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Computational model of methane and ammonia emissions from dairy barns: Development and validation

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ABSTRACT

The increased global demand for milk and other dairy products over the past decades is a cause for concern due to the potential for environmental impact. Ammonia produced by housed dairy cows can contribute to the formation of particulate matter and nitrous oxide which both contribute to the greenhouse effect. The methane produced by these cows also contributes to the greenhouse effect. Scientists and engineers face the challenge of developing methods to reduce the environmental impact of dairy production while not inhibiting the ability of producers to keep up with demand. Emission of methane and ammonia are highly dependent on feed composition, barn design and operation, manure management making this a challenging topic to study experimentally. Using computational models to simulate the generation and dispersion of gaseous species within dairy housing can facilitate the exploration of cost-effective gas mitigation strategies. Thus a steady-state computational fluid dynamics (CFD) model capable of simulating biologically based generation of methane, ammonia, and heat and their transport within the domain was developed and validated. The effect of buoyancy forces on the accuracy and stability of the solutions was explored. The model was validated with experimental data collected from emission chambers located at USDA-ARS Dairy Forage Research Center in Wisconsin, USA. Concentration of ammonia and methane, due to controlled injections from cylinders and biological generations from a dairy cow, were measured in the chambers using a FTIR gas analyzer. Results of the validated CFD model could be used to predict gaseous emissions under a range of environmental, design, and experimental treatment parameters.

1. Introduction

Intensification of the United States dairy sector is leading to concerns about the sustainability and environmental impact dairy production (Croney and Anthony, 2011; Steinfeld et al., 2006). The global dairy sector is estimated to represent upwards of four percent of global anthropogenic greenhouse gas emissions (Gerber et al., 2010). The reduction and mitigation of methane and ammonia emissions from the dairy sector is a promising pathway to decrease the environmental impact of dairy production since these gasses or their products have global warming potential many times greater than carbon dioxide.

Numerous life-cycle assessment (LCA) studies have shown the potential of management strategy (Dutreuil et al., 2014), dietary modification (Van Middelaar et al., 2013), and manure management (Cabrera et al., 2007; Aguirre-Villegas et al., 2015) to reduce emissions while maintaining economic viability. However, these LCA studies are typically based on large-scale empirical models of gaseous generation from animals and manure and do not provide data about the spatial concentration of gas within the barns. Methane is generated through enteric fermentation and is dependent on cow genetics and diet (Knapp et al., 2014). Ammonia is volatized from manure and is affected by diet (Aguerre et al., 2010) and environmental conditions (Powell et al., 2008a, 2008b). Understanding the generation and transport of these gasses at the cow scale is critical to making accurate predictions of novel mitigation strategies.

Computational fluid dynamics (CFD) is increasingly being used to model complex problems in agriculture such as ventilation in animal housing (Norton et al., 2007), ammonia transport within livestock housing and manure pits (Tong et al., 2013; Bjerg et al., 2013), and transport of heat between livestock and their environment (Gebremedhin and Wu, 2003; Mondaca et al., 2013; Rojano et al., 2015). CFD can also be used to model the complex transport phenomena that occur in dairy housing. By coupling ventilation

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design, gaseous generation of methane from enteric fermentation and ammonia from manure, and biological heat production within a comprehensive model, researchers could evaluate potential mitigation strategies.

Thus, the objective of this study was to develop a CFD model capable of predicting methane and ammonia emissions from cows housed in emission chambers. Experimental parameters related to cow diet, fecal nitrogen content, and physiological parameters were used to define the emission of methane and ammonia. The study finding should also facilitate the establishment of best modeling practices for future models. To that end, models of ventilation, ammonia production, and methane production were incorporated into a comprehensive, steady-state model that could be capable of evaluating the effects of cow diet and environmental conditions. In addition the effect of buoyancy on thermal and gas species transport was examined. The model was validated with experimental data of gas concentration within an emission chamber. The model is expected to be a powerful tool in identifying and evaluating methods to mitigate greenhouse gas emissions as the dairy industry continues to grow to keep up with the ever-increasing demand for milk products while reducing their environmental impact.

2. Materials and methods

2.1. Experimental apparatus

Experimental validation data was collected at the USDA-ARS Dairy Forage Research Center in Prairie du Sac, Wisconsin, USA in retrofitted tie stall dairy barns (Drewry et al., 2017). Each of the four chambers, capable of housing up to three cows, were constructed to the same dimensions, Fig. 1. The chambers are located at one end of a mechanically ventilated barn and can be isolated with an overhead door. The chambers were instrumented to measure the generation rate of gasses within the chambers based on a mass balance of the system.

Each chamber is outfitted with two small overhead doors to provide access to the feed lane and one large overhead door to provide access to the cow (Figs. 2 and 4). Metal stanchions divided each chamber into four stalls with a supply duct over each stall (Fig. 3).

Variable frequency drives (Automation Direct, model GS2 AC drive; Northwest Envirofan, model 215F) power supply (Dayton, Model 3C010) and exhaust fans (Soler and Palau, model TD-315) provided ventilation to each chamber. The supply and exhaust ducts were outfitted with a custom fabricated, equal-area radial gas sampler, a pitot tube (Ultraprobe AMPS, Ultratech Industries Inc.) and a temperature and relative humidity probe (Campbell Scientific, HC2S3). Measurements from the pitot tubes and temperature and relative humidity probes were taken every 500 ms and stored as 1-minute averages (Model CR5000, Campbell Scientific, Logan, UT). The gas sample lines (0.0032 m i.d, Nalgene, Rochester, N.Y.) from the supply and exhaust ducts were run to an integrated stream switching system and FTIR gas analyzer (Gasmet, model DX4015). Under standard operating conditions, the FTIR sample cell was flushed for 40 seconds prior to the sample, followed by three consecutive 20-s measurements. All gas samples were analyzed using Calcmet software (Calcmet, 2013, Finland).

The cows were removed from the chambers three times per day for milking at approximately 5:00, 12:00, and 18:00. Feed was delivered once per day during the second milking. The manure gutters are scraped twice per day during the first and second milkings.

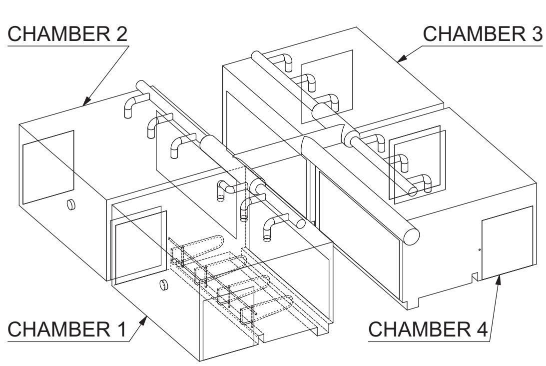

Fig. 1. Isometric view of chambers and ventilation assembly. Interior lines of chambers 2–4 are hidden for clarity.

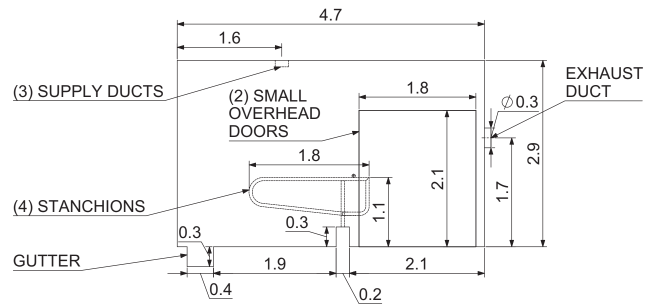

Fig. 2. Side view of single chamber, all dimensions in meters.

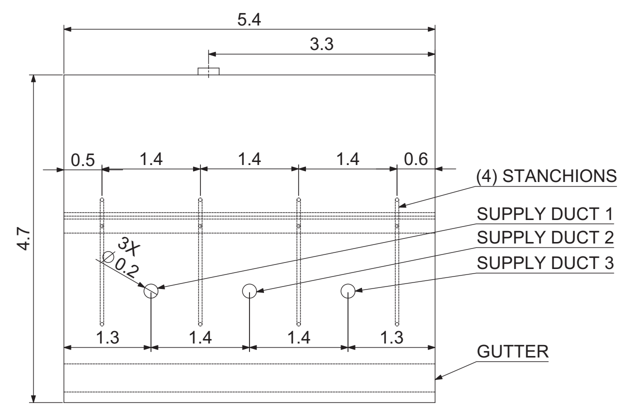

Fig. 3. Top view of single chambers, all dimensions in meters.

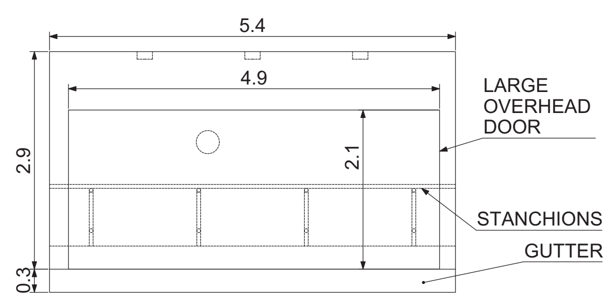

Fig. 4. Front view of single chambers, all dimensions in meters.

2.2. Spatial gas measurements

Gas concentration within chamber 2 was sampled at six locations, twice per day, over a period of four days under standard operating conditions. Prior to the experiment, the single cow was housed in the chamber, with the doors open, for four days. The