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WAGENINGEN UNIVERSITY & RESEARCH

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Samenvatting: Door het gescheiden houden van mest en urine kan de methaan- en ammoniakemissie van een melkveestal mogelijk verminderen. In het kader van een onderzoek naar verschillende technieken in de stal om mest en urine zo goed mogelijk gescheiden te houden zijn metingen uitgevoerd aan het 'CowToilet' van de firma Hanskamp. Metingen zijn uitgevoerd in een zogenaamde case-control opzet in de emissie-units van Dairy Campus in Leeuwarden volgens het protocol voor meting van ammoniakemissie uit huisvestingssystemen in de veehouderij. Uit de metingen bleek de emissie van ammoniak door het 'CowToilet' met 35-47% af te nemen ten opzichte van de controle afdeling. Wanneer gebruikt voor het vaststellen van een emissiefactor in het kader van de Regeling ammoniak en veehouderij zou dit op basis van de puntmetingen en nat-chemische bepaling van de ammoniakconcentratie met gaswasflessen resulteren in een ammoniakemissie van 6,9 kg per dierplaats per jaar en op basis van continue metingen en bepaling van de ammoniakconcentratie met een NOx-monitor en $NH_3$ converters tot een ammoniakemissie van 8,5 kg $NH_3$ per dierplaats per jaar.

Summary: The CowToilet was included in a project looking at the effect of different techniques for separation of urine and faeces to reduce emissions of ammonia and methane from dairy housing. The CowToilet keeps part of the urine of dairy cows separated by collecting right after urination. This can lead to a reduction of the ammonia emission. Ammonia emission was measured according to the Dutch protocol for measurement of ammonia emission from housing systems in livestock production. Measurements were done in the emission units at Dairy Campus, Leeuwarden. A case-control approached was followed. The ammonia emission of the unit with the CowToilet was reduced by 35-47% compared to the control unit with a concrete slatted floor. This would result in an emission factor of 6.9 kg $NH_3$ per animal place per year using point measurements and 8.5 kg $NH_3$ per animal place per year using continuous measurements.

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# Foreword

This study was part of the project 'PPS Mestscheiden in melkveestallen' (AF-18036). This is a project financed by public as well as private sources and has been commissioned by both the ministry of Agriculture, Nature and Food Quality (LNV), ZuivelNL (Organisation of the Dutch dairy supply chain) and participating companies Hanskamp BV, Zeraflex BV and V17-Agro BV. It has been carried out with a team of researchers, research technicians and animal caretakers at the environmental research barn of Dairy Campus (Leeuwarden, the Netherlands). We acknowledge Jos Tuinier and others working at Dairy Campus for taking care of the animals and the research facilities. Finally, we would like to thank everyone involved for the pleasant and fruitful cooperation.

Ir. Paul Galama, Project Leader

# Summary

Ammonia emission from dairy housing originates from the urea in the excreted urine. This urea is converted to ammonia in the first hours after excretion and emits from urine puddles that lay on walking floors or from the top layer of the mixture of urine and faeces (slurry) in the slurry pits. In past decades development of alternatives for the concrete slatted floors have focussed on drainage or removal of urine from the floor and reduction of the air exchange between pits headspace and rest of the barn. The CowToilet offers an alternative by collecting (part of) the urine before it reaches the floor. In this way urine and faeces are (partially) kept separated and the main source of ammonia emission is removed from the housing system and stored elsewhere with presumably limited emissions. The CowToilet has been added as a low-emission system to the Rav legislation under Rav code A 1.36 and BWL 2021.05 (see Appendix 1 to this report) with a provisional ammonia emission factor of 8.4 kg per animal place per year. To obtain a definitive emission factor for the system the manufacturer (Hanskamp BV) must provide a data set of emission measurements that meet the appropriate requirements. These measurement have been carried out within the project 'Mestscheiding melkveestallen' in which several techniques are evaluated to keep urine and faeces separated. Emission measurements were part of this evaluation. This report described the ammonia emission measurements in the context of the application for a definitive ammonia emission factor.

The objective of the measurements described in this report was to determine the ammonia emission reduction of the CowToilet using the "case-control" approach as described in the measurement protocol for determination of ammonia emission from housing systems in livestock production (Ogink et al., 2017).

The measurements have been carried out in the environmental research barn of Dairy Campus in Leeuwarden (The Netherlands) between 1-12-2020 and 30-11-2021. In this barn, the CowToilet was installed in one unit (70) that acted as the "case" whereas another unit (72) acted as the reference or "control". The rooms were climate separated and mechanically ventilated with two ventilators per unit. Both units were equipped with 16 cubicles and had concrete slatted floor with slurry pits under the entire surface area. Each room was equipped with a drinking trough. The CowToilet acted also as a concentrate feeding station. Both units housed 16 lactating cows of the Holstein Frisian breed. The composition of both groups was such that they had comparable mean milk production and mean urea milk content on group level. Cows were fed with a mixed ration of mainly grass and maize silage completed with additional components. Cows were milked twice a day in a rotary milking parlour outside the units and housed for the rest of the day in the units. No grazing was applied. Ventilation rate of each ventilator was recorded constantly using a free running propellor. Ammonia concentration was measured in each ventilator and four background points, two on both sides of the barn. Ammonia concentration was measured using three methods: an acid wet trap impinger gas washing method resulting in one 24 hour average concentration for each measurement point and two continuous measurement techniques for ammonia concentration. A NOx-analyzer combined with ammonia converters and a Picarro multi gas analyser, both resulting in an hourly average concentration for each measurement point.
Six measurement periods were defined per measurement technique. For the acid trap impinger method each measurement period lasted 24 hours. They are referred to as 'point measurements'. Measurement periods of continuous techniques lasted four days (Tuesday-Friday) in the measurement week. They are referred to as NOx-measurements and Picarro measurement. Picarro measurements were taken from the same week as acid trap impinger method. NOx measurements were taken in the week prior (NOx-A) and after (NOx-B) the measurement week of the acid trap impinger and Picarro method.

Concentration measurements of daily emissions per unit were calculated excluding the two time two hours milking times and were standardized for outside temperature, milk urea content and fouled area. Emission reduction and an emission factor proportional to the emission factor of the traditional housing system (A1.100; 13 kg $NH_3$ per animal place per year) was calculated per measurement period. The average reduction and emission factor resulted in an emission factor the CowToilet.

The CowToilet collected on average 10.4 litres of urine per cow per day. Averages measurement conditions during the acid trap impinger measurements are given in table S1.

***Table S1*** *Conditions during point measurements.*

| Variable | Measurement period | | | | | | |
|---|---|---|---|---|---|---|---|
| | **1** | **2** | **3** | **4** | **5** | **6** | **Mean** |
| **Climate conditions** | | | | | | | |
| Temperature ambient air (°C) | 7.5 | 3.5 | 4.3 | 18.2 | 17.3 | 9.9 | 10.1 |
| Relative humidity ambient air (%) | 96 | 96 | 78 | 80 | 86 | 97 | 88.7 |
| Ambient air pressure (hPa) | 1013 | 1001 | 1032 | 1016 | 1013 | 1023 | 1016 |
| Wind direction (degrees) | 177 | 129 | 249 | 147 | 239 | 202 | 191 |
| Wind speed at 10 meters (m/s) | 4.2 | 3.4 | 3.3 | 3.6 | 4.2 | 4.2 | 3.8 |
| Temperature inside air (°C) | | | | | | | |
| - Case room (70) | 10.3 | 7.0 | 9.1 | 21.8 | 20.3 | 13.0 | 13.6 |
| - Control room (72) | 10.6 | 7.2 | 9.6 | 22.1 | 20.7 | 12.6 | 13.8 |
| Relative humidity (%) | | | | | | | |
| - Case room (70) | 88 | 85 | 62 | 69 | 76 | 84 | 77 |
| - Control room (72) | 97 | 95 | 67 | 73 | 81 | 98 | 85 |
| **Animal performance** | | | | | | | |
| Milk production (kg/animal per day) | | | | | | | |
| - Case room (70) | 31.6 | 29.4 | 29.1 | 24.6 | 28.8 | 26.0 | 28.3 |
| - Control room (72) | 30.5 | 28.7 | 28.7 | 24.0 | 31.0 | 27.0 | 28.3 |
| Milk fat content (%) | | | | | | | |
| - Case room (70) | 4.7 | 5.0 | 5.2 | 4.7 | 4.7 | 4.8 | 4.8 |
| - Control room (72) | 4.7 | 4.8 | 5.0 | 4.7 | 4.7 | 4.9 | 4.8 |
| Milk protein content (%) | | | | | | | |
| - Case room (70) | 3.8 | 3.9 | 3.8 | 3.7 | 3.5 | 3.8 | 3.8 |
| - Control room (72) | 3.9 | 4.0 | 3.7 | 3.7 | 3.5 | 3.9 | 3.8 |
| Milk urea concentration (mg/100 g) | | | | | | | |
| - Case room (70) | 21 | 17 | 22 | 28 | 18 | 25 | 22 |
| - Control room (72) | 18 | 14 | 21 | 27 | 16 | 23 | 20 |

The statistical analysis showed that differences between the rooms of temperature, milk production, fat content and protein content were not statistically different ($p>0.1$). Only relative humidity and urea content differed between units ($p<0.001$). The results of the emissions (calculated based on different ammonia concentration methods) are given in Table S2.

***Table S2*** Ventilation rates, ammonia concentration and ammonia emission and reduction during point measurements.

| Variable | Measurement period | | | | | | |
|---|---|---|---|---|---|---|---|
| | **1** | **2** | **3** | **4** | **5** | **6** | **Mean** |
| **Ventilation rate ($m^3$/h)** | | | | | | | |
| - Case room (70) | 15,923 | 14,904 | * | 22,997 | 16,402 | 15,503 | 17,146 |
| - Control room (72) | 15,923 | 15,244 | * | 23,053 | 14,589 | 21,177 | 17,997 |
| **Carbon dioxide concentration (ppm)** | | | | | | | |
| - Case room (70) | 692 | 777 | * | 762 | 758 | 791 | 756 |
| - Control room (72) | 560 | 795 | * | 808 | 771 | 749 | 736 |
| **Ammonia concentration (ppm)** | | | | | | | |
| - Background | 0.05 | 0.05 | * | 0.05 | 0.08 | 0.06 | 0.06 |
| - Case room (70) | 1.22 | 0.62 | * | 1.34 | 1.89 | 1.18 | 1.25 |
| - Control room (72) | 1.90 | 1.35 | * | 2.41 | 2.78 | 1.99 | 2.08 |
| **Ammonia emission rate (kg/animal place per year)** | | | | | | | |
| - Case room (70) | 7.5 | 3.4 | * | 11.6 | 11.6 | 7.0 | 8.2 |
| - Control room (72) | 11.9 | 8.0 | * | 21.2 | 15.4 | 16.7 | 14.6 |
| **Emission reduction** | | | | | | | |
| - Absolute (kg/animal place per year) | 4.4 | 4.6 | * | 9.6 | 3.7 | 9.6 | 6.4 |
| - Relative (%) | 37% | 57% | * | 45% | 24% | 58% | 44% |
| **Emission factor** | 8.2 | 5.6 | * | 7.1 | 9.8 | 5.5 | 7.2 |
| **Ammonia emission rate (standardized for milk urea and outdoor temperature (kg/animal place per year)** | | | | | | | |
| - Case room (70) | 8.2 | 4.4 | * | 8.9 | 12.0 | 6.6 | 8.0 |
| - Control room (72) | 13.9 | 10.9 | * | 17.0 | 16.4 | 16.7 | 15.0 |
| **Emission reduction** | | | | | | | |
| - Absolute (kg/animal place per year) | 5.7 | 6.5 | * | 8.1 | 4.5 | 10.1 | 7.0 |
| - Relative (%) | 41% | 60% | * | 48% | 27% | 71% | 47% |
| **Emission factor** | 7.6 | 5.3 | * | 6.8 | 9.5 | 3.7 | 6.9 |

* no data. Measurement period was skipped because of plans at that time to start an optimalisation period and restart the emission measurements afterwards.

The reduction of the ammonia emission as a result of the use of the CowToilet, compared to a traditional concrete slatted floor (Rav code: A 1.100) amounts 47.2%.
This reduction is equivalent with a proportional emission rate of 0.528. Multiplied with the emission factor of the control room of 13 kg/animal place per year, the ammonia emission rate of the CowToilet amounts 6.9 kg per animal place per year.
The categorized emission factor based on the point measurements presented in this report would be 7 kg $NH_3$ per animal place per year.
The emission reduction and resulting emission factor are influenced by the method for measuring the ammonia concentration.

- Use of the NOx method resulted in an emission reduction of 35% and an standardized emission factor of 8.5 kg $NH_3$ per animal place per year.
- Use of the Picarro method resulted in an emission reduction of 37% and an standardized emission factor of 8.2 kg $NH_3$ per animal place per year.

Results from a second case-control approach, or results from emission measurements on at least two other barns with the CowToilet are needed to obtain an official emission factor for the Rav legislation.

# Samenvatting

Bron van de ammoniakemissie uit een melkveestal is het ureum in de uitgescheiden urine van de aanwezige dieren. Dit ureum wordt in de eerste uren na uitscheiding omgezet in ammoniak en komt vrij uit urineplassen die op loopvloeren liggen of uit de toplaag van het mengsel van urine en feces (mest) in de mestputten. De afgelopen decennia heeft de ontwikkeling van emissiearme huisvesting gericht op alternatieven voor de betonnen roostervloeren. Het werkingsprincipe van vrijwel al deze vloertype is het snel afvoeren van de urine van de vloer naar de kelder en het verminderen van de luchtuitwisseling tussen kelder en de rest van de stal. Het 'CowToilet' biedt een alternatief voor deze aanpak door (een deel van) de urine al op te vangen voordat het de vloer bereikt. Op deze manier worden urine en ontlasting (gedeeltelijk) gescheiden gehouden en wordt een deel van de belangrijkste bron van ammoniakemissie uit het huisvestingssysteem verwijderd en elders opgeslagen. Daar moet de opgevangen urine alsnog emissiearm worden opgeslagen. Het 'CowToilet' is als emissiearm systeem toegevoegd aan de bijlage 1 van de Regeling ammoniak en veehouderij (Rav) onder nummer A 1.36 (BWL 2021.05) (zie bijlage 1 bij dit rapport). Aan dit systeem is een voorlopige ammoniakemissiefactor van 8,4 kg $NH_3$ per dierplaats per jaar toegekend. Om een definitieve emissiefactor voor het systeem te verkrijgen moet de fabrikant (Hanskamp BV) een dataset van emissiemetingen aanleveren die aan de gestelde eisen voldoen. De emissiemetingen die zijn uitgevoerd binnen het project 'Mestscheiding melkveestallen', waarin verschillende technieken worden geëvalueerd om urine en ontlasting gescheiden te houden, kunnen hiervoor gebruikt worden. In dit rapport zijn de metingen van de ammoniakemissie beschreven die gebruikt kunnen worden voor de aanvraag van een definitieve ammoniakemissiefactor.

Het doel van de in dit rapport beschreven metingen was het bepalen van de ammoniakemissiereductie van het 'CowToilet' met behulp van de "case-control" aanpak zoals beschreven in het protocol voor bepaling van ammoniakemissie uit huisvestingssystemen in de veehouderij (Ogink et al., 2017).

De metingen zijn uitgevoerd in de milieuonderzoekstal van Dairy Campus in Leeuwarden tussen 1-12-2020 en 30-11-2021. In deze stal werd het 'CowToilet' geïnstalleerd in één afdeling (70) die fungeerde als testafdeling ('case') terwijl een andere afdeling (72) fungeerde als referentie of controle afdeling ('control'). De ruimtes zijn klimaatgescheiden en mechanisch geventileerd met twee ventilatoren per afdeling. Beide afdelingen waren voorzien van 16 ligboxen en hadden een betonnen roostervloer met mestputten onder de gehele oppervlakte. Elke afdeling was uitgerust met een drinkbak en een koeborstel. In de referentieafdeling was een krachtvoerbox aanwezig. Het 'CowToilet' fungeerde in de andere afdeling ook als krachtvoerstation. In beide afdelingen stonden 16 lacterende HF koeien. De samenstelling van beide groepen was zodanig dat zij op groepsniveau een vergelijkbare gemiddelde melkproductie hadden. Koeien kregen een gemengd rantsoen van voornamelijk gras- en maïskuilvoer aangevuld met bijproducten en mineralen. Koeien werden twee keer per dag gemolken in een draaimelkstal buiten de afdelingen en de rest van de dag in de afdelingen gehuisvest. Er werd geen beweiding toegepast. De ventilatieniveau van elke ventilator werd constant geregistreerd met behulp van een meetwaaier. In elke ventilator en op vier achtergrondpunten, twee aan weerszijden van de stal, werd de ammoniakconcentratie gemeten. Deze ammoniakconcentratie werd gemeten met behulp van drie methoden: een nat-chemische methode met impingers, resulterend in één gemiddelde concentratie over 24 uur voor elk meetpunt, en twee continue meettechnieken voor de ammoniakconcentratie. Een NOx-analysator gecombineerd met ammoniakconverters en een Picarro multi-gas analyser, beide resulterend in een uurgemiddelde concentratie voor elk meetpunt.

Er zijn zes meetperioden gedefinieerd. Voor nat-chemische impinger methode duurde elke meetperiode 24 uur. Ze worden 'puntmetingen' genoemd. Meetperioden van continue technieken duurden vier dagen (dinsdag-vrijdag) in elke meetweek. Ze worden NOx-metingen en Picarro-metingen genoemd. Picarro-metingen werden uitgevoerd in dezelfde week als de puntmetingen. NOx-metingen zijn uitgevoerd in de week vóór (NOx-A) en na (NOx-B) de meetweek van de puntmetingen.

Concentratiemetingen van de dagelijkse emissies per eenheid werden berekend exclusief de twee maal twee uur melktijden en werden gestandaardiseerd voor buitentemperatuur, melkureumgetal en vervuild oppervlakte. Per meetperiode is een emissiereductie berekend op basis waarvan een emissiefactor gerelateerd aan die van het traditionele huisvestingssysteem (A1.100; 13 kg $NH_3$ per dierplaats per jaar) is bepaald.

Het 'CowToilet' verzamelde gemiddeld 10,4 liter urine per koe per dag. De gemiddelde meetomstandigheden tijdens de nat-chemische puntmetingen worden gegeven in tabel S1.

***Tabel S1*** *Omstandigheden tijdens puntmetingen.*

| **Variabele** | **Meetperiode** | | | | | | |
|---|---|---|---|---|---|---|---|
| | **1** | **2** | **3** | **4** | **5** | **6** | **Gemiddelde** |
| **Klimaatomstandigheden** | | | | | | | |
| Temperatuur buitenlucht (°C) | 7.5 | 3.5 | 4.3 | 18.2 | 17.3 | 9.9 | 10.1 |
| Relatieve vochtigheid buitenlucht (%) | 96 | 96 | 78 | 80 | 86 | 97 | 88.7 |
| Temperatuur (°C) | | | | | | | |
| Luchtdruk (hPa) | 1013 | 1001 | 1032 | 1016 | 1013 | 1023 | 1016 |
| Windrichting (graden) | 177 | 129 | 249 | 147 | 239 | 202 | 191 |
| Windsnelheid op 10 meter (m/s) | 4.2 | 3.4 | 3.3 | 3.6 | 4.2 | 4.2 | 3.8 |
| - Testafdeling (70) | 10.3 | 7.0 | 9.1 | 21.8 | 20.3 | 13.0 | 13.6 |
| - Controleafdeling (72) | 10.6 | 7.2 | 9.6 | 22.1 | 20.7 | 12.6 | 13.8 |
| Relatieve vochtigheid (%) | | | | | | | |
| - Testafdeling (70) | 88 | 85 | 62 | 69 | 76 | 84 | 77 |
| - Controleafdeling (72) | 97 | 95 | 67 | 73 | 81 | 98 | 85 |
| **Diergegevens** | | | | | | | |
| Melkproductie (kg/dier per dag) | | | | | | | |
| - Testafdeling (70) | 31.6 | 29.4 | 29.1 | 24.6 | 28.8 | 26.0 | 28.3 |
| - Controleafdeling (72) | 30.5 | 28.7 | 28.7 | 24.0 | 31.0 | 27.0 | 28.3 |
| Melkvetgehalte (%) | | | | | | | |
| - Testafdeling (70) | 4.7 | 5.0 | 5.2 | 4.7 | 4.7 | 4.8 | 4.8 |
| - Controleafdeling (72) | 4.7 | 4.8 | 5.0 | 4.7 | 4.7 | 4.9 | 4.8 |
| Melkeiwitgehalte (%) | | | | | | | |
| - Testafdeling (70) | 3.8 | 3.9 | 3.8 | 3.7 | 3.5 | 3.8 | 3.8 |
| - Controleafdeling (72) | 3.9 | 4.0 | 3.7 | 3.7 | 3.5 | 3.9 | 3.8 |
| Melkureumgetal (mg/100 g) | | | | | | | |
| - Testafdeling (70) | 21 | 17 | 22 | 28 | 18 | 25 | 22 |
| - Controleafdeling (72) | 18 | 14 | 21 | 27 | 16 | 23 | 20 |

Uit de statistische analyse bleek dat de verschillen tussen de afdelingen wat betreft temperatuur, melkproductie, vetgehalte en eiwitgehalte niet statistisch verschillend waren ($p>0,1$). Alleen de relatieve vochtigheid en het ureumgehalte verschilden tussen de afdelingen ($p<0,001$). De resultaten van de emissies (berekend op basis van verschillende ammoniakconcentratiemethoden) zijn weergegeven in Tabel S2.

***Tabel S2*** Resultaten meting ventilatiedebiet en emissie(reductie) tijdens puntmetingen.

| Variabele | Meetperiode | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | Gemiddelde |
| **Ventilatiedebiet ($m^3/h$)** | | | | | | | |
| - Testafdeling (70) | 15,923 | 14,904 | * | 22,997 | 16,402 | 15,503 | 17,146 |
| - Controleafdeling (72) | 15,923 | 15,244 | * | 23,053 | 14,589 | 21,177 | 17,997 |
| **Kooldioxideconcentratie (ppm)** | | | | | | | |
| - Testafdeling (70) | 692 | 777 | * | 762 | 758 | 791 | 756 |
| - Controleafdeling (72) | 560 | 795 | * | 808 | 771 | 749 | 736 |
| **Ammoniakconcentratie (ppm)** | | | | | | | |
| - Achtergrond | 0.05 | 0.05 | * | 0.05 | 0.08 | 0.06 | 0.06 |
| - Testafdeling (70) | 1.22 | 0.62 | * | 1.34 | 1.89 | 1.18 | 1.25 |
| - Controleafdeling (72) | 1.90 | 1.35 | * | 2.41 | 2.78 | 1.99 | 2.08 |
| **Ammoniakemissie (kg/dierplaats per jaar)** | | | | | | | |
| - Testafdeling (70) | 7.5 | 3.4 | * | 11.6 | 11.6 | 7.0 | 8.2 |
| - Control room (72) | 11.9 | 8.0 | * | 21.2 | 15.4 | 16.7 | 14.6 |
| **Emissiereductie** | | | | | | | |
| - Absolute (kg/dierplaats per jaar) | 4.4 | 4.6 | * | 9.6 | 3.7 | 9.6 | 6.4 |
| - Relatieve (%) | 37% | 57% | * | 45% | 24% | 58% | 44% |
| **Emissiefactor** | 8.2 | 5.6 | * | 7.1 | 9.8 | 5.5 | 7.2 |
| **Ammoniakemissie (gestandaardiseerd voor melkureum en buitentemperatuur (kg/dierplaats per jaar)** | | | | | | | |
| - Testafdeling (70) | 8.2 | 4.4 | * | 8.9 | 12.0 | 6.6 | 8.0 |
| - Controleafdeling (72) | 13.9 | 10.9 | * | 17.0 | 16.4 | 16.7 | 15.0 |
| **Emissiereductie** | | | | | | | |
| - Absolute (kg/dierplaats per jaar) | 5.7 | 6.5 | * | 8.1 | 4.5 | 10.1 | 7.0 |
| - Relatieve (%) | 41% | 60% | * | 48% | 27% | 60% | 47% |
| **Emissiefactor** | 7.6 | 5.3 | * | 6.8 | 9.5 | 5.2 | 6.9 |

* geen gegevens. Meetperiode is overgeslagen vanwege plannen voor optimalisatie die naderhand zijn afgeblazen.

De reductie van de ammoniakemissie als gevolg van het gebruik van het 'CowToilet', ten opzichte van een traditionele betonnen roostervloer (Rav-code: A 1.100) bedraagt 47.2%.
Deze reductie komt overeen met een proportioneel emissiecijfer van 0,528. Vermenigvuldigd met de emissiefactor van de controleafdeling van 13 kg $NH_3$/dierplaats per jaar bedraagt de ammoniakemissie van het 'CowToilet' 6,9 kg per dierplaats per jaar. De gecategoriseerde emissiefactor op basis van de in dit rapport gepresenteerde puntmetingen zou 7 kg $NH_3$ per dierplaats per jaar bedragen.
De emissiereductie en de daaruit voortvloeiende emissiefactor worden beïnvloed door de methode voor het meten van de ammoniakconcentratie:

- Toepassing van de NOx-methode resulteerde in een emissiereductie van 35% en een gestandaardiseerde emissiefactor van 8,5 kg NH3 per dierplaats per jaar.
- Toepassing van de Picarro-methode resulteerde in een emissiereductie van 37% en een gestandaardiseerde emissiefactor van 8,2 kg NH3 per dierplaats per jaar.

Resultaten uit een tweede case-control aanpak of resultaten uit emissiemetingen op minimaal twee andere stallen met het 'CowToilet' zijn nodig om een officiële emissiefactor voor de Rav-wetgeving te verkrijgen.

# 1 Introduction

## 1.1 Context and problem definition

Ammonia ($NH_3$) one of the main form of gaseous reactive nitrogen produced in agriculture. It has negative effects on the ecosystem like eutrophication, acidification and loss of biodiversity. Livestock in general and dairy farming in particular is and importance source of ammonia emission and needs to be reduced. With this aim a set of laws and regulations is active in the Netherlands. The two most important are the 'Besluit emissiearme huisvesting (Beh)[1]' that regulates the maximum emission per animal and the 'Regeling ammoniak en veehouderij (Rav)[2]' that contains a list of housing systems. Each housing system on that list contains a detailed description and has an emission factor expressed in kg $NH_3$ per animal place per year. The most common housing system for dairy cows is the cubicle system with concrete slatted floors and slurry storage in pits underneath this floor. Around 75-80 % of the dairy cows in the Netherlands are housed in such a system (CBS, 2022). This housing system is referred to as the traditional system with an ammonia emission factor of 13 kg $NH_3$ per animal place per year.

Ammonia from dairy housing originates from the urea in the excreted urine. The urea is converted to ammonia in the first hours after excretion and emits from urine puddles that lay on walking floors or from the top layer of the mixture of urine and faeces (slurry) in the slurry pits. In past decades development of alternatives for the concrete slatted floors have focussed on closed concrete floors sometimes combined with rubber for animal welfare reasons. The working principle behind those floors is to restrict the air exchange of pits headspace and fast drainage of the urine to these pits. Disadvantages of closed concrete floors are that they are difficult to clean and provide minimal comfort to the cows. The CowToilet offers an alternative by collecting (part of) the urine before it reaches the floor. In this way urine and faeces are (partially) kept separated and the main source of ammonia emission is removed from the housing system and stored elsewhere with negligible emissions. The CowToilet has been added as a low-emission system to the Rav legislation under Rav code A 1.36 and BWL 2021.05 (see Appendix 1 to this report) with a provisional ammonia emission factor of 8.4 kg per animal place per year. To obtain a definitive emission factor for the system the manufacturer (Hanskamp BV) must provide a data set of emission measurements to the 'Rijksdienst voor Ondernemend Nederland' (RVO)[3] that meet the appropriate requirements. These measurements have been carried out within the project 'Mestscheiding melkveestallen' in which several techniques are evaluated to keep urine and faeces separated. Emission measurements were part of this evaluation. This report described the emission measurements in the context of the application for a definitive ammonia emission factor.

## 1.2 Objective

The objective of the measurements described here was to determine the ammonia emission reduction of the CowToilet using the "case-control" approach as described in the measurement protocol for determination of ammonia emission from housing systems in livestock production (Ogink et al., 2017). This report aims to provide part of a basis to obtain a definitive ammonia emission factor.

[1] Beh: Decree on low emission housing (https://wetten.overheid.nl/jci1.3:c:BWBR0036748&z=2022-05-05&g=2022-05-05)
[2] Rav: Regulation on ammonia and livestock husbandry (https://wetten.overheid.nl/jci1.3:c:BWBR0013629&z=2023-04-01&g=2023-04-01)
[3] RVO: Netherlands Enterprise Agency (https://www.rvo.nl/)

## 1.3 Structure of this report

This report has been set up as a measurement report, following the criteria described in the protocol for determination of ammonia emission from housing systems in livestock production (Ogink et al., 2017). Chapter two describes the CowToilet as well as the methodology of the study. Chapter three presents the results of the measurements. The report ends with the conclusions and a list of references.

# 2 Material and methods

## 2.1 The CowToilet

The CowToilet has been designed following the physiology of a cow. It is developed by Hanskamp AgroTech BV, Doetinchem. The supply of concentrate in automatic feeding stations to meet individual cow needs is common in dairy farming. The walk-through feeding station offers the opportunity for the cows to leave the feeding station without walking backwards. The CowToilet is the addition of an automatic urinal to a walk through feeding station. The availability of concentrate is a good stimulus to visit the CowToilet. Based on the expired time since the last successful visit the cow has to leave the CowToilet or is rewarded with an amount of concentrate. After the available amount of concentrate is supplied the urinal is lowered to just below the vulva of the cow. Part of the automatic urinal touches the nerval ends in the perineum to induce an urination. The urine is collected in a small reservoir and from there pumped to a storage. More background on urination behavior of cows and details of the CowToilet are described in Verdoes and Bokma (2017).
The main emission reducing principle of the CowToilet is lowering the source strength of nitrogen in the animal housing by collecting part of the urine. This urine represents an amount of urea nitrogen that is no longer available for ammonia emission from housing. The collected urine is stored separately. In this storage the urea is eventually converted to ammonia and can lead to considerable emission of ammonia when not covered appropriately. Doing so it is expected that storage of the urine will not significantly contribute to ammonia emissions. The rest of the urine (not collected) and the faeces are stored in the traditional way as slurry in pits underneath the concrete slatted floor.

During the measurements described here the amount of urine collected by the CowToilet was measured every three to four days and stored outside the units. The average amount in that period was calculated by dividing the recorded amount (in litres) by the number of days since the last recording and the number of animals in the room during that period.

## 2.2 Test location

### 2.2.1 Description of the case-control barn

The measurements have been carried out in the environmental research barn of Dairy Campus in Leeuwarden, the Netherlands. Figure 1 shows the location of the environmental research barn in the Netherlands and on the Dairy Campus site. The following buildings are located in the immediate vicinity of the from environmental research barn:

1) Dairy housing for feed research. Distances from environmental research barn is approximately 75 meter.
2) Milking parlour and separation pens.
3) Dairy housing for dry cows including calving pens. Both buildings are connected and share a feeding lane but air exchange is prevented by constructional measures and an overhead door.
4) Former dairy housing currently in use as straw and equipment storage.
5) Silage storages.

None of them represents a potentially disturbing source of ammonia emission.

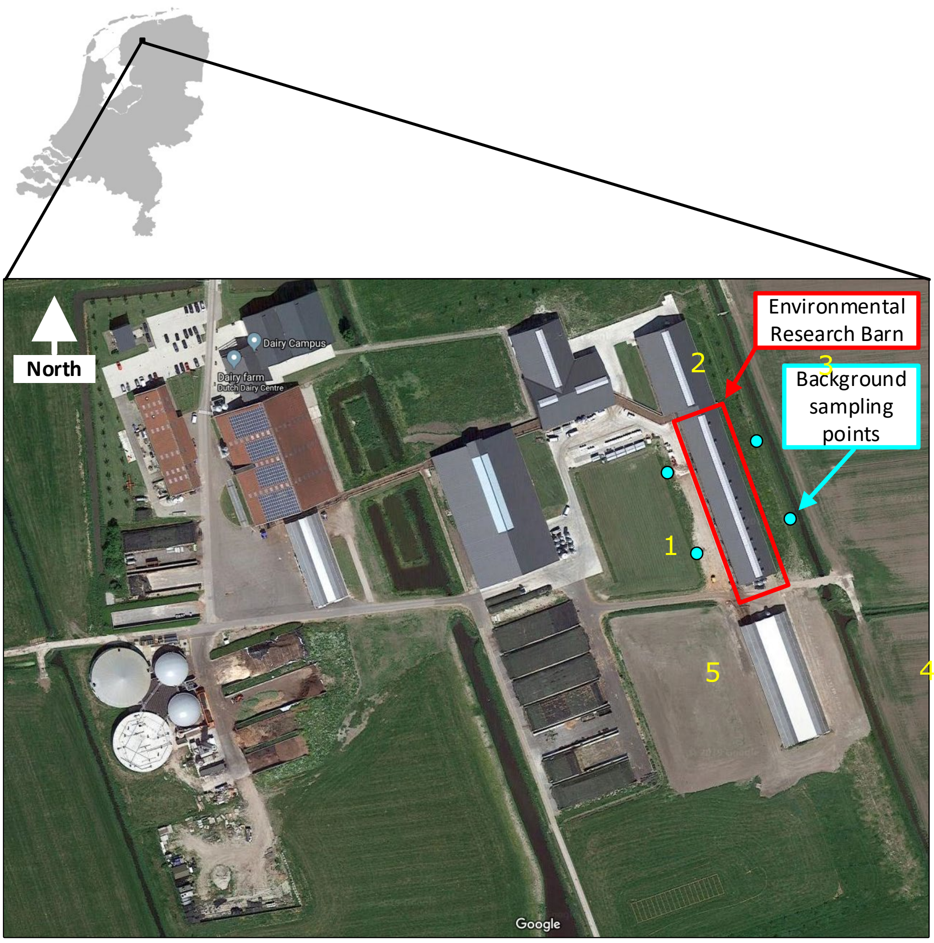


**Figure 1** *Location of the environmental research barn in the Netherlands and on the Dairy Campus terrain including background sampling points.*

Figure 2 shows the general lay-out of the environmental research barn. In this barn, the CowToilet was installed in unit 70 ("case") whereas unit 72 served as the control. Figure 3 shows the detailed lay-out of the measured and neighbouring units and Figure 4 a schematic cross-section of one of the cubicle units. Figure 5 is a combination of two pictures giving a view inside one of the units. The main characteristics of these units are summarised in Table 1.

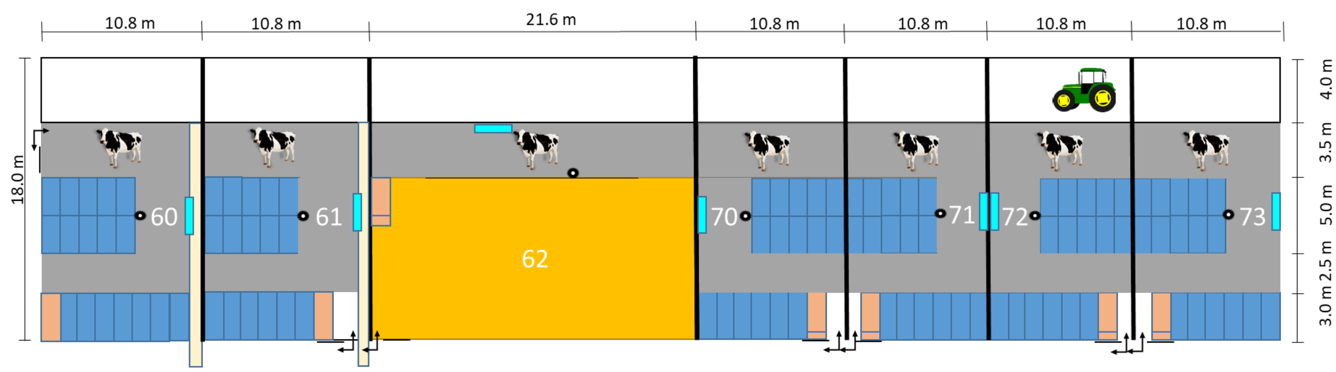


**Figure 2** *Lay-out of the environmental research barn at Dairy Campus.*


***Figure 3*** *Detailed lay-out of the four cubicle rooms. The CowToilet was installed in unit 70 (case) and unit 72 served as the control.*

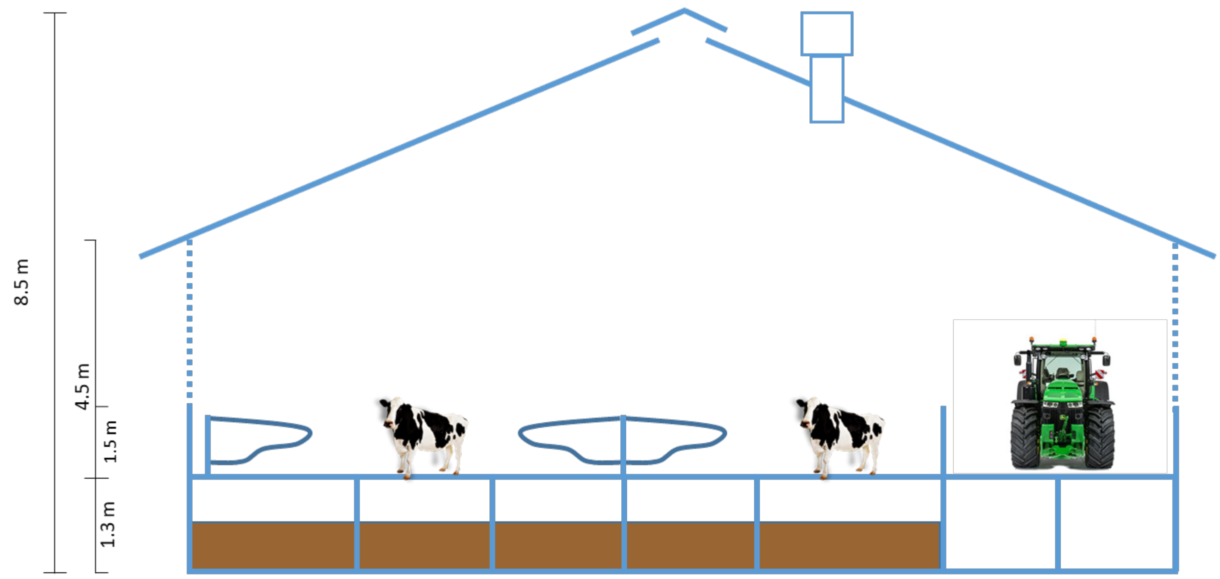


***Figure 4*** *Schematic cross section of one of the cubicle units in the environmental research barn at Dairy Campus.*

***Table 1*** *Main characteristics of the case and control room in the environmental research barn.*

| **Parameter** | **Unit** | **Unit 70 CowToilet** | **Unit 72 Control** |
|---|---|---|---|
| **Rooms and dimensions** | | | |
| Length × width | [m] | 10.8 × 18.5 | |
| Height gutter / ridge | [m] | 4.5 / 8.2 | |
| Total surface area | [$m^2$] | 201 | |
| Total volume (excluding manure pits) | [$m^3$] | 1,278 | |
| Roof shape | - | Gable roof | |
| Orientation building | - | NNW-SSE | |
| **Ventilation** | | | |
| Principle | - | Mechanical | |
| Ventilation capacity | [$m^3$/h] | 42,000 at 0 Pa | |
| Air inlet | - | Open side walls with bird netting and wind curtains | |
| Air outlet | - | 2 Ventilation shafts in the roof | |
| **Slurry pits** | | | |
| Surface area of slurry in pits | [$m^2$] | 126 | |
| Depth | [m] | 1.3 | |
| Volume | [$m^3$] | 201 (12.6 per cow) | |
| **Walking floor** | | | |
| Floor type | - | Concrete slats | |
| Slurry scraper | - | No[2] | |
| Surface area of walking floor[1] | [$m^2$] | 72.8 (4.6 per cow) | |
| **Cubicles** | | | |
| Number of cubicles | - | 16 | |
| Width | [m] | 1.15 | |
| Length | [m] | 2.5 (10 cubicles) / 3.0 (6 cubicles) | |
| Surface area of cubicles | [$m^2$] | 49.5 (3.1 per cow) | |

[1]) "Mest besmeurd oppervlak" in Dutch. [2] See also paragraph 3.1

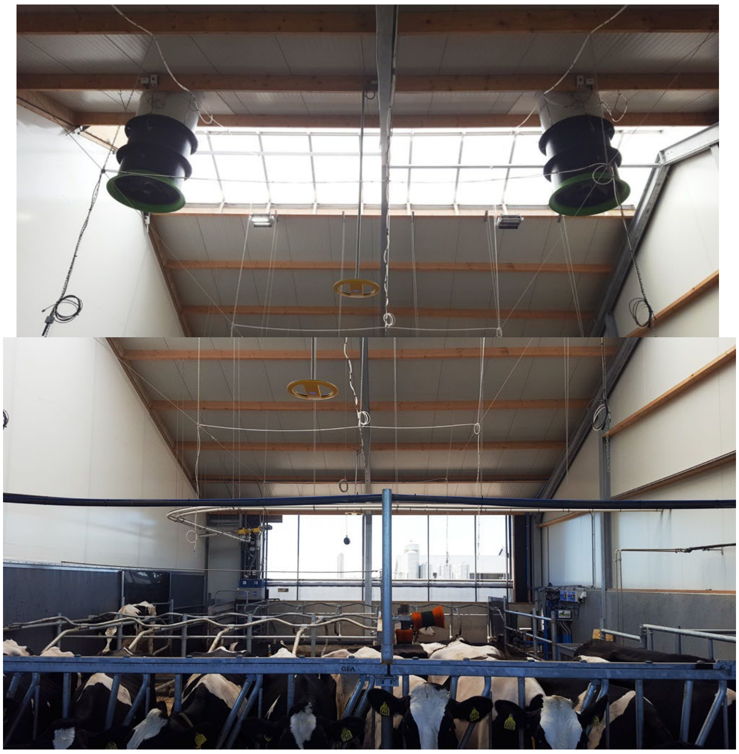

***Figure 5*** *Combination of two photos of one of the cubicle rooms of the environmental research barn. Note the two ventilation shafts mounted from the ceiling.*

The seven rooms inside the environmental research barn are climate separated. The barn has concrete walls, steel frame and insulated roof panels. Side walls are closed to a level of 1.5 m from the floor; the remaining distance to the gutter is open with bird netting and wind curtains which can be controlled automatically (based on a weather station) or manually. In this project, the wind curtains were always closed (which leaves a 10 cm wide gap for air inlet, to ensure no cross-ventilation could take place). The ridge is made of transparent panels with switch-operated valves that can be opened in case natural ventilation is needed. The barn has slurry pits under the entire surface area behind the feed fence (i.e., except the area under the feed alley). Rooms are lit by 2 LED lights mounted from the ceiling. The feed fence has 12 feed places. Each room was equipped with a drinking trough, a cow brush, a concentrate feeding station and 16 cubicles.

### 2.2.2 Description of the CowToilet in unit 70

The CowToilet was installed in unit 70 at the place of the cow brush which was removed during the measurements (Figure 6). Cows entered the CowToilet from the feeding fence side and left the CowToilet on the other side. All concentrate feeding was supplied in the CowToilet. The other feeding station was blocked and not accessible for cows during the measurements. The collected urine was pumped away by a pump that was installed in the unit to an Intermediate Bulk Container (IBC) container outside the unit.

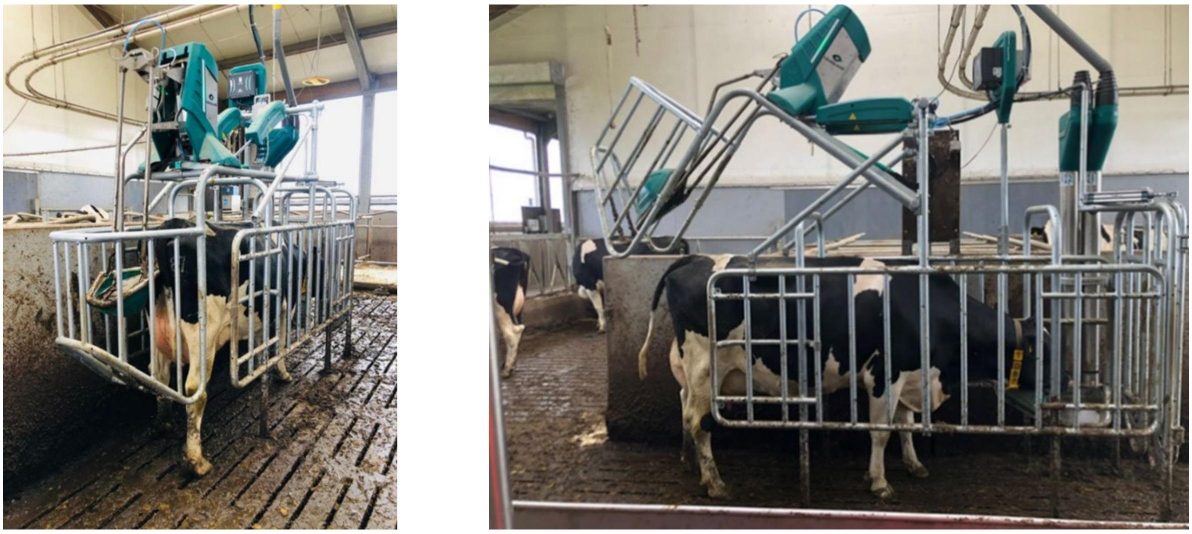

***Figure 6*** *Photo's showing the location of the CowToilet in unit 70.*

### 2.2.3 Management of animals and climate

**Animals**
Both the case and control room housed only 16 lactating cows of the Holstein Frisian breed. The animal groups in all rooms of the environmental research barn were composed and monitored such that they had similar mean milk productions (kg/cow per day, ± 10%; based on the milk production in the milking parlour) and similar mean urea milk contents (mg/100 g, ± 10%; based on the weekly individual milk quality analyses).

**Feed and water**
Cows were fed ad libitum a ration primarily composed of grass silage (45%) and corn silage (26%). By-products in the ration where: barley (4%), soya (3%), and a mixture of acid buffers, vitamins and minerals (1%). The afore mentioned percentages are based on fresh weight composition and represent the overall mean contribution in the ration based on the digital reports from the feed mixing wagon for the six measurement periods in this study. The crude protein content of the roughage ration was on average 146 g/kg DM throughout the study. The aforementioned components were mixed and deposited along the feed fence using a feed mixing wagon. Feeding was done once a day during morning milking. During the afternoon milking and in the evening (around 22:00) the ration was pushed up towards the feed fence. Cows received portions of concentrate feed, when they visited the concentrate feeding box (unit 72) or the CowToilet (unit 70), spread over the day in total amounts of 2 to 10 kg, depending on their nutritional needs. Daily intake of concentrate feed was registered daily per individual cow. Water was provided ad libitum in the drinking troughs in the units.

**Grazing**
Apart from milking times cows were kept inside. No grazing was offered.

**Milking**
Cows were milked in the morning and the afternoon in a 40-stands rotary milking parlour situated in another building at the Dairy Campus premises. Cows walked from the environmental research barn to the milking parlour and back via an outside animal path along the westside of the barn. On their way back selection gates (activated by collar transponders) directed each animal into the right unit again.

**Animal welfare and veterinary care**
The units of the environmental research barn and the animal management were in agreement with regulations on animal welfare and health and common agricultural practices. General signs related to health and well-being were assessed by the animal caretakers when cows were collected from their rooms for milking. Cows received standard veterinary care.

**Ventilation**
Units were ventilated mechanically by two ventilators mounted in roof shafts (Fancom, Panningen, the Netherlands; Ø 80 cm; max. 21,000 $m^3$/h at 0 Pa). Each ventilator was equipped with a free running fan wheel anemometer and a control valve (ATM80). Ventilation level was controlled per unit by a climate computer (Fancom, Panningen, the Netherlands; type FC14) in combination with a variable-frequency drive (VLT HVAC Drive, Danfoss, Denmark). The ventilation rate was set at 50% of the capacity, which resulted in a ventilation rate of approximately 16,000 $m^3$/h (1,000 $m^3$/h per cow). Wind curtains in the side walls were kept in the closed position. In the closed position, an opening of approximately 10 cm wide remained between the bottom of the curtain and the side wall along the length of the room for air inlet preventing possible cross-ventilation. Units were kept strictly climate separated. Only during milking the animal doors to the animal path were allowed to be opened, as well as the sliding doors in the feed alley for feeding or pushing up feed. These two "open door periods" lasted for max. 2 h (max. 4 hours daily). The data from these periods were excluded from the analysis (for more information see par. 2.6).

**Lighting**
Rooms were lit by natural daylight via the transparent roof ridge and additionally by two LED lights in the morning and evening hours. Cows received a natural (nocturnal) dark period of at least 6 hours.

**Manure management**
The level of slurry in the slurry pits was determined weekly. When slurry was mixed and removed (either because slurry was applied directly to the fields or pit levels became too high), wind curtains and sliding doors in the feed alley were fully opened to avoid dangerous concentrations of manure gasses. Such events were planned outside measurement periods.

## 2.3 Measurement strategy and sampling points

Since units were ventilated mechanically (with wind curtains in the closed position, a closed ridge and slight underpressure inside the rooms), the two ventilation shafts represented the emission points of the rooms where the measurement of ventilation rate and ammonia concentration took place. The background (ambient) concentration of ammonia was determined outside the barn at two to four locations at 10 m distance at both sides of the barn (Figure 1). The point with the minimum value of the concentration was considered to be the upwind point and therefor the best estimate of the background concentration .

This project used measurement strategy B as described in the protocol for determination of ammonia emission from housing systems in livestock production (Ogink et al., 2017). The main criteria of this strategy were worked out as follows:

- *Measurements must be conducted at two different farm locations which are equipped with a room with the housing system of interest (case) and a room with a traditional housing system with a known emission rate (control)*.
  This project has been carried out in *one* case-control farm. Results from a second case-control farm location, or results from emission measurements at another two barns with the housing system of interest, are needed to obtain an official emission factor for the Rav legislation;

- *A measurement period must have a duration of at least 24 h or a multitude of this*.
  In this project different ammonia measurement methods were used (see paragraph 2.4). For the continuous measurement methods the ventilation rates and ammonia concentrations were aggregated to hourly values. A measuring period (see par. 2.6 for more information) lasted for 96 hours and was carried out from Tuesday 0:00 until Friday 23:59. Due to the "open door periods" and the absence of cows during milking (see paragraph 2.2.2), 2 hours of data in the morning and 2 hours of data in the afternoon, were excluded from the analyses. One measurement period therefore contained (96 minus 4 × 4 =) 80 hourly values.
- *At each farm location, 6 measurement periods must be performed, spread over one year.*
  In this projects the 6 measurements periods were performed evenly spread within 12 months after the first measurement.
- *Emission measurements of houses with animals with a stable emission pattern must be carried out in consecutive time periods of two months in which a measurement period must be chosen randomly.*
  In this project the continuous measurements of ammonia concentration were done using two devices: a NOx monitor and a Picarro multi-gas analyser (see paragraph 2.4.2). Each ventilator has only two sampling lines. Therefore, during the 24 hour point measurements only Picarro and no NOx-data are available. The measurement periods of the different measurement methods for ammonia (see paragraph 2.4.2) were defined by the first 24 hour refences measurement. Subsequently, each next point measurement period was set in consecutive periods of two months according to the measurement protocol. Target weeks were set by adding + 8, 16, 24, 32, and 40 weeks after the first measurement period. When this target week could not be realised a week within an interval of 2 weeks earlier until 2 weeks later than the target week was selected (see Table 2 and
- Table ***3*** for resulting schedule). This way, measurement periods were always well away from previous and next measurement periods and always within a different 2-months period (see vertical dashed lines in Figure 7). The measurements periods of other ammonia measurement methods were determined by these periods. Measurement periods of NOx were one week before (A) of one week after (B) the point measurements. Measurement periods of the Picarro were in the same week as the point measurements.

***Table 2*** *Start and end date of point measurements and continuous measurements during the total measurement period.*

| **Measurement** | **Point measurements** | | | | **NOx** | | | **Picarro** | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Start** | **End** | **Week** | **Day** | **Start** | **End** | **Week** | **Start** | **End** | **Week** |
| 1 | 16-12-2020 | 17-12-2020 | 51 | 351 | 22-12-2020 | 25-12-2020 | 50/52 | 15-12-2020 | 18-12-2020 | 51 |
| 2 | 2-2-2021 | 3-2-2021 | 6 | 33 | 9-2-2021 | 12-2-2021 | 5/7 | 2-2-2021 | 5-2-2021 | 6 |
| 3 | 13-4-2021 | 14-4-2021 | 16 | 103 | 20-4-2021 | 23-4-2021 | 15/17 | 13-4-2021 | 16-4-2021 | 16 |
| 4 | 17-6-2021 | 18-6-2021 | 25 | 168 | 22-6-2021 | 25-6-2021 | 24/26 | 15-6-2021 | 18-6-2021 | 25 |
| 5 | 15-9-2021 | 16-9-2021 | 38 | 258 | 21-9-2021 | 24-9-2021 | 37/39 | 14-9-2021 | 17-9-2021 | 38 |
| 6 | 10-11-2021 | 11-11-2021 | 46 | 314 | 16-11-2021 | 19-11-2021 | 44/46 | 9-11-2021 | 12-11-2021 | 46 |

Point measurements and Picarro measurements were done in the same week using both sampling lines per ventilator. The NOx-periods were defined as the week before (NOx-A) and after (NOx-B) this week (see Table ***3***).

***Table 3*** *Example of one measurement period and relation of different ammonia measurement methods in time.*

| **Measurement** | **Week X** | | | | | | | **Week Y** | | | | | | | **Week Z** | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **Su** | **Mo** | **Tu** | **We** | **Th** | **Fr** | **Sa** | **Su** | **Mo** | **Tu** | **We** | **Th** | **Fr** | **Sa** | **Su** | **Mo** | **Tu** | **We** | **Th** | **Fr** | **Sa** |
| Point | | | | | | | | | | 24h | | | | | | | | | | | |
| NOx | | | A | | | | | | | | | | | | | | B | | | | |
| Picarro | | | | | | | | | | Picarro | | | | | | | | | | | |

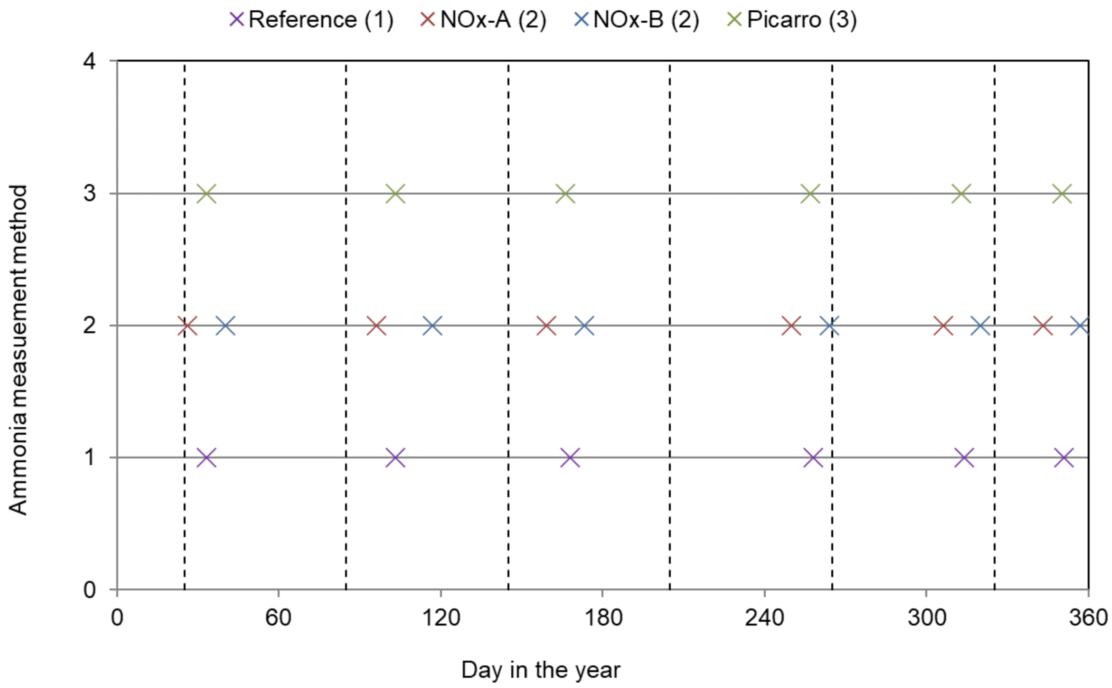


***Figure 7*** *Measurement periods for different ammonia measurements methods divided over the total measurement period. Vertical dashed lines represents the different 2 months periods.*

## 2.4 Measurement methods

### 2.4.1 Ventilation rate

The ventilation rate was measured by the fan wheel anemometer in the Fancom ATM 80 measuring and control valve units under each ventilation shaft. The output signals (pulse frequency, Hz) of the units were stored in a data storage box (Campbell Scientific, Logan, USA; type CR1000). The frequencies were converted into ventilation rates using a single calibration line. These calibration line was based on wind tunnel measurements performed in November 2018 and February 2019 with eight fan wheel anemometers of the same type. These fan wheel anemometers were of different age ranging from new to six years old. The individual calibration lines and the single calibration lines based on the total outcome of these wind tunnel measurements are included in Appendix 2.

### 2.4.2 Ammonia concentration

For the determination of ammonia concentration air was sampled from the interior of the ventilation shafts and transported to the measuring room of the barn via polyethylene tubes. Each ventilator has two sampling tubes. Three methods for determining the ammonia concentration in the air transported through the tubes were used:

- **Ammonia concentration measurement using acid wet trap impinger gas washing method**

This method is described by Mosquera *at al.* (2019). One sampling line per ventilator shaft was used resulting in duplo measurements per unit. Content of flasks were analyzed using photo-spectrometry at Wageningen Livestock Research. Other parts of measurement setup are described in Figure 8. Concentration from all four ventilation shafts and two background points (Southeast and Northwest of the barn) were sampled for 24h per measurement. This method is referred to as 'point measurements'.

***Figure 8*** *Set-up WLR gas washing method. Left: absorption flasks (measurements in duplicate; per train (in series) two absorption flasks filled with absorption medium and one empty absorption flask for protection of the pump). Middle: Dry gas flow meter (DryCal® Defender 510-m, Bios Int. Corp, USA). Right: pump (Thomas Industries Inc., model 617CD32, Wabasha, Minnesota ,VS), sampling lines (Teflon or polyethylene), and critical orifices (borosilicate glass (diameter: 8 mm; length: 80 mm), housed in a stainless steel container for protection; flow: ~1000 ml/min).*

- **Ammonia concentration measurement using a NOx analyzer.**

This method is based on the chemo-luminescence principle and described in detail by Mosquera *et al.* (2002) in paragraph 4.2.13 referring to Scholtens (1990) and Bleijenberg & Ploegaert (1994). The air from one set of sampling tubes per ventilator first passed a 12 channel manifold (produced by the central workshop of Wageningen University and Research) connecting two ventilators of one room at a time to the following steps. The air of each ventilator was then heated in an ammonia converter (produced by the central workshop of Wageningen University and Research) to 775 °C. In the presence of a metal catalyst, ammonia is oxidised into nitric oxide (NO). The conversion efficiency of the ammonia converter was calibrated before the project. The concentration of NO in the sampled air was then measured by a $NO_x$-analyser (Teledyne Advanced Pollution Instrumentation, Inc., San Diego, USA; type T200).
The measuring time of each unit was 10 minutes. The averaging time for logging of the ammonia concentration was 1 minute. Of the total sampling duration of 10 minutes, the first 9 minute values were used to obtain a stable concentration level. These values were excluded from further calculation of the ammonia emission. Only the tenth minute value was used as the ammonia concentration. The manifold had 12 inlets which were used for six units with two fan shafts each. This means that each of the two units (case room 70, control room 72) were sampled once every hour. The time interval between the units was 20 minutes. No background concentration points were measured with this method. The NOx-analyser was calibrated, and if needed adjusted, 4 times during the measurement period using a gas cylinder with NO concentration of 39.43 ± 0.39 ppm related to international standards. Concentrations obtained from the NOx-analyser were corrected for the conversion efficiency of the ammonia converter. Data from the $NO_x$-analyser were stored in the aforementioned data storage box (Campbell Scientific, Logan, USA; type CR1000X). This method is referred to as 'NOx measurements'.

- **Ammonia concentration measurement using a multi gas analyzer**

The method is based on cavity ring down spectroscopy (CRDS). A detailed description of this measurement principle and techniques can be found in several handbooks, papers and websites (EPA, 2018; Picarro, 2023; https://www.picarro.com/company/technology/crds). The air from one set of sampling tubes per ventilator first passed a 16 channel manifold produced by Picarro (A0311S SilcoNert, Picarro, Picarro Inc., Santa Clara (Ca), USA). Each ventilator of the two units and two background points (Southeast and Northwest) were connected to the manifold. The switching time of the manifold was 5 minutes. The averaging time for logging of the ammonia concentration was 1 minute. Of the total sampling duration of 5 minutes, the first 3 minutes values were utilized to obtain a stable concentration level. These values were excluded from further calculation of the ammonia emission. Only the average of the fourth and fifth minute value were used as the ammonia concentration. The manifold had 16 inlets which were used for six units and four background points. This means that each of the two units (case room 70, control room 72) were sampled at least once every hour. The time interval between the units was 20 minutes. All four background sampling points were connected to the manifold. The concentration of ammonia in the sampled air was measured by a Cavity Ring-Down Spectroscope (CRDS) of Picarro (G2508, Picarro Inc., Santa Clara (Ca), USA). Validation measurements according to the VERA protocol were described by Zhuang et al. (2020). The Picarro instrument was calibrated between 0 and 100 ppm in the airy quality laboratory of Wageningen Livestock

Research prior to the measurements. Correction factor of 1.09 and a systematic differences of -0.01 ppm were used to correct the measured values. This method is referred to as 'Picarro measurements'.

### 2.4.3 Air temperature, relative humidity and weather conditions

Air temperature and relative humidity in the units were measured using two sensors (Vaisala HPM60; Vaisala Oyj, Helsinki, Finland) with a precision of ± 0.5 °C en ± 3-5% respectively. The data were stored in the aforementioned data storage box (Campbell Scientific, Logan, USA; type CR1000X).
Daily outside weather conditions (temperature, relative humidity, windspeed, wind direction and air pressure) were obtained from the Royal Netherlands Meteorological Institute measuring station Leeuwarden.

### 2.4.4 Animal performance

The milk production (kg/cow) was recorded during each milking and automatically logged in a central database. The milk quality of each cow was determined during the monthly individual milk quality assessments (MPR, Milk Production Registration) and included fat content (%), protein content (%), and urea content (mg/100 g). Animal weight was recorded twice a day during the milking process. These data were also stored in the central database.

## 2.5 Data storage and processing

The data on ventilation rate, ammonia concentration, temperature and relative humidity were stored in the aforementioned data storage box and were send to the servers of Wageningen University and Research frequently. Data processing and calculation of emissions were done with MS Excel by using the template provided by RVO.

## 2.6 Calculation of ammonia emission and reduction

Calculations were done with use of and according to the Microsoft Excel template provided by RVO. Concentrations were measured in part per million (ppm) and converted to mg/m$^3$ using:

$$C = \frac{M * p}{1000 * R * T} * C'$$

where:
C or C' = gas concentration in mg/m$^3$ or ppm respectively
M = molar mass (for ammonia 17.034 gram/mol)
p = air pressure (hPa)
R = gas constant (0.082057 L*atm/(K*mol))
T = temperature (K)

### 2.6.1 Point measurements

The absolute ammonia emission (kg per year per animal place) during a point measurement *j* (1, 2, …, 6) in room *k* (1=case, 2=control) was calculated by the following equation:

$$E_{jk} = Q_{jk} * \left(Cout_{ijk} - Cin_{ijk}\right) * \frac{24 * 365}{10^6 * AP}$$

where:
- $E_{jk}$ = the emission of ammonia (kg/year per animal place) during point measurement *j* in room *k*
- $Q_{jk}$ = the average ventilation rate (m$^3$/h per animal place) during point measurement *j* in room *k*

- $Cout_{jk}$ = the average concentration of ammonia (mg/m$^3$) in the outgoing air during point measurement $j$ in room $k$
- $Cin_{jk}$ = the average concentration of ammonia (mg/m$^3$) in the incoming air during point measurement $j$ in room $k$
- $AP$ = number of animal places (=16)

Background concentration ($Cin_{jk}$) was calculated as the minimum value of the two background sampling points (Southeast and Northwest) around the environmental research barn that were used (see Figure 1).

### 2.6.2 Continuous measurements (NOx and Picarro)

The absolute emission (kg per year per animal place) of day *i* (1, 2, 3, 4) during measuring period *j* (1, 2, …, 6) in room *k* (1=case, 2=control) was calculated by the following equation:

$$E_{ijk} = Q_{ijk} * (Cout_{ijk} - Cin_{ijk}) * \frac{24 * 365}{10^6 * AP}$$

where:

- $E_{ijk}$ = the emission of ammonia (kg per year per animal place) of day *i* during measuring period *j* in room *k*
- $Q_{ijk}$ = the average ventilation rate (m$^3$/h per animal place) of day *i* during measuring period *j* in room *k*
- $Cout_{hijk}$ = the average concentration of ammonia (mg/m$^3$) in the outgoing air of day *i* during measuring period *j* in room *k*
- $Cin_{hijk}$ = the average concentration of ammonia (mg/m$^3$) in the incoming air of day *i* during measuring period *j* in room *k*
- $AP$ = number of animal places (=16)

Daily average concentrations and ventilation were based on 20 hours per day leaving the milking times (2 times 2 hours) out.
Background concentrations ($Cin_{ijk}$) of ammonia for the emission calculation based on Picarro measurements were calculated as the minimum value of the four background sampling points around the environmental research barn (see Figure 1).
For emissions calculated based on NOx measurements the background of the point measurements of that measurement period was used. For the third measurement period the average of all background concentrations during point measurements was used.
The daily emissions were standardized for outside temperature (°C), milk urea content (mg/100 ml) and fouled area (m$^2$/animal) according to the procedure in Ogink et al. (2017):

$$E'_{ijk} = \left(e^{\left(\ln(E_{ijk}) - 0.015*(T-10.5) - 0.025*(M-23)\right)}\right) * \left(1 + 0.1 * (4.5 - A)\right)$$

The absolute ammonia emission per measuring period in kg per year per animal place $E'_{jk}$ was calculated as the average of the daily emissions in that period.
Where:

- $E'_{ijk}$ = the standardized emission of ammonia of day *i* during measuring period *j* in room *k* (kg/year per animal place)
- $E_{ijk}$ = the emission of ammonia of day *i* during measuring period *j* in room *k* (kg/year per animal place)
- T = outside temperature (°C)
- M = milk urea content (mg/100 ml)
- A = fouled area (m$^2$/animal place)

Subsequently, the proportional emission reductions $P_j$ of the "case" room to the "control" room were calculated following the equation:

$$P_j = \frac{E'_{j1}}{E'_{j2}}$$

Subsequently, the mean proportional emission reduction *P* was calculated as the arithmetic mean of the $P_j$ values:

$$P = \overline{P_j}$$

According to the protocol for determination of ammonia emission from housing systems in livestock production (Ogink et al., 2017), the emission factor of the housing system in the case room is obtained by multiplying *P* with the emission factor of the housing system applied in the control room (i.e., 13 kg/year per animal place). This final step in the calculation procedure has been performed too and results are presented in the Results and discussion chapter.

## 2.7 Statistical analysis

Linear mixed model tests using room as fixed and measuring period as random effects were performed using the residual maximum likelihood (REML) procedure of Genstat (VSN International, 2022) to determine statistically significant differences between the case room and the control room for the following variables:

Measurement conditions related to the ammonia emission process:
- Temperature of the inside air (°C);
- Relative humidity of inside air (%)
- Milk production (kg/day)
- Milk fat and protein content (%)
- Milk urea concentration (mg/100 ml);

Direct emission variables:
- Ventilation rate ($m^3$/h)
- Ammonia concentration (mg/$m^3$)
- Ammonia emission rate (kg/animal place per year)

The input for the REML tests were the mean values for each measurement period (n=6 per room). These values were assumed to be independent observations (i.e., not auto-correlated in time). A statistical significant difference was declared at *P*-values ≤ 0.05.
REML tests using ammonia concentration method as fixed and measuring period as random effect were performed to determine statistically significant differences of emission reduction between ammonia concentration methods. All statistical tests were performed with GenStat software $22^{nd}$ edition.

The boxplot interquartile method for outlier analyses was applied on relative differences between case and control unit of ventilation rate, ammonia concentration and standardized ammonia emission using formula:

$$Q_1-3*(Q_3-Q_1) \le x \le Q_3+3*(Q_3-Q_1)$$

with $Q_1$ and $Q_3$ the 25% and 75% quartile and x the relative difference between case and control ((case-control)/control).

# 3 Results and discussion

The CowToliet was installed in room 70 of the environmental research barn in the autumn of 2020. The measurements took place between December 1st, 2020 and November 30th, 2021. At that starting moment, the CowToilet had already been in use for more than two months. However the floor of the unit has been in use since the opening of these research barn in June 2016.

## 3.1 CowToilet

The performance of the CowToilet in terms of collected litres urine per day is given in Figure 9 and the average values per measurement period for the different ammonia concentration measurement techniques in Table 4. The average amount of urine during the whole period was 166.0 litre per day (10.4 litre per cow per day). Standard deviation of volume per day was 34.4 litre per day (2.2 litre per cow per day). The amount of urine per measurement period is given in Table 4.

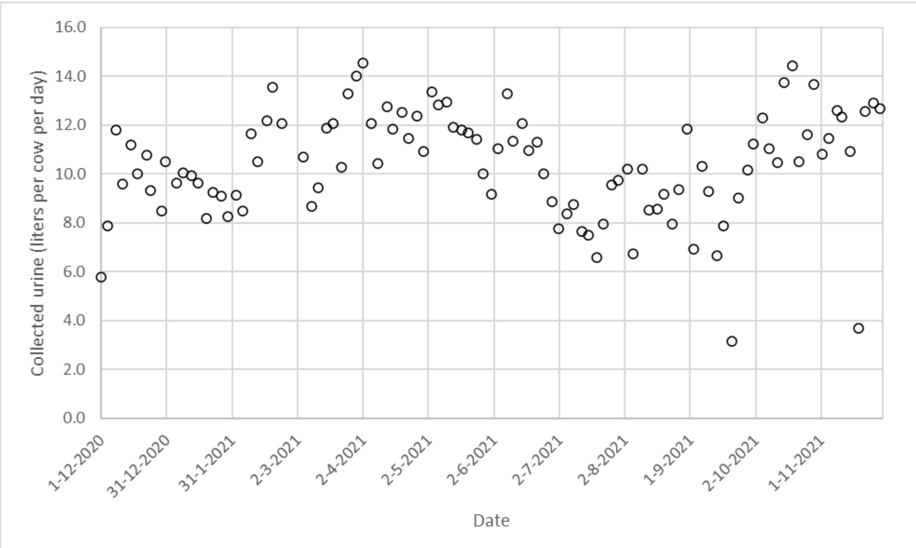


***Figure 9*** *Amount of urine collected by the CowToilet during the year in liter per animal per day.*

***Table 4*** *Average amount of urine collected by the CowToilet for each measurement period in litres per day.*

| Measuring technique | Measurement period | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | Mean |
| Point | 179.1 | 146.2 | 204.0 | 184.1 | 106.2 | 199.3 | 175.3 |
| NOx-A | 171.2 | 138.8 | 180.0 | 196.8 | 157.0 | 178.3 | 170.3 |
| NOx-B | 160.7 | 177.3 | 191.9 | 170.4 | 97.4 | 59.2 | 150.4 |
| Picarro | 169.6 | 141.1 | 196.7 | 184.1 | 116.2 | 199.3 | 167.8 |

Collected urine volume did not differ significantly between methods.

Between the 12th of March 2021 and 11th of July 2021 (covering period 3 and 4) the slatted floor in the room with the CowToilet was scraped with a scraping robot (Lely Discovery). The average scraping frequency was once every two hours. From the 1st of May (covering period 4) some water was sprayed by the robot to improve scraping results.

## 3.2 Measurement conditions during point measurements

The protocol for determination of ammonia emission from housing systems in livestock production (Ogink et al., 2017) lists a number of conditions on various pages that must be met during the study. They were met in this project as follows:

- ✓ Six measurement periods were carried out each of which lasted for a multitude of 24 hours;
- ✓ During measurement periods all animals were kept inside the rooms (i.e., no grazing) except for two times two hours of milking;
- ✓ More than 4 of 6 measurement periods (namely 5 out of 6) are available for calculation of the emission factor;
- ✓ The number of dry cows per room was less (i.e., zero) than 25% of the total number of cows;
- ✓ The number of pregnant young stock was less (i.e., zero) than 30% of the total number of cows;
- ✓ The occupation during measurement periods was within 90 and 110% (i.e., 100%) of the number of cubicles;
- ✓ In the eight weeks prior to the measurement periods, the animals were kept inside the rooms for more than 12 hours per day (i.e., continuously except for milking times);
- ✓ The concentration of carbon dioxide was determined continuously since rooms were ventilated mechanically. Hourly measurements of carbon dioxide concentration showed that concentrations were always well below 3,000 ppm;
- ✓ The fraction of roughage in the ration was well over 50%;
- ✓ The crude protein (CP) content of the roughage ration of both case and control were not over 160 g/kg dry matter but between 132 and 156 g/kg dry matter. However, the urea content of the milk produced by the cows was always well over 15 mg/100 ml except for the second point measurement in the control unit (72);
- ✓ The mean milk production was always well over 25 kg FPCM per animal per day except during the fourth Picarro measurement period;
- ✓ The cows received standard veterinary care. No irregular events occurred with regard to animal welfare or health during the study;
- ✓ The number of cows per case or control room amounted more than 15 (i.e., 16).

Table 5 shows the conditions during the point measurements. Measurement conditions during NOx and Picarro measurement periods are available in Appendix 3.

*Table 5* *Conditions during point measurements.*

| Variable | Measurement period | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | Mean |
| **Measurement period** | | | | | | | |
| Week number in calendar year | 51 | 6 | 16 | 25 | 28 | 46 | |
| Interval between periods (weeks) | | 6 | 10 | 9 | 13 | 8 | 9.2 |
| Start date of measurement period | 16-12-2020 | 2-2-2021 | 13-4-2021 | 17-6-2021 | 15-9-2021 | 10-11-2021 | |
| Day number in calendar year | 351 | 33 | 103 | 168 | 258 | 314 | |
| End date of measurement period | 17-12-2020 | 3-2-2021 | 14-4-2021 | 18-6-2021 | 16-9-2021 | 11-11-2021 | |
| **Climate conditions** | | | | | | | |
| Temperature ambient air (°C) | 7.5 | 3.5 | 4.3 | 18.2 | 17.3 | 9.9 | 10.1 |
| Relative humidity ambient air (%) | 96 | 96 | 78 | 80 | 86 | 97 | 88.7 |
| Ambient air pressure (hPa) | 1013 | 1001 | 1032 | 1016 | 1013 | 1023 | 1016 |
| Wind direction (degrees) | 177 | 129 | 249 | 147 | 239 | 202 | 191 |
| Wind speed at 10 meters (m/s) | 4.2 | 3.4 | 3.3 | 3.6 | 4.2 | 4.2 | 3.8 |
| Temperature inside air (°C) | | | | | | | |
| - Case room (70) | 10.3 | 7.0 | 9.1 | 21.8 | 20.3 | 13.0 | 13.6 |
| - Control room (72) | 10.6 | 7.2 | 9.6 | 22.1 | 20.7 | 12.6 | 13.8 |
| Relative humidity (%) | | | | | | | |
| - Case room (70) | 88 | 85 | 62 | 69 | 76 | 84 | 77[a] |
| - Control room (72) | 97 | 95 | 67 | 73 | 81 | 98 | 85[b] |
| **Animal performance** | | | | | | | |
| Milk production (kg/animal per day) | | | | | | | |
| - Case room (70) | 31.6 | 29.4 | 29.1 | 24.6 | 28.8 | 26.0 | 28.3 |
| - Control room (72) | 30.5 | 28.7 | 28.7 | 24.0 | 31.0 | 27.0 | 28.3 |
| Milk fat content (%) | | | | | | | |
| - Case room (70) | 4.7 | 5.0 | 5.2 | 4.7 | 4.7 | 4.8 | 4.8 |
| - Control room (72) | 4.7 | 4.8 | 5.0 | 4.7 | 4.7 | 4.9 | 4.8 |
| Milk protein content (%) | | | | | | | |
| - Case room (70) | 3.8 | 3.9 | 3.8 | 3.7 | 3.5 | 3.8 | 3.8 |
| - Control room (72) | 3.9 | 4.0 | 3.7 | 3.7 | 3.5 | 3.9 | 3.8 |
| FPCM production (kg/animal per day) | | | | | | | |
| - Case room (70) | 35.1 | 33.8 | 33.9 | 27.3 | 31.4 | 29.2 | 31.8 |
| - Control room (72) | 34.2 | 32.7 | 32.7 | 26.5 | 34.1 | 30.7 | 31.8 |
| Milk urea concentration (mg/100 g) | | | | | | | |
| - Case room (70) | 21 | 17 | 22 | 28 | 18 | 25 | 22[a] |
| - Control room (72) | 18 | 14 | 21 | 27 | 16 | 23 | 20[b] |
| **Feed composition** | | | | | | | |
| Crude protein content (g/kg DM) | 154 | 152 | 144 | 132 | 145 | 159 | 148 |

[a,b] Different superscripts for the mean case and control values indicate a significant difference ($p<0.05$) for the tested parameter.

The six measurement periods were evenly distributed over the whole year in intervals of 6 to 13 weeks (mean 9.2 weeks). The mean ambient outside temperature (10.1˚C) and relative humidity (89%) are in close agreement with the long-term average values for the Netherlands (10.6 ˚C and 82%; Royal Netherlands Meteorological Institute, based on measuring station De Bilt, 1992-2020). On average, the temperature in the case and control room were 3.6 ˚C above the ambient outside temperature due to the heat production of the cows, the insulated roof and the ventilation regime with closed wind curtains and mechanical ventilation. Table 5 furthermore shows that the temperature in the case and control room were very similar (differences around 2%). The statistical analysis showed that differences between the rooms of temperature, milk production, fat content and protein content were not statistically different ($p>0.1$). Only relative humidity and urea content differed between units ($p<0.001$). No outliers were detected. Different milk urea content between case and control was reason to use standardized emissions for further analyses. Relative humidity differences in this range (69-97%) most likely do not have significant influence on ammonia emissions.

## 3.3 Ventilation rates, concentrations, emissions and reduction of point measurements

The ventilation rate, the concentration of outgoing and incoming air and the resulting emissions and emission reduction are summarized in Table 6 (point measurements) and in Appendix 4 for the NOx and Picarro measurement periods.

***Table 6*** *Ventilation rates, ammonia concentration and ammonia emission and reduction during point measurements.*

| **Variable** | **Measurement period** | | | | | | |
|---|---|---|---|---|---|---|---|
| | **1** | **2** | **3** | **4** | **5** | **6** | **Mean** |
| **Ventilation rate ($m^3$/h)** | | | | | | | |
| - Case room (70) | 15,923 | 14,870 | * | 22,997 | 16,402 | 15,503 | 17,146[a] |
| - Control room (72) | 15,923 | 15,223 | * | 23,053 | 14,589 | 21,177 | 17,997[a] |
| **Carbon dioxide concentration (ppm)** | | | | | | | |
| - Case room (70) | 692 | 777 | * | 762 | 758 | 791 | 756 |
| - Control room (72) | 560 | 795 | * | 808 | 771 | 749 | 736 |
| **Ammonia concentration (ppm)** | | | | | | | |
| - Background | 0.05 | 0.05 | * | 0.05 | 0.08 | 0.06 | 0.06 |
| - Case room (70) | 1.22 | 0.62 | * | 1.34 | 1.89 | 1.18 | 1.25[a] |
| - Control room (72) | 1.90 | 1.35 | * | 2.41 | 2.78 | 1.99 | 2.08[b] |
| **Ammonia emission rate (kg/animal place per year)** | | | | | | | |
| - Case room (70) | 7.5 | 3.4 | * | 11.6 | 11.6 | 7.0 | 8.2[a] |
| - Control room (72) | 11.9 | 8.0 | * | 21.2 | 15.4 | 16.7 | 14.6[b] |
| **Emission reduction** | | | | | | | |
| - Absolute (kg/animal place per year) | 4.4 | 4.6 | * | 9.6 | 3.7 | 9.6 | 6.4 |
| - Relative (%) | 37% | 57% | * | 45% | 24% | 58% | 44% |
| **Emission factor** | 8.2 | 5.6 | * | 7.1 | 9.8 | 5.5 | 7.2 |
| **Ammonia emission rate (standardized for milk urea and outdoor temperature (kg/animal place per year)** | | | | | | | |
| - Case room (70) | 8.2 | 4.4 | * | 8.9 | 12.0 | 6.6 | 8.0[a] |
| - Control room (72) | 13.9 | 10.9 | * | 17.0 | 16.4 | 16.7 | 15.0[b] |
| **Emission reduction** | | | | | | | |
| - Absolute (kg/animal place per year) | 5.7 | 6.5 | * | 8.1 | 4.5 | 10.1 | 7.0 |
| - Relative (%) | 41% | 60% | * | 48% | 27% | 60% | 47% |
| **Emission factor** | 7.6 | 5.2 | * | 6.8 | 9.5 | 5.2 | 6.9 |

*: no data. Measurement period was skipped because of plans at that time to start an optimalisation period and restart the emission measurements afterwards.

[a,b] Different superscripts for the mean case and control values indicate a significant difference ($p<0.05$) for the tested parameter.

During point measurement 6 the air flow through of the impinger of one of the duplo measurements in the case unit was partially blocked during the measurements. This duplo was excluded from further analyses. The statistical analysis showed that ventilation rate did not differ between the rooms ($p=0.54$) but ammonia concentration ($p<0.001$) and (standardized) emission rate ($p=0.01$) did. Analyses of relative differences of ventilation, ammonia concentration and ammonia emission between case and control did not result in detected outliers.

## 3.4 Comparison of results to the literature

It is not possible to compare the results from this work with values from scientific journal articles or research reports since no emission measurements are available on this innovative CowToilet.

## 3.5 Discussion of the results

This study followed the "case-control strategy" as described in the protocol for determination of ammonia emission from housing systems in livestock production (Ogink et al., 2017). This was carried out in the environmental research barn of Dairy Campus. The advantage of this approach is the sound basis of comparison as described in material and methods chapter. The way of housing dairy cows in the environmental research barn was very similar to common practice.

The results in Table 6 illustrate that most factors except the milk urea content and relative humidity were kept similar. Due to this differences in milk urea content between the units the emissions were standardized using the procedure described Ogink *et al.* (2017) for calculation of emission factor.

The crude protein content of the roughage ration was below 160 gram per kg DM reflecting the general decrease in protein level in roughage for dairy cows in the Netherlands. At one occasion this resulted in a milk urea content lower than 15 mg/100 ml. Other conditions and criteria listed throughout the ammonia emission protocol were met.

The ammonia emission of the case room was significantly lower than the emission of the control room. This all means that the emission reduction in the case room has most likely been caused by the CowToilet.

The mean emission rate of the control room was 14,6 kg/animal place per year which is 1.6 kg/animal place per year or 12.3% higher than the emission factor of 13. The latter emission factor is based on the study of Mosquera et al. (2014). This report states that the true emission factor lies within a 95% confidence interval of ± 15%, i.e., between 11 and 15 kg/animal place per year. The measured emission of the control lies within this interval and is therefore not significantly different from the traditional system.

To correct for possible unit effects the CowToilet could have been changed between the rooms periodically. However, this would demand drastic activities during the project and high costs and the control room acted also as control for other treatments in other rooms. For these reasons, the CowToilet was not changed between rooms.

Between the 12$^{th}$ of March 2021 and 11$^{th}$ of July 2021 (covering period 3 and 4) the slatted floor in the room with the CowToilet was scraped with a scraping robot. According to Bleijenberg *et al.* (1994) and de Haan & Ogink (1994) the effect of scraping of concrete slatted floors on the ammonia emission is small (<5%). When the fourth measurement period would be deleted from the measurements results the average emission of room 70 (case) would be 6.9 kg/animal place per year, the emission of room 72 (control) would be 13.0 kg/animal place per year and the ammonia emission reduction and the ammonia emission factor would remain 47% and 6.9 kg/animal place per year respectively. The standardized averages would be 7.3 kg/animal place per year (case), 14.5 kg/animal place per year (control), 50% (reduction) and 6.5 kg/animal place per year (emission factor).

It can be concluded that based on the point measurements described in this measurement report the ammonia emission of the CowToilet is 6.6 kg $NH_3$ per animal place per year which can be classified as an emission factor of 7 kg $NH_3$ per animal place per year.

It must be noted, that results from a second case-control approach, or results from emission measurements on at least another two barns with the CowToilet are needed to obtain an official emission factor for the Rav legislation.

# 3.6 Emissions based on continuous ammonia concentration measurements

The availability of two other methods to measure the ammonia concentrations in the case and control unit continuously make it possible to calculate alternative ammonia emissions. These methods were already described in paragraph 2.4.2. The relation in time between these measurements and the point measurements was described in paragraph 2.3. Measuring conditions and results of ventilation, ammonia concentration measurements and emission calculations of this NOx and Picarro method are presented in appendix 3 and 4.
The decision to use the acid wet trap impinger gas washing method and the cavity ring down spectroscopy method simultaneously was made to make field calibration of the Picarro device possible. Although laboratory tests showed a high precision, linearity and repeatability, this type of the Picarro device used for measuring ammonia concentrations have not been exposed to a field test according to Vonk *et al.* (2021) before. Therefore, equivalence to other already accepted methods is not proved yet. Field trials by Zhuang et al. (2020) were done with another type of instrument of the same manufacturer but could be seen as an alternative.

The NOx method is already allowed for measurement of ammonia concentration according to the protocol for determination of ammonia emission from housing systems in livestock production (Ogink et al., 2017). The fact that only two independent sampling lines are available in each ventilator shaft of both the case and the control unit made it necessary to deploy this method in the week before and the week after the point measurement. Measurement of background concentrations in these weeks are missing due to the fact that all capacity of the manifold connected to the analyser was assigned to other units in research. The background ammonia concentration during the point measurements was used to correct the case and control ammonia concentration measured with the NOx method. The background concentration of the third period of the point measurement was calculated as the average of the other periods. Coefficient of variation of background concentration over the measuring periods was 0.19 (average 0.06 ppm and a standard deviation of 0.011) ppm. The use of background values of the point measurements for calculation of emissions with the NOx method in the week before and the week after seems reasonable and the possible error is assumed to be small.

The results of the different measurement methods are summarized in Table 7. The effect of methods on differences in ventilation rate and emissions of case and control unit, and calculated emission factor was statistically tested using a REML procedure as described in paragraph 2.7 with method as fixed effect and measurement period as random effect. The NOx-A and NOx-B periods are considered as replications combined as NOx.

***Table 7*** *Standardized emission results for different measurement methods and periods.*

| Variable | NOx | Picarro | Point |
|---|---|---|---|
| **Ventilation ($m^3$/h)** | | | |
| - Case room (70) | 15516[a] | 16353[a] | 17146[a] |
| - Control room (72) | 14556[a] | 16634[a] | 17997[a] |
| **Emission (kg/animal place per year)** | | | |
| - Case room (70) | 7.7[a] | 6.8[a] | 8.0[a] |
| - Control room (72) | 11.8[b] | 10.9[b] | 15.0[a] |
| **Emission reduction** | | | |
| - Absolute (kg/animal place per year) | 3.8 | 4.0 | 7.0 |
| - Relative (%) | 35% | 37% | 47% |
| **Emission factor (kg/animal place per year)** | 8.5[b] | 8.2[b] | 6.9[a] |

[a,b] Different superscripts per row indicate significant differences ($p<0.05$). For least significant differences (LSD's) see Appendix 5

Differences in the emission reduction between the different methods are caused by the differences of emission level in de control unit. The reason for this difference could not be explained from raw data of data processing procedure. Possible cause might be the higher ventilation rate in control unit during sixth point measurement. Although relative difference between case and control during this measurement cannot be considered as an outlier the absolute difference between case and control was larger than during other measurements (see Figure 10). However, Emission results of point measurement lied within variation of daily emissions during NOx and Picarro measurements (see Figure 11).

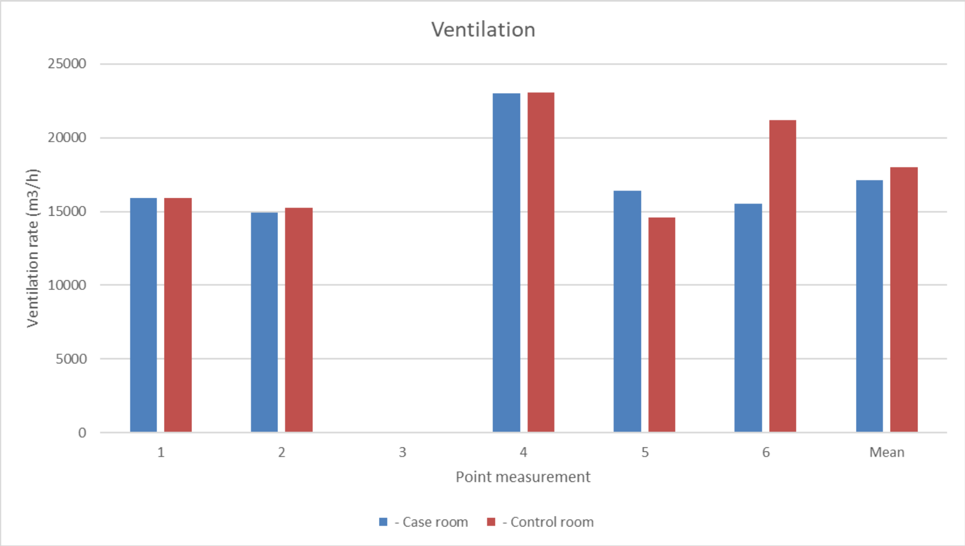


***Figure 10*** *Ventilation rate in case and control room during point measurements.*

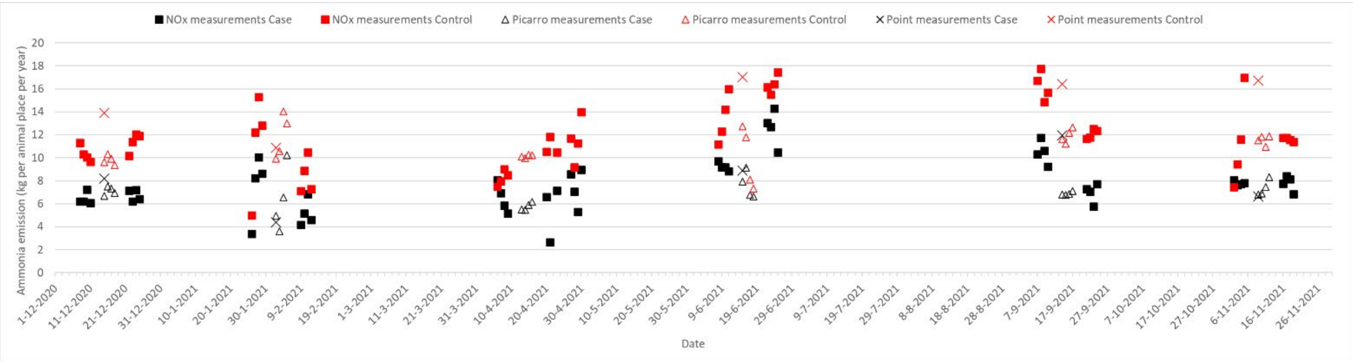


***Figure 11*** *Overview of emission results during NOx, Picarro (daily) and point measurements for case and control unit.*

# 4 Conclusions

- The reduction of the ammonia emission as a result of the use of the CowToilet, compared to a traditional concrete slatted floor (Rav code: A 1.100) amounts 47.2%.
- This reduction is equivalent with a proportional emission rate of 0.528. Multiplied with the emission factor of the control room of 13 kg/animal place per year, the ammonia emission rate of the CowToilet amounts 6.9 kg per animal place per year.
- The categorized emission factor based on the point measurements presented in this report would be 7 kg $NH_3$ per animal place per year.
- The emission reduction and resulting emission factor are influenced by the method for measuring the ammonia concentration.
    - Use of the NOx method resulted in an emission reduction of 35% and an standardized emission factor of 8.5 kg $NH_3$ per animal place per year.
    - Use of the Picarro method resulted in an emission reduction of 37% and an standardized emission factor of 8.2 kg $NH_3$ per animal place per year.

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# Appendix 1 Description CowToilet (BWL2010.05)

| | | |
|---|---|---|
| **Nummer systeem** | | **BWL 2021.05** |
| **Naam systeem** | | **Ligboxenstal met urine-opvangstation** |
| **Diercategorie** | | **Melk- en kalfkoeien ouder dan 2 jaar** |
| **Rav-code** | | **A 1.36** |
| **Systeembeschrijving van** | | **Mei 2021** |
| | | |
| **Werkingsprincipe** | | Ammoniakemissiebeperking is gebaseerd op het opvangen en het afvoeren van de urine naar een aparte afgesloten opslag voordat deze in contact kan komen met de feces. Dit voorkomt de omzetting van ureum uit de urine in ammoniak.<br>Doordat deze apart opgevangen urine niet in de mestkelder onder de roostervloer terecht komt heeft de drijfmest in deze kelder een lagere zuurgraad. Hierdoor komt ook minder ammoniak uit de kelder vrij.<br>Het urine-opvangstation laat de koe op de gewenste plaats urineren door gebruik te maken van het natuurlijke plasreflex. Dit reflex wordt aangesproken door het geautomatiseerd aanraken van de uierbanden. Een lokmiddel, zoals krachtvoer, zorgt ervoor dat de koe het urine-opvangstation bezoekt. |
| | | |
| **DE TECHNISCHE UITVOERING VAN HET SYSTEEM; TECHNISCHE VOORZIENINGEN** | | |
| | **Onderdeel** | **Uitvoeringseis** |
| 1a | Vloer | De loopgangen worden uitgevoerd als een betonnen roostervloer of als een dichte vloer[1] |
| 1b | | Uitgezonderd van deze eisen zijn de doorsteken, de wachtruimte en de doorlopen; deze hoeven niet te worden voorzien van boven beschreven systeem. Deze ruimten moeten echter wel emissiearm worden uitgevoerd door gebruik te maken van een in de Rav opgenomen emissiearm systeem dan wel een dichte vloer. In deze ruimtes mag de breedte van de vloerplaten afwijken van de maat die voor het betreffende emissiearme systeem is vereist, mits dit de emissiereducerende werking niet nadelig beïnvloedt. |
| 2a | Urine-opvangstation | In de loopruimte is een urine-opvangstation aanwezig waarin de koe ongestoord kan gaan staan om haar plas te doen |
| 2b | | In het urine-opvangstation wordt een lokmiddel (krachtvoer) verstrekt. |
| 2c | | Het urine-opvangstation is voorzien van een geautomatiseerd systeem met opvangbak dat:<br>• De koe stimuleert om te gaan urineren;<br>• De urine in de opvangbak opvangt, en;<br>• De urine vervolgens afvoert naar een aparte afgesloten opslag voor de urine. |
| 2d | | Versie softwarepakket volgens opgave leverancier. |
| 3a | Mestkelder en mestafvoer | Onder het gehele oppervlak van de roostervloer is een mestkelder aanwezig, bij een dichte vloer is tenminste een mestkelder aanwezig onder de mestafstorten. |
| 3b | | De afvoer van mest en het deel van de urine dat niet in het urine-opvangstation wordt opgevangen vindt plaats via de roosterspleten naar de mestkelder, of wordt vanaf de dichte vloer met behulp van een mestschuif afgevoerd naar de mestafstort. |

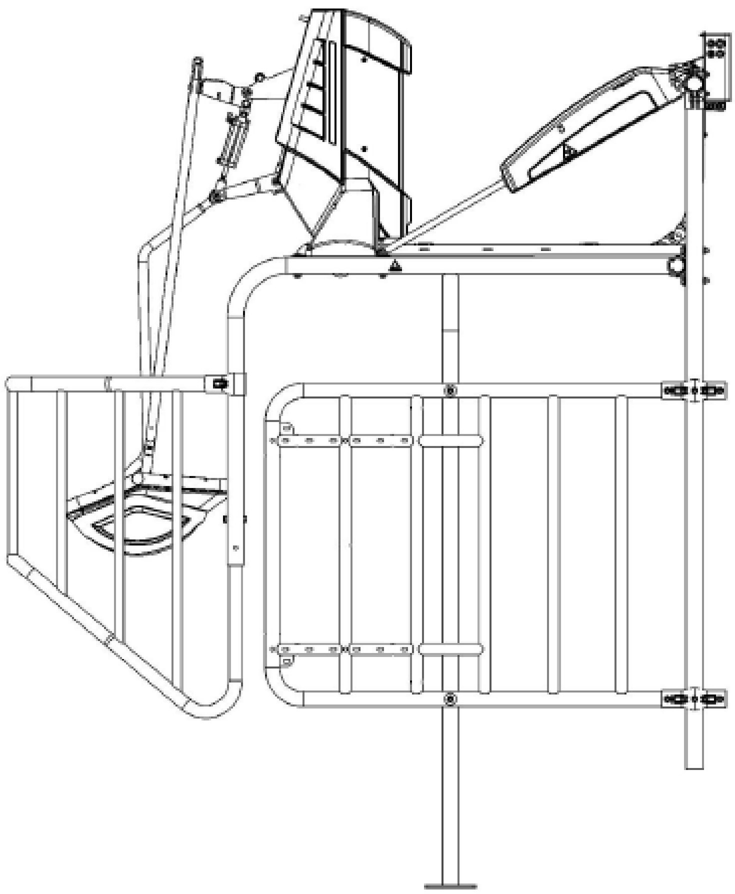
[1] Het gaat hierbij om een aangegeven vloer welke behoort tot een overig huisvestingssysteem.

| | | |
|---|---|---|
| 3c | | Indien in de doorsteken, de wachtruimte en de doorlopen een ander emissiearm systeem wordt toegepast en daardoor extra emissie vanuit de kelder daaronder kan optreden (schoorsteeneffect), dient bij elke overgang van vloersysteem in de mestkelder een stank afsluitende voorziening te worden aangebracht. |
| 4a | Emitterend vloeroppervlak | Het met mest besmeurd vloeroppervlak per dierplaats is maximaal 5,5 $m^2$. Dit oppervlak omvat de loopgangen, doorsteken, wachtruimte en doorlopen. Niet inbegrepen is het vloeroppervlak van de melkstal en de voerstoep (indien aanwezig). |
| 4b | | Voor de wachtruimte geldt dat deze niet meetelt bij het bepalen van het met mest besmeurd oppervlak, wanneer deze met een dichte vloer is uitgevoerd. Wanneer de wachtruimte op een andere wijze is uitgevoerd, telt het oppervlak wel mee bij het bepalen van het met mest besmeurd oppervlak per dierplaats. |
| 5 | Registratieapparatuur | De volgende registratieapparatuur dient aanwezig te zijn:<br>- apparatuur voor het registreren van het aantal bezoeken per melkkoe aan het urine-opvangstation waarbij urine is opgevangen. |
| | | |
| **Het gebruik van het systeem** | | |
| | **Onderdeel** | **Gebruikseis** |
| a1 | Urine-opvangstation | Per 25 melkkoeien is ten minste één urine-opvangstation aanwezig. |
| a2 | | Alle melkkoeien in de stal moeten altijd toegang hebben tot het urine-opvangstation, behalve wanneer deze melkkoeien voor een beperkte tijd uit de ruimte met het urine-opvangstation zijn afgezonderd voor een behandeling of bij het gebruik van de wachtruimte tijdens de melkbeurten.[2] |
| a3 | | Elke melkkoe moet gemiddeld minimaal vijf keer per etmaal een bezoek brengen aan het urine-opvangstation waarbij urine van deze melkkoe wordt opgevangen.[3] |
| b1 | Wachtruimte | De gebruiksduur van de wachtruimte beperkt zich tot de melktijden. Buiten de melktijden worden in de wachtruimte geen dieren gehouden. Wanneer de wachtruimte buiten de melktijden wel beschikbaar is voor de dieren maakt deze deel uit van de loopruimte. In dat geval moet de wachtruimte wel worden meegeteld als onderdeel van het mest besmeurd vloeroppervlak. |
| b2 | | Na elk gebruik moet de wachtruimte direct worden gereinigd waarbij alle mest en urineplassen worden afgevoerd naar de mestkelder. Deze eis geldt niet indien de wachtruimte buiten de melktijden toegankelijk is voor de melkkoeien. |
| c | Reiniging | De opvangbak en de transportleidingen voor de urine in het urine-opvangstation moeten wekelijks met water worden schoongemaakt en doorgespoeld. |
| d | Onderhoud | Het urine-opvangstation dient ten minste eenmaal per zes maanden te worden gecontroleerd op beschadigingen en, indien nodig, te worden onderhouden. Aanbevolen wordt hiertoe een onderhoudscontract met de leverancier van het urine-opvangstation of een andere deskundige partij af te sluiten. |

[2] In de perioden dat de melkkoeien weidegang krijgen hoeft het urine-opvangstation niet beschikbaar te zijn.
[3] Wanneer de melkkoeien weidegang krijgen wordt het aantal bezoeken per etmaal afgestemd op het aantal uren dat de melkkoeien in de stal verblijven.

| | | |
|---|---|---|
| e1 | Registratie | Ten behoeve van een controle op de werking van het systeem moeten de volgende gegevens automatisch worden geregistreerd:<br>- per melkkoe het aantal bezoeken per dag aan het urine-opvangstation waarbij urine is opgevangen.<br>De geregistreerde gegevens moeten minimaal vijf jaar worden bewaard. |
| e2 | | Er moet een logboek worden bijgehouden waarin wordt aangetekend wanneer en door wie de reiniging, de controle en het onderhoud van het urine-opvangstation heeft plaatsgevonden. |
| | | |
| **Emissiefactor** | | 8,4 kg $NH_3$ per dierplaats per jaar |
| **Verwijzing meetrapport** | | Deze emissiefactor is voorlopig vastgesteld en zal aan de hand van de meetresultaten worden herzien. |

**Foto / tekening stal met urine-opvangstation**



| Naam:<br>Ligboxenstal met urine-opvangstation | Nummer:<br>BWL 2021.05 |
|---|---|
| | Systeembeschrijving:<br>Mei 2021 |

# Appendix 2 Calibration lines of fan anemometers

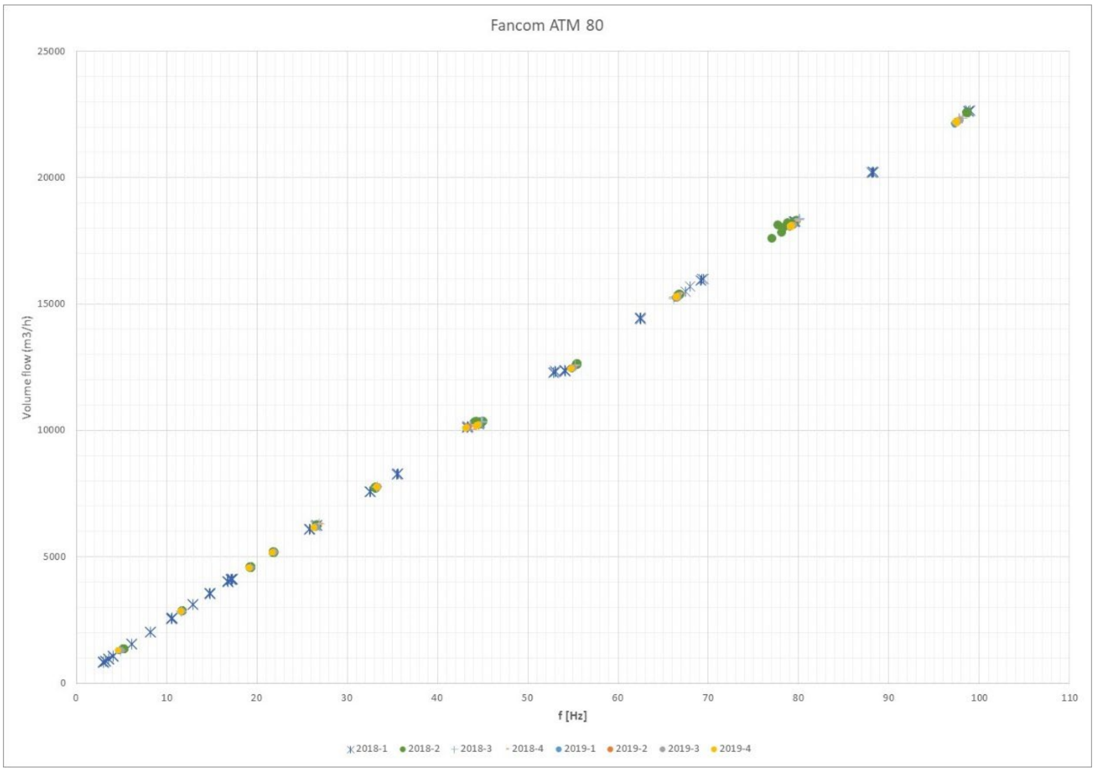



***Figure A1:*** Outcomes of calibration of eight Fancom ATM80 measuring units

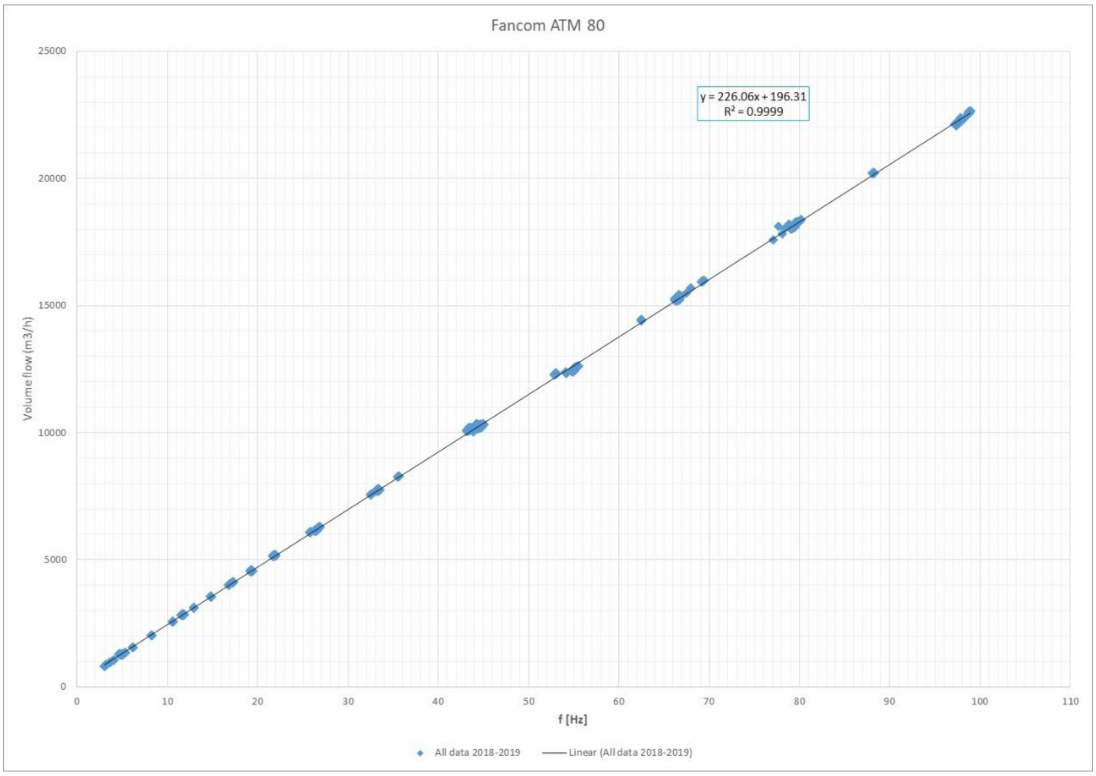



***Figure A2:*** Single calibration equation using outcomes of eight Fancom ATM80 measuring units

# Appendix 3 Measurement conditions during continuous measurements

*Table A1* *Measurement conditions during NOx-A measurements.*

| Variable | Measurement period | | | | | | |
|---|---|---|---|---|---|---|---|
| | NOx-1A | NOx-2A | NOx-3A | NOx-4A | NOx-5A | NOx-6A | Mean |
| **Measurement period** | | | | | | | |
| Week number in calendar year | 50 | 5 | 15 | 24 | 37 | 45 | |
| Interval between periods (weeks) | | 6 | 10 | 9 | 13 | 8 | 9.2 |
| Start date of measurement period | 8-12-2020 | 26-1-2021 | 6-4-2021 | 8-6-2021 | 7-9-2021 | 2-11-2021 | |
| Day number in calendar year | 343 | 26 | 96 | 159 | 250 | 306 | |
| End date of measurement period | 11-12-2020 | 29-1-2021 | 9-4-2021 | 11-6-2021 | 10-9-2021 | 5-11-2021 | |
| **Climate conditions** | | | | | | | |
| Temperature ambient air (°C) | 1.9 | 3.0 | 4.4 | 17.5 | 19.8 | 7.4 | 9.0 |
| Relative humidity ambient air (%) | 93 | 93 | 78 | 81 | 77 | 95 | 86 |
| Ambient air pressure (hPa) | 1004 | 1005 | 1014 | 1021 | 1015 | 1007 | 1011 |
| Wind direction (degrees) | 136 | 162 | 277 | 197 | 161 | 230 | 194 |
| Wind speed at 10 meters (m/s) | 3.7 | 4.3 | 6.7 | 2.8 | 2.7 | 2.8 | 3.8 |
| Temperature inside air (°C) | | | | | | | |
| - Case room (70) | 5.5 | 6.2 | 7.9 | 21.6 | 22.1 | 11.6 | 12.5 |
| - Control room (72) | 5.7 | 6.3 | 8.5 | 22.2 | 22.5 | 12.0 | 12.9 |
| Relative humidity (%) | | | | | | | |
| - Case room (70) | 85 | 84 | 66 | 67 | 72 | 79 | 76 |
| - Control room (72) | 94 | 95 | 75 | 74 | 82 | 91 | 85 |
| **Animal performance** | | | | | | | |
| Milk production (kg/animal per day) | | | | | | | |
| - Case room (70) | 32.2 | 29.8 | 30.3 | 25.4 | 29.6 | 26.1 | 28.9 |
| - Control room (72) | 31.6 | 29.2 | 30.1 | 24.8 | 31.3 | 26.7 | 28.9 |
| Milk fat content (%) | | | | | | | |
| - Case room (70) | 4.5 | 4.7 | 4.9 | 4.8 | 4.4 | 5.0 | 4.7 |
| - Control room (72) | 4.5 | 4.8 | 4.7 | 4.6 | 4.7 | 5.0 | 4.7 |
| Milk protein content (%) | | | | | | | |
| - Case room (70) | 3.8 | 4.0 | 3.8 | 3.6 | 3.5 | 3.8 | 3.7 |
| - Control room (72) | 3.9 | 4.0 | 3.8 | 3.6 | 3.6 | 3.8 | 3.8 |
| FPCM production (kg/animal per day) | | | | | | | |
| - Case room (70) | 35.2 | 33.5 | 34.4 | 28.1 | 31.4 | 29.8 | 32.1 |
| - Control room (72) | 34.6 | 33.1 | 33.5 | 27.1 | 34.2 | 30.4 | 32.1 |
| Milk urea concentration (mg/100 g) | | | | | | | |
| - Case room (70) | 21 | 20 | 21 | 25 | 18 | 21 | 21.0 |
| - Control room (72) | 19 | 19 | 21 | 25 | 18 | 18 | 19.9 |
| **Feed composition** | | | | | | | |
| Crude protein content (g/kg DM) | 156 | 151 | 147 | 140 | 149 | 153 | 149 |

*Table A2* *Measurement conditions during NOx-B measurements.*

| Variable | Measurement period | | | | | | |
|---|---|---|---|---|---|---|---|
| | NOx-1B | NOx-2B | NOx-3B | NOx-4B | NOx-5B | NOx-6B | Mean |
| **Measurement period** | | | | | | | |
| Week number in calendar year | 50 | 5 | 15 | 24 | 37 | 45 | |
| Interval between periods (weeks) | | 6 | 10 | 9 | 13 | 8 | 9.2 |
| Start date of measurement period | 8-12-2020 | 26-1-2021 | 6-4-2021 | 8-6-2021 | 7-9-2021 | 2-11-2021 | |
| Day number in calendar year | 343 | 26 | 96 | 159 | 250 | 306 | |
| End date of measurement period | 11-12-2020 | 29-1-2021 | 9-4-2021 | 11-6-2021 | 10-9-2021 | 5-11-2021 | |
| **Climate conditions** | | | | | | | |
| Temperature ambient air (°C) | 1.9 | 3.0 | 4.4 | 17.5 | 19.8 | 7.4 | 9.0 |
| Relative humidity ambient air (%) | 93 | 93 | 78 | 81 | 77 | 95 | 86 |
| Ambient air pressure (hPa) | 1013 | 1024 | 1024 | 1020 | 1021 | 1023 | 1021 |
| Wind direction (degrees) | 163 | 66 | 260 | 52 | 243 | 230 | 169 |
| Wind speed at 10 meters (m/s) | 4.6 | 3.3 | 4.1 | 2.9 | 5.0 | 4.7 | 4.1 |
| Temperature inside air (°C) | | | | | | | |
| - Case room (70) | 5.5 | 6.2 | 7.9 | 21.6 | 22.1 | 11.6 | 12.5 |
| - Control room (72) | 5.7 | 6.3 | 8.5 | 22.2 | 22.5 | 12.0 | 12.9 |
| Relative humidity (%) | | | | | | | |
| - Case room (70) | 85 | 84 | 66 | 67 | 72 | 79 | 76 |
| - Control room (72) | 94 | 95 | 75 | 74 | 82 | 91 | 85 |
| **Animal performance** | | | | | | | |
| Milk production (kg/animal per day) | | | | | | | |
| - Case room (70) | 32.2 | 29.8 | 30.3 | 25.4 | 29.6 | 26.1 | 28.9 |
| - Control room (72) | 31.6 | 29.2 | 30.1 | 24.8 | 31.3 | 26.7 | 28.9 |
| Milk fat content (%) | | | | | | | |
| - Case room (70) | 4.5 | 4.7 | 4.9 | 4.8 | 4.4 | 5.0 | 4.7 |
| - Control room (72) | 4.5 | 4.8 | 4.7 | 4.6 | 4.7 | 5.0 | 4.7 |
| Milk protein content (%) | | | | | | | |
| - Case room (70) | 3.8 | 4.0 | 3.8 | 3.6 | 3.5 | 3.8 | 3.7 |
| - Control room (72) | 3.9 | 4.0 | 3.8 | 3.6 | 3.6 | 3.8 | 3.8 |
| FPCM production (kg/animal per day) | | | | | | | |
| - Case room (70) | 35.2 | 33.5 | 34.4 | 28.1 | 31.4 | 29.8 | 32.1 |
| - Control room (72) | 34.6 | 33.1 | 33.5 | 27.1 | 34.2 | 30.4 | 32.1 |
| Milk urea concentration (mg/100 g) | | | | | | | |
| - Case room (70) | 21 | 20 | 21 | 25 | 18 | 21 | 21.0 |
| - Control room (72) | 19 | 19 | 21 | 25 | 18 | 18 | 19.9 |
| **Feed composition** | | | | | | | |
| Crude protein content (g/kg DM) | 156 | 151 | 147 | 140 | 149 | 153 | 149 |

*Table A3* *Measurement conditions during Picarro measurements.*

| Variable | Measurement period | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | Mean |
| **Measurement period** | | | | | | | |
| Week number in calendar year | 51 | 6 | 16 | 25 | 38 | 46 | |
| Interval between periods (weeks) | | 6 | 10 | 9 | 13 | 8 | 9.2 |
| Start date of measurement period | 15-12-2020 | 2-2-2021 | 13-4-2021 | 15-6-2021 | 14-9-2021 | 9-11-2021 | |
| Day number in calendar year | 350 | 33 | 103 | 166 | 257 | 313 | |
| End date of measurement period | 18-12-2020 | 5-2-2021 | 16-4-2021 | 18-6-2021 | 17-9-2021 | 12-11-2021 | |
| **Climate conditions** | | | | | | | |
| Temperature ambient air (°C) | 7.6 | 2.6 | 4.8 | 19.2 | 16.4 | 9.3 | 10.0 |
| Relative humidity ambient air (%) | 94 | 95 | 76 | 77 | 87 | 95 | 87 |
| Ambient air pressure (hPa) | 1013 | 1002 | 1032 | 1015 | 1014 | 1023 | 1016 |
| Wind direction (degrees) | 183 | 119 | 229 | 102 | 210 | 199 | 174 |
| Wind speed at 10 meters (m/s) | 4.4 | 3.5 | 3.8 | 3.5 | 3.8 | 4.0 | 3.8 |
| Temperature inside air (°C) | | | | | | | |
| - Case room (70) | 10.4 | 6.1 | 9.8 | 22.5 | 19.6 | 12.7 | 13.5 |
| - Control room (72) | 10.7 | 6.3 | 10.3 | 22.8 | 20.3 | 12.5 | 13.8 |
| Relative humidity (%) | | | | | | | |
| - Case room (70) | 87 | 84 | 59 | 66 | 76 | 82 | 76 |
| - Control room (72) | 96 | 94 | 63 | 70 | 87 | 95 | 84 |
| **Animal performance** | | | | | | | |
| Milk production (kg/animal per day) | | | | | | | |
| - Case room (70) | 31.5 | 29.2 | 29.0 | 24.6 | 28.9 | 26.1 | 28.2 |
| - Control room (72) | 30.6 | 28.6 | 28.5 | 24.0 | 30.9 | 27.2 | 28.3 |
| Milk fat content (%) | | | | | | | |
| - Case room (70) | 4.7 | 5.0 | 5.2 | 4.7 | 4.7 | 4.8 | 4.8 |
| - Control room (72) | 4.7 | 4.8 | 5.0 | 4.7 | 4.7 | 4.9 | 4.8 |
| Milk protein content (%) | | | | | | | |
| - Case room (70) | 3.8 | 3.9 | 3.8 | 3.7 | 3.5 | 3.8 | 3.8 |
| - Control room (72) | 3.9 | 4.0 | 3.7 | 3.7 | 3.5 | 3.9 | 3.8 |
| FPCM production (kg/animal per day) | | | | | | | |
| - Case room (70) | 35.0 | 33.6 | 33.8 | 27.3 | 31.6 | 29.3 | 31.8 |
| - Control room (72) | 34.3 | 32.5 | 32.5 | 26.5 | 33.9 | 30.8 | 31.8 |
| Milk urea concentration (mg/100 g) | | | | | | | |
| - Case room (70) | 21 | 17 | 22 | 28 | 18 | 25 | 21.9 |
| - Control room (72) | 18 | 14 | 21 | 27 | 16 | 23 | 19.8 |
| **Feed composition** | | | | | | | |
| Crude protein content (g/kg DM) | 153 | 152 | 141 | 132 | 144 | 182 | 151 |

# Appendix 4 Measurement results of continuous measurements

***Table A4*** *Ventilation rates, concentrations, emissions and emission reductions during NOx-A measurements.*

| **Variable** | **Measurement period** | | | | | | |
|---|---|---|---|---|---|---|---|
| | **NOx-1A** | **NOx-2A** | **NOx-3A** | **NOx-4A** | **NOx-5A** | **NOx-6A** | **Mean** |
| **Ventilation rate ($m^3/h$)** | | | | | | | |
| - Case room (70) | 15,662 | 15,753 | 15,860 | 15,489 | 20,781 | 15,580 | 16,521 |
| - Control room (72) | 15,647 | 15,582 | 14,400 | 13,972 | 19,143 | 11,662 | 15,068 |
| **Ammonia concentration (ppm)** | | | | | | | |
| - Background | 0.05 | 0.05 | 0.06 | 0.05 | 0.08 | 0.06 | 0.06 |
| - Case room (70) | 0.89 | 1.05 | 0.94 | 1.83 | 1.42 | 1.20 | 1.22 |
| - Control room (72) | 1.36 | 1.50 | 1.31 | 2.93 | 2.33 | 2.12 | 1.92 |
| **Ammonia emission rate (kg/animal place per year)** | | | | | | | |
| - Case room (70) | 5.38 | 6.37 | 5.72 | 10.85 | 10.84 | 7.11 | 7.7 |
| - Control room (72) | 8.34 | 9.16 | 7.23 | 15.70 | 16.60 | 9.76 | 11.13 |
| **Emission reduction** | | | | | | | |
| - Absolute (kg/animal place per year) | 3.0 | 2.8 | 1.5 | 4.8 | 5.8 | 2.7 | 3.4 |
| - Relative (%) | 35% | 30% | 21% | 31% | 35% | 27% | 30% |
| **Emission factor** | 8.4 | 9.0 | 10.3 | 9.0 | 8.5 | 9.5 | 9.1 |
| **Ammonia emission rate (standardized for milk urea and outdoor temperature (kg/animal place per year)** | | | | | | | |
| - Case room (70) | 6.42 | 7.58 | 6.51 | 9.24 | 10.47 | 7.80 | 8.00 |
| - Control room (72) | 10.34 | 11.33 | 8.24 | 13.42 | 16.24 | 11.39 | 11.83 |
| **Emission reduction** | | | | | | | |
| - Absolute (kg/animal place per year) | 3.9 | 3.8 | 1.7 | 4.2 | 5.8 | 3.6 | 3.8 |
| - Relative (%) | 38% | 33% | 21% | 31% | 36% | 31% | 32% |
| **Emission factor** | 8.1 | 8.7 | 10.3 | 8.9 | 8.4 | 8.9 | 8.9 |

*Table A5* *Ventilation rates, concentrations, emissions and emission reductions during NOx-B measurements.*

| Variable | Measurement period | | | | | | |
|---|---|---|---|---|---|---|---|
| | NOx-1B | NOx-2B | NOx-3B | NOx-4B | NOx-5B | NOx-6B | Mean |
| **Ventilation rate ($m^3/h$)** | | | | | | | |
| - Case room (70) | 15,709 | 8,198 | 14,598 | 16,983 | 16,027 | 15,556 | 14,512 |
| - Control room (72) | 15,572 | 8,055 | 15,666 | 16,052 | 14,395 | 14,525 | 14,044 |
| **Ammonia concentration (ppm)** | | | | | | | |
| - Background | 0.05 | 0.05 | 0.06 | 0.05 | 0.08 | 0.06 | 0.06 |
| - Case room (70) | 0.99 | 1.53 | 0.95 | 1.93 | 1.10 | 1.35 | 1.31 |
| - Control room (72) | 1.62 | 2.39 | 1.70 | 2.56 | 2.03 | 2.04 | 2.06 |
| **Ammonia emission rate (kg/animal place per year)** | | | | | | | |
| - Case room (70) | 5.99 | 5.14 | 5.35 | 12.69 | 6.50 | 8.18 | 7.31 |
| - Control room (72) | 9.90 | 7.96 | 10.39 | 16.02 | 11.12 | 11.67 | 11.18 |
| **Emission reduction** | | | | | | | |
| - Absolute (kg/animal place per year) | 3.9 | 2.8 | 5.0 | 3.3 | 4.6 | 3.5 | 3.9 |
| - Relative (%) | 39% | 35% | 49% | 21% | 42% | 30% | 36% |
| **Emission factor** | 7.9 | 8.4 | 6.7 | 10.3 | 7.6 | 9.1 | 8.3 |
| **Ammonia emission rate (standardized for milk urea and outdoor temperature (kg/animal place per year)** | | | | | | | |
| - Case room (70) | 6.74 | 5.20 | 5.47 | 12.63 | 6.96 | 7.79 | 7.47 |
| - Control room (72) | 11.39 | 8.45 | 10.95 | 16.38 | 12.07 | 11.62 | 11.81 |
| **Emission reduction** | | | | | | | |
| - Absolute (kg/animal place per year) | 4.6 | 3.3 | 5.5 | 3.7 | 5.1 | 3.8 | 4.3 |
| - Relative (%) | 41% | 38% | 50% | 23% | 42% | 33% | 38% |
| **Emission factor** | 7.7 | 8.0 | 6.5 | 10.0 | 7.5 | 8.7 | 8.1 |

*Table A6* *Ventilation rates, concentrations, emissions and emission reductions during Picarro measurements.*

| Variable | Measurement period | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | Mean |
| **Ventilation rate ($m^3/h$)** | | | | | | | |
| - Case room (70) | 15,880 | 14,803 | 15,447 | 20,780 | 15,768 | 15,440 | 16,353 |
| - Control room (72) | 15,897 | 15,004 | 15,520 | 20,867 | 13,924 | 18,593 | 16,634 |
| **Ammonia concentration (ppm)** | | | | | | | |
| - Background | 0.29 | 0.30 | 0.24 | 0.34 | 0.39 | 0.23 | 0.30 |
| - Case room (70) | 1.31 | 1.10 | 1.06 | 1.64 | 1.46 | 1.46 | 1.34 |
| - Control room (72) | 1.60 | 1.70 | 1.64 | 1.99 | 2.41 | 1.78 | 1.85 |
| **Ammonia emission rate (kg/animal place per year)** | | | | | | | |
| - Case room (70) | 6.57 | 4.85 | 5.22 | 10.05 | 6.63 | 7.72 | 6.84 |
| - Control room (72) | 8.39 | 8.61 | 8.92 | 12.55 | 11.03 | 11.41 | 10.15 |
| **Emission reduction** | | | | | | | |
| - Absolute (kg/animal place per year) | 1.8 | 3.8 | 3.7 | 2.5 | 4.4 | 3.7 | 3.3 |
| - Relative (%) | 22% | 44% | 41% | 20% | 40% | 32% | 33% |
| **Emission factor** | 10.2 | 7.3 | 7.6 | 10.4 | 7.8 | 8.8 | 8.7 |
| **Ammonia emission rate (standardized for milk urea and outdoor temperature (kg/animal place per year)** | | | | | | | |
| - Case room (70) | 7.11 | 6.33 | 5.76 | 7.62 | 6.89 | 7.37 | 6.85 |
| - Control room (72) | 9.80 | 11.89 | 10.15 | 9.99 | 11.93 | 11.54 | 10.88 |
| **Emission reduction** | | | | | | | |
| - Absolute (kg/animal place per year) | 2.7 | 5.6 | 4.4 | 2.4 | 5.0 | 4.2 | 4.0 |
| - Relative (%) | 27% | 47% | 43% | 24% | 42% | 36% | 37% |
| **Emission factor** | 9.4 | 6.9 | 7.4 | 9.9 | 7.5 | 8.3 | 8.2 |

# Appendix 5 Least Significant Difference (LSD)

***Table A7*** *Least significant differences (LSD) for p=0.05 of ventilation of case unit of different methods for measuring ammonia concentration and periods.*

| Method | NOx | Picarro | Point |
|---|---|---|---|
| NOx | * | | |
| Picarro | 2470 | * | |
| Point | 2658 | 3017 | * |

***Table A8*** *Least significant differences (LSD) for p=0.05 of ventilation of case unit of different methods for measuring ammonia concentration and periods.*

| Method | NOx | Picarro | Point |
|---|---|---|---|
| NOx | * | | |
| Picarro | 2974 | * | |
| Point | 3181 | 3615 | * |

***Table A9*** *Least significant differences (LSD) for p=0.05 of emissions from case unit of different methods for measuring ammonia concentration and periods.*

| Method | NOx | Picarro | Point |
|---|---|---|---|
| NOx | * | | |
| Picarro | 1.713 | * | |
| Point | 1.847 | 2.095 | * |

***Table A10*** *Least significant differences (LSD) for p=0.05 of emissions from control unit of different methods for measuring ammonia concentration and periods.*

| Method | NOx | Picarro | Point |
|---|---|---|---|
| NOx | * | | |
| Picarro | 1.953 | * | |
| Point | 2.104 | 2.384 | * |

***Table A11*** *Least significant differences (LSD) for p=0.05 of emission factor of different methods for measuring ammonia concentration and periods.*

| Method | NOx | Picarro | Point |
|---|---|---|---|
| NOx | * | | |
| Picarro | 1.373 | * | |
| Point | 1.458 | 1.659 | * |

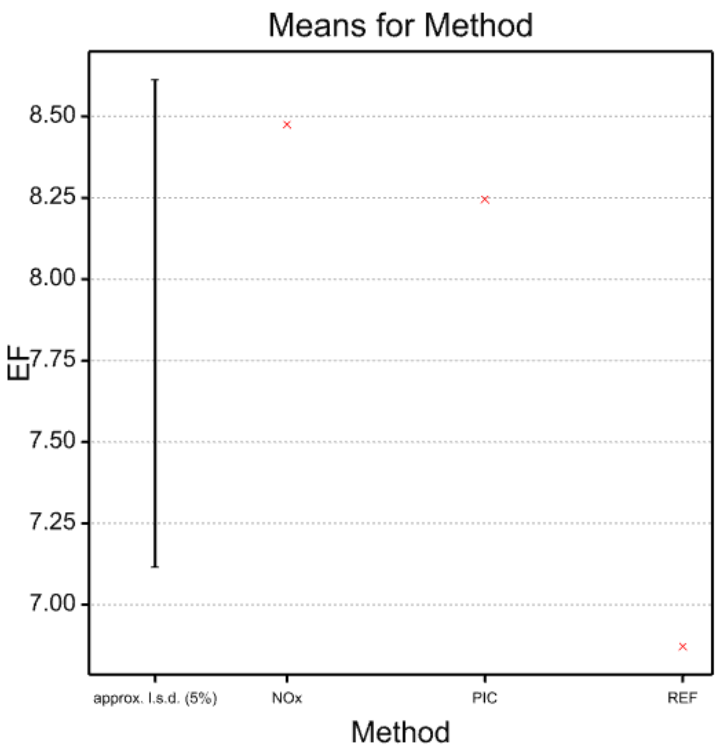



***Figure A1*** *Means and LSD of Emission factor for different ammonia concentration measurement methods.*

To explore the potential of nature to improve the quality of life

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Wageningen Livestock Research creates science based solutions for a sustainable and profitable livestock sector. Together with our clients, we integrate scientific knowledge and practical experience to develop livestock concepts for future generations.

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