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CANMILK

GREENHOUSE GAS REDUCTION IN AGRICULTURE USING PLASMA-BASED SOLUTIONS

DELIVERABLE D5.1

AN OPERATIONAL MODEL OF THE BARN AND INTERNAL AIR QUALITY

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DISSEMINATION LEVEL		
PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

CHANGE CONTROL

DOCUMENT HISTORY

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V0	30.08.2024	Document drafted	Richard Williams	DU

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EXECUTIVE SUMMARY

This deliverable reports the results of WP5 Task 5.1, dairy barn building modelling, in which the test barn of WP4 Task 4.1 was modelled using computational fluid dynamics (CFD). The modelling provided insights into how methane (CH_4) levels and temperature within the barn fluctuate based on the amount of natural ventilation, influenced by wind and thermal buoyancy, and mechanical control through adjustments to the ventilation opening area.

A literature survey was undertaken to establish the range of CH_4 emissions produced within a barn and the amount of ventilation required within a barn. The range of CH_4 highlighted the large spread of emission rates and the important parameters which determine that rate. The ventilation rate determines the air quality within the barn and therefore the welfare standards within the barn, again a significant variation in values was found within the literature. The modelling of the barn was able to determine the impact of both variables on the air quality CH_4 concentrations and temperature within the barn.

The CFD modelling determined that the concentration of CH_4 within the barn has a linear relationship with the emission rate of CH_4. For example, doubling the rate of CH_4 emissions doubled the concentration of CH_4. The amount of ventilation is determined primarily by the wind speed, curtain opening and secondary by the temperature, this is not a linear relationship as the ventilation is also influenced by the geometry of the barn.

An analytical model was developed based on the relationships between the ventilation and CH_4 emission rate. This analytical model was shown to fit the simulation data and captured the primary effect of ventilation rate well, the effect of temperature was small and of secondary importance when predicting CH_4 concentrations. D4.1 measured the CH_4 centration to be very dilute and in the order of 20 ppmv and only increasing when the ventilation was significantly reduced to maximum levels around 175 ppmv, these numbers are complimentary to the numbers produced in the simulation providing validation of the results.

The CANMILK system will need to process all the air within the barn to capture the CH_4 emissions fully. In the final phase of this task, two mechanical ventilation strategies were implemented in the test barn. Natural ventilation was minimised by closing the roof and wall vents. The mechanical ventilation system successfully processed all the barn's air, effectively capturing all the CH_4. Both systems performed effectively; however, careful consideration must be given when designing the system to eliminate natural ventilation caused by wind. This is essential to reduce the amount of ventilating air required, because the mechanical system must counteract the natural ventilation to prevent CH_4 from escaping.

Overall, the computational model has provided an understanding of CH_4 emissions and temperature within a barn, the results were validated by the data of WP4 Task 4.1 and guided by the literature survey at the start of this deliverable. Processing of the barn air to capture all the CH_4 is possible and the required flow rates of the CANMILK system were determined.

DEVIATIONS

There were no major deviations from the workplan. The work plan was to:

"DU will construct a building model of a working dairy barn will be established using IES software and calibrated against internal barn air quality data obtained in WP4. Different modes of operation, layouts and strategies of air conditioning/processing will be explored (with technical support/data from Valio and VTT) to facilitate the CANMILK process. The model will be used to identify the most promising locations for installing air processing ducts for the system and scrubber. It will be used to produce a representative air quality (concentration, humidity temperature) profile for use in T5.2. This Task will be reported in deliverable 5.1."

The original plan was to use IES software, but CFD was ultimately chosen instead. CFD offers the advantage of detailed flow analysis, enabling precise tracking of CH_4 concentrations within the barn—an analysis that would not have been possible with IES and enabled the location of air processing ducts to be trialled.

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LIST OF ABBREVATIONS

ACRONYM	DESCRIPTION
CFD	Comuptaitonal fluid dynamics
D	Deliverable
DU	Durham University (project partner)
EC	European Commission
GHG	Green house gas
VTT	VTT Technical Research Centre of Finland Ltd (project coordinator)
WP	Work Package (of CANMILK project)
WT	Work task

1 INTRODUCTION

Methane (CH_4) is a potent green house gas (GHG). In 2019, agricultural activities in the EU accounted for 52% of the region's total CH_4 emissions and 5.1% of its total greenhouse gas (GHG) emissions. The majority (80%) of this agricultural CH_4 comes from enteric fermentation in livestock, and 85% of the enteric CH_4 is generated by cattle. Reducing CH_4 from cattle will therefore contribute significantly to addressing climate change both in the short and long term.

Within the EU there are ca. 77 million cattle and ca. 1.8 million farms meaning that there is a vast number of small agricultural CH_4 emissions sources which are diluted to very low concentrations. The CANMILK, direct air capture technology, will process air from cattle permanently housed in barns to remove the dilute CH_4 from the ventilated air. To be effective cattle will need to be housed within a barn and so it is envisaged that the first adopters of the technology will be large modern barns.

Deliverable 4.1 of CANMILK undertook and reported on a measurement campaign of a modern barn in Finland which housed 240 cattle. The deliverable reported extensive measurements of the CH_4 concentrations within and outside the barn, at several locations and heights, on different days and over different time periods.

This deliverable, D5.1, compliments the measurement campaign by using computational fluid dynamics (CFD) to explore the CH_4 concentrations within the same barn for several weather and operational conditions. This modelling method provides greater granularity of the flow structures and CH_4 concentration within the barn, whilst also allowing for controlled changes to the barns operation, a precise amount of CH_4 emissions and inclusion of the CANMILK air handling system into the model to identify possible locations for air ventilation extraction.

First this report explores the available literature regarding the amount of CH_4 produced from cattle, the required ventilation rates and the available measured concentrations within cattle sheds; this piece of work was undertaken by Durham University with support from Valio. Then the model of the barn is presented, details of the method, results, analytical model and conclusions; this work was undertaken by Durham University.

Secondly this report models the naturally ventilated barn. The design of a dairy barn is tailored to the local (Finland) climate to maintain adequate comfort and welfare of the cattle. Cows generate heat, moisture and CO_2 amongst other trace gases, necessitating adequate ventilation to maintain welfare and milk yield. Excessive heat, for example above 25 °C during the day will impact milk production. Barns require ventilation even during winter when the outside temperatures can drop below 0 °C.

Third the report implements mechanical ventilation as required by the CANMILK system. In order to capture all of the CH_4 produced within the barn then the CANMILK system will need to process all the ventilating air. The required volume of ventilating air will therefore size the CANMILK system. The amount of ventilation also directly impacts the concentration of CH_4, reducing the ventilation rate increases the concentration of CH_4, and decreasing the ventilation rate increases the CH_4, this is a balance which needs to be determined when operating a low GHG emission barn between comfort of the cattle, milk yield and concentration of CH_4. Increasing the ventilation increases the CapEx and OpEx cost of the CANMILK unit as more air needs to be processed, furthermore the CH_4 concentration decreases with increased ventilation making any CH_4 harder to capture.

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2 ASSESSMENT OF THE BARN ENVIRONMENT

This section is a brief survey of existing research into emissions from cattle and the amount of ventilation typically required for a cattle, barn both important parameters for the modelling of a barn. The survey includes secondary effects such as temperature and manure handling.

In the UK and EU there are no specified welfare limits. For example, in the UK, The Welfare of Farmed Animals (England) Regulations 2000 (S.I. 2000 No. 1870) Schedule 1, paragraph 13, states that: - air circulation, dust levels, temperature, relative humidity and gas concentrations shall be kept within limits which are not harmful to the animals.

2.1 CH_4 EMISSIONS FROM CATTLE

CH_4 emissions from the dairy industry are primarily due to enteric fermentation, a natural digestive process occurring in ruminant animals which produces CH_4 as a by-product. This process accounts for approximately 80% of the total CH_4 emissions associated with cattle [1]. As an example average milk yielding cows, with a body mass of about 600 kg and a daily milk yield of 30 kg per day, produce between 351 and 585 litters of CH_4 per day [1]. This translates to an emission rate of approximately 12-21 g/hour/cow (105-184 kg/year/cow). CH_4 emissions from ruminant livestock, can be addressed in a number of ways, dietary interventions and improved manure management are possibly the easiest intervention but are not able to fully remove the CH_4, conversely direct air capture as proposed by CANMILK could almost fully remove CH_4 emissions from housed cattle barns [2].

The amount of CH_4 produced by cattle rumination is well understood and there are several established methods to predict how much CH_4 will be produced for a given diet and the breed of cow [3]. Others have quantified the rate of CH_4 emissions from cattle using experimental measurements, these studies are summarised in Figure 1. The bars represent the range of emissions reported in each study. Notably, there is a significant variation in the reported rate of emissions, with some studies indicating as low as 5 g/hour/cow and others exceeding 50 g/hour/cow, therefore highlighting how the emissions from cattle can vary significantly between farms, breeds, diets, housing, weather and other factors. The wider ranges of reported emissions shown in Figure 1 highlights the variability of CH_4 emissions, therefore when designing a system to remove the CH_4 from the barn air then it is important to fully understand the cattle and conditions within the barn. The amount of CH_4 produced is not constant with time, for example, it is reported that CH_4 emissions increase after feeding when the fermentation process occurs and lessens while the animal is asleep.

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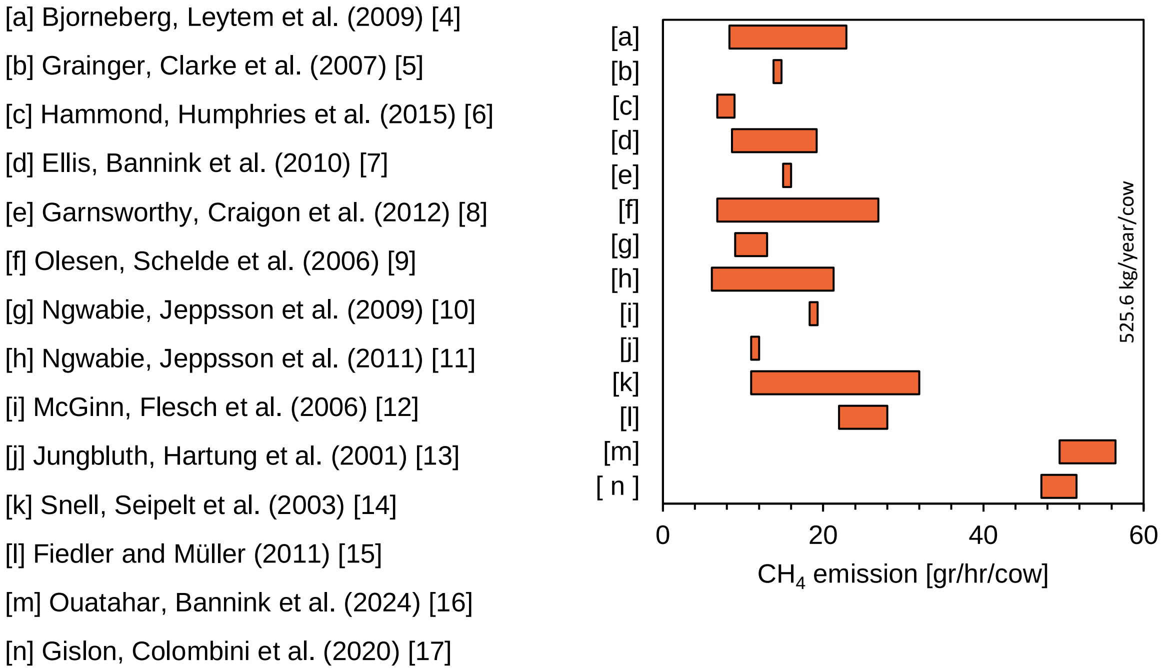

Figure 1, Reported CH_4 emission from cattle.

This image collates the reported CH_4 emission from cattle found in a literature survey. The numbers have been corrected to grams per hour per cow.

2.1.1 CH_4 EMISSION MODELS

The CH_4 emission from cattle depends on numerous variables, as such several models have been developed to estimate the CH_4 emissions of a cow.

A significant method was developed by Ramin [3], who derived equations, using mixed model regression analysis, to predict a variety of diets and feeding levels. The equation considers various dietary and animal factors that influence CH_4 production such as dry matter intake (DMI), organic matter digestibility, and dietary concentrations (dietary fat (EE), non fiber carbs (NFC), and neutral detergent fiber (NDF)). The model indicates that CH_4 production increases linearly with DMI. This equation and its variables provide a comprehensive method to estimate the daily CH_4 emissions from cattle based on feed intake and diet composition, however, the model does not address the impact of temperature or other secondary effects on CH_4 emissions from livestock. It primarily focuses on dietary and animal factors such as dry matter intake, organic matter digestibility, and dietary composition, including fat content and carbohydrate types, as determinants of CH_4 production in ruminants.

Another model by Eggleston [18], determined equations with increasing complexity depending on the level of information one may have for model inputs. Three complexity levels were specified, namely gross energy, dietary, and animal complexity. In the gross energy level (GEI), emissions are predicted using the animal's gross energy intake. In the dietary complexity level, diet characteristics (fiber fractions, crude protein, ether extract, and metabolizable energy), as well as gross energy intake. In the animal complexity level, milk composition (fat, protein, and non fat soluble), and animal information (body weight, and breed), as well as variables from the dietary level are included. Gross energy intake was selected as a measure of animal's feed consumption to be consistent and comparable with current national greenhouse gas inventories and to examine CH_4 emissions from an energy loss perspective which the various model of it based on the complexity level can be found in Moraes, *et al.* research supplementary files [19].

2.1.2 IMPORTANT PARAMETERS

The hourly amount of CH_4 produced by a cow, as shown in Figure 1, can vary significantly. Not all influencing factors are typically considered when considering the CH_4 emission from a single cow. The cows' diet and feed supplements have received significant focus. Fewer studies have considered external factors such as temperature and manure management. These latter secondary influences are harder to incorporated into the CH_4 emission models. This section discusses the parameters of significance which can influence the amount of CH_4 released from cattle.

2.1.2.1 DIET AND FEEDING STRATEGY

As discussed, feed has a close relationship to CH_4 emissions from cows [17]. Both the timing of eating and the composition of the feed will change the amount of CH_4 produced [20]. The inclusion of supplements in the feed is a way of altering the composition of the feed to reduce CH_4 emissions and so there is a large research focus on additives within animal husbandry to control emissions, one example showed how feeding interval as well as supplement varied the amount of CH_4 [20].

2.1.2.2 MILK YIELD

Milk production is closely linked to the amount of feed the cow eats. Therefore, since increasing the feed intake will increase milk yield, and the feed intake increases CH_4 emissions, then it follows that increasing milk yield will increase CH_4 emissions per cow. Milk yield per cow has continuously increased in many countries over the last few decades [21] and so it follows that the GHG emissions per cow have also increased. Nevertheless, it should be noted that the proportional increase of milk yield is much higher than the proportional increase of CH_4.

Increasing the milk yield leads to using diets which may also increase CH_4 emission from the animal. For example in one study [17], CH_4 production in grams per day (g/day) was significantly higher for cows fed the Parmigiano Reggiano (PR) diet (413 g/d) compared to those fed the corn silage (CS) diet (378 g/d). The alfalfa silage (AS) and wheat silage diets resulted in intermediate CH_4 emissions (396 g/d each). However, there were no significant differences in CH_4 emissions when expressed as grams per kilogram of dry matter intake or grams per kilogram of milk across the different diets. On average, cows produced 18.6 g of CH_4 per kg of DMI and 14.5 g of CH_4 per kg of milk [17].

2.1.2.3 TEMPERATURE

One of the important parameters is temperature. Temperature not only influences the welfare and milk yield of cattle, but it also affects the amount of CH_4 produced. A study from Sweden found that if the temperature was increased from 5 °C to 15 °C then the amount CH_4 emissions was reduced by 2.1 g/hour/cow [11], which could be as much as 10% of the total CH_4 produced.

The relationship between CH_4 emissions and temperature is complex and non-linear [1]. In one study, NH_3 and CH_4 concentrations were measured and analysed in a dairy barn in Northern Germany from 2010 to 2012. The researchers used multilinear and non-linear regression models to analyse the data, focusing on the dependency of emission rates on temperature. It was concluded that the relationship between CH_4 emissions and temperature is parabolic with a minimum CH_4 emission rate at 10°C. Emissions increased above 10 °C because higher temperatures can cause heat stress in cows, leading to changes in their feeding and resting behaviour. Emissions increased below 10 °C again likely due to changes in animal activity and metabolism due to clod stress [1]. The study showed the importance of the non-linear relationship between temperature when predicting emissions from cattle.

A cow's welfare is depending on the temperature in which it is housed. The range should be kept within limits to avoid heat stress and to maintain milk yield, outside these limits the yield of milk is vastly reduced. Within the literature there are several reported optimal ranges of ambient temperature for cattle barns. The highest milk yield is reported to be when the air temperature is between -4 to 18 °C (in some other recommendation between 0 to 20 °C). Temperature above or below this range will lead to a decrease in milk yield because the animal reduces its feed intake. In these cases, an ambient temperature above 26 °C dramatically reduced the milk yield by 20% [22, 23].

Another study, summarised in Table 1, reported the optimal barn temperature range in four different European locations [9], the values are averaged but farmers try to keep the barn temperature in these ranges.

Table 1, Reported temperature range with a barn [9]

LOCATION	TEMPERATURE RANGE (°C)
Netherland	2.5 to 17.1
Germany (central)	0.2 to 17.5
Austria	-1.6 to 17.9
Finland (south)	-7.3 to 15.8
Italy	1.3 to 25

2.1.2.4 HUMIDITY

Relative humidity, expressed as a percentage, indicates the amount of water vapour in the air. Similarly to temperature, high levels of humidity will result in heat stress which reduces movement and therefore the CH_4 emissions and milk yield [24, 25]. Cows can tolerate higher temperatures if the relative humidity is lower. An optimal relative humidity range of 40-80% is often recommended [26]. However relative humidity inside a well-ventilated barn will largely follow the outside weather conditions and so there is no control over the relative humidity. Humidity levels can therefore vary widely outside these limits.

Since temperature and humidity both effect the onset of heat stress then the Temperature-Humidity-Index (THI) can be used to assess the probability of heat stress, which can be calculated as:

$$THI = 0.8 \times T_a + RH(T_a - 14.4) + 46.4$$

Equation 1. THI [25]

Where T_a is the ambient temperature and RH is the relative humidity. Other equations for THI exist [27]. At a THI > 64 then the cow will undergo 'mild' heat stress, THI > 72 'moderate' heat stress, THI > 77 'severe' heat stress, THI > 84 then death will occur. There are charts and tables available to assess the THI for different temperature and RH combinations, as described by Noordhuizen, [25, 28, 29], these charts are often based on data produced by Dr Frank Wiersma (1990), Department of Agricultural Engineering, The University of Arizona, Tucson, Arizona, USA. Ventilation, shade and water must be provided to reduce heat stress in warm climates. It is imperative when the temperature increases above 19 °C that the heat stress should be considered. As an example, at an air temperature of 22 °C the high relative humidity of 90% will not produce heat stress, however if the temperature is increased only by only 2 °C to 24 °C then a relative humidity of 70% will cause mild stress.

2.1.2.5 BARN/HOUSING

Movement and physical activity of a cow throughout the day contributes to variations in CH_4 emissions. This includes walking, standing, and other movements within their housing area. Ngwabie et.al., [11] were able to correlate the activity of the cows with higher CH_4 emissions.

Since the barn design and housing system can influence the cows' movement then the CH_4 emissions and other emissions like NH_3 or N_2O are influenced by the cows' movement. For example, tied stalls with solid floor can reduce CH_4, NH_3 and N_2O emissions significantly compared to the cubicle housing system [30]. NH_3 and N_2O emissions are also harmful to animal welfare. The reason for this is Housing systems alter the movement of the cattle within the barn and reducing movement reduces emissions.

Poteko [31] reported that cows in a system where the movement is limited, such as tied housing where cows are restrained in individual stalls, will produce CH_4 it the range of 5 g/hour/cow and 8.1 g/hour/cow. Whereas, for loose housing where cows are free to move and lie down in individual cubicles, typically show higher variability and higher CH_4 emissions (5.88 g/hour/cow and 35.6 g/hour/cow), more than 4 times that of the restrained system.

The type of flooring in loose housing systems does not significantly affect CH_4 emissions. Both solid and perforated floors have been studied extensively, and no substantial differences were observed [31].

2.1.2.6 MANURE MANAGEMENT

The CANMILK system will capture CH_4 produced within the barn, primarily this is from the cattle but there are other sources, such as from fermentation of the manure. The handling of the manure is therefore important from a CH_4 emissions perspective. A study of two different barns one with a slatted floor and one closed, found that there was a much higher concentration of CH_4 underneath a slotted floor of the barn compared to above the floor [32]. Furthermore, the temperature of the stored manure will significantly change the emissions from a manure source, an increase in manure temperature will increase the CH_4 emission emitting from the manure [31].

The CH_4 emission from manure can be a significant percentage of the total emissions from the farm and the type of animal housing. From the CH_4 emissions released from the manure Ouatahar [16] showed that 44% of the CH_4 was directly from the cow excretion, 37% from the barn, 6% from manure management and 13% from the soil after spreading. This was for a system where the cattle were housed in a bedded barn. Other systems reported different percentages.

Separately from the CANMILK system, storage of manure will release CH_4 emissions. There are several parameters that have influence on the emission such as residence time of the manure in the storage facilities, ambient temperature, storage method (like anaerobic digestion and slurry tanks) and the type of manure. For example cows with a higher milk production contains more organic materials and therefore emits more CH_4 during storage. There are several actions that can reduce the CH_4 emission from manure storage including reducing storage time, using anaerobic digestion and/or covering the storing facilities. The indirect CH_4 emissions produced from spreading manure on land will vary due to the climate, soil type and how the soil is going to be used [16].

One effective method to mitigate the CH_4 emission is anaerobic digestion which captures the emitted CH_4 from barns and produces biogas (a renewable energy source). This approach can reduce manure CH_4 emissions by 59%, depending on the specific system and management practices. Frequent manure removal, proper storage to prevent anaerobic conditions, and techniques such as separating solids from liquids and ensuring rapid oxidation of manure significantly reduce CH_4 production [2].

2.2 VENTILATION OF CATTLE BARNS

It is important to provide enough ventilation to maintain the health and well-being of cattle in the barn. Ventilation regulates the temperature, remove excess moisture, and reduces the concentration of harmful gases like NH_3, CH_4, S or N_2O or dust. Inadequate ventilation can lead to poor respiratory health, heat, and excess moisture. Respiratory problems can be caused by dust, ammonia, and other harmful gases. Excess moisture will lead to damp, bacteria, and hoof problems. Poor thermal comfort will leave to heat stress and reduced milk yield.

In modern barns, it is preferred to use natural ventilation whilst some older barns used mechanical ventilation, but this can be expensive to operate as it requires energy and the associated GHG emissions.

The ventilation rate is dynamic and influenced by external and internal environmental conditions, such as the wind and temperature and so the management of the ventilation is essential. Barns are generally naturally ventilated and so in some climates this will need to be controlled, such as cold or hot countries. For example, at high temperature the ventilation requirement will be greater than at low temperature. Often there are mechanical systems to control the rate of ventilation for example openings, fans or air mixing systems can be installed. Geometry will also play a part with higher roofs allowing for better mixing and opening/closing being positioned to promote air flow. The CANMILK test barn used fans, automated moveable curtain walls and automated roofing ducts to control the ventilation within the barn. Since the ventilation rate is driven by wind and thermal gradients then there will be a difference between the night and day as thermal gradients may be higher at night when the external temperature falls [32]. Other aspects such as the floor type can change the ventilation, for example slats in the floor for manure handling will also aid to ventilate the barn.

There are no legal standards for ventilation rates of cattle barns but instead only a requirement for there to be sufficient ventilation to provide good welfare standards. The benefit to farmers is to maintain good levels of milk production and to prevent sickness often through the passive or dynamic control of the ventilation. The regulations of animal husbandry in agriculture are mainly related to the feeding or housing conditions of the animal. In the UK, The Welfare of Farmed Animals (England) Regulations 2000 (S.I. 2000 No. 1870) Schedule 1, paragraph 13, states that: 'air circulation, dust levels, temperature, relative humidity and gas concentrations shall be kept within limits which are not harmful to the animals.

Figure 2 provides a range of document ventilation rates of cattle barns from several sources. The numbers are mostly measured ventilation rates rather than required ventilation rates and are reported with significant scatter. The amount of ventilation is a function of the method of ventilation, which is dependent on the number, size and arrangements of the openings and the prevailing weather [15]. Within a barn there may be several sections for different purposes, such as a bedded areas for carves, so different sections within a barn may require different ventilation rates [33].

[a] Demmers, T.G.M., et al. (2001) [34]

[b] Fiedler, A.M. and H.J. Müller (2011) [15]

[c] Ngwabie, N.M., et al. (2009) [10]

[d] House, H.K. Dairy housing [23]

[e] Jungbluth, Hartung et al. (2001) [13]

[f] Snell, Seipelt et al. (2003) [14]

[g] Turnbull, J. and H. Huffman [33]

[h] Seedorf, J., et al. (1998) [35]

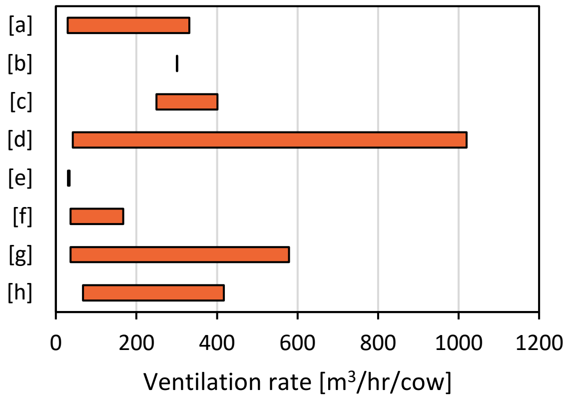

Figure 2, Reported ventilation rates of cattle barns

2.3 SUMMARY

This section has briefly investigated the amount of CH_4 produced by cattle and the reason for ventilation in cattle barns. This has illustrated how the amount of CH_4 produced and the required ventilation amount of ventilation can vary significantly. Therefore, when modelling the barn, it was important to consider and to understand the impact of a wide range of these two variables.

3 COMPUTATIONAL MODELLING OF CH_4 EMISSIONS FROM CATTLE IN A BARN

Computational fluid dynamics (CFD) allows for the simulation of complex fluid problems, it provides a means to interrogate detailed flow features and to rapidly change boundary conditions or geometries to assess their impact, it is therefore an ideal tool for this piece of work. The modelling is divided into the following three sections.

1. CH_4 concentrations within a naturally ventilated barn.
2. Influence of ventilation rates on the CH_4 concentrations within a naturally ventilated barn.
3. Mechanical ventilation and implementation of the CANMILK system.

3.1 THE BARN

The CFD modelling was of the same barn used in D4.1 of CANMILK, as such this works compliments the experimental campaign and allowed for detailed inspection of flow structures within the barn not depicted by the experimental campaign. The experimental results were also used for results validation. This test barn represented a modern European design which can be easily modified for the CANMILK system.

The test barn is a commercial farm in Pöytyä, in the Southwest region of Finland and was built in 2019. The barn permanently houses 240 cows which are inside all year round. It has automated retractable walls (curtains) and adjustable ridge ventilation (chimneys) meaning that the amount of ventilation can be adjusted for the weather conditions to maintain animal welfare and comfort levels. The building is approximately 33 x 91 meters. The animals are free to roam but have individual stalls for resting on a mattress and concrete isles with manure handling. Within the north-west corner of the barn there was a bedded area (wheat straw) for pregnant and sick cows. The building was not heated or cooled and there were 12 large fans inside the barn to promote mixing of the air. Further details of the barn and the cattle can be found in CANMILK D4.1. Images of the test barn are included in Figure 3.

3.2 CFD METHODS

CFD uses numerical methods to solve the Navier-Stokes equations of a discretised domain. The geometry generation and meshing were undertaken using ICEM CFD 19.2, computations and post processing were undertaken using ANSYS Fluent 2023 R2.

3.2.1 GEOMETRY / MESHING

A simplified 2-dimensional geometry of the barn was created in ICEM CFD 19.2. Computational modelling requires a balance between the number of features modelled and computational time to solve those details. The main objective of the CFD was to investigate the distribution of CH_4 within the barn with different weather and ventilation rates, for this reason only including the main barn structural features in 2D was sufficient to fulfil the objectives. In Fluent, a 2D simulation essentially has a depth of 1 m, therefore all boundary values are corrected to account for this depth.

Figure 4 shows the boundaries of the 2D computational domain. The large domain ensured that the boundary conditions had no influence on the flow structures around or within the barn. The inlet was positioned 4.5 x the barn width (BW) upstream of the barn and the domain outlet was positioned 5.5 BW downstream of the barn, the sky was simulated as a symmetry plane at 10 x the barn height from the ground.

Figure 3. Images of the test barn taken during the experimental campaign.

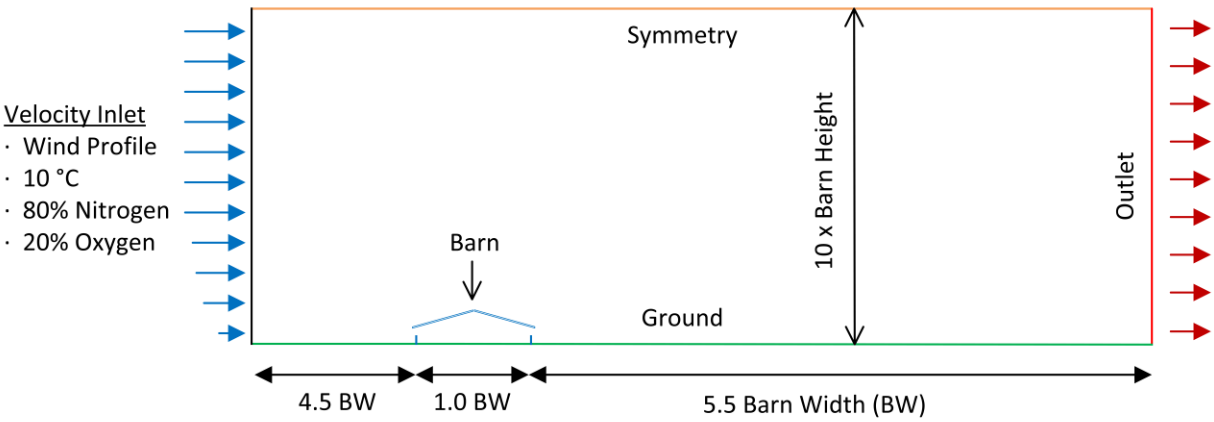

Figure 4, Boundaries of the computational domain.

Details of the barn boundaries are shown in Figure 5. The 2D simulation models the most important aspects of the barn, including cows or other features in 2D would not have made sense since these 3D structures would have prevented flow moving within the 2D plane. 3D would be required for example to model a cow, but the computational expense would be significant and was not warranted for this work. The following can be observed in Figure 5:

- The blue lines indicate the barn and roof, the opening in the roof is simplified to resemble a slot as opposed to the individual chimneys of the real barn; modelling of the real chimney in 2D would have meant incorrect flow structures across most of the roof, this simplified geometry enables flow to exit the ridge and for a realistic separation of flow over the ridge. The slot width was sized to give the same area as the individual chimneys. The real test barn chimneys had an internal dimensions of 0.9 m x 0.9 m.

- The orange line indicates the upstream and downstream walls which were altered in height to simulate the curtain opening and closing, pictured is the curtain fully open. Below the curtains were solid walls as pictured in Figure 3. The curtain walls increase in height when closing.

- The solid black line is the floor.

- The red line represents the stalls where the cows rest, these 3 sections were heated to simulate the heat produced by a cow.

- The 6 purple squares are the CH_4 emission inlets, at an appropriate height representing 6 cows standing up.

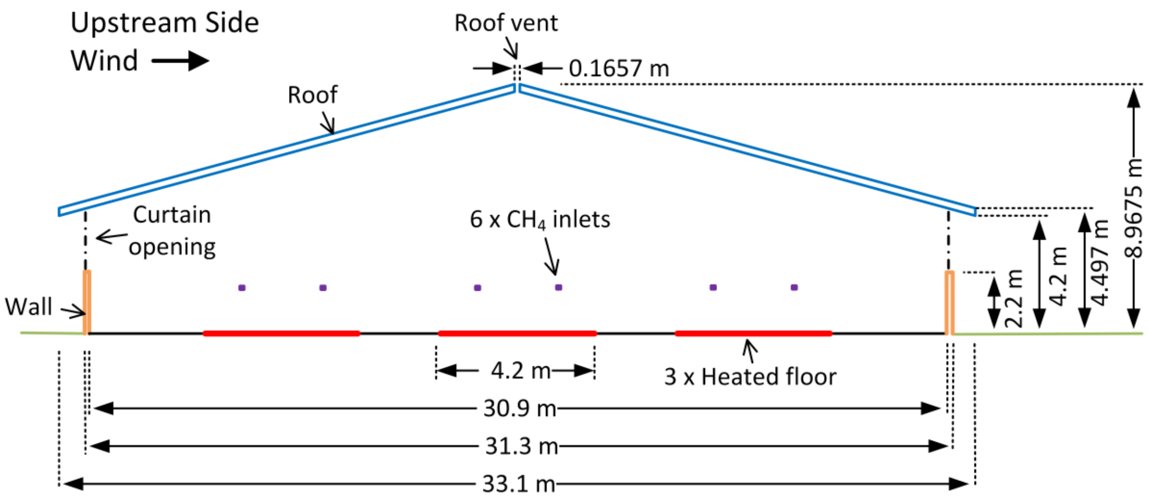

Figure 5, Details of the 2D barn.

The domain was discretised using a hexahedral mesh with a y-plus of <1 on all important surfaces. Figure 6 shows details of the mesh within the upstream half of the barn. The mesh had 422506 cells (425288 nodes) for the fully open walls case pictured.

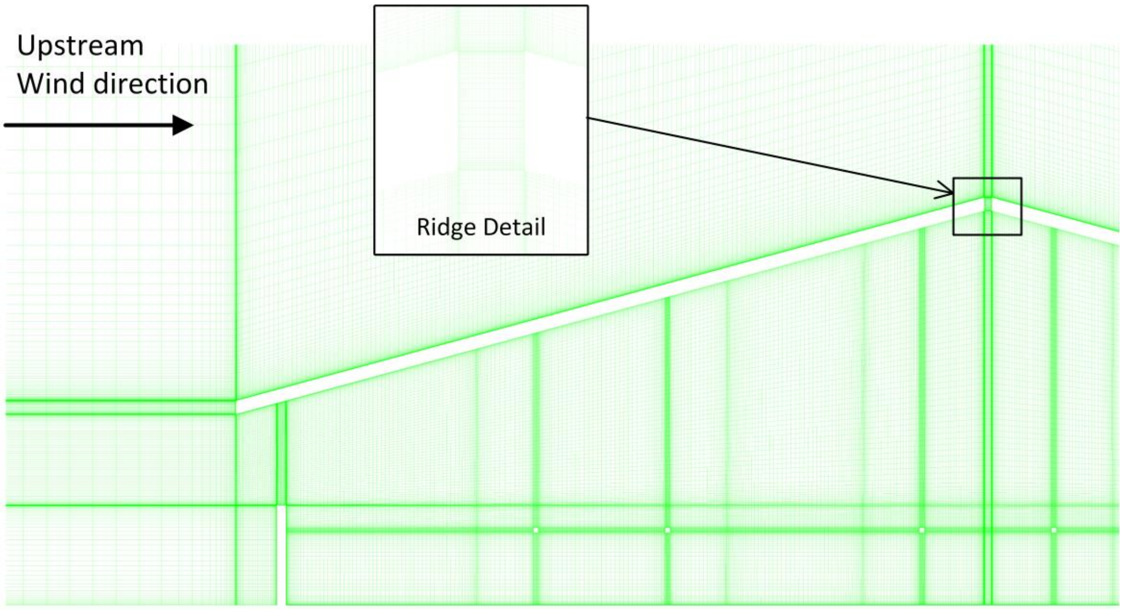

Figure 6, Detailed mesh.

3.2.2 BOUNDARY CONDITIONS

Inlet Wind Profile

The barn was modelled with a wind speed from 1 – 5 m/s, no wind gusts were simulated, the turbulence intensity was 5% with a turbulent viscosity ratio of 10 for the full height of the inlet boundary layer. The upstream wind velocity varied with height, with increasing speed from the ground. This wind profile was defined by a Wiebull function, Equation 2:

$$v_2 = v_1 \frac{ln\left(\frac{h_2}{z_0}\right)}{ln\left(\frac{h_1}{z_0}\right)} \quad \text{Equation 2}$$

Where z_0 is the roughness length dependent on the terrain. A roughness of $z_0 = 0.3$ was selected, suitable for agricultural land with trees or forests and uneven terrain, corresponding to conditions at the barn used in the CANMILK campaign as viewed in Figure 3. v_1 is the reference wind speed at h_1. The reference height was set at 10 m from the ground as this is the standard elevation for wind speed recording, i.e., a wind speed of 5 m/s means that the wind velocity is 5 m/s at 10 m from the ground, the wind speed will be higher above 10 m and lower towards the ground. Finland has a prevailing wind direction from the southwest, perpendicular to the length of the barn as seen in Figure 3. This wind direction allows for the 2D model to represent the most common wind direction for this geographical location.

The inlet air was defined as 80% Nitrogen and 20% Oxygen.

Methane inlets

The 100% CH_4 was discharged into the simulation from 6 discreet locations, with a length of 0.1 m, at 1.7 m from the ground. These locations simulated 6 cows standing within the stalls. The temperature of the CH_4 was 37 °C (the resting body temperature for a cow) for all calculations.

The CH_4 mass flow rate was determined by the average rate of CH_4 emissions per cow. Three rates of CH_4 emissions were computed, 100, 200 & 300 kg/yr/cow. Considering the length of the barn and 240 cows this meant that for each individual location the emission rates were as detailed in Table 2.

Table 2. Rate of computed CH_4 emissions

RATE OF CH_4 FROM A COW	SIMULATION RATE OF CH_4 PER INLET	SIMULATION RATE OF CH_4 TOTAL
100 kg/yr/cow	1.4 x10^{-6} kg/s/m	8.4 x10^{-6} kg/s/m
200 kg/yr/cow	2.8 x10^{-6} kg/s/m	16.8 x10^{-6} kg/s/m
300 kg/yr/cow	4.2 x10^{-6} kg/s/m	25.2 x10^{-6} kg/s/m

Heating

Due to buoyancy of the gasses, it was important to include the main sources of heat in the simulation. The test barn was unheated however there were still sources of heat within the barn, the cattle being the largest source of heat. Therefore, the heat from the cows was considered within the simulation, it was assumed that each cow produced 1.5 kW of heat at 37 °C [36]. The amount of heat emitted by a cow has a complex relationship with many factors therefore this value was a good approximation for this work. Since the cows where not geometrically simulated then the heat energy was added to the simulation by heating the floor of the individual stalls, the red lines in Figure 5. Considering the length of the barn and 240 cows and the surface area of the floor then the stalls were heated at 240 kW/m^3.

3.2.3 CFD METHODS

The simulation, in Fluent 2023 R2, was steady state and time dependent variables such as wind gusts or CH_4 emission variability were not modelled transiently. The pressure-based solver was used, which is suitable for low Mach number flows. The CFD settings followed the recommendations in the Ansys Fluent theory guide.

The time averaged Reynolds-averaged Navier–Stokes equations (RANS equations) required a viscous turbulence model to solve the turbulent flows. This was undertaken using the generalized κ-ω two equation model (GEKO). This model is suitable for both near wall and free stream flows.

Three species were included in the simulation, oxygen, nitrogen and CH_4. The density was considered as an ideal gas, with molecular weights of 31.9988, 28.0134 and 16.04303 kg/kmol respectively.

Species transport was required to allow for the addition of CH_4, this included the following models: ‘diffusion energy source’ to take account of the effect of enthalpy transport due to species diffusion; ‘full multicomponent diffusion’ to account for chemical species diffusion, especially important within laminar flows; and ‘thermal diffusion’ to account for the effect of molecular weight on diffusion around a heat source.

The energy equation was solved to account for thermal effects of the different temperature flows, solar heating of the barn was not accounted for, and the temperature of the oncoming wind was uniform. Gravity was accounted for as the flow was determined to have strong buoyancy contributions through examination of the Gradhof number. To account for this the operating density, in the body-force term of the momentum equation was set to zero which suppressed the subtraction of hydrostatic pressure from the gauge pressure, introducing a hydrostatic pressure component, i.e., the density varied with height. The variation in density with height meant that an outlet vent was used as the downstream boundary condition to prevent reverse circulations in the free stream.

Simulation convergence was determined by inspection of the residuals and concentration of CH_4 within the domain, residual of at least the 5^{th} order, and the area weighted average concentration of CH_4 within the entire domain reaching a steady state was achieved. Typically, all simulations were run for 10,000 iterations, the large number of iterations was required due to the very low mass flow rate of CH_4 compared to the inlet wind therefore taking a long time to converge.

3.2.4 SIMULATIONS

3.2.4.1 NATURALLY VENTILATED BARN

Four simulation variables were adjusted: wind speed, wind temperature, CH_4 emission and curtain opening. A full factorial of all variables was conducted and so in all 360 different simulations were undertaken for the naturally ventilated barn. The values are included in Table 3.

Post processing of the results was undertaken using fluent to integrate or average the results before plotting. Integration was undertaken either by area or mass averaging depending on the variable.

Table 3, list of simulations variables and their values

VARIABLE	VALUES
Natural Ventilation cases	
Wind speeds	1, 2, 3, 4 & 5 m/s
Wind Temperature	5, 10, 15, 20, 25, 30 °C
Curtain Opening:	100, 50, 25, 10%
CH_4 Emissions levels (Table 2)	100, 200, 300 kg/yr/cow
Mechanical Ventilation cases	
Wind speeds	1, 5 m/s
Wind Temperature	5, 25 °C
Curtain Opening:	10%
CH_4 Emissions levels (Table 2)	100 kg/yr/cow
Mechanical Ventilation	0.25, 0.5, 1, 2, 4 & 6 barn air exchanges per hour 0.015, 0.030, 0.060, 0.120, 0.241 & 0.602 m^3/s

3.2.4.2 MECHANICALLY VENTILATED BARN

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The inclusion of mechanical extraction was investigated in two different positions, firstly converting the ridge vent into a vent outlet, and secondly using a 1x1 m square, with a centre of 5 m from the ground, in the middle of the barn simulating a ventilation duct. In both cases there was no natural ventilation through the ridge. Figure 7 shows the location of both vents, but only one type of vent was included in each of the simulations. In both cases the outlet mass flow rate was controlled to set the rate of mechanical ventilation.

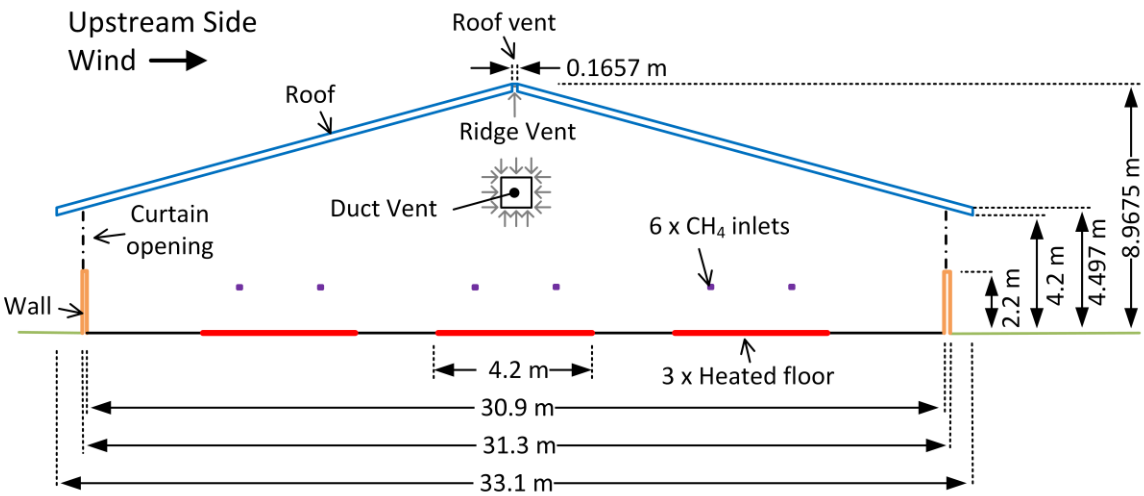


Figure 7, Details of the 2D barn with mechanical ventilation at the ridge and a central duct.

The simulated variables are included in Table 3. The mechanical ventilation simulations were undertaken at two wind speeds and two wind temperatures. Both curtains were 10% open to allow for air to enter the barn. One CH_4 emission rate was chosen (100 kg/yr/cow).

Six extraction rates were simulated, chosen to provide a wide range of ventilation rates, these were 0.25, 0.5, 1, 2, 4 & 6 barn air exchanges per hour. Again, a full factorial of these parameters was undertaken with a further 48 simulations in total.

3.3 METHANE CONCENTRATIONS WITHIN A NATURALLY VENTILATED BARN

This section provides the results of the naturally ventilated barn, which corresponds to the conditions of the experimental barn. First the sensitivity to the amount of CH_4 emissions is investigated.

3.3.1 INFLUENE OF CH_4 EMISSION ON THE CONCENTRATION OF METHNANE WITHIN THE BARN

The average concentration of CH_4 is shown in Figure 8, for a single wind speed and wind temperature, for the four different curtain wall settings. The x-axis corresponds to the amount of CH_4 produced by the cattle. 100% curtain opening is the same geometry as shown in Figure 5, 10% open means there is only a small gap at the top of the wall.

Figure 8 shows that there is a linear relationship between the mean concentration of CH_4 within the barn and the amount of CH_4 being produced by the cows. If the amount of CH_4 being produced within the barn is doubled then the concentration of CH_4 within the barn will double. This linear relationship means that the specific concentration for a specific amount of CH_4 released can simply be scaled from these results.

Changing the curtain opening reduces the amount of wind, or ventilation, entering the barn. This is a complex relationship driven by the aerodynamics of the structure and is therefore not a linear relationship, i.e., halving the opening does not double the concentration of the CH_4. Nevertheless, closing the curtains significantly increases the concentration of CH_4 within the barn, closing the curtains from fully open to 10% open increases the concentration of CH_4 by more than 600%.

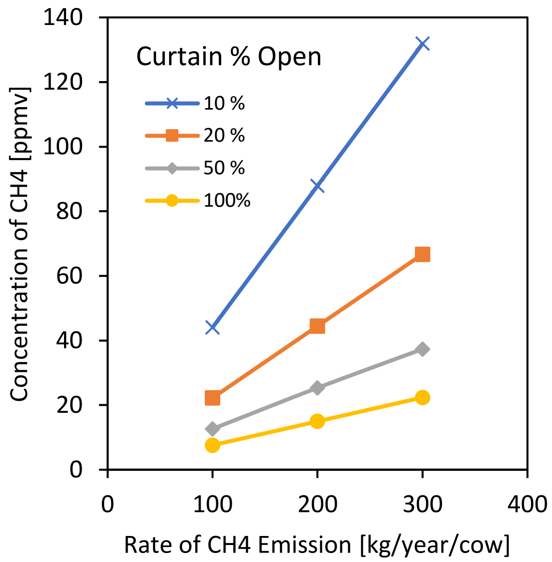
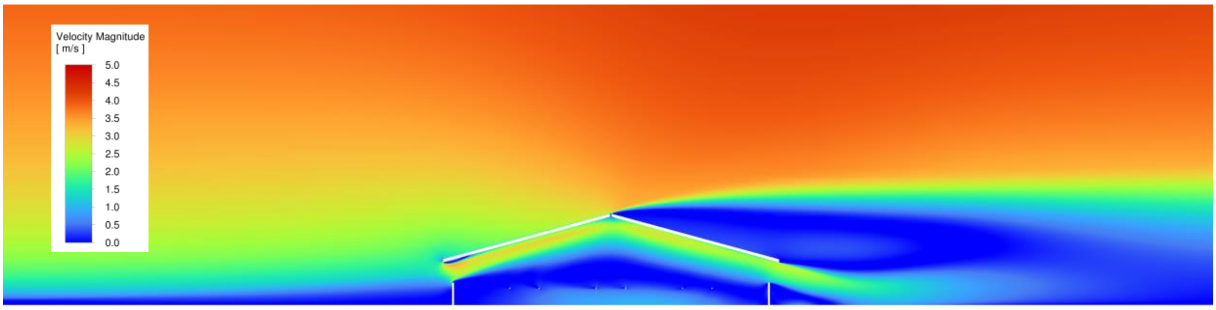


Figure 8, Influence of CH_4 emission mass flow rate on the average concentration of CH_4 within the barn. Ambient temperature = 20 °C. Wind speed = 3 m/s.

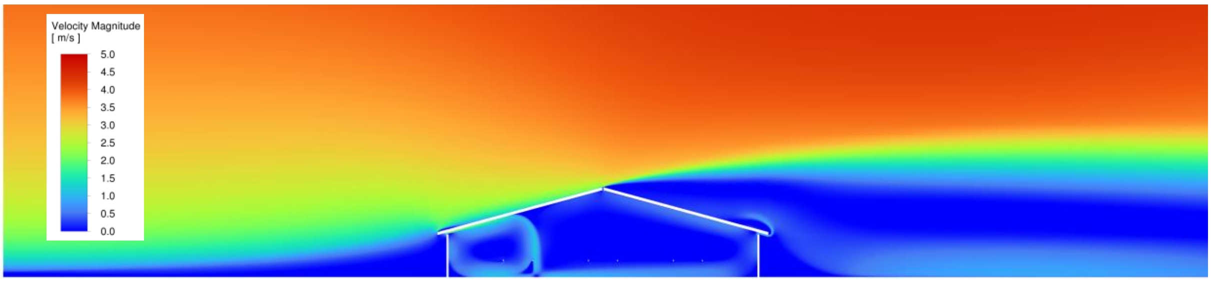
3.3.2 FLOW STRUCTURES AND DISTRIBUTION OF CH_4 WITHIN THE BARN

The wind produces a complex flow field as it passes over and through the barn, Figure 9 . This flow structure changes with wind speed and curtain wall opening. Two examples are shown in Figure 9, firstly with the curtain open and secondly with the curtain 90% closed. The inlet boundary layer can be clearly seen with a wind speed of 3 m/s at 10 m from the ground, reducing to 0 m/s at the ground level. As the air passes over the barn roof, it increases in speed and then separates from the ridge, forming a large recirculation on the downstream side, the low momentum fluid then remains well down stream of the barn.

The ventilating air which passes through the barn varies significantly with the operation of the barn walls and the wind speed. With the wall fully open then the ventilating air can pass through the barn from the upwind side to the downwind side, closer to the ground and under the jet of air there is a slow recirculation of air the full width of the barn. When this occurs, little air passes out of the ridge. When the walls are closed the amount of air passing through, the barn is reduced and a more complex flow structure occurs within the barn, promoting better mixing of the incoming ventilating air and the air within the barn. More air passed from the ridge when the curtain walls were closed.



(a) 100% Curtain Open, 3 m/s Wind Speed



(b) 10% Curtain Open, 3 m/s Wind Speed

Figure 9, Wind velocity around the barn.

Ambient temperature = 5 °C CH_4 emission rate = 8.40x10-6 kg/s/m = 100 kg/year/cow.

The wind entering the barn mixes with the barn air, providing natural ventilation and removal of the stale air from the barn. Since the wind and curtain opening has a significant influence on the air flow structures within the barn then it follows that they also have a significant effect on the concentration of CH_4 within the barn. Figure 10 and Figure 11 are examples of the CH_4 distribution within the barn, the former is a cold day and the latter is a warm day; both figures include 3 velocities and 2 curtain positions, fully open and 90% closed.

When the curtain walls were fully open then the barn was well ventilated and the CH_4 concentration within the barn is very low, both on cold day (Figure 10 (a-c)) and on a warm day (Figure 11 (a-c)). The CH_4 concentration was slightly higher near the source or CH_4 within the lower part of the barn and under the wind passing straight through the barn as see in Figure 9.

When the curtain walls were 90% closed the ventilation was reduced and the concentration of CH_4 was increased, both on a cold day (Figure 10 (d-f)) and a warm day (Figure 11 (d-f)). The flow structures within the barn were primarily linked to wind speed rather than temperature, although there was a small effect from buoyancy which meant slightly lower concentration CH_4 on a cold day compared to a warm day. This makes sense since the temperature differential between inside and outside the barn was greater on a cold day meaning a large bouncy force was present.

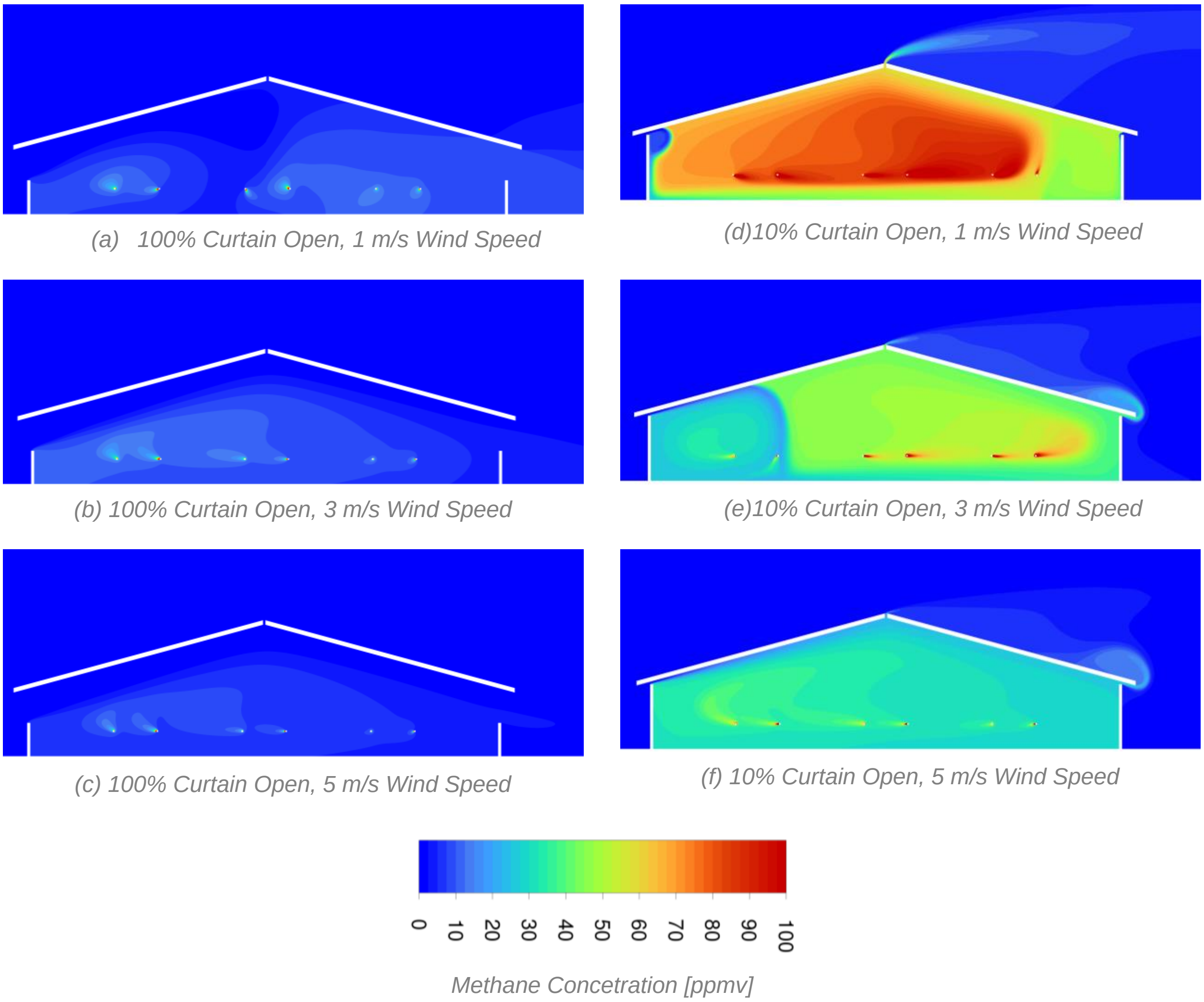


Figure 10, CH4 Concentration within the barn, ambient temperature = 5 °C.
CH_4 emission rate = 8.40x10-6 kg/s/m = 100 kg/year/cow.

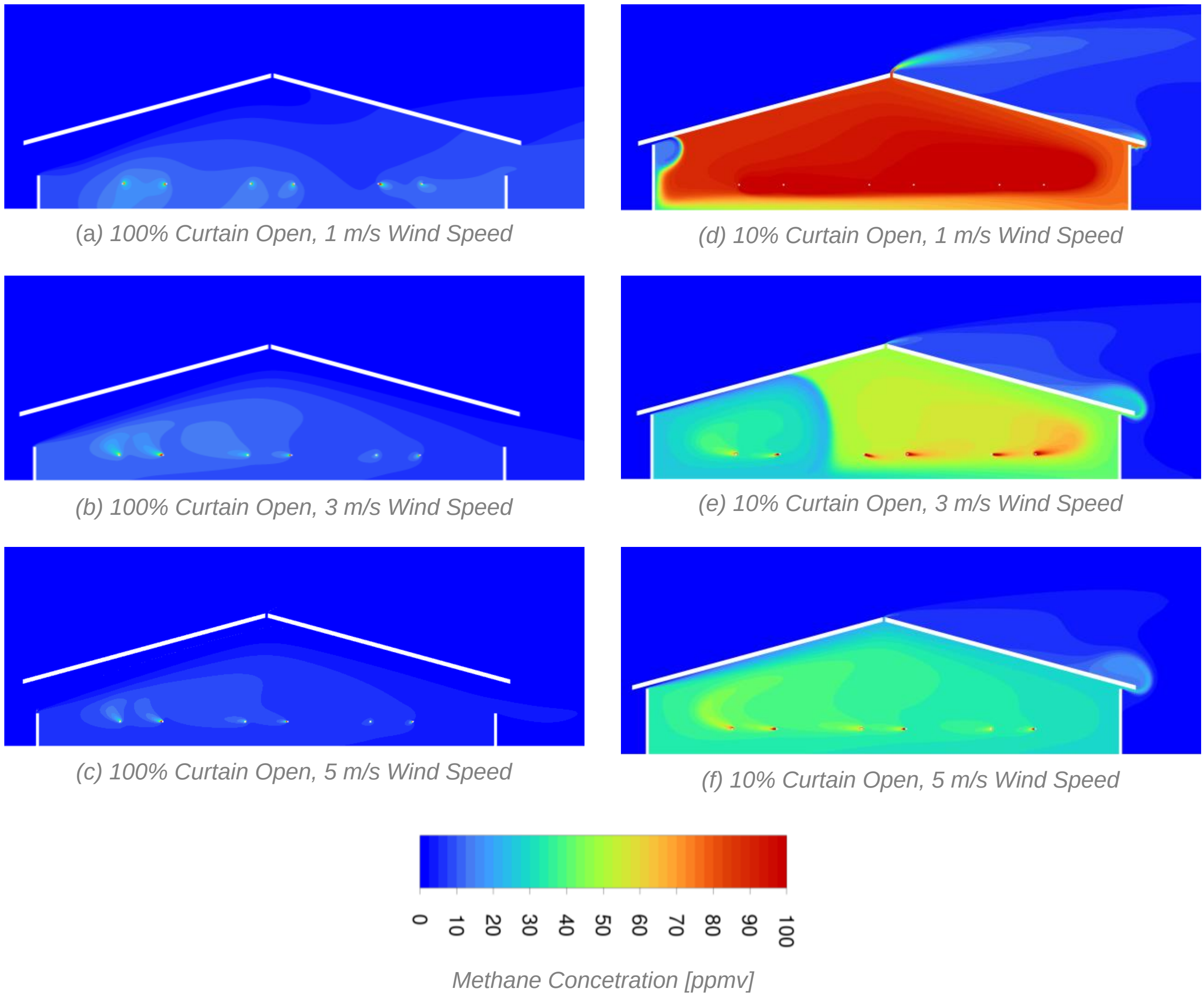


Figure 11, CH_4 concentration distribution within the barn, ambient temperature = 20 °C. CH_4 emission rate = 8.40x10-6 kg/s/m = 100 kg/year/cow.

The temperature within the barn is a function of the outside temperature, the amount of heat generated within the barn and the amount of ventilation. All simulations were undertaken with the same amount of heat produced by the cows. The temperature distribution within the barn is shown in Figure 12 and Figure 13, for a cold and warm day respectively. Figure 14, shows the mean temperature within the barn for a range of outside temperature and all wind speeds and curtain openings. The barn temperature is highly dependent on the amount of ventilation, a function of the curtain opening, the wind speed, and the outside temperature.

Generally, with adequate ventilation then the internal temperature is increased by ≈ 2 °C but with low ventilation the internal temperature is increased by over 4 °C. As an example, on a warm day of 20 °C and little ventilation then the barn could reach temperatures more than 26 °C, but with natural ventilation then the internal temperature is only 22 °C. Care must be taken with this generalisation since only convection is accounted for and the simulation does not account for the solar radiation.

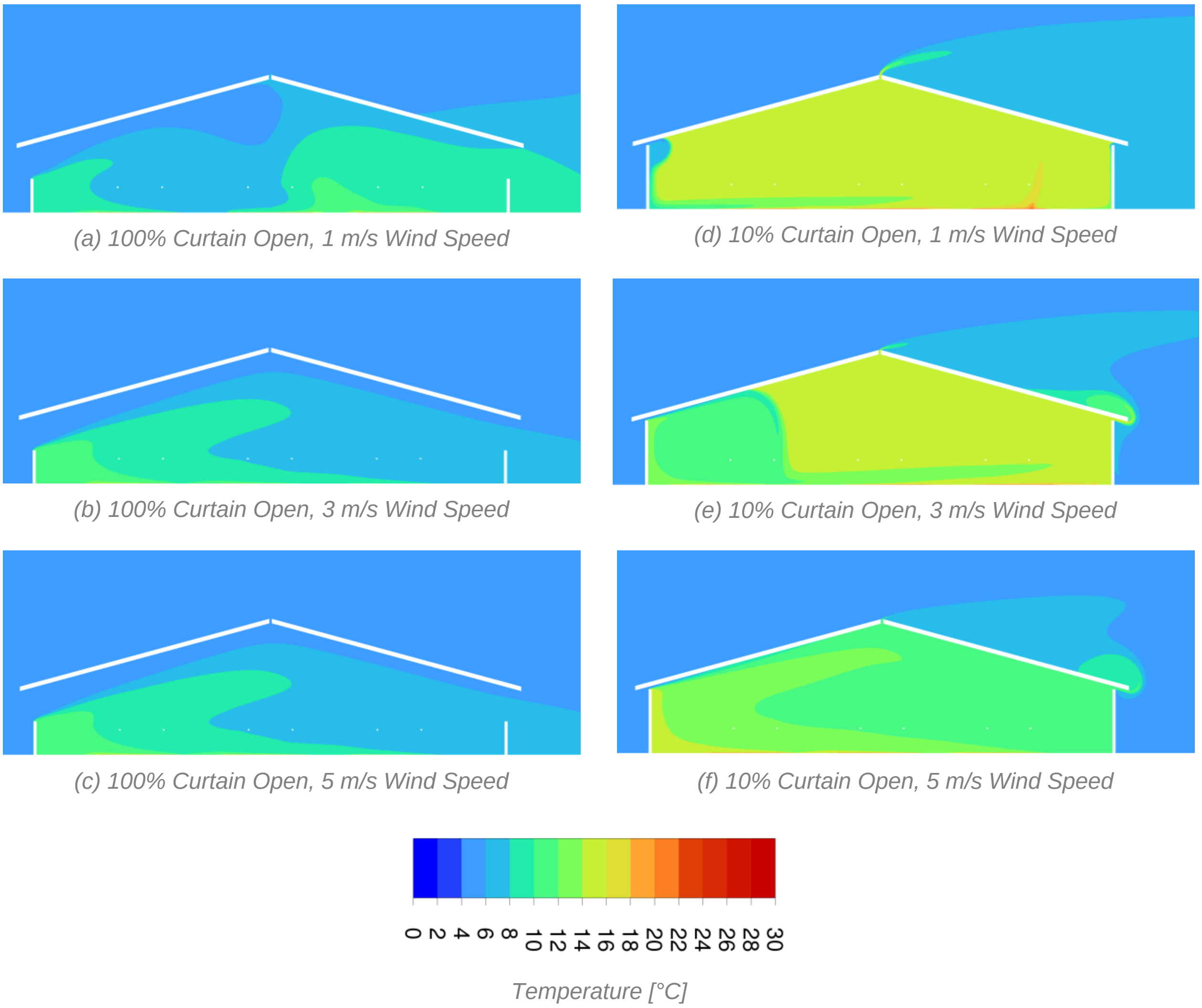
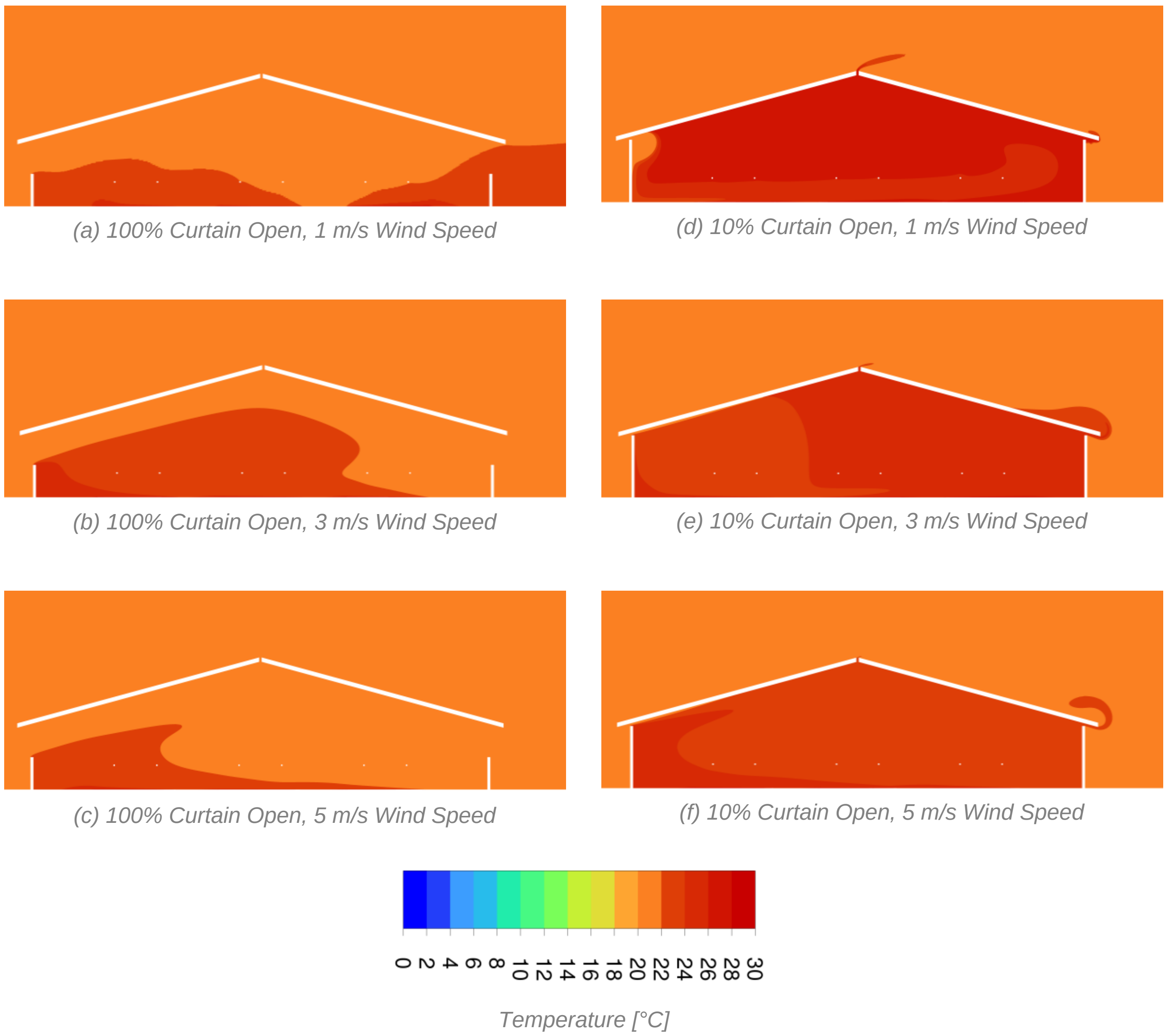


Figure 12, Temperature distribution within the barn, ambient temperature = 5 °C. CH_4 emission rate = 8.40x10-6 kg/s/m = 100 kg/year/cow.



(a) 100% Curtain Open, 1 m/s Wind Speed

(d) 10% Curtain Open, 1 m/s Wind Speed

(b) 100% Curtain Open, 3 m/s Wind Speed

(e) 10% Curtain Open, 3 m/s Wind Speed

(c) 100% Curtain Open, 5 m/s Wind Speed

(f) 10% Curtain Open, 5 m/s Wind Speed

Figure 13, Temperature distribution within the barn, ambient temperature = 20 °C.
CH_4 emission rate = 8.40x10-6 kg/s/m = 100 kg/year/cow.

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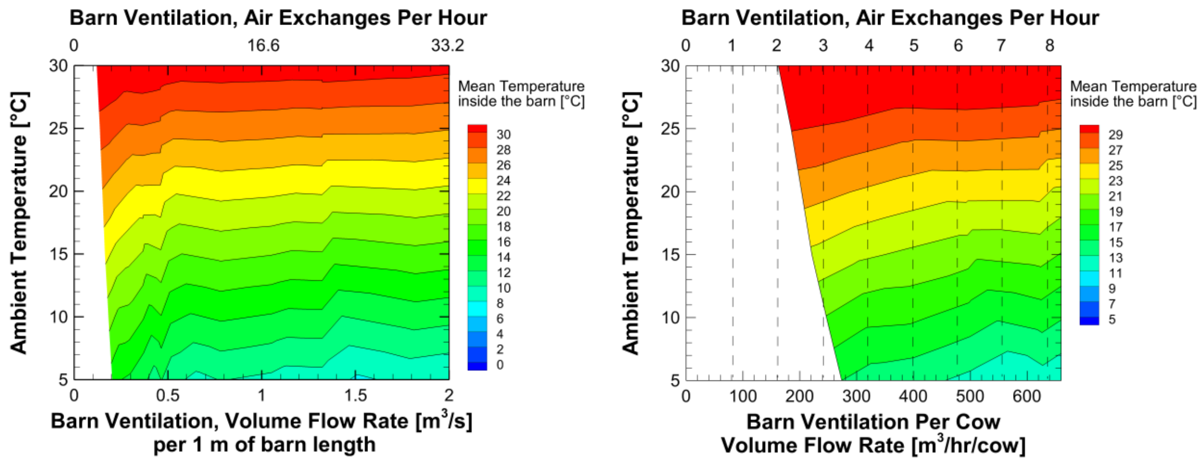

(a) Barn Ventilation (per 1m of barn length) *(b) Ventilation Per Cow*

Figure 14, Influence of ventilation rate and ambient temperature on the mean temperature wihin the barn CH_4 emission rate = 8.40x10^{-6} kg/s/m = 100 kg/year/cow.

3.3.3 INFLUENCE OF WEATHER AND OPERATION ON THE CONCENTRATION OF METHNANE WITHIN THE BARN

As would be expected, either a higher wind speed or a higher curtain opening increases the ventilation rate through the barn. For a given curtain setting, the wind speed primarily establishes the amount of ventilation through the barn. Previously it was shown that at higher wind speeds, the wind simply passed through the barn with very little air passing out of the ridge. Closing the curtains reduces the amount of air entering the barn but at higher wind speeds the wind still passes through the barn. There is therefore a direct linear corelation between the wind speed and barn ventilation rate at all the curtain wall settings, this is shown clearly in the trends presented in Figure 15. In the figure, the *x*-axis corresponds to wind speed and the *y*-axis corresponds to the amount of air entering the barn per 1 m of barn length, for the full ≈90 m of barn length then this number should be multiplied by 90.

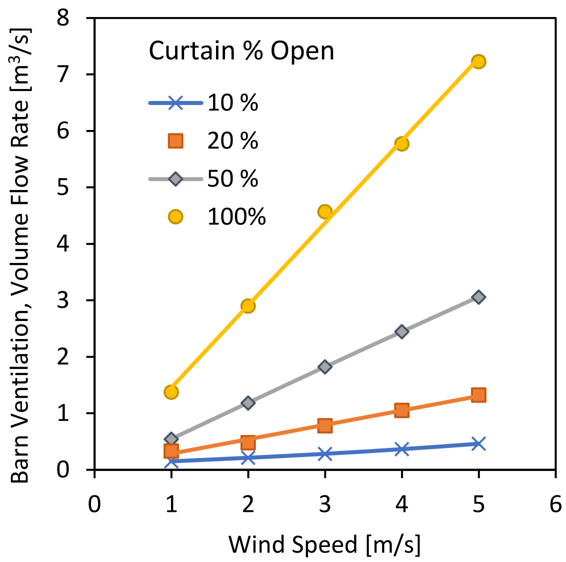

Figure 15, CFD Results - Influence of wind speed on the ventilation entering the barn per meter of the barn length. Ambient temperature = 20 °C. CH_4 emission rate = $8.40x10^{-6}$ kg/s/m = 100 kg/year/cow.

Figure 16 shows velocity contours of the air exiting the roof vent for different wind speeds (*x*-axis) and wind temperatures (*y*-axis), at 4 different curtain settings. The velocity of the air through the vent is influenced by the internal air flows, air passing over the roof and the buoyancy of the air within the barn.

With a small curtain opening then the air temperature influencing the buoyancy of the air, has a greater impact on the amount of air passing through the vent, Figure 16. This is an observation most prominent at lower wind speeds. When the curtains were closed, more air passed through the ridge vent at low outdoors temperatures, for example during the winter months, and at low wind speeds. When the curtain walls were open, more air passed out of the roof vent at higher wind speeds whilst the outdoor temperature had little effect.

When the curtains were fully open, only a small fraction of the ventilating air passed through the roof vent, Figure 16 (d). As the curtain was closed, as presented in Figure 16 (d to a), an increased fraction of the ventilating air passed through the roof vent. With the walls only 10% open and a low wind speed then more than 90% of the ventilating air passed through the roof vent. For all curtain wall settings, a greater percentage of air passed through the ridge vent at colder outside temperatures such as in the winter. Unsurprisingly buoyancy therefore has a greater role to play when the outdoor temperature was lower than the inside temperature of the barn, but this is a secondary effect to the amount of ventilation air primarily associated with the wind speed.

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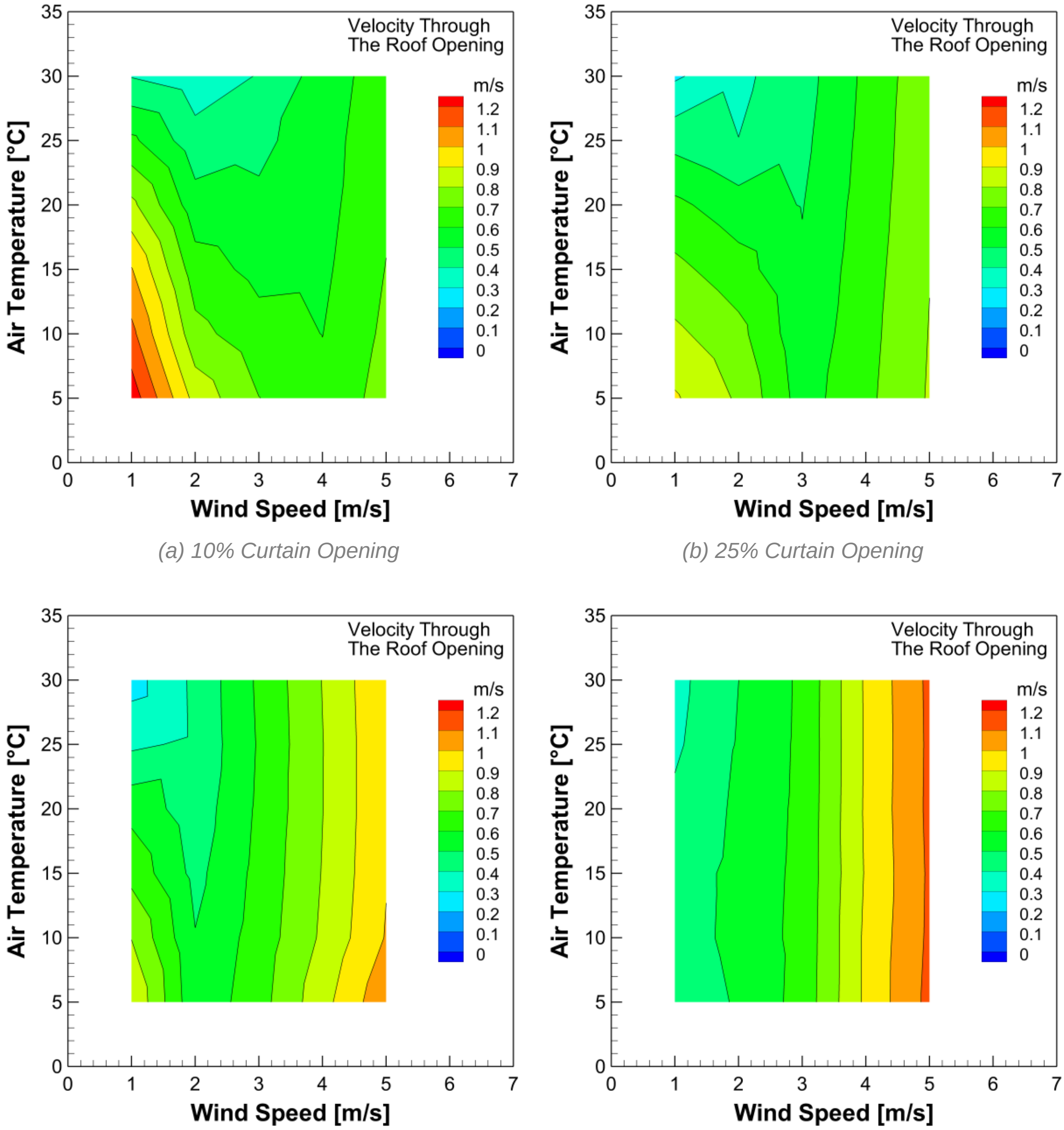


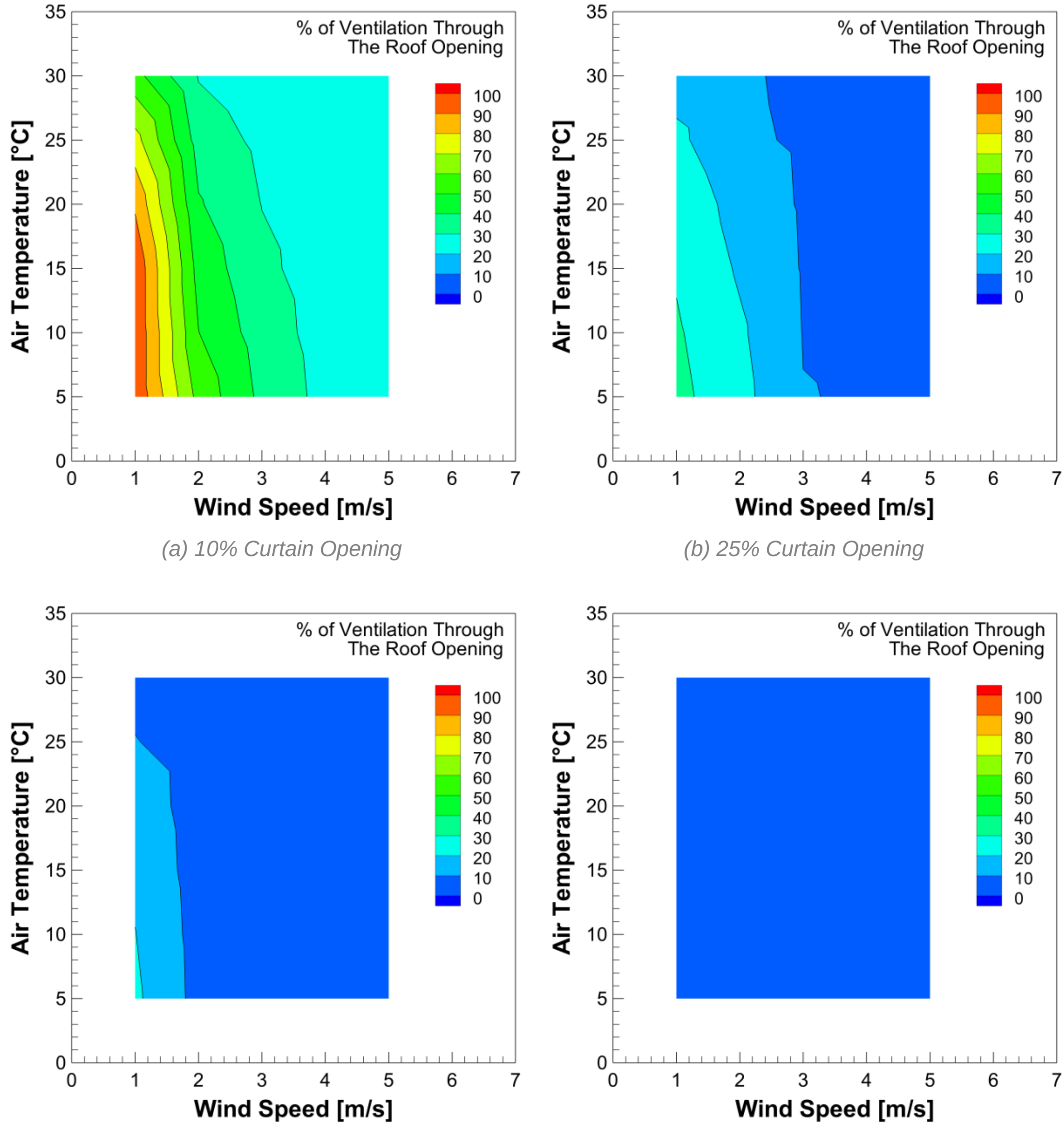
(a) 10% Curtain Opening

(b) 25% Curtain Opening

(c) 50% Curtain Opening

(d) 100% Curtain Opening

Figure 16, CFD Results - Influence of wind speed and air temperature on the air velocity through the roof vent, for different curtain settings. CH_4 emission rate = 8.40x10^{-6} kg/s/m = 100 kg/year/cow.



(a) 10% Curtain Opening

(b) 25% Curtain Opening

(c) 50% Curtain Opening

(d) 100% Curtain Opening

Figure 17, CFD Results - Influence of wind speed and air temperature on the percentage of ventilation through the roof vent, for different curtain settings. CH_4 emission rate = 8.40x10^{-6} kg/s/m = 100 kg/year/cow.

3.3.4 INFLUENCE OF THE LOCATION OF THE CH_4 MEASUREMNT WITHIN THE BARN

To establish how the CH_4 concentrations were distributed throughout the barn, and the position of a CH_4 measurement within the barn, then the averaging of concentration at three different heights was undertaken and compared to the mean concentration of the whole barn, Figure 18. The 2, 4, and 7 m were the average CH_4 concentration of a point rake across the full width of the internal barn. The 3 m height was a single point at the centre of the barn. These positions were the same as the experimental locations of CANMILK D4.1. Individual points in Figure 18 are the computed CH_4 concentrations of different wind speeds and curtain positions, for one CH_4 emission rate and one outside temperature level, during post-processing linear trend lines were fitted to these points.

At low mean concentration levels, high ventilation rates, then the concentration of CH_4 was similar at all sampling/measurement locations. At higher CH_4 concentrations, low ventilation rate, there was a small difference between the different sampling locations. In all cases, the mean concentration of CH_4 for the full barn was higher than the individual locations, by up to 20% at the higher concentration. The lowest CH_4 concentrations were within the roof as would be expected due to the wind passing straight through the barn and not mixing. Therefore, the concentration of CH_4 within the barn is not uniform and the positioning of a CH_4 sensor within the barn could produce an error of up to 20% when compared to the average concentration of the whole barn.

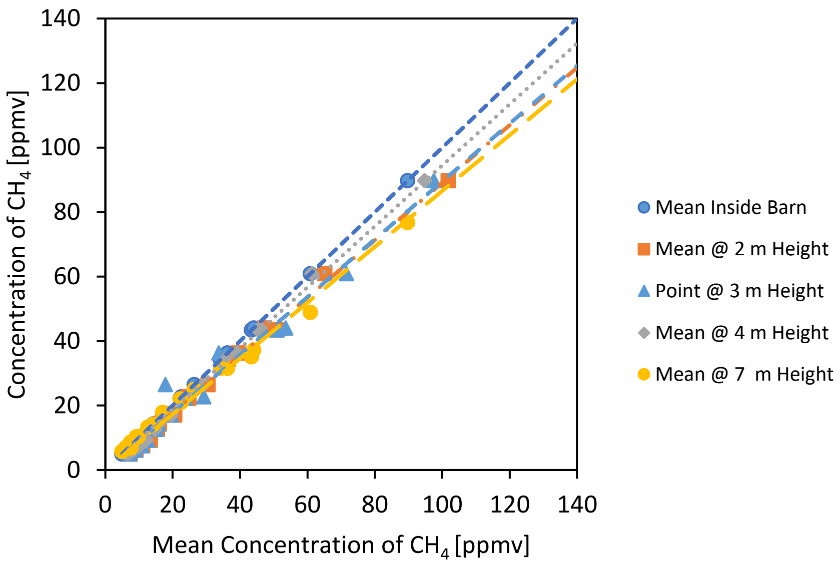
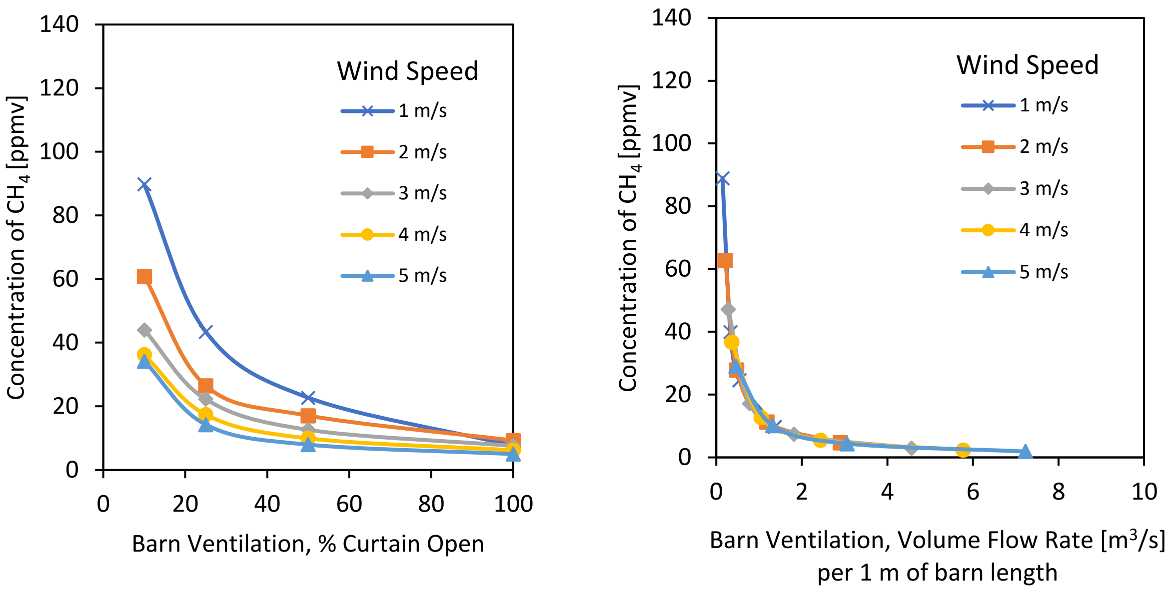


Figure 18, CFD Results - Influence of CH_4 concentration measurement/analysis location within the barn. Ambient temperature = 20 °C. CH_4 emission rate = 8.40x10-6 kg/s/m= 100 kg/year/cow.

3.3.5 INFLUENCE OF THE WEATHER CONDITIONS AND CURTAIN POSITIONS ON CH_4 CONCENTRATION

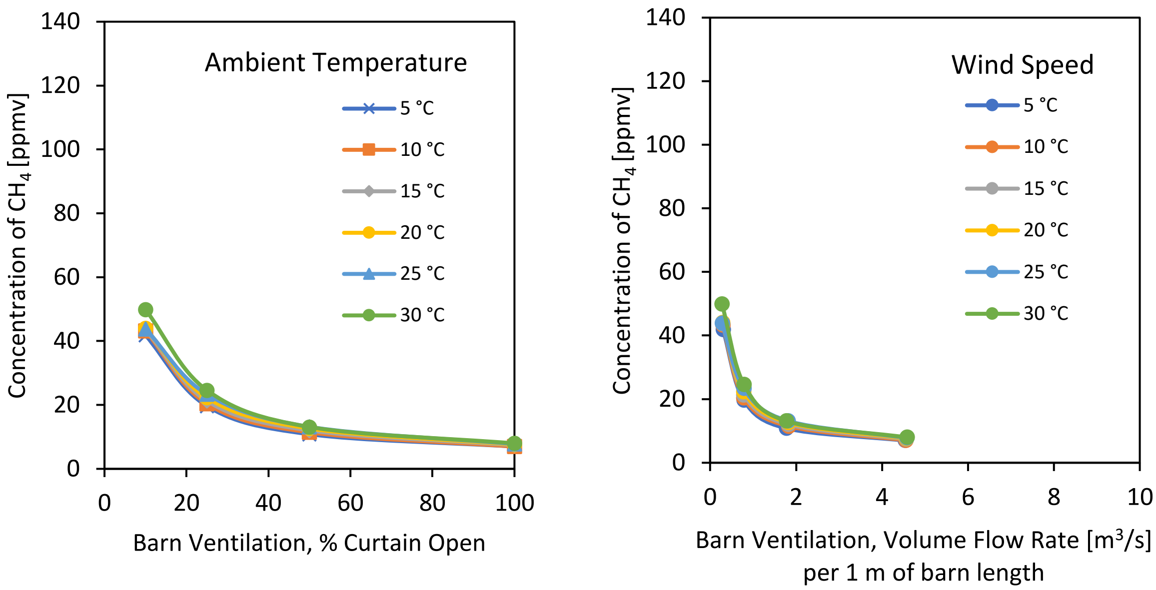
The concentration of CH_4 within the barn is lower with an increased wind speed and increased opening of the curtain wall, Figure 19 (a). This figure presents lines of constant wind speed at the lowest CH_4 emission rate and an outside temperature of 20 °C. As already discussed, the wind speed and curtain wall opening dictate the amount of ventilation passing through the barn, Figure 19 (b) shows the same data points/lines as Figure 19 (a) but the *x*-axis now shows the amount of ventilation entering the barn per meter. This plot shows that the concentration of CH_4 within the barn is only relative to the barn ventilation rate and all wind speed curves have formed a single curve on the chart, meaning that for a given temperature the concentration of CH_4 can be predicted by the amount of ventilating air and the amount of CH_4 from the cattle.



(a) Curtain Opening *(b) Ventilation Rate*

Figure 19, CFD Results - Influence of wind speed and curtain opening on the average concentration of CH_4 within the barn. Ambient temperature = 20 °C. CH_4 emission rate = 8.40×10^{-6} kg/s/m = 100 kg/year/cow.

Figure 20, shows constant temperature lines for a single wind speed (3 m/s). This data shows that on warmer days, with a higher external temperature, the CH_4 will be increased slightly within the barn for the same ventilation conditions, this is likely due to a decrease in the rate of buoyancy driven ventilation. This is however a secondary effect to the rate of ventilation and physically means that on a warm day then slightly more ventilation will be required to maintain the same level of CH_4 than on a cold day.



(a) Curtain Opening *(b) Ventilation Rate*

Figure 20, CFD Results - Influence of ambient air temperature and curtain opening on the average concentration of CH_4 within the barn. Wind speed = 3 m/s. CH_4 emission rate = 8.40×10^{-6} kg/s/m= 100 kg/year/cow.

3.4 VENTILATION RATES AND THE ANALYTICAL MODEL

As we have seen the amount of CH_4 within the barn is largely correlated to the amount of ventilation, other factors such as buoyancy, driven by temperature differentials, are a secondary effect. Figure 21 shows the CH_4 concentrations for all 360 simulation points, including all temperatures, wind speeds and CH_4 emission rates. The ventilation is the amount of air entering the barn due to the wind, this is a similar plot to Figure 19 and Figure 20 but now all points are included. The secondary *x*-axis shows the number of barn volume exchanges per hour which is a function of the rate of ventilation and the volume of the barn. The points for the three different rates of emissions are coloured differently and grouped around 3 different curves.

Since we know that the concentration of CH_4 within the naturally ventilated barn, to first order, is a function of the wind speed and geometry of the barn openings then the analytical prediction can be calculated using the following simple equation:

$$ppmv_{CH_4} = \frac{\dot{Q}_{CH4}}{\dot{Q}_{Ventilation} + \dot{Q}_{CH4}} \times 1{,}000{,}000$$

Equation 3, Analytical calculation of CH_4 concentration

This equation formed the solid analytical lines in Figure 21, the CFD simulation predictions are well predicted by the analytical model. Figure 22, shows lines of the analytical model at the three different flow rates. The test barn was predicted to have a rate of CH_4 nearing the 100 kg/year/cow, represented by the blue line. This line predicts a CH_4 concentration from ≈25 ppmv CH_4 at high ventilation rates, to ≈200 ppmv CH_4 at a low barn ventilation rate of one barn air exchanges per hour. Importantly the ventilation rates match those of the literature well, which were shown in Figure 2.

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The experimental campaign showed that if the curtain was fully open then the concentration of CH_4 was typically less than 40 ppmv both in winter and summer. When the barn curtain walls were partially closed then the concentrations were more than 40 ppmv. The numbers therefore align well with the computational simulations and the analytical model. Reducing the rates of ventilation can increase the CH_4 concentration significantly.

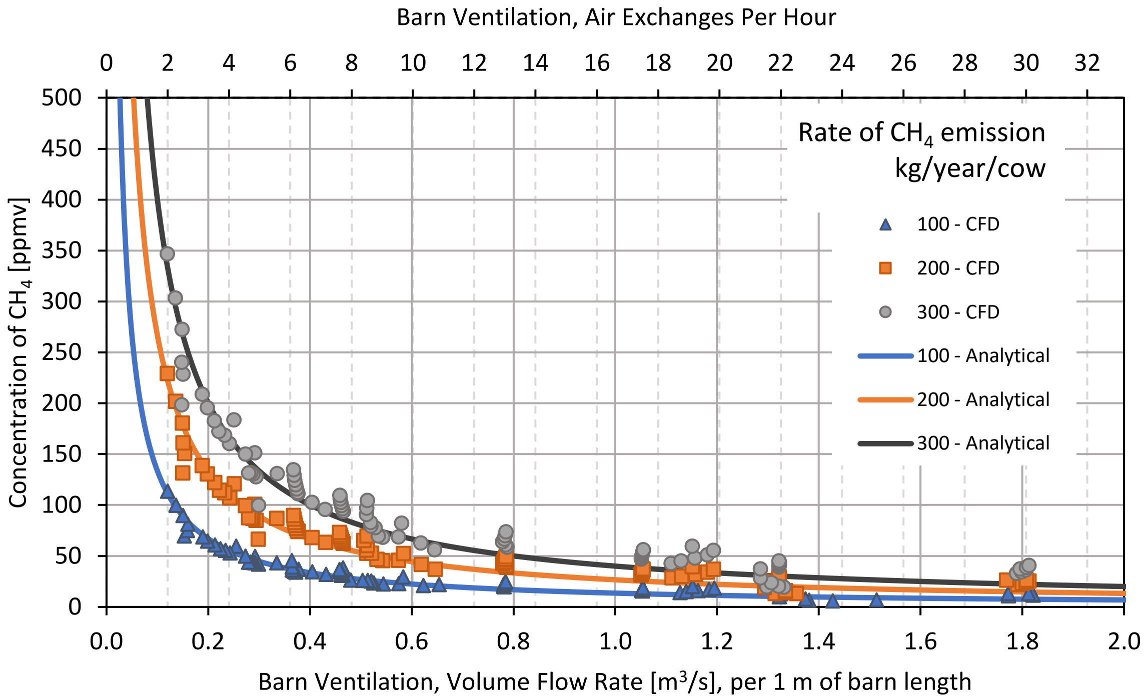
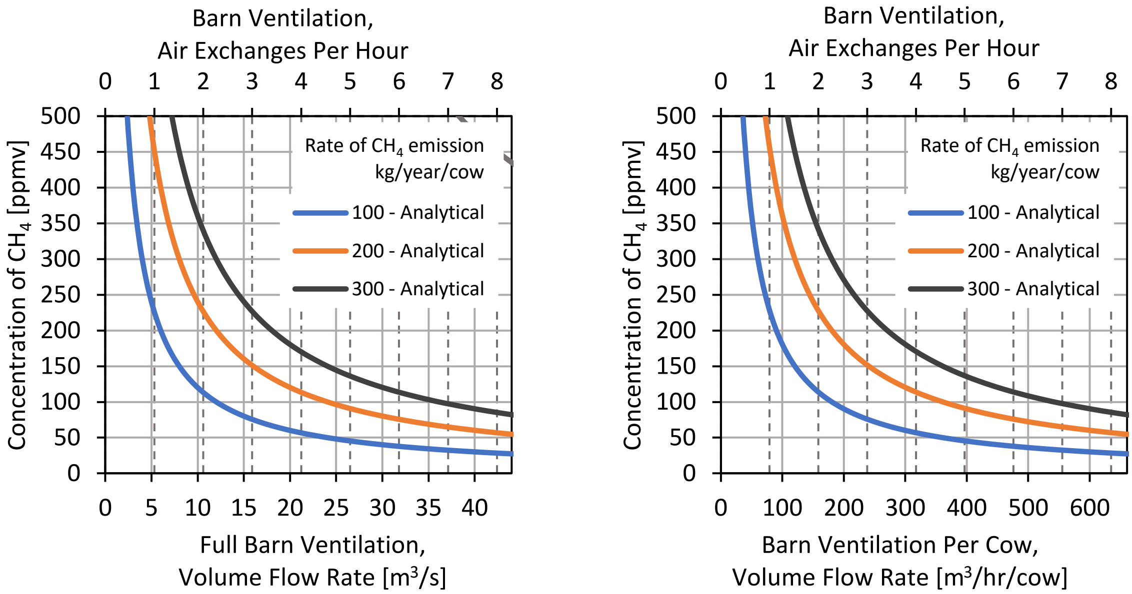


Figure 21, Analytical Model vs CFD Results - Influence of ventilation rate on the average concentration of CH_4 within the barn, for 3 different CH_4 emission levels. Data points are CFD, Lines are the Analytical Model.



(a) Total Barn Ventilation (240 Cows) *(b) Ventilation Per Cow*

Figure 22, Analytical Model - Influence of ventilation rate on the average concentration of CH_4 within the barn, for 3 different CH_4 emission levels.

3.5 MECHANICAL VENTILATION AND IMPLEMENTATION OF THE CANMILK SYSTEM.

The CANMILK system will capture and process the air from the barn to directly capture the CH_4, to do this the barn will need to be ventilated using extraction fans to suck the air from the barn into the CANMILK device. The positioning of the extraction was investigated in two ways as described in Section 3.2.4.2. Firstly, the ridge vent was converted into an outlet vent, and secondly a duct was positioned in the middle of the barn at a suitable height. For both methods, the curtain walls were closed to the 90% setting which allowed for air to enter the barn and not to cause a vacuum. The rate of CH_4 was 100 kg/year/cow. The rate of ventilation was altered from only capturing some of the air to all the barn air. This was undertaken for two wind speeds and two outdoor temperatures. These results are shown in Figure 23.

The data points for each of the mechanically ventilated simulations are positioned on the exact same curve as for the fully naturally ventilated barn, Figure 23, meaning that the concentration of CH_4 is primarily linked to the ventilation rate and not the method of ventilation, there may be some secondary localised effects but in general as long as the correct ventilation is provided and distributed along the full length of the barn then the average CH_4 concentrations can be predicted by Equation 3.

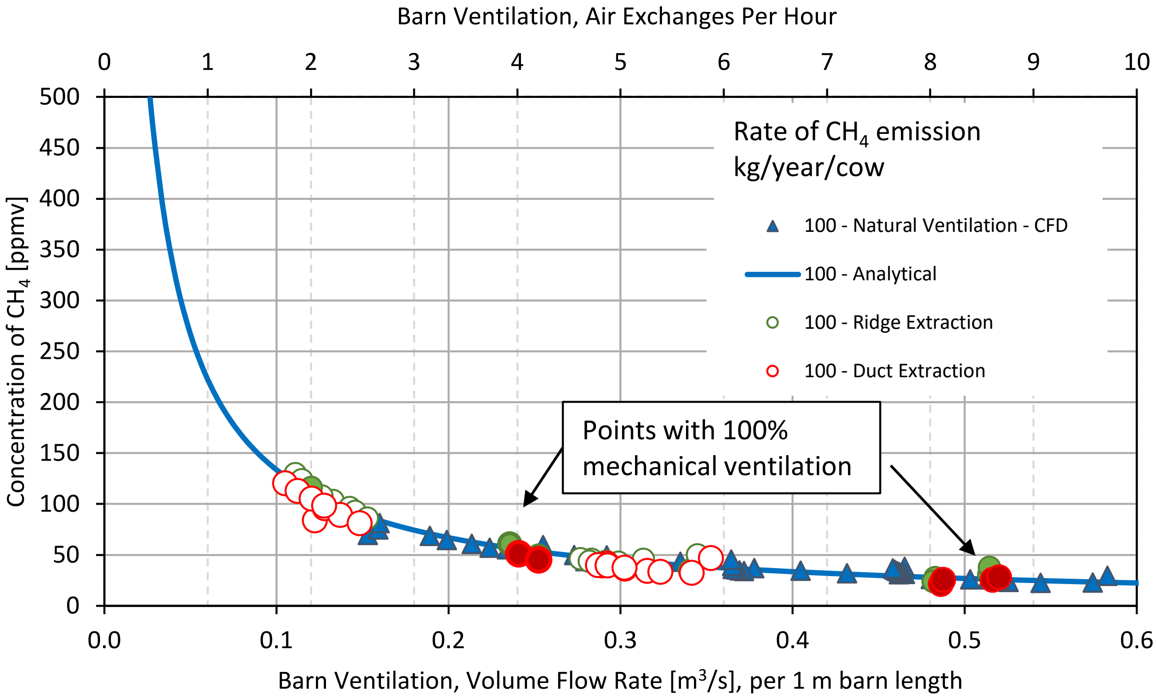


Figure 23, Analytical Model vs CFD Results - Influence of mechanical ventilation rate on the average concentration of CH_4 within the barn, for 100 kg/cow/year CH_4 emissions level. Data points are CFD, Lines are the Analytical Model. circles points indicate points with mechanical ventilation.

At the lower levels of mechanical ventilation, there was a mixture of natural and mechanical ventilation. The mechanical ventilation was not enough to overcome the natural ventilation driven by the wind. In Figure 23 those points with solid colouring had sufficient mechanical ventilation to overcome the natural ventilating and therefore captured all the CH_4. The other points with a white background had a combination of natural and mechanical ventilation. The natural ventilation was still present due to the pressure gradient across the barn caused by the external wind, this is due to the rudimentary inlet condition essentially being a slot at the running the full length of the barn at the top of the curtain walls. Care must therefore be undertaken when designing the ventilating system to ensure that no natural ventilation, driven by the wind can occur.

Figure 24 shows the percentage of CH_4 which was captured versus the amount of ventilation through the ventilation system. At 100% on the *y*-axis all the CH_4 is processed by the CANMILK system since all the ventilating air exits the barn through the ventilation system. Applying more ventilation than where the line crosses the 100% line for a given set of conditions will capture all the CH_4.

Primarily the wind speed affects the required ventilation rate the most, due to the mechanical ventilation having to overcome the naturally driven ventilation caused by the wind. A secondary affect is that a lower outdoor temperature slightly increases the amount of ventilation required.

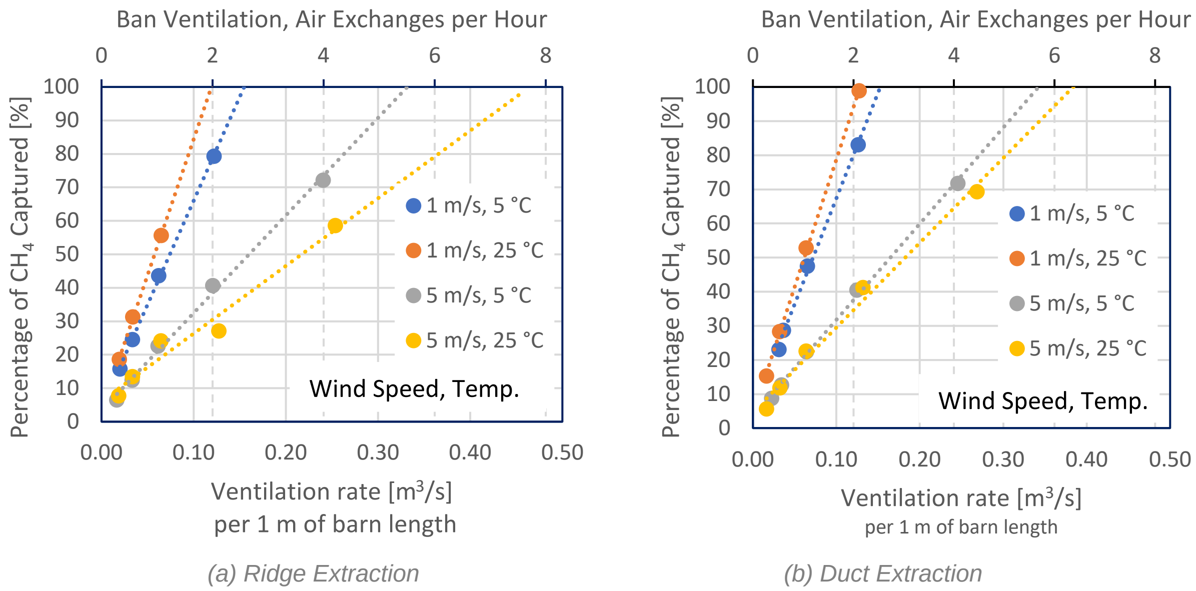


Figure 24, Analytical Model - Influence of the amount of mechanical ventilation on the mount of CH_4 captured.

When designing the barn and the implementation of the inlet ventilation for the CANMILK system, then care must be taken to prevent natural ventilation, which is primarily produced by the wind, otherwise not all the CH_4 will be captured, or very high rates of ventilation will be required to overcome the natural ventilation. The mechanical modelling undertaken although capable of extracting all the CH_4 required four times more mechanical ventilation at 5 m/s wind speed than at 1 m/s wind speed caused by the position of the inlet ventilation.

4 CONCLUSION

This report has investigated the conditions within cattle barns for determining the input parameters to the CANMILK system. First the amount of methane produced by the cattle within the barn, the temperature, the humidity levels, and the amount of ventilation within the barn was investigated. Then computational modelling of the barn to determine the concentrations of CH_4 within the barn was undertaken both for natural and mechanical ventilation at different atmospheric temperatures, these simulations were used to validate an analytical model.

To capture the majority of CH_4, then the barn will be sealed, and the ventilation will be provided mechanically, care must be taken to ensure secondary natural ventilation does not occur. The concentration of CH_4 within the barn is a function of the amount of CH_4 produced within the barn and the amount of ventilation. Reducing the ventilation will increase the concentration of CH_4 which is helpful to reduce the amount of air the CANMILK system is required to process and because higher concentrations of CH_4 are easier to capture. However, on the other hand, the amount of ventilation required within the barn is increased with atmospheric temperature to maintain comfort levels for the cattle. Inspection of Figure 14 (b) and Figure 22 (b), can provide the inlet conditions for the CANMILK system, the former image is the internal temperature and the latter is the expected concentration of CH_4 for different amounts of ventilation. Figure 25, shows how these figures can be used to determine the required ventilating flow rate and the resulting concentration of methane within the barn.

In this example the amount of ventilation was determined to maintain an internal barn air temperature of 20 °C for different external ambient temperatures using Figure 14 (b). The flow rate was then used to calculate the expected concentration of CH_4 with a Ch4 production of 100 kg/year/cow, using Figure 22 (b). This example was chosen as the minimum requirements of ventilation to maintain comfort levels.

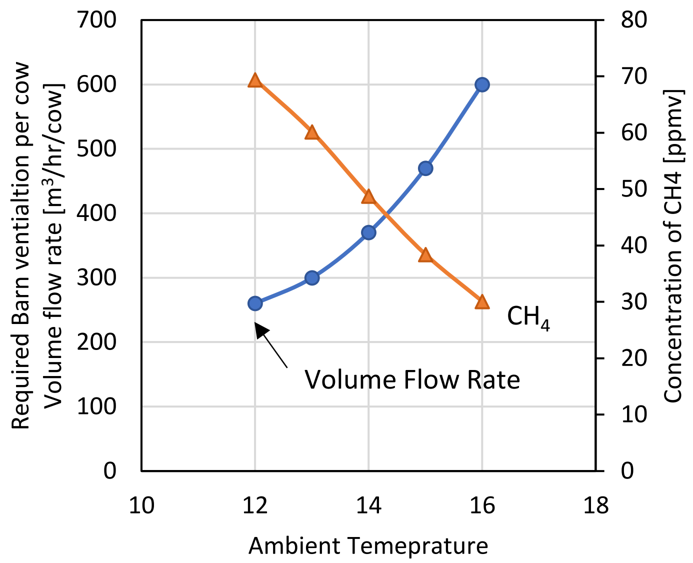


Figure 25, Ventilation flow rate required to maintain 20 °C within the barn at different external temperatures and the resulting concentration of CH_4, for 100 kg/cow/year CH_4 emissions level.

To summarise the following table gives an estimate range of parameters which could be expected in the emission stream of a mechanically ventilated barn.

Table 4, Approximate range of parameters for the exhaust stream of a mechanically ventilated cattle barn.

PARAMETER	RANGE	COMMENT
Temperature	-5 °C to 20 °C	There are several recommended temperatures for cattle. In humid conditions the temperature should be reduced to avoid heat stress of the cattle.
Relative Humidity	40% to 95%	Relative humidity is slightly increased above atmospheric conditions
Volumetric Flow Rate	50 to 600 m^3/hr/cow	In very warm conditions the volumetric flow rate may need to be significantly increased beyond 600 m^3/hr/cow to maintain comfort levels.

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