Simulation and control of indoor air quality in buildings

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Abstract: That is why the enclosed spaces must insure the possibility for both physical and intellectual work, as well as for some recreation activities, for rest and sleep under most favourable conditions. The achievement of these conditions depends on very many factors that decisively influence the sensation of comfort perceived, the work capacity and man’s regeneration capacity. This paper approaches the indoor air quality simulation and control. It is developed a computational model for indoor air quality numerical simulation, as well a methodology to determine the outside airflow rate and to verify the indoor air quality in enclosed spaces, according to the European Standard CEN 1752. On the bases of this mathematical model there was elaborated the COMFORT 2.0 computer program, implemented on compatible microsystems IBM-PC. The COMFORT 2.0 program computes the outside airflow rate for a room ventilation, the number of air exchanges per hour, and the variation in time of contaminants concentration of room air according to European and national norms and analyses influence of different parameters on these sizes. The performance of the developed computational model and the advantages of the proposed computer program is illustrated by using a numerical comparative application for one constructive type building.

Key-Words: Enclosed spaces, Olfactory comfort analysis, Outside airflow rate, Indoor air quality control, Mathematical models, Computer program, Numerical comparative analysis.

1 Introduction
Reducing energy consumption in buildings is one of the main current directions of research in building constructions. An important part of household energy consumption is necessary to achieve, in living spaces, indoor microclimate parameters. Therefore, is particularly important the achievement of structural elements, building equipments and operating modes to allow getting both adequate comfort parameters and energy saving.

The greatest majority of people carry on 80…90% of their lives inside buildings, which must satisfy the objective and subjective requests linked to vital functions of the occupants. That is why the enclosed spaces must insure the possibility for both physical and intellectual work, as well as for some recreation activities, for rest and sleep under most favourable conditions. The achievement of these conditions depends on very many factors that decisively influence the sensation of comfort perceived, the work capacity and man’s regeneration capacity. The design of the rooms must take into consideration these conditions and present tendencies to reduce the energy consumption, that are decisively influencing the optimal or admissible values of comfort parameters. Thus the inside microclimate of a building must be the result of a computation of multicriterial optimization, taking into account technical and psychological comfort and the energy saving.

The concept of technical comfort comprises all parameters achieved and controlled with HVAC systems that act upon building occupants senses. This includes thermal, acoustic, olfactory and visual comfort. In accordance with the dissatisfied person percent of the ensured comfort: 10%, 20%, 30%, rooms are classified into three categories: A, B, C.

The perception and appreciation of basic comfort elements to man are influenced by some psychological factors, but at the same time evolution and man psychological equilibrium are closely linked with the environment. So, between psychological and technical comfort is a reciprocal connection. Human psyche depends also by other independent factors like: age, gender, etc, influencing the technical comfort level appreciation. So pleasant sensation may occur as a result of optimum technical and psychological comfort parameters.

Subjective comfort of persons in a room depends on many factors: temperature, humidity and air circulation; smell and respiration; touch and touching; acoustic factors; sight and colours effect; building vibrations; special factors (solar–gain, ionization); safety factors; economic factors; unpredictable risks. Because of some technical conditions the common influence of these factors can not be analysed, and
the adaptation of the human body to a certain environment is a complex process, this one reacting to the common action of more parameters.

In this paper an olfactory comfort analysis in enclosed spaces is performed.

2 Olfactory comfort
Comfort and indoor air quality (IAQ) depend on many factors, including thermal regulation, control of internal and external sources of pollutants, supply of acceptable air, occupant activities and preferences, and proper operation and maintenance of building systems. Ventilation and infiltration are only part of the acceptable indoor air quality and thermal comfort problem.

Air composition in living spaces differs from that of the outside air. Carbon dioxide (CO\textsubscript{2}) concentration in outside air is between 300 and 400 ppm, and in living spaces is of about 900 ppm. The maximum admitted limit of CO\textsubscript{2} concentration in the inhaled air is of 1000 ppm (Pettenkofer’s number). Table 1 presents the effect of different CO\textsubscript{2} concentrations on human body.

Table 1. The effect of CO\textsubscript{2} concentration on human body

<table>
<thead>
<tr>
<th>CO\textsubscript{2} concentration [%]</th>
<th>Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>30000 Deep breathing, strong</td>
</tr>
<tr>
<td>4</td>
<td>40000 Head aches, pulse, dizziness, psychic emotions</td>
</tr>
<tr>
<td>5</td>
<td>50000 After 0.5…1 hours may cause death</td>
</tr>
<tr>
<td>8...10</td>
<td>80000...100000 Sudden death</td>
</tr>
</tbody>
</table>

Air quality is prevailingly determined by people’s sensations to different odorants.

Odorant perception depends, on one side, on objective factors: concentration and toxicity of air pollutants (bio–effluents), activity level, outside (fresh) airflow rate, and on the other hand, on psychological factors with subjective character.

The relation between perceived odorant intensity and its concentration conforms to a power function [23]:

\[
S = k C^\beta \tag{1}
\]

where: \(S\) is odorant intensity (magnitude); \(C\) – odorant concentration, in ppm; \(\beta\) – exponent (0.2…0.7) of psychophysical function; \(k\) – constant characteristic of material.

The percentage of persons dissatisfied PPD with air polluted by human bio–effluent (1 olf) can be calculated from the equations [14]:

\[
PPD = 395 \exp \left( -3.66 L_p^{0.36} \right) \quad \text{for} \quad L_p \geq 0.332 \text{ l/s} \tag{2}
\]

\[
PPD = 100 \quad \text{for} \quad L_p < 0.332 \text{ l/s} \tag{3}
\]

where: \(L_p\) is the outside airflow rate, in l/s.

Outdoor air requirement for acceptable indoor air quality have long been debated. Historically, the major considerations have included the amount of outdoor air required to control moisture, carbon dioxide and tobacco smoke generated by occupants. These considerations have led to prescriptions of a minimum rate of outdoor air supply per occupant.

Tables 2 and 3 present the minimum rate of outdoor airflow per occupant for different activities, according to European Standard CEN 1752, that also takes into consideration the smokers in ventilated rooms.

Table 2. Minimum rate of outdoor airflow

<table>
<thead>
<tr>
<th>No.</th>
<th>Activity</th>
<th>Outdoor airflow rate [m\textsuperscript{3}/(h\cdot pers)]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1 Intellectual</td>
<td>2</td>
</tr>
<tr>
<td>1</td>
<td>Physical very easy</td>
<td>30</td>
</tr>
<tr>
<td>2</td>
<td>Physical easy</td>
<td>40</td>
</tr>
<tr>
<td>3</td>
<td>Physical hard</td>
<td>50</td>
</tr>
</tbody>
</table>

Table 3. Minimum rate of outdoor airflow for rooms with smokers

<table>
<thead>
<tr>
<th>Room category</th>
<th>Outdoor airflow rate [m\textsuperscript{3}/(h\cdot pers)]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Without smokers 20% smokers 40% smokers 100% smokers</td>
</tr>
<tr>
<td>0</td>
<td>1 2 3 4</td>
</tr>
<tr>
<td>A</td>
<td>36.0 72.0 108.0 108.0</td>
</tr>
<tr>
<td>B</td>
<td>25.2 50.4 75.6 75.6</td>
</tr>
<tr>
<td>C</td>
<td>14.4 28.8 43.2 43.2</td>
</tr>
</tbody>
</table>

The perceived olfactory sensation depends not only on the pollutant source but also to a great extent, on the dilution degree with outside air.

The olfactory pollution degree of a room is given by:

\[
C_i = C_p + \frac{10 G}{L_p} \tag{4}
\]

where: \(C_i\) is the indoor air quality (in decipol); \(C_p\) – outdoor air quality (in decipol); \(G\) – contaminants concentration of room air.

3 Indoor air quality simulation model
Consider a single zone compartment, where there is a source of pollution that has gas exchanges with the outside air, and where an air purifier may be used. Admitting the possibility of deposition and absorption of the pollutant on the walls and other surfaces, the temporal evolution of the concentration of a pollutant is modeled by the following differential equation [15]:

\[
\frac{dC}{dt} = \frac{Q}{V} (C_i - C) - \frac{C}{	au} + \frac{1}{V} \int_0^t Q(t - \tau) (C_i - C) \, d\tau + \frac{1}{V} \int_0^t g(t - \tau) \, d\tau + \frac{1}{V} \int_0^t h(t - \tau) \, d\tau
\]
\[
\frac{dc}{d\tau} = \frac{P}{V} + nc_p - nc - \nu_d \frac{S}{c} - \frac{L_p}{V} c e_p
\] (5)
in which: \( c \) is the instantaneous average contaminant concentration, in mg/m\(^3\); \( P \) – pollutant generation inside the compartment, in mg/h; \( V \) – room volume, in m\(^3\); \( n \) – air exchange rate, in h\(^{-1}\), i.e., the fresh air flowrate divided by the room volume; \( c_p \) – concentration of the contaminant in outside air, in mg/m\(^3\); \( \nu_d \) – deposition rate of pollutant, in mg/(h⋅m\(^2\)); \( S \) – surface of deposition, in m\(^2\); \( L_p \) – flow rate through the air purifier, in m\(^3\)/h; \( e_p \) – efficiency of the air purifier.

The effects of absorption or deposition of the pollutant inside the compartment and the removal of filtering through the air purifier system may be considered in a simplified form, reducing the intensity of the sources of their value to them. Thus, for purposes or simplification, their terms in the equation may be despised, coming:

\[
\frac{dc}{d\tau} = \frac{P}{V} + nc_p - nc(\tau)
\] (6)

That, integrated for a situation where \( V, P, c_p, L_p \) remain constant, since an initial time instant \( \tau = 0 \), where the initial concentration \( c_0 = c_p \), till a generic time instant \( \tau \), will come:

\[
c(\tau) = c_{eq} + \left(c_0 - c_{eq}\right) e^{-n}\tau
\] (7)
in which \( c_{eq} \) is the equilibrium concentration.

The equilibrium concentration \( c_{eq} \), in the equation (7), is the value that occurs when it ceases the variation in concentration. Thus, it is obtained equalizing the first member of equation (6) to zero, which gives:

\[
c_{eq} = c_p + \frac{P}{Vn}
\] (8)

that as \( n = L_p/V \), comes:

\[
c_{eq} = c_p + \frac{P}{L_p}
\] (9)

The equations are solved numerically. The outputs of the simulation are instantaneous concentration of the pollutant and the graphical results of the time–evolution of the pollutant concentration.

In [11], the expressions to calculate the volumes of oxygen \((O_2)\) and carbon dioxide \((CO_2)\) in the human respiration process are given, as a function of the metabolic rate and the corpulence of the studied person. The volume of consumed \( O_2 \) is given by:

\[
V_{O2} = \frac{0.00276A_B M}{0.23r + 0.77} \frac{1}{S}
\] (10)

where:

\[
A_B = 0.202 m^{0.425} h^{0.725}
\] (11)
in which: \( A_D \) is the nude body surface area [10], in m\(^2\); \( M \) – metabolic rate, in met (1 met = 58.15 W/m\(^2\)); \( r \) – ratio between the volume of released \( CO_2 \) and the consumed volume of \( O_2 \); \( M \) – mass of human body, in kg; \( h \) – height of human body, in m.

The ratio \( r \) usually takes the value of 0.83, but that may vary till 1, for a person with a very high metabolic rate (more than 5 met).

Once the volume of \( O_2 \) has been calculated, the volume of released \( CO_2 \), for normal metabolic rate cases is computed from:

\[
V_{CO2} = 0.83 \times V_{O2}
\] (12)

4 Computation of outside air flow–rate and indoor air quality control

4.1 Mathematical model

Computation of outside air flow–rate in a room can be performed function of:

- number of occupants, keeping \( CO_2 \) concentration under the maximum admitted level (according to Romanian Norm I 5);
- number of occupants and room surface (according to German Norm, DIN 1946);
- indoor air quality (according to European Standard CEN 1752, described below).

Ventilation efficiency \( e_v \) is a criterion for energy and fan performances. This is used to evaluate a ventilation system and is defined by following expression:

\[
e_v = \frac{c_i - c_p}{c_{zl} - c_p}
\] (13)

where: \( c_i \) is the contaminants concentration in the exhausted air; \( c_p \) – contaminants concentration the supply outside air; \( c_{zl} \) – contaminants concentration in the working area.

The value of \( e_v \) depends on the entrance place and the exhaust way of outside air, and on the difference between the outside air temperature \( t_e \) and indoor air temperature \( t_i \) (Table 4).

The outside air flow–rate \( L_p \), in l/s, can be computed function of IAQ from equation:

\[
L_p = \frac{G}{\left(C_i - C_p\right)e_v}
\] (14)

where:

\[
G = G_{oc} + G_{ob}
\] (15)
in which: \( G \) is the contaminants concentration of room air, in olf; \( C_i \) – indoor air quality, in dp (Table 5); \( C_p \) – outside air quality, in dp (Table 6); \( G_{oc} \) – contaminants quantity from the occupants (Table 7); \( G_{ob} \) – contaminants quantity from room objects (building elements, furniture, carpets, etc.) having the values in Table 8.
Table 4. Ventilation efficiency, $\varepsilon_v$

<table>
<thead>
<tr>
<th>System type</th>
<th>$t_t - t_i$ [°C]</th>
<th>$\varepsilon_v$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>&gt;5</td>
<td>0.4...0.7</td>
</tr>
<tr>
<td></td>
<td>2...5</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>0...2</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>&lt;0</td>
<td>0.9...1.0</td>
</tr>
</tbody>
</table>

Table 5. Indoor air quality, $C_i$

<table>
<thead>
<tr>
<th>Room category</th>
<th>$C_i$ [dp]</th>
<th>Percent dissatisfied [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1.0</td>
<td>2</td>
</tr>
<tr>
<td>B</td>
<td>1.4</td>
<td>20</td>
</tr>
<tr>
<td>C</td>
<td>2.5</td>
<td>30</td>
</tr>
</tbody>
</table>

Table 6. Outside air quality, $C_p$

<table>
<thead>
<tr>
<th>No.</th>
<th>Air source</th>
<th>$C_p$ [dp]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1 Mountain, sea</td>
<td>0.05</td>
</tr>
<tr>
<td>1</td>
<td>2 Locality, fresh air</td>
<td>0.1</td>
</tr>
<tr>
<td>2</td>
<td>3 Locality, mean air</td>
<td>0.2</td>
</tr>
<tr>
<td>3</td>
<td>4 Locality, polluted air</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Table 7. Contaminants quantity from the occupants, $G_{oc}$

<table>
<thead>
<tr>
<th>No.</th>
<th>Contaminants source</th>
<th>$G_{oc}$ [olf/pers]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1 Adults resting, if the percentage of smokers is:</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0 %</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>20 %</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>40 %</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>100 %</td>
<td>6</td>
</tr>
<tr>
<td>1</td>
<td>2 Adults, if metabolic rate is:</td>
<td></td>
</tr>
<tr>
<td></td>
<td>reduced (3 met)</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>medium (6 met)</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>high (10 met)</td>
<td>20</td>
</tr>
<tr>
<td>2</td>
<td>3 Children:</td>
<td></td>
</tr>
<tr>
<td></td>
<td>children under school age (2.7 met)</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>pupils (1…1.2 met)</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Table 8. Contaminants quantity from room objects, $G_{ob}$

<table>
<thead>
<tr>
<th>No.</th>
<th>Building destination</th>
<th>$G_{ob}$ [olf/m²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>1</td>
<td>Offices</td>
<td>0.02...0.95</td>
</tr>
<tr>
<td>2</td>
<td>Schools</td>
<td>0.12...0.54</td>
</tr>
<tr>
<td>3</td>
<td>Kindergarten</td>
<td>0.20...0.74</td>
</tr>
<tr>
<td>4</td>
<td>Meeting rooms</td>
<td>0.13...1.32</td>
</tr>
<tr>
<td>5</td>
<td>Houses</td>
<td>0.05...0.10</td>
</tr>
</tbody>
</table>

The outside air flow-rate $L_p$, in m³/h, can be computed and function of hygienic sanitary conditions follow as:

$$L_p = \frac{P}{(c_{i\text{max}} - c_{p\text{max}})\varepsilon_v}$$  \hspace{1cm}(16)$$

where: $P$ is the power of the indoor pollutant source, in mg/h; $c_{i\text{max}}$ – maximum admitted concentration of the most critical contaminant of room air, in mg/m³; $c_{p\text{max}}$ – maximum admitted concentration of the most critical contaminant of outside air, in mg/m³.

To determine the time evolution of the contaminant concentration $c_i$ in indoor air two hypotheses are assumed:

- constant pollution in time, where the balance equation within an infinitesimal time interval $d\tau$ is:
  $$L_p c_p d\tau + P d\tau - L_p c_i d\tau = V dc_i$$  \hspace{1cm}(17)$$
  where $V$ is the room volume.
  Integrating the equation (17), with the initial condition $c_i = c_p$, for $\tau = 0$, we obtain:
  $$c_i = c_p + \frac{P}{L_p} \left(1 - e^{-n}\tau\right)$$  \hspace{1cm}(18)$$
  where $n$ is the air exchange rate.
  - instantaneous pollution at moment $\tau = 0$; consequently, the contaminant initial concentration is given by the equation:
\[ c_o = \frac{P}{V} \]  

(19)

The balance equation for an infinitesimal time interval \( d\tau \) is:

\[ L_p c_p d\tau - L_p c_i d\tau = V d c_i \]  

(20)

Integrating equation (20) with the initial condition \( c_i = c_{io} \) for \( \tau = 0 \), is obtained following expression:

\[ c_i = c_p - c_{io} e^{-\alpha \tau} \]  

(21)

4.2 Computer program COMFORT 2.0

The computer program COMFORT 2.0 allows to determine the outside air flow–rate and air exchange rate for the ventilation of a room and the variation in time of contaminants concentration of room air both on the basis of the mathematical model described above and on some national norms (I 5, DIN 1946), as well as to analyse the influence of different parameters on these characteristics.

- The inputs data are: geometrical characteristics of the room, in m; number of occupants; activity type; room category; outside air quality, in dp; ventilation system type; ventilation efficiency; smokers existence in room.

- The results of program are the following: outside air flow–rate; air exchange rate; polluting substances of indoor air; time variation of \( CO_2 \) concentration of room air.

4.3 Numerical application

It is considered an A category room with geometrical dimensions \( 10 \times 10 \times 2.7 \) m, where there are 11 persons having an intellectual activity, and smoking is forbidden. Production rate of \( CO_2 \) for the occupants is of 15 l/(h-pers) and \( CO_2 \) concentration in outdoor air has the value of 350 ppm. The floor finishing is made of parquet floor or PVC.

A comparative study for computation of outside air flow–rate and indoor air quality control according to the European Standard CEN and national norm I 5 and DIN is performed using the computer program COMFORT 2.0.

The values obtained for the outside air flow–rate and the air exchange rate are reported in Table 9. In Figure 1 is represented the variation of outside air flow–rate function of the indoor and outdoor air quality. Figure 2 shows the time variation of \( CO_2 \) concentration in room air.

<table>
<thead>
<tr>
<th>Computation norm</th>
<th>Method</th>
<th>( L_p ) ([ m^3/h] )</th>
<th>( \alpha ) ([ h^{-1} ] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>CEN 1752</td>
<td>Air quality – parquet floor</td>
<td>2306</td>
<td>8.54</td>
</tr>
<tr>
<td></td>
<td>Air quality – PVC floor</td>
<td>8494</td>
<td>31.46</td>
</tr>
<tr>
<td>I 5</td>
<td>Number of occupants</td>
<td>330</td>
<td>1.22</td>
</tr>
<tr>
<td>DIN 1946</td>
<td>Surface of the room</td>
<td>600</td>
<td>2.22</td>
</tr>
</tbody>
</table>

Table 9. Outside air flow–rate \( L_p \) and air exchange rate, \( \alpha \)

From Table 9 it is to be seen that the outside air flow–rate computed according to norm I 5 has the smallest value, leading to the highest values of \( CO_2 \) concentration of room air. This \( CO_2 \) concentration determines a state of strong tiredness and head aches for the occupants.

5 Conclusions

Computer model developed offer the possibility of detailed analyses on olfactory comfort in enclosed spaces, being of a real use for the design and research activity and in the environmental studies. Results show that the microclimate in rooms influence not only the comfort but also the health of the occupants, and preserving the comfort para-
meters at the optimal values is the mission of the engineer for designing and operating of HVAC systems.

The indoor environment is influenced by the way the equipments are designed, produced and operated. That is why it is necessary to decide upon the equipments that are able to give the proper microclimate conditions, permanently observing the elimination of all secondary effects (professional illnesses) that have negative influences upon human health.

It is possible at the design stage of HVAC systems and buildings to take into account most of the comfort criteria.

References:


