Full-scale measurements and numerical simulation of cross-flow ventilation of farm buildings in a cold, windy coast climate

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ABSTRACT: New demands in farming industry in Norwegian sub-arctic regions has caused a need for larger animal buildings. To minimize the cost of the buildings, they are built without insulation. Uninsulated animal buildings in cold climate raise an array of new engineering challenges. One challenge is to maintain the animal welfare. Because of the lack of insulation, the walls of the buildings are exposed to a high risk of condensation. This is met with a high ventilation rate to remove the excess moisture. The present study is performed on a farm at the coast in northern Norway. Numerical simulations of cross flow ventilation of an animal house are performed for several wind directions and for different openings. Both the internal and external air movements are simulated in the same simulation domain. The ventilation openings in the walls are varied to assure that the animals are not exposed to draught in periods of cold weather and high wind speed. The simulation results are used to develop an algorithm for automatic control of ventilation openings based on meteorological parameters. The air velocity inside the animal building was measured in the event of artificially produced wind pressure on the surface with the help of a fan.

KEYWORDS: Cross flow ventilation, numerical simulations

1 INTRODUCTION

Animal welfare of cattle has been studied by several. A useful parameter for assessing animal exposure to climate is the Lower Critical Temperature (LCT). “LCT is the temperature below which the animal will increase its rate of heat production above normal in order to maintain a constant body temperature” (Gregory, 1995). LCT varies according to wind speed, the condition of the coat of the animal and the feeding level. For cattle LCT is reported in table 1 (Holmes and Sykes, 1984)

Table 1. Lower critical temperatures (°C) for cattle (Holmes and Sykes, 1984)

<table>
<thead>
<tr>
<th>Wind speed [m/s]</th>
<th>Maintenance feed</th>
<th>2xMaintenance feed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dry coat</td>
<td>Wet coat</td>
</tr>
<tr>
<td></td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Coat depth 2 cm</td>
<td>9</td>
<td>17</td>
</tr>
<tr>
<td>Adult 400 kg liveweight</td>
<td>-9</td>
<td>4</td>
</tr>
<tr>
<td>Coat depth 2 cm</td>
<td>-2</td>
<td>7</td>
</tr>
<tr>
<td>Adult 400 kg liveweight</td>
<td>-19</td>
<td>13</td>
</tr>
<tr>
<td>Coat depth 3 cm</td>
<td>-7</td>
<td>3</td>
</tr>
<tr>
<td>Adult 400 kg liveweight</td>
<td>-36</td>
<td>20</td>
</tr>
</tbody>
</table>

Table 1 presents the air velocity in two steps 0.3 m/s and 3.9 m/s for dry cattle. This is usually the condition of the cattle in the houses in the study. The upper threshold value is probably also a limit of what is practical inside a building. If the air velocity should exceed 3.9 m/s, a number of...
other problems would arise, such as flying debris or dust. In this study, the preferred air velocity inside the animal house is therefore set to maximum 3.9 m/s in 0.7 m height.

During the last years there has been built several un-insulated animal buildings in Norway. The climate in Norway varies from cold to polar climate according to the Köeppen climate classification index. The combination of cold climate and the large moisture emission from the cattle increase the risk of condensation of water on the cold interior surfaces of the building. To avoid the condensation, the ventilation rate of the building must be high. To avoid the installation of a ventilation system, parts of the walls of the buildings are made semipermeable, thus the ventilation of the buildings is driven by the wind. The internal climate and the comfort of the animals is thus directly linked to the surrounding climate.

The indoor temperature should not fall below the LCT at the given feeding level and indoor air velocity. One can assume that the animal coat is dry when the animals are indoors. For high ventilation rates one can also assume that the outside and inside air temperature is the same. However, measurements of indoor air temperature together with outside air velocity shows that for lower ventilation rates there is a close correlation between the indoor/outdoor temperature difference and the wind velocity.

1.1 The building in the study

The building in the study is 29 meters long and 18 meters wide. Inside of the building, there is a section consisting of the milking area, which is ventilated separately and not included in the calculations. There is also a 1.4 meter fence dividing the building in two long rows where the cattle can walk freely around. The longest outer walls of the building consist of a semi permeable, slotted wall from the eave and 1 m down. The rest of the wall is non permeable to air.

2 METHODS

2.1 Numerical method

To simulate the wind field around and inside the building, a general-purpose finite volume CFD code was applied. The CFD code solves the incompressible, time averaged Navier-Stokes equations, using a \( k-\varepsilon \) turbulence model to close the equations. The turbulence model is known to compute excessive turbulence near the edges of the windward walls, which also can affect the downwind wakes. It is however widely used, and it is capable of producing realistic wind patterns around buildings. The number of grid cells in the simulations is around 3.6 million with grid refinement near the surfaces.

The simulation of the wind pattern around and inside the building is performed for 12 wind directions; 0, 30, 60, 90, 120, 150, 180, 210, 240, 270, 300 and 330 degrees. These simulations are performed with an inlet wind velocity of 15 m/s in 10 meter height outside the building.

To verify that the flow pattern inside the building remains independent of the wind velocity, there is also performed a range of simulations with inlet wind velocity varying according to table 1. In these simulations, the permeability of the wall and the wind direction is kept constant.

The inlet wind profile follows the logarithmic expression

\[
u(z) = \frac{U_h}{K} \ln \left( \frac{z}{z_0} \right) \]  

(eq.1)
where \( u(z) \) is the wind speed in height \( z \), \( z_0 \) is the roughness of the surface, set to 0.1m, \( u^* \) is the friction velocity set to according to table 1 and \( \kappa \) is the von Karman constant, equal to 0.4. The turbulence intensity at the inlet boundary is set to 5%. The outlet boundary is continuative, meaning that the normal derivatives of all quantities are set to zero. On the wall surface boundaries the boundary conditions are set to “no-slip” i.e. the velocity at the surface is zero. The lateral and top boundaries of the simulation domain have symmetry conditions.

Table 1. Friction velocities used in equation 1.

<table>
<thead>
<tr>
<th>( u(10) )</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>25</th>
</tr>
</thead>
<tbody>
<tr>
<td>( u^* )</td>
<td>0.43</td>
<td>0.87</td>
<td>1.30</td>
<td>2.17</td>
</tr>
</tbody>
</table>

2.2 *Permeable wall*

To avoid excessive use of grid cells, the slotted walls were modelled as a permeable wall with a pressure drop. The pressure drop over slotted walls of different permeability was found simulating the air flow trough the wall, using the CFD solver. The fraction of the wall open to flow and the air velocity was varied to produce the velocity dependent pressure loss curves. Miguel (1998) used a similar procedure on physical measurements of the pressure loss over insect screens.

2.3 *Full-scale measurements*

Full-scale measurements of the air velocity inside the building were performed with the help of a 1.5 meter radial fan which produced the wind pressure on the wall. The pressure was applied on a 3.4 meter section of the building.

3 RESULTS AND DISCUSSION

3.1 *Air flow around and inside of the building*

It is assumed that the air inside the building is well mixed and that the inside temperature equals the outside temperature. The air velocity inside the building has a spatial variability. It is therefore defined a residential zone were the climatic conditions should be better than outlined in

![Graphs showing air flow and velocity](image1.png)

Figure 1 a) position of the residential zone in the building b) Air velocity in the residential zone
The residential zone is where the cattle rest, and is indicated in figure 1a with tree lines positioned 0.7 meters above the floor. Figure 1b shows the air velocity along these lines for different wind velocities and a 50% permeability of the wall section. Figure 1b also shows the predicted velocity along the lines when 15 m/s is used as a reference velocity, marked with a C. The correlation between the simulated velocity and the predicted velocity with 15 m/s as basis is very good for 25 m/s and 10 m/s and somewhat poorer for 5 m/s. This means that the flow pattern is independent of the wind velocity and that it is adequate to use only the simulation with a velocity of 15 m/s in 10 meter height to assess also other wind velocities.

Figure 2 shows the maximum allowed wind velocity in 10 meter height outside of the building, above which the air velocity in the residential zone exceeds 0.3 m/s. A similar graph is produced for the 3.9 m/s threshold given in table 1. Combining the two graphs produces figure 3, which shows the allowed combinations of wind velocity ($u_{10}$), permeability of the wall and outdoor temperature ($T$) for wind direction 270°. A regression analysis of the data presented in figure 3 produces an algorithm for automatic control of the permeability shown in equation 2.

$$\text{permeability}(u_{10}, T) = 141.5 - 10.93 u_{10} + 0.2853 u_{10}^2 - 0.002486 u_{10}^3 + 10.75 T$$

### 3.2 Full-scale measurements

Figure 6 shows the air velocity measured longitudinally from the ventilation openings in 2.3 meter height and the simulated air velocity in the same height.

### REFERENCE

