A BIO-INSPIRED VENTILATING ENVELOPE OPTIMIZED BY AIR-FLOW SIMULATIONS

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Summary
A bio-inspired ventilating envelope is presented. The ventilating envelope consists of a distribution and arrangement of a basic component. In order to examine and optimize the performance of the ventilating envelope, we simulated the airflow inside two different rooms for different cases of component numbers, locations and distributions. For the simulations we used the computational fluid dynamics (CFD) solution tool, Fluent, with the re-normalization group (RNG) \( k - \varepsilon \) and second order discretization schemes. Distribution of velocity profiles and mean age of air over various virtual planes for the different cases were analyzed and compared to the comfort level of a standard ventilation system. The analyzes show that, for specific cases, the fresh air is uniformly distributed due to a good mixing layer close to the inlet. Moreover, by choosing the right configuration of the components, it is possible to have either a diagonal or a vertical distribution of the mean age of air (MAA) in the middle of the room, thus, the ventilating envelope has the characteristics of two different standard systems being placed on the wall or at the ceiling.

1. Introduction
The primarily focus in current ventilation system developments is reducing indoor air quality problems with minimizing energy use (Addington 2000). Ventilation in buildings is provided either naturally or mechanically. In natural ventilation, the flow process is induces by wind and temperature (Liddament 1996), and the main negative aspect is the difficulty to control air flow. However, natural ventilation could be found in many buildings in order to provide fresh air. Mechanical ventilation controls air flow via systems that respond to the needs of the occupants. There are different ways to ventilate mechanically, such as extract-only, supply-only, supply and exhaust or balanced, and recirculation (Roulet 2008). Some of them have the risk of back draught from flues, and others require empty floor spaces in order to allow air flow from diffusers places in the floor (Liddament 1996). Mechanical ventilating systems include several components: fans, ducts, diffusers, air-intakes, air-inlets, air grilles, and silencers (Liddament 1996), where they have to be maintained from time to time (Roulet 2008).

The bio-inspired ventilating system acts as a breathing skin that has the ability to control the amount of intake and outlet of air through it (Badarnah et al 2007). The evaluated system in this paper could be considered as a combination of natural and mechanical ventilation, where the components create pressure differences in order to suck the air inside and the fresh air is moved from outside to inside through and via the skin. The integration of the system in the envelope creates a situation where the envelope is permeable, but still controlled.

The application of computational fluid dynamics (CFD) has been widely used in recent years with aiding in predicting ventilation strategies. One of the first studies using CFD methods for predicting air movement and heat transfer in buildings was done by Nielsen (1974).

In the present work, airflow simulations for rooms (3×3×3 m³ and 1×1×1 m³) with integrated ventilation system are presented. The 3×3×3 m³ room was chosen due to its minimal size as an occupied room, and the 1×1×1 m³ room was chosen for initial simulation tests that can be used later to compare with experiments in a similar room. The simulation tool, Fluent, was used with re-normalization group (RNG) \( k - \varepsilon \) turbulence models. Details on the \( k - \varepsilon \) model are given by Gatski et al (1996).

The tested ventilation system consists of components that suck air from outside to the interior spaces; these components are part of the building envelope. Section 2 presents the breathing skin with its components for ventilation, and it is based on the work done by Badarnah et al (2007). In the simulations section, different variation of intake and outlet distributions are shown, which resulted in determining the effective distributions...
of components for better air-flow circulation and lower mean-age of air (section 4). Finally, a discussion and the conclusions are presented in section 5.

2. Background

The bio-inspired ventilation system is part of the envelope and reacts to changing environmental conditions and influences the air pressure at the surface to perform a process of inhaling and exhaling, and it consist of a basic component with a special arrangement.

The Lung-Like-Chamber (LLC) consists of two surfaces attached to each other at their edges creating a specific volume in the basic component (Figure 2a). Piezoelectric wires are attached on the sucking surface of the lung like chamber. The sucking surface is controlled separately (Figure 2b&c). When a voltage is applied to the piezoelectric wires on the sucking surface, the lung expands and increases its volume and by that increases the inner and outer surface area. A low pressure is created in the lung which results in sucking the air inside the lung (Figure 5b). The air flows into the lung through shafts on the surface of the lung. The shafts are designed in a way that allows the air to flow in one direction; valves are attached to the inner surface of the shafts, when the air pushes on the inner surface outwards, the valves are contracted and closed. Stopping the voltage from the surface results in contraction and creating over pressure (Figure 5c), which results in expelling the air out of the LLC through the other side, where the air pushes on the inner side of the expelling surface and results in opening the valves. By this action the air flow is controlled to flow through the lung in one direction.

The expansion and contraction of the LLC is combined with the movements of the basic component (Figure 3a-d). When the lung expands the basic component deforms and opens to create a bigger volume on that side where the lung had expanded (Figure 6b). Creating a bigger volume increases the low pressure and increases the air sucking from the surrounding environment. When the lung contracts and creates over pressure inside (Figure 3c), the basic component is deforming and closing the side where the air was sucked inside the lung, and opening the other side (Figure 3d). In this way the skin sucks air from one side and expels it to the other side. The skin consists of LLCs that take air from outside to inside, and LLC’s that take air from inside to outside. In this way the air is exchanged continuously through the same system.

![Figure 1](image1.png) **The breathing skin at inhaling (far left) and exhaling (middle); at the right: the special arrangement of the components and a cross section.**

![Figure 2](image2.png) **The expansion and contraction of the Lung-Like-Chamber (LLC).**

![Figure 3](image3.png) **The process of air-exchange that occurs in the breathing skin, basic component and LLC combination.**
The main advantages of this ventilation system are its direct contact with the fresh air, where the air doesn’t have to flow through ducts and long distances to get to the occupied places, and the system has fewer components involved in the ventilation process than other standard systems. The system creates a controlled permeable envelope, where its porosity reacts to the interior needs and requirements of the occupants in terms of air quality.

3. Simulations

3.1 Geometry of Rooms

Two different rooms were considered in the simulations. The first room is a 1 m³ testing room with equal width (x-direction), length (z-direction) and height (y-direction). The second room is a standard room with width, length and height being all 3 m. The origin (0,0,0) was placed on the right back bottom corner of the rooms. The components of the simulated ventilating systems, such as the LLC or the openings of a standard ventilating system, were placed on the front wall for both rooms, the xz plane.

3.2 Lung-Like-Chamber (LLC)

3.2.1 Geometry and Inlet Conditions

A schematic representation of LLC geometry is given in Figure 4. Each LLC consists of 17 openings with velocity vectors being inclined in x-, y- and z-axis as shown in the figure. Each opening has a velocity vector of 0.2 and 2 m/s in the case of the testing and standard room, respectively. It is notable that the simplified representation of the geometry of the LLC was considered. Thus, velocity vectors with different angles were considered expelling air in or out, while the original spherical shape of the component was neglected. It is also noticeable that there are two types of LLC’s, the first expels air inside the room (LLC-in), and the second expels it outside (LLC-out). In principle the two types are identical, except that the direction of the velocity vectors is flipped. The airflow angles at the openings, as shown in Figure 4 for any axisymmetric line, relative to the axisymmetric line are 30°, 60°, 90°, 120° and 150°.

Figure 4 LLC characteristics considered for the simulations. (middle) Velocity vectors through the middle section. (right) LLC’s holes distribution and amount.

3.2.2 Configuration

Equal numbers of LLC-in and LLC-out were considered in all of the simulations for each room. A summary of the different cases simulated is given in Table 1, and the configuration and number of the LLC’s for the different cases is shown in Figure 5.

Figure 5 Numbers 1-13 present different cases of LLC configurations; Number 14 is a scheme of a standard ventilation system.
3.3 Standard Ventilating System

An additional simulation of the airflow in the standard room with a rectangular ventilating system was carried out for comparison matters. The height of the inlet and outlet is 0.2m and the width is 0.4m. The inlet has a flow rate of 0.0855 m³ (equal to the flow rate of cases 11-13). The inlet and outlet were placed in the middle of the front wall at distances 0.2m from the ceiling and floor, respectively (see Figure 5).

3.4 Solution Setup

3.4.1 Grid Spacing

A hexahedron cell has been chosen due to its homogeneity with the rooms. Different types of grid spacing were chosen: 0.01-0.05m for the testing room; and 0.1-0.3m for the standard room. The number of elements and nodes of the hexahedron cells are given in Table 1.

3.4.2 Approach

The approach that was used to treat turbulence in the rooms is the Reynolds averaged Navier-Stokes equations (RANS). The assumption in this approach is that flow quantities are averaged in time allowing fluctuating quantities from the mean term. These fluctuating terms produce additional turbulence terms that require closure models. Among these models, we chose the zero-equation model and the re-normalization group (RNG) \( k-\varepsilon \) in order to treat turbulence near the openings.

Convergence was reached when the normalized residuals reached below \( 10^{-3} \), and below \( 10^{-7} \) for temperature. Details on the computational time and number of iterations for the different cases are presented in Table 1.

<table>
<thead>
<tr>
<th>Room (m³)</th>
<th>( 1\times1\times1 )</th>
<th>( 3\times3\times3 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Airflow rate (m³/s)</td>
<td>0.0011</td>
<td>0.032</td>
</tr>
<tr>
<td>Configuration case (Figure @)</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Maximum Grid spacing (m)</td>
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<td>0.05</td>
</tr>
<tr>
<td>Number of elements ( \times10^3 )</td>
<td>141</td>
<td>162</td>
</tr>
<tr>
<td>Number of nodes ( \times10^3 )</td>
<td>153</td>
<td>174</td>
</tr>
<tr>
<td>Computational time (min)</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>Number of Iterations</td>
<td>85</td>
<td>70</td>
</tr>
</tbody>
</table>

4. Results

Results of the mean age of air (MAA) for the different cases of LLC configurations are presented in Figures 6 and 7. It is observed, in Figure 6, that the MAA is strongly related to the configuration of the LLC. Cases 3, 6 and 10, where the LLC’s were placed at the bottom of the wall, have the highest MAA compared to the other cases with the same number of LLC's. However, larger number of LLC's, and thus higher flow rates, doesn’t guaranty a lower MAA. As an example, in cases 4 and 8 the flow rates entering the room are, respectively, 0.032 and 0.0427 m³, even though, the MAA in case 4 is lower than in case 8. The circulation near the inlet, of case 8, causes the fresh air close to the front wall to be expelled through the outlet at higher flow rates than the rates at which air enters further inside the room.

Figure 7 compares between two different solutions for cases 11-13. In the first solution the zero equation with first order scheme was applied, and in the second the \( k-\varepsilon \) solver was addressed with the following discretization schemes: standard pressure; first order momentum; second order temperature; and second order turbulent kinetic energy and turbulent dissipation rate. The zero equation can be used as an initial solution of the problem, then \( k-\varepsilon \) with second order discretization schemes is used in order to account for convection and diffusion of turbulent energy in the solution. Nevertheless, it is possible to use the zero equation for case 12 if only the MAA over the total volume is of interest.

It is notable that the MAA of case 12 is the lowest among all other cases with LLC’s. However, this doesn’t necessarily mean that the distribution of the comfort level of case 12 is the best. In order to evaluate the

comfort level of case 12, additional simulation for a standard ventilating system, such as case 14, was considered for comparison matters.

Results of the MAA and flow velocity profiles for cases 12 and 14 are presented in Figures 8 and 9. The values in Figures 8(A) and 9(A) were calculated on the central vertical line, and in Figures 8(B) and 9(B) on the central horizontal line in the \( z \)-direction. In Figure 8 it is shown that the MAA of case 12 is higher than case 14, along the chosen line, however, the distribution of the MAA of case 12 is uniform. This means that fresh air is more uniformly distributed in case 12 than in case 14. This can be explained by the better turbulent mixing produced in case 12 due to the distribution of the inlet openings over larger distances with varied angles of airflow inlet and outlet. As a result, a noticeably lower mean air speed is obtained in case 12 as shown in Figure 9.

![Figure 6](image1)

**Figure 6** Mean and maximum age of air for cases 1-10.

![Figure 7](image2)

**Figure 7** Mean and maximum age of air for cases 11-13; left: zero-equation; right: RNG with second order discretization schemes.

Figure 10 and 11 show isolines of the MAA in the \((-x)\) and \((-z)\) planes respectively. The figures compare isolines from case 12, on the right, with isolines from case 14, on the left. It is also notable, in Figure 10, that more isolines of the fresh air, in case 14, are located in the upper part of the room. Except this observation, the two plots in Figure 10 seem to have similar trend. However, a basic difference is noticed in Figure 11 between the isolines of cases 12 and 14. The change in the MAA isolines is diagonal in case 14 (left plot of Figure 11), whereas vertical in case 12 (right plot).

Figure 12 presents particle trace from the upper LLC plane (inlet) colored by MAA. The airflow enters at different angles and then, due to the LLC’s that are situated at the bottom and expel air at different angles, the airflow moves almost vertically in the middle part of the room.
Figure 8  Variation of the mean age of air (MAA): (A) along the central vertical line; (B) along the central horizontal line in the $z$-direction.

Figure 9  Variation of the mean air velocity profiles: (A) along the central vertical line; (B) along the central horizontal line in the $z$-direction.

**Figure 10** Isolines of mean age of air (MAA) in the (-x) plane at $x = 2.5$ m; left: case 14; right: case 12.

**Figure 11** Isolines of mean age of air (MAA) in the (-z) plane at $z = 1.5$ m; left: case 14; right: case 12.

**Figure 12** Particle trace from the upper LLC planes of case 12, coloured by mean age of air.
5. Discussion and Conclusions

Simulations of 13 cases of different configurations, locations and numbers of components in a bio-inspired ventilating envelope have been carried out. By analyzing the MAA, of the different cases, it has been observed that increasing the amount of LLC-in and LLC-out does not guarantee a better distribution of the fresh air. Thus, the location of the different components has a significant effect on the distribution of the fresh air. For example, in case 13 there are almost three times the amount of components found in case 4, however, the MAA of case 13 is only a factor of two times lower.

Among the simulated cases we found that by increasing the amount of components, a larger distance between the LLC-in and LLC-out is required for effective ventilating. At short distances between the LLC-in and LLC-out, increasing the number of components results in higher rate at which fresh air is being expelled outside before mixing, in this case the component special property of sucking and expelling air at varying angles might become a disadvantage. Whereas, given the ‘right’ balance between the number of components and the distance separating the inlets and outlets results in a turbulent mixing layer which distributes the fresh air almost homogenously at each constant horizontal line parallel to the inlet plane.

An interesting result is the fact that when the LLC-in and LLC-out are, respectively, situated at the top and bottom of the wall, the isolines of the MAA show vertical distribution, which is a characteristic property of ventilating systems located at the ceiling.

Furthermore, improving the fresh air quality inside the room could be achieved via standard sliding windows, but the bio-inspired ventilating system is considered as a ventilating wall, where there is no need to open windows and no requirements for temperature difference during its operation.

In order to further optimize the ventilating envelope for specific operating conditions, the effect of inlet-outlet distance, other configurations and possibly simulations of occupied rooms need to be investigated in more details. Moreover, in this paper we only considered the inlet and outlet being at the same wall, whereas it is possible to look at the effect of components distribution on multiple walls. This is left for future work.

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References


