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Numerical study on the ventilation performance of a livestock house built in porous panels in Cold Regions

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Abstract. This paper presents a numerical prediction on the assessment of natural ventilation on a livestock house built in porous panels, aided by Computational Fluid Dynamics techniques. A typical climatic environment in Cold Regions was taken into consideration. The ventilation performances have been assessed by the distribution of indoor air velocity, turbulence intensity and local mean age of air through the cases: the house without porous panels, with wind erosion porous panels, and with snow erosion porous panels. The study has found that the porous panels improve the indoor environment in term of the reduction of air velocity and turbulence, and the wind erosion panel performs better than the snow erosion panel. However, applying porous panels may have negative effects on air exchange effectiveness. The presented numerical model is easy to be constructed, flexible to investigate different case scenarios, and quick and cheap to get solutions.

1. Introduction

Cold Regions are part of the Earth system characterized by the presence of snow and ice at least part of a year. A broadly accepted definition of Cold Region is to use the 0°C isotherm in the coldest month of the year [1]. Climate in Cold Regions during warm and cold seasons is significantly different. In warm seasons, the climate could be mild. In cold seasons, the climate however goes to extreme, with the presence of low temperature, severe snow & ice, and strong wind. Tromsø is located over 300 kilometres north of the Arctic Circle at 69°40'33"N 18°55'10"E that is a typical city in Cold Regions. The warm season in Tromsø lasts less than 3 months, and the cold season about 5 month. The snowy period of a year lasts for 8 months, from October, the last year to May, the next year.

Porous panel systems like fences are widely applied to create a sustainable environment for human being, livestock and machinery under the harsh climate conditions in wintry Cold Regions. A fence is an artificial structure with openings of certain shape, size and distribution to effectively mitigate the damages caused by wind and sediments transported (i.e. drifting snow and accumulating ice). The significant feature of fences is in the form of windbreaks allowing the natural climate to be controlled [2-5]. Fence Porosity β, defined as the ratio between the perforated area and the total area of the fence screen, is widely recognized as the most influential factor determining the characteristics of windbreak and the performance of the fence [2] [4] [6].

An optimal fence should offer the possible maximum wind reduction over the possible longest shelter distance. These are two contradictory factors that maximizing wind reduction will sacrifice the length of the shelter distance. The concept of optimal porosity β_{opt} is to identify the porosity where the best balance between the wind reduction and the shelter distance is achieved. β_{opt} varies depending on the applications. For wind erosion fences, β_{opt} is in the range from 0.25 to 0.35 [2] [4] [6]. For snow erosion fences, β_{opt} is in the range around 0.5 [5]. The characteristics of windbreak induced by the porous panel system essentially affects the ventilation conditions in its confined space.

Many countries and societies have developed their standards related to ventilation for buildings. Norway follows the European standards. A recent movement of the European Committee for Standardization (CEN) standards is the publication of EN 19798:2017, dealing with the designs of natural ventilation in buildings (including non-residential buildings). A clear guidance of assessing the quality of air in a purely fence-confined environment is still absent today. Nevertheless, the utilization of porous materials in buildings to improve natural ventilation is increasing nowadays. In particular, for those natural ventilation dominant non-residential buildings. Porous materials like porous panels, ventilated clads and space boards are built in the buildings, together with walls and roofs to form an indoor environment, which ventilation and Indoor Air Quality (IAQ) can be assessed by the relevant standards.

Applying porous materials in livestock houses to improve the well-being of the animals is common practice in Cold Regions. These livestock houses are usually naturally ventilated. Attentions have been paid on the issues of the effect of the different porous materials and configurations, wind velocity distribution, the mean age of air (MAA), and thermal comfort, etc. [7-9]. These research works assessed the effectiveness of porous materials on natural ventilations, mainly focusing on the porous materials with the porosity of 0.5. This paper presents a study focusing on the assessment of ventilation conditions of a livestock house built in porous panels with different porosities, bearing in mind the significance of porosity influencing the performance of porous panels.

2. Methods

2.1. Feasibility of CFD technique

CFD technique has attracted increasing research and industrial interest today. Blocken B [10] described a bright future of the application of CFD technique in Wind Engineering, based on the research works done over the last 50 years. The feasibility of CFD technique on the performance of porous systems and indoor environment assessments have been proven by considerable researches with successes [8] [11-13]. Compared with physical experiments, CFD solutions create virtual testing models and virtual environments that require no cost on true model preparations and measurement equipment. Additionally, CFD solution provides detailed information in the calculated domain without similarity constraints, which is a big challenge for physical experimental tests. However, physical experiments are not dispensable, it is imperative that the accuracy and reliability of CFD solutions must be validated and verified against the related physical experimental tests.

2.2. Study case

Figure 1 shows the 2D domain for the study case. The livestock house was in the middle of the domain. The cross section of the house was the width of 9.6 m, the wall height of 3 m, and the roof ridge height of 5.2 m. There was a gap of 0.6 m between the wall and the eave, where the porous panels were situated. The size of the entire 2D domain was 60m high and 39.6 m long. Symmetry wall was applied to the top of the domain, which made half height of the domain needed to be modelled. The blockage ratio for the domain was less than 5%.

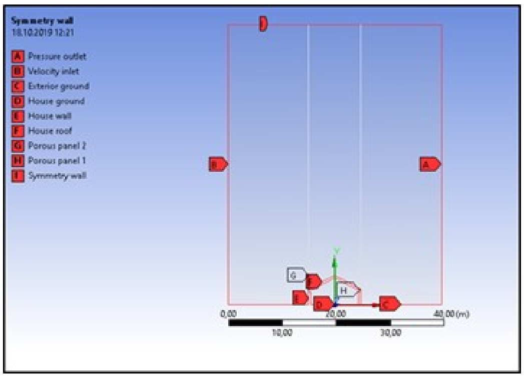

Figure 1. The creation of 2D domain.

For the convenience of study, the cell zone enclosed by the house was named as the interior zone, and the cell zone outside the house was the exterior zone.

Three case scenarios were investigated in this paper as follows:

- Case A: The house without porous panel ($\beta = 1.00$) that the gap is totally open
- Case B: The house with porous panel of $\beta = 0.50$ that the porosity is in the optimal range for snow erosion
- Case C: The house with porous panel of $\beta = 0.27$ that the porosity is in the optimal range for wind erosion

ANSYS FLUENT workbench v.18.2 was employed in the simulations.

2.3. Boundary condition

Yr is the joint online weather service from the Norwegian Meteorological institute and the Norwegian Broadcasting Corporation. According to its report, the maximum average wind speed in Tromsø was 4.3 m/s from September 2018 to September 2019, and the average temperature was -3.4ºC [14]. Neutral stability condition is assumed to apply the atmospheric boundary layer (ABL). Hence, the wind profile in this modelling follows the power law relationship as the following:

$$u = u_r(y/y_r)^{\alpha} \tag{1}$$

where: u is the wind speed at the height y, and u_r is the known wind speed (4.3 m/s) at a reference height y_r (10m). The exponent α is 0.143.

The inlet velocity profile in this study was described in equation (1). The inlet boundary condition, including wind velocity, turbulent kinetic energy, turbulent dissipation rate and specific turbulent dissipation rate, was written in programming C language and interpreted into the model.

At the pressure out, the Gauge pressure was set to zero. Both of the backflow turbulence intensity and the backflow turbulent viscosity ratio were set as 5% in the simulation. A no-slip condition was applied onto all of the walls in the domain.

2.4. Element arrangement and mesh independence

The arrangement of finite elements in CFD simulation is vital to the accuracy and computational efficiency. Figure 2 is the meshed domain. Quadrilateral elements were applied in the entire domain. Cares have been taken as follows:

- Symmetry wall was applied to the top of the domain that made half height of the domain needed to be meshed;
- Since the house interior zone was of interest for this study, dense elements were arranged in this area, and coarse elements were applied to the house exterior zone;
- In the ground wall region, elements were inflated from the ground-adjacent layer up to ten layers, with the total thickness of 0.06m at the growth rate of 0.2, which ensured each ground-adjacent cell's centroid within the viscous sublayer $y^+ < 5$. Such treatment was essential to the fidelity of simulating wall-bounded turbulent flow by $k - \varepsilon$ turbulence model [15];
- Apart from the ground wall, the elements near the regions of the rest walls were refined.

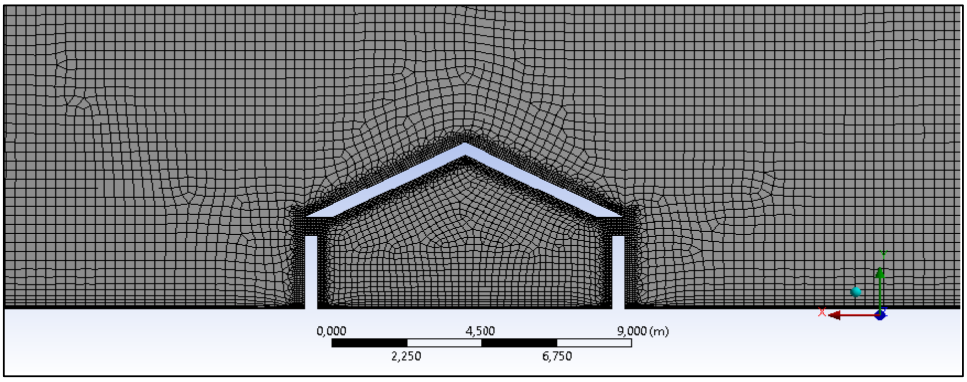

Figure 2. The arrangement of elements.

In the present CFD simulations, the mathematical model was governed by the RANS equations, describing time-averaged motion of fluid flow. The additional unknown variables (called Reynolds stresses) exhibited from the RANS were solved by the Standard $k - \varepsilon$ turbulence model. The model sensitivity analysis in this paper focused on the assessment of mesh independence. Mesh independence is that the numerical solution must be ensured to be independent of the mesh resolution. A good quality of mesh should be efficient and economic which is as close to the ideal mesh as possible. During the mesh sensitivity analysis, the velocity magnitudes and turbulence intensities at the positions of comparing vertical lines (y-axial) were selected as the monitoring variables. These positions of comparing lines were carefully chosen to reflect the sensitive regions in the domain, such as the porous panel influencing zones. The initial mesh guess was used by ANSYS default mesh, then increasing the quality of mesh by a factor of 1.5 as the second guess, and so on. When the solution was close to the one solved by the last mesh, decreasing the quality of mesh by a factor of 0.5 until the mesh independence was identified. Mesh independence was achieved at the number of elements of 33973.

2.5. Porous jump

The characteristics of the porous panel itself was not physically modelled in the simulations. It was treated as a pressure discontinuity surface by applying a porous jump condition, where momentum was absorbed from the flow as a momentum sink and added to the Reynolds-averaged Navier-Stokes (RANS) fluid flow equations.

For turbulent flow around a perforated plate like planar porous panels, the viscous loss term can be neglected [11]. Hence, the face permeability α for the porous panel was assigned as $1e + 20m^2$. The inertial resistance C_2 was associated with the resistance coefficient or pressure loss coefficient k_r as follows:

$$C_2 = k_r/\Delta m \tag{2}$$

$$k_r = 0.52\,(1-\beta^2)/\beta^2 \tag{3}$$

where Δm is the thickness of the porous panel, and β is the porosity.

Porous jump must be constructed as an interface in the modelling, which porous cells are treated as 100% open to the domain that differs the fact where the porous panel is only partially open to the airflow. Presuming the flow rate unchanged with or without the fence of $\beta = 0.27$, $u_{27\%open}$ $= 3.7u_{100\%open}$. Therefore, k_r needs to be adjusted to k_r':

$$k_r' = k_r\left(u_{27\%open}^2/u_{100\%open}^2\right) \tag{4}$$

Table 1 lists the calculated variables for the porous jump (the porous panel), where: α, Δm and C_2 are the input parameters for modelling the porous panels.

Table 1. The variables for the porous jump (the porous panel).

Item	Unit	Case A	Case B	Case C
Panel height $\boldsymbol{H}$	m	N/A	0.6	0.6
Porosity $\boldsymbol{\beta}$		N/A	0.50	0.27
Panel thickness$\boldsymbol{\Delta m}$	m	N/A	0.005	0.005
Pressure loss coefficient $\boldsymbol{k_r}$		N/A	1.56	6.61
Adjusted pressure loss coefficient $\boldsymbol{k_r'}$		N/A	6.24	90.67
Inertial resistance $\boldsymbol{C_2}$	m^{-1}	N/A	1248	18134
Face permeability $\boldsymbol{\alpha}$	m^2	N/A	1e+20	1e+20

2.6. Local MAA

In building physics, local MAA is defined as the average time for a parcel of air from a supply inlet are to any location in a ventilated room. It is used to define an air change effectiveness parameter named as the air change ratio (ACR).

MAA is not automatically included as a predefined variable in ANSYS FLUENT. It can however be defined in the pre-processing stage as an additional variable by the method in (5). MAA, denoted as T_{mean}, is obtained by solving the following advection equation as:

$$d\,T_{mean}/dt = 1 \tag{5}$$

In ANSYS FLUENT Solvers, scalar quantities are multiplied by the density ρ in the transport equation. Therefore, the advection equation is written as:

$$d(\rho T_{mean})/dt = \rho \tag{6}$$

The derivative with respect of time of the source is ρ that the integral itself is time. When integrated, the age scalar will equal to the residence time. Equation (6) was written in programming C language and interpreted into Fluent during the simulations. The term on the right hand side of equation (6) is the source term that should be assigned to the cell zones. A diffusivity term should be assigned to the properties of the air.

2.7. Other considerations

No-slip condition was applied to all of the walls. Standard $k - \varepsilon$ turbulence model was selected to address the 'closure problem' of the governing equation- RANS equations in the study.

The convergence criteria were assessed by monitoring the scaled continuity, x-velocity, y-velocity and turbulence kinetic energy residuals, and the convergence absolute criteria was 0.001. The solution initialization run the hybrid method at 10 of iterations. The ultimate solution was obtained on the Second Order Upwind discretization.

3. Results and discussions

3.1. Indoor air velocity

When indoor air velocity above 0.2 - 0.3 m/s, it may cause draughty indoor environments for livestock houses [16-17]. It has been reported that the risk of infection from diarrhoea, respiratory diseases increased when young calves (0-90 days old) were kept in draughty regions of a calf house [18]. Therefore, understanding the relationship between outdoor wind speed and indoor air velocity is important to livestock house design.

Figure 3 displays the contours of velocity magnitudes in the clip range from 0-0.86 m/s that was 80% reduction of the outdoor wind velocity of 4.3 m/s. From Figure 3, it can be observed that the indoor air velocities were reduced with reducing the porosity of the fence. Considering the breather height of 1m for the animals, only Case C offers the covering region of the air velocity less or equal to 0.86 m/s at such a height.

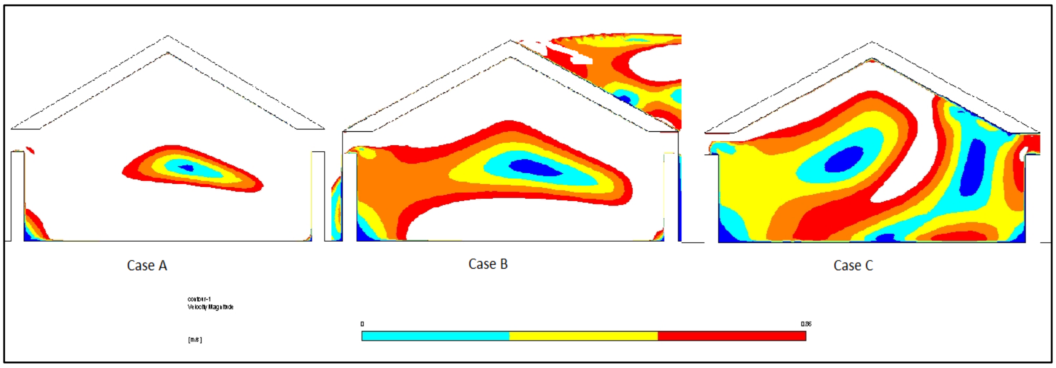

Figure 3. Contours of velocity magnitude in the clip range from 0 to 0.82 m/s.

Tromsø often experiences heavy wind in the cold seasons. The study found that this livestock house cannot create an indoor environment with the indoor air velocity less than 0.2 - 0.3 m/s, which may cause draughty indoor environment that is a potential risk for animal diseases.

3.2. Indoor turbulence

Turbulence is another factor to induce draughty indoor environment. High-level turbulence in livestock houses may cause animal diseases and discomfort. Fanger's draught model is commonly used and accepted in Europe that proposed a DR (draught rate) number to qualify the indoor environment. This model use turbulence intensity to evaluate the level of turbulence. CEN standards suggest that an average turbulence intensity 40% for draught comfort design in mixing ventilation. Figure 4 shows the contours of turbulence intensity in the clip range less or equal to 40% for the livestock house.

The turbulence level in the livestock was reduced with the reduction of the porosity of the fence. Case C create an almost entire indoor environment with the turbulence intensity no more than 40%, while Case A suffered the strongest turbulence level that its turbulence intensities were almost all above 40%.

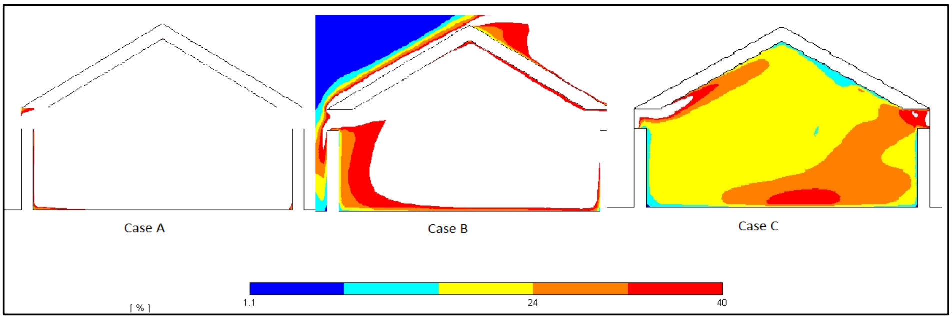

Figure 4. Contours of turbulence intensity in the clip range no more than 40%.

3.3. Indoor MAA

By adding equation (6) as a user defined scalar (UDS) into the simulations, the information of local MAA in the entire domain can be obtained. Figure 5 is the contour of MAA for Case C. According to the simulation results, the maximum MAA value is 24 seconds, 67 seconds, and 110 seconds for Case A. Case B and Case C, respectively. The presence of the fences has retarded the air travel in the house with significance.

Figure 6 is a comparison of the distribution of local MAA at the breath height of 1m for each case. The local MAA was increased with the reduction of the fence porosity. Wind erosion fence (with the porosity ≤ 0.35) creates a more complex structure of flow than snow erosion fence (with the porosity around 0.50) does, resulting in a region of recirculating air leeward of the fence [12]. It is the reason to explain why there was fluctuations on the pattern of Local MAA for Case C in Figure 6.

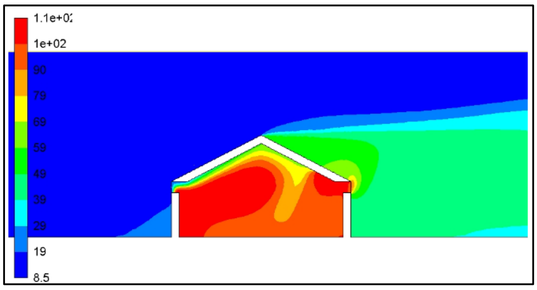

Figure 5. Contour of MMA for Case C.

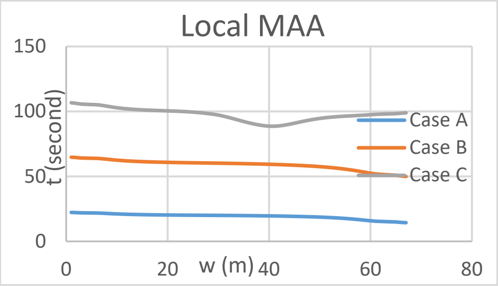

Figure 6.Comparison of the local MAA at the breath height of 1m.

4. Conclusions

This paper presents a numerical study through the analyses of indoor air velocity, turbulence and local MAA for a livestock house in Cold Regions. The conclusions are as follows:

1. The porous panel is numerically modelled as a porous jump, instead of creating a true physical panel model. By this mean, the CFD model is easy to be constructed in terms of domain creation and element arrangement, flexible to different scenarios, and quick and cheap to get solutions. By adding an additional transport equation into the modelling, the model can explicitly present the information of MAA in full resolution.
2. The built in porous panels significantly improve the indoor environment in terms of air velocity and turbulence if subjected strong outdoor wind. The study has found that the wind erosion panel performs better than the snow erosion panel. It is useful information that most porous materials used in livestock houses are the porosity around 0.5 today.
3. The use of porous materials in livestock house may have negative impact on indoor air change effectiveness (ACE).

4. The studied livestock house may cause draughty indoor environment under the wintry climate in Tromsø. Improvement of the livestock house in design and other measures is of necessity for the welfare of the animals.

The limitations of this study mainly lie on as follows:

1. The current work is informative, since the model has not been fully validated. The validation will be done in the future work.
2. Two equation based turbulence models are weak to predict airflow turbulence. As such, the results of the indoor turbulence in this work may suffer in question.

Acknowledgement

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