitive populations, such as children and the elderly).

Upon this, some prediction of CO_2 concentration development or trend within the monitored space may effectively prevent frequent switching on/off the air ventilation system. For that reason are kept the adequate values of water vapor content (CO concentrations) in a few time steps ago in order to assess the trend in the nearest future. Mathematically, (vertical) CO_2 checkpoints for given concrete location of a rectangular net over the space meridian:

```
      DO 15  J = 1,N
        DO 15         I = 1,M
                   WRITE (8,*) X(I,J), Y(I,J), PRES(I,J)
15         CONTINUE
```

Figure 4: Input file data sorting at Fortran source code structure for y-dimension.

are saved into 5-dimensional matrix with the 2 coordinates, time and three CO_2 samplings over 3 last time steps denoted *c* in Fig. 5:



$c_{0,k}$	$c_{1,k}$	$c_{2,k}$	$x_{,k}$	$y_{,k}$	$\tau_{,k}$
$c_{0,k-1}$	$c_{1,k-1}$	$c_{2,k-1}$	$x_{,k}$	$y_{,k-1}$	$\tau_{,k-1}$

Figure 5: 5-dimensional CO_2 matrix structure with records of profiles in two immediate vertical screening grids (x_k , y_k), (x_k , y_{k-1}).

Within the modeled room the checkpoints are grids of computational the 2-dimensional net matching the margins of occupied zone on the space main meridian (in Fig. 3 blue dashed line). Both quantities, i.e. relative humidity (r.h. in %) and CO_2 concentration (ppm) are filled in MATLAB matrices **f**(τ) and **C**(τ) respectively, Fig. 6:

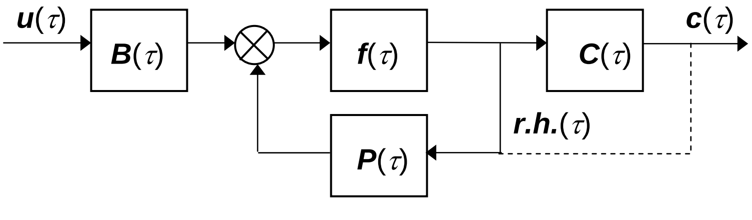


Figure 6: Block scheme of control closed loop of controller unit *P* and the system (space) *f* with the CO_2 concentration/rel. humidity (r.h.) on-line screening (matrix C).

The input vector **u**(τ) denotes disturbances and **P**(τ) any suitable control unit able to manage volume of outdoor air flow rate supply into the room. The connected circuit with common PI-function on the controller was realized with Simulink toolbox [8].

For the checked room with dimensions below and one adult person present (≤1.2 met, sedentary activity):

1. *Reference room dimensions:* $L \times B \times H$ *7250 x 4550 x 3000 (mm)*
(Model 1:6 *1200 x 760 x 500 (mm))*
2. *Occupied zone:* $L_z \times B_z \times H_z$ *6050 x 3350 x 1900 (mm)*

H - reference room height (2850 mm),
H_z - occupied zone height (CO_2 checkpoint at 1900 mm),
H_2 - mean radiant temperature checkpoint (ISO 7721),
H/L - reference room aperture of 0,42.

was evaluated the average carbon dioxide concentration over an 8-hour period well below the allowed limit (10,000 ppm) [10]. It should be noted that the controller cannot target any required CO_2 concentration value due to the limit given by natural CO_2 content of ‘fresh’ outdoor air. The outdoor concentration of carbon dioxide can vary from 350-400 ppm to significantly higher values in areas with high traffic or industrial activity.

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