Releases of ammonia (NH₃), hydrogen sulphide (H₂S) and carbon dioxide (CO₂) from deep manure pits were investigated in two overnight tests to minimize the influence of solar radiation and sudden outdoor temperature changes using two pig fattening buildings. The rooms of the buildings had been emptied and cleaned between groups of pigs. The identical buildings had tunnel and pit ventilation fans and 2.4 m deep under-floor pits with a surface area of 800 m² each. The first test was conducted in Building 3A. A new manure additive was applied in the pit to reduce gas and odour emission. The pit ventilation mode was used and the building was heated for about 1 h with one direct-fired propane space heater. The second test was conducted in Building 3B, in which the pit did not receive the additive application. The tunnel ventilation mode was used and the building was heated for about 2 h with two space heaters. Gas concentrations, ventilation, temperatures and differential pressure were continuously measured overnight. Gas release rates in the tests were compared with the gas release rates in the same buildings when they were fully occupied.

Ammonia release rates during heating were 167 ± 11 g/h (mean ± 95% confidence interval) in the first test and 46 ± 2 g/h in the second test, equivalent to 65-5 and 24-9% of the rates from fully occupied buildings, respectively. The maximum H₂S release rates measured after 1 h of heating were 9.6 g/h in the first test and 3.1 g/h in the second test, equivalent to 80 and 41% of the full buildings, respectively. The maximum CO₂ release rates after heating were 3.4 kg/h in the first test and 7.0 kg/h in the second test. Heating immediately increased NH₃, H₂S and CO₂ concentrations and release rates in the under-floor pits in both tests. Ventilation modes and rates affected the indoor gas concentrations at different locations. Higher ventilation rate was related to higher gas release rate in the first test. A peculiar behaviour of H₂S characterized by burst releases was found in the two tests. It was a new phenomenon not yet reported in the literature and might be related to some unexpected incidents involving acute H₂S concentrations in animal facilities.

1. Introduction

Pollutant gases, odour and dust constitute three major types of air pollution from animal husbandry. In many pig buildings, manure is stored for a long time in deep under-floor pits before it is removed. Manure stored in animal buildings produces agricultural pollutant gases. There are more than 130 major and minor gases in animal houses (Hartung & Phillips, 1994). Ammonia (NH₃), hydrogen sulphide (H₂S) and carbon dioxide (CO₂) are the main gases related to manure in pig houses (Muehling, 1970; Heber et al., 1997).

Agricultural NH₃ emission has become one of the major air pollution problems in recent years (van Breemen et al., 1982; Slanina, 1994). Ammonia from animal wastes and fertilizers was believed to constitute about 90% or more of the anthropogenic NH₃ emission (Buijsman et al., 1987). A significant part of it was considered to be emitted from animal wastes. High concentrations of NH₃ inside animal houses represent potential health hazards to humans and animals (Drummond et al., 1980; Reece et al., 1980; Crook et al., 1991; Busse, 1993). The loss of NH₃ from manure, during its storage or its application in fields, causes significant reductions in the
value of slurries as fertilizers (Pain et al., 1989). Moreover, some reports demonstrated that there existed certain relationships between NH$_3$ and nuisance odour (Liu et al., 1993). Odour nuisance from animal houses has been one of the major air pollution complaints received from the manure pit.

Hydrogen sulphide is considered the most dangerous gas when at acute concentration among the by-products of manure decomposition. It has been responsible for many animal as well as human deaths (Donham et al., 1982). Although several reports about typical and acute H$_2$S concentrations in pig houses were found in the literature, information about H$_2$S release in pig facilities is lacking. Only three direct measurements of H$_2$S production in pig houses were reported (Avery et al., 1975; Heber et al., 1997; Ni et al., 1998). No information was found concerning the dynamic behaviour of H$_2$S release from the manure pit.

The concern over CO$_2$ production in pig houses is more related to the health of humans and animals inside the house than to its global influence on environment and ecology outside the house. It was reported that the climate-related respiratory diseases of animals, such as sneezing, coughing or pneumonia, was greater for CO$_2$ concentrations of 0.2–0.9% than for CO$_2$ concentrations of 0.1–0.3% (Busse, 1993). Carbon dioxide has been used for a long time as a parameter to determine the minimum ventilation rate. Some suggested that the maximum allowed CO$_2$ concentration be 3000 p.p.m. for animals and 5000 p.p.m. for workers (CIGR, 1992). In some research on air quality and ventilation rate control, CO$_2$ was used as a tracer (Feddes & DeShazer, 1988; van Ouwerkerk & Pedersen, 1994; van’t Klooster & Heitlager, 1994). However, Ni et al. (1999c) found that a significant quantity of CO$_2$ was released from the pit in a commercial pig fattening house. This release of CO$_2$ from the manure complicates the use of CO$_2$ as a tracer.

Gas release in this paper refers to the process of gas transferring from the immediate surface of liquid manure into the free air stream in the house. Gas emission is the process of gas emanating from the pig house into the outdoor atmosphere. The gas release from the underfloor pit in a pig building can usually be estimated by the measured gas emission. Better estimation can be obtained when the room is emptied and cleaned between groups of pigs. This information is important because it helps to determine the maximum potential benefit of manure pit additives on gas emission reduction. The gas release study in buildings without pigs can also help to understand gas release behaviour and the influence of temperature and ventilation on gas release, since there is no interference from the animals’ presence.

The objectives of this paper are to study (1) the quantities of NH$_3$, H$_2$S and CO$_2$ releases from deep manure pits after the rooms of the buildings were emptied and cleaned; (2) the influence of propane heater operation on gas concentration and release; (3) the influence of different ventilation rates and modes on the gas releases; and (4) the release behaviour of H$_2$S.

### 2. Materials and methods

Two tests of gas release from manure pits were conducted in Buildings 3A and 3B, respectively, on a commercial pig farm. The buildings were instrumented to test a new manure additive to reduce gas and odour emission (Heber et al., 1998). Both buildings were identical, 1000-head, mechanically ventilated, fattening buildings. Each had a 2.4 m deep pit under a fully slatted floor with a pit surface area of 800 m$^2$ (Fig. 1). The buildings had curtains on the side walls and on the west end wall. There were four pit ventilation fans (each with a diameter of 0.46 m), five end wall ventilation fans (one with a diameter of 0.9 m and four with a diameter of 1.2 m), and two 72 kW direct-fired propane space heaters in each building. The four pit fans were moved to the top of a 3.6 m high and 0.8 m by 0.8 m wooden chimney. The under-floor manure pit of Building 3A received a daily spray with the additive (as a 300 p.p.m. solution in water at an estimated delivery rate of 0.43 kg/s) beginning at 09:00 for 4 min every 4 h. Building 3B was untreated.
Both tests were done at night to minimize the influence of solar radiation and sudden outdoor temperature changes. All the curtains were closed. The first test was conducted in Building 3A between 12 and 13 June, five days after the last group of 115 pigs of 120 kg each had been moved out. The room of the building including the floor had been cleaned with water under high pressure. The manure depth (Fig. 1) in the deep pit was 102 cm. The test began with measuring gas concentrations, temperatures and ventilation rate, followed by operation of the east heater from 20:30 to 21:37 to test the effect of temperature. During the entire test, all five end wall fans were shut off. An automatic controller adjusted the chimney ventilation rate based on the inside room temperature. The building was continuously monitored overnight.

The second test was conducted in Building 3B between 18 June and 19 June, started 4 days after the last group of 169 pigs of 120 kg each had been removed. The manure depth was 131 cm. The room of the building was cleaned before the test began. All the chimney outlets were covered during the entire test to prevent air flowing through. Three end wall fans were turned on for 22 min to flush the trapped gas and heat from the building. To test the effect of temperature, the two heaters were operated from 21:00 to 23:06 with only the 0.9 m end wall fan running. The 0.9 m fan was kept running after heating. The building was continuously monitored from the beginning of air flushing until the next morning at 08:00.

Pit fan ventilation rates in the first test were measured with one full-size fan wheel anemometer (FanCom FMS 50). Airflow readings were recorded every minute. Since the four pit fans were identical and controlled by one controller, the total airflow rate of the pit fans was taken as four times the airflow measured by the one sensor. Ventilation rate \( Q_{Vw} \) from the 0.9 m end wall fan in the second test was calculated based on a fan curve [Eqn (1)] supplied by the manufacturer and the static differential pressure \( P \) between indoor and outdoor air:

\[
Q_{Vw} = -118.9P + 22022 \quad (1)
\]

The differential static pressure was measured with a \( \pm 25 \) Pa (accuracy 0.25%) static pressure transmitter (Model C1, Dresser Industries, Stratford, CT). Room temperatures were measured at several locations (Fig. 1) with semiconductor temperature sensors (Model AD592, Analog Devices, Norwood, MA). Outdoor temperature was measured at a height of 3 m with a combination
Ammonia concentration was measured with an NH$_3$ Analyser [Model 17C, Thermo Environmental Instruments (TEI), Franklin, MA], after the NH$_3$ was converted to nitric oxide (NO) by a converter unit (Model 17, TEI) at 875°C. Hydrogen sulphide concentration was measured with an SO$_2$ Analyser (Model 43C, TEI), after the H$_2$S was converted to sulphur dioxide (SO$_2$) with an H$_2$S Converter (Model 340, TEI) at 325°C. Carbon dioxide concentration was measured with an infra-red photo-acoustic CO$_2$ monitor (Model 3600, Mine Safety Appliance Company, Pittsburgh, PA). The gas instruments were calibrated on 6 and 18 June with certified gases. Running averages of gas concentrations and temperatures were recorded every 20 s.

There were two gas-sampling locations in each test. In the first test, they were at the centre of the room (1·5 m above the floor) and at the inlets of the four pit ventilation chimneys. In the second test, they were at 0·5 m upwind of the centre of the 0·9 m diameter end wall fan and at the inlets of the four-pit ventilation chimneys. The room centre and the end wall fan were both one-point sampling. A gas sample pump drew air at 100 ml/s from the sampling location through a dust filter. For the four sampling points in the pit chimney inlets, a gas sample pump drew air at 100 and 25 ml/s from each chimney inlet with four filtered gas sampling tubes connected in parallel. Air sample streams were pumped through a heated Teflon sampling tube, and into a Teflon sampling manifold located in an instrument trailer. The gas measuring instruments switched between the two sampling locations (room centre/end wall fan and chimney inlets) every 5 min, resulting in six, 20 s gas concentration data from each location every hour. Only the last minute of the 5 min data collecting period was averaged and used for analysis to exclude the purge time for gas tubing and instruments.

Outdoor concentrations of NH$_3$, H$_2$S and CO$_2$ were measured on 9 June from 09:05 to 09:35 and on 18 June from 13:47 to 15:39, in two independent measurements prior to the tests during daytime. Air was sampled at one location 10 m east of the building with an easterly wind. Both measurements were conducted continuously using the same gas instruments. The first 5 min of data collection were excluded in each measurement. For these tests, it was assumed that diurnal variations of outdoor gas concentrations were insignificant.

The data continuously acquired with computerized data acquisition system during the tests were divided into four periods: (1) before heating; (2) during heating; (3) the first hour beginning from when the heaters were turned off; and (4) from 1 h after the heaters were turned off until the end of the tests. The indoor temperature and the ventilation rate were considered stabilized during the fourth period, which is termed ‘1 h after heating’ in the following text.

Gas emission rates were determined by multiplying the gas concentration by the ventilation rate, which were both measured at the same location, using Eqn (2) for the first test and Eqn (3) for the second test:

\[
Q_{Ge} = C_{Gp} Q_{Vp} \quad (2)
\]

\[
Q_{Ge} = C_{Gw} Q_{Vw} \quad (3)
\]

where \(Q_{Ge}\) is the gas emission rate in g/h, \(C_{Gp}\) the gas concentration in the pit headspace in g/m$^3$, \(Q_{Vp}\) the ventilation rate of the pit chimney fans in m$^3$/h; \(C_{Gw}\) the gas concentration at the wall fan in g/m$^3$, and \(Q_{Vw}\) the ventilation rate of the wall fan in m$^3$/h.

To obtain gas release rates in the emptied buildings, the rates of gas derived from the outdoor air and from the heaters, and change in gas concentrations in the buildings should be considered [Eqn (4)]:

\[
Q_{Gr} = Q_{Ge} - Q_{Gi} - Q_{ Gh} + \frac{dC_{Gr}}{dt} V_r + \frac{dC_{Gr}}{dt} V_p \quad (4)
\]

where \(Q_{Gr}\) is the gas release rate in g/h, \(Q_{Gi}\) the incoming gas flow rate in g/h, \(Q_{Gh}\) the gas generation rate from the heaters in g/h, \(C_{Gr}\) the gas concentration in the room in g/m$^3$, \(V_r\) the room air volume in m$^3$, \(C_{Gp}\) the gas concentration in the pit headspace in g/m$^3$, and \(V_p\) the pit air volume, m$^3$.

It was assumed that the propane heaters did not generate NH$_3$ and H$_2$S. Calculation of CO$_2$ release during the heating period was avoided, because of unknown CO$_2$ generation rates of the heaters. Therefore, calculation of the gas generation from the heaters in this work was not involved. The gas concentration in the room was determined by the concentration measured in the room centre for the first test and at the wall fan for the second test. The gas concentration in the pit headspace was represented by the concentration measured in the pit chimney fans for both tests. To use the sampled data in the tests, Eqn (4) was discretized as Eqn (5) with a value for \(Q_{Gh}\) of 0. The gas release rates during the 22 min flush before heating in the second test was not calculated because there was a drastic change of indoor gas concentrations during the flush period and this might result in unacceptable calculation errors:

\[
Q_{Gr}(k) = Q_{Ge}(k) - Q_{Gi}(k) + \frac{C_{Gr}(k + 1) - C_{Gr}(k)}{\Delta t} V_r + \frac{C_{Gp}(k + 1) - C_{Gp}(k)}{\Delta t} V_p \quad (5)
\]
where, $\Delta t$ is the sampling interval in h, and $k$ the sampling number with $k = 0, 1, 2, \ldots$

To compare the NH$_3$ and H$_2$S releases between the emptied buildings with those in occupied buildings, 44 h of measurements from 18 March to 17 April (before the test dates) in the same buildings were extracted. The 44 h of data were selected during ‘tranquil times’ at night (between 19:00 and 09:00). ‘Tranquil times’ refer to periods when the overall activity of the pigs was relatively low, during which the influence of pigs’ activity on the indoor environment are minimal and stable (Ni et al., 1999a). Times were also selected when only the pit ventilation fans were operating. The NH$_3$ and H$_2$S release rates during the selected 44 h were approximated with a simplified equation by neglecting the change of gas mass retained inside the building and by assuming that the pigs did not produce NH$_3$ and H$_2$S by respiration:

$$ Q_{Gr} = Q_{Ge} - Q_{Gi} $$

(6)

Heater operation was not recorded during the 44 h measurement period. Therefore, the CO$_2$ releases from manure in the 44 h were not calculated to avoid potential errors resulting from CO$_2$ generation by the heaters.

The gas releases in the emptied buildings were also compared with the gas releases or emissions reported in the literature. In this case, gas release flux, or release from unit surface area instead of gas release rate were used.

### 3. Results

#### 3.1. Outdoor gas concentrations

Outdoor concentrations of NH$_3$ were undetectable. Mean concentrations of H$_2$S and CO$_2$ on 9 June were 25-4 p.p.b. (parts per billion, $10^{-9}$) and 488 p.p.m., respectively (Table 1). These two values were used for H$_2$S and CO$_2$ release calculations in the first test. Mean concentrations of H$_2$S and CO$_2$ on 18 June were 21-9 p.p.b. and 465 p.p.m., respectively, and were used as background concentrations for the second test.

#### 3.2. Temperatures, ventilation rates and gas responses during empty building tests

##### 3.2.1. Temperatures and ventilation rates

During a 30 min measurement before heating in the first test, there were decreases of the outdoor temperature from 20-3 to 19-1 C and the ventilation rate from 22 500 to 19 500 m$^3$/h (Fig. 2). During the 67 min heater operation, the indoor temperature increased rapidly from 21 to 29 C in the first 30 min. The mean ventilation rate during heating was 23 000 $\pm$ 480 m$^3$/h (mean $\pm$ 95% confidence interval) (Table 2). The indoor temperature and ventilation rate both decreased quickly after heating and entered into a quasi-steady state 1 h after heating, when they were 18-6 $\pm$ 0-2 C and 9100 $\pm$ 200 m$^3$/h, respectively. The outdoor temperature was stable (16-3 $\pm$ 0-4°C) during the entire test.

During the flushing time before heating in the second test, the mean ventilation rate was 114 100 $\pm$ 5770 m$^3$/h and the indoor temperature was close to the outdoor temperature of about 25°C. At the time when the heating began, the ventilation rate was controlled to an average of 22 200 $\pm$ 20 m$^3$/h until the end of the test. Indoor temperature increased from 25 to 32°C during the first 20 min. After that, it decreased slowly as the outdoor temperature decreased during heating (Fig. 6). At 1 h after heating, both indoor and outdoor temperatures became relatively constant and decreased slightly and steadily until the early next morning at about 06:00.
3.2.2. Ammonia response

Mean NH$_3$ concentration in the chimneys was 6.3 ± 0.4 p.p.m. and mean NH$_3$ release rate was 93 ± 11 g/h before heating during the first test (Table 2). The NH$_3$ concentrations increased in the chimneys but decreased in the room centre when the heater began to operate (Fig. 3). The mean concentrations during heating were 10.6 ± 0.6 and 24 ± 0.5 p.p.m. at the pit chimneys and in the room centre, respectively. Under relatively constant conditions of temperatures and ventilation rate during this period were 10.6 ± 0.4 p.p.m. 1 h after heating. The NH$_3$ concentrations at both locations increased. The NH$_3$ concentration in the room centre increased more quickly. Mean NH$_3$ concentrations during this period were 10.6 ± 0.4 and 14.7 ± 1.1 p.p.m. in the room centre and at the pit chimneys, respectively. The mean NH$_3$ release rates during heating and 1 h after heating were 167 ± 11 and 68 ± 2 g/h, respectively.

The responses of NH$_3$ concentrations and release rates during the second test were different. During the 22 min of building air flush, NH$_3$ concentrations dropped very rapidly from 14.6 to 4.1 p.p.m. at the chimneys and from 9.1 to 4.4 p.p.m. at the wall fan (Fig. 7). The NH$_3$ concentration in the pit chimneys began to increase quickly but the concentration at the wall fan began to decrease slightly when the heating period started. These trends continued until the heating stopped. The increase of concentration at the pit chimneys slowed and the mean value was 12.7 ± 0.4 p.p.m. 1 h after heating. The NH$_3$ concentration at the wall fans still decreased slowly and

<table>
<thead>
<tr>
<th>Building status</th>
<th>Number of samples</th>
<th>Before heating</th>
<th>Heating</th>
<th>One hour after heating</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Outdoor temperature, °C</strong></td>
<td>19.6 ± 0.6</td>
<td>18.6 ± 0.2</td>
<td>15.7 ± 0.3</td>
<td>17.6</td>
</tr>
<tr>
<td><strong>Indoor temperature, °C</strong></td>
<td>20.7 ± 0.1</td>
<td>28.1 ± 1.2</td>
<td>18.6 ± 0.2</td>
<td>20.2</td>
</tr>
<tr>
<td><strong>Chimney ventilation, m$^3$/h</strong></td>
<td>21,000 ± 1,400</td>
<td>23,000 ± 480</td>
<td>9,100 ± 210</td>
<td>11,500</td>
</tr>
<tr>
<td><strong>NH$_3$</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Chimney concentration, p.p.m.</strong></td>
<td>6.3 ± 0.4</td>
<td>10.6 ± 0.6</td>
<td>10.6 ± 0.4</td>
<td>12.3</td>
</tr>
<tr>
<td><strong>Centre concentration, p.p.m.</strong></td>
<td>50 ± 0.7</td>
<td>24 ± 0.5</td>
<td>14.7 ± 1.1</td>
<td>19.2</td>
</tr>
<tr>
<td><strong>Emission rate, g/h</strong></td>
<td>94 ± 12</td>
<td>167 ± 11</td>
<td>68 ± 2</td>
<td>94</td>
</tr>
<tr>
<td><strong>Release rate, g/h</strong></td>
<td>93 ± 11</td>
<td>167 ± 11</td>
<td>68 ± 2</td>
<td>93</td>
</tr>
<tr>
<td><strong>Release flux, mg/m$^2$h</strong></td>
<td>117 ± 14</td>
<td>209 ± 14</td>
<td>85 ± 3</td>
<td>118</td>
</tr>
<tr>
<td><strong>H$_2$S</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Chimney concentration, p.p.b.</strong></td>
<td>192 ± 5</td>
<td>219 ± 25</td>
<td>324 ± 51</td>
<td>742</td>
</tr>
<tr>
<td><strong>Centre concentration, p.p.b.</strong></td>
<td>178 ± 24</td>
<td>115 ± 7</td>
<td>382 ± 67</td>
<td>1001</td>
</tr>
<tr>
<td><strong>Emission rate, g/h</strong></td>
<td>57 ± 0.5</td>
<td>6.9 ± 0.8</td>
<td>41 ± 0.6</td>
<td>9.9</td>
</tr>
<tr>
<td><strong>Release rate, g/h</strong></td>
<td>49 ± 0.5</td>
<td>6.1 ± 0.8</td>
<td>38 ± 0.6</td>
<td>9.6</td>
</tr>
<tr>
<td><strong>Release flux, mg/m$^2$h</strong></td>
<td>62 ± 0.6</td>
<td>7.7 ± 1</td>
<td>48 ± 0.8</td>
<td>12.0</td>
</tr>
<tr>
<td><strong>CO$_2$</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Chimney concentration, p.p.m.</strong></td>
<td>574 ± 10</td>
<td>999 ± 137</td>
<td>623 ± 10</td>
<td>708</td>
</tr>
<tr>
<td><strong>Centre concentration, p.p.m.</strong></td>
<td>560 ± 13</td>
<td>1462 ± 110</td>
<td>657 ± 12</td>
<td>746</td>
</tr>
<tr>
<td><strong>Emission rate, kg/h</strong></td>
<td>22 ± 1.1</td>
<td>40.7 ± 5</td>
<td>10.4 ± 0.2</td>
<td>13.1</td>
</tr>
<tr>
<td><strong>Release rate, kg/h</strong></td>
<td>3.3 ± 0.2</td>
<td>NC</td>
<td>22 ± 0.2</td>
<td>3.4</td>
</tr>
<tr>
<td><strong>Release flux, g/m$^2$h</strong></td>
<td>41 ± 0.2</td>
<td>NC</td>
<td>28 ± 0.2</td>
<td>4.2</td>
</tr>
</tbody>
</table>

NC, not calculated.

Table 2
Mean values of measurement and calculation during the first test in Building 3A

![Fig. 3. Ammonia release rate (---) and ammonia concentrations at the pit chimneys (- - - -) and at the room centre (— — ) during the first test](image-url)
its mean value was $2.0 \pm 0.1$ p.p.m. 1 h after heating. The 
$NH_3$ release rates during and 1 h after heating were
$46.1 \pm 1.7$ and $31.8 \pm 1.1$ g/h, respectively (Table 3).

3.2.3. Hydrogen sulphide response

The responses of the concentration and release of $H_2S$ 
before heating and during heating in the first test 
demonstrated similar patterns as those of $NH_3$. The $H_2S$ 
concentrations at the pit chimneys ($19.2 \pm 5$ p.p.b.) and in the room 
centre ($17.8 \pm 24$ p.p.b.) were similar in value before 
heating (Table 2). They increased at the pit chimneys and 
decreased in the room centre during heating. However, 
they remained fairly similar 1 h after heating until about 
01:30, when there was a sudden increase of $H_2S$ concentrations at both locations. The $H_2S$ concentration in the room centre became higher than that in the chimney. At 04:00, another burst of $H_2S$ concentration, which was higher than the previous one and lasted for about 2 h, 
was detected. The mean $H_2S$ concentrations at the pit 
chimneys and in the room centre 1 h after heating were 
$32.4 \pm 51$ and $382 \pm 67$ p.p.b., respectively. The maximum concentrations at these two locations during that

time were 742 and 1001 p.p.b., respectively. The mean $H_2S$ release rates before, during heating and 1 h after 
heating were $4.9 \pm 0.5$, $6.1 \pm 0.8$ and $3.8 \pm 0.6$ g/h, respectively (Table 2).

In the second test, the $H_2S$ concentrations dropped 
very rapidly during the air flush, from 723 to 94 p.p.b. at 
the chimneys and from 414 to 77 p.p.b. at the wall fan 
(Fig. 8). The concentration at the wall fan remained 
relatively constant beginning from the heating period 
until the end of the test. There were more variations of 
the $H_2S$ concentration in the pit chimney, which 
increased steadily during heating and decreased suddenly 
when the heaters were turned off. Then it increased with 
a steady slope until about 04:50, when a burst of high 
concentration was detected with a peak value of 1492 
p.p.b. Two more bursts of $H_2S$ concentration and release 
rate occurred later. The mean $H_2S$ concentrations at the 
pit chimneys and the wall fan 1 h after the heaters were 
turned off were 427 $\pm 82$ and 78 $\pm 4$ p.p.b., respectively. 
The $H_2S$ release rates during heating and 1 h after heating were $1.3 \pm 0.2$ and $1.7 \pm 0.1$ g/h, respectively (Table 3).
3.2.4. Carbon dioxide response

Carbon dioxide showed different response patterns than NH$_3$ and H$_2$S. The CO$_2$ concentrations at the pit chimneys and in the room centre were quite similar before heating in the first test (Table 2). The concentrations at both locations increased quickly with operation of the heater which produced large quantities of CO$_2$, and reached the maximum values (1128 p.p.m. at the chimneys and 1558 p.p.m. in the room centre) about 40 min later (Fig. 5). The concentrations decreased dramatically when the heater was turned off. There were only small variations of these concentrations at 1 h after heating. The mean CO$_2$ concentrations at the pit chimneys and in the room centre were 623 ± 10 and 657 ± 12 p.p.m., respectively (Table 2). The CO$_2$ release rates before heating and 1 h after heating were 3.3 ± 0.2 and 2.2 ± 0.2 kg/h, respectively.

In the second test, the CO$_2$ concentrations dropped suddenly from 1113 to 505 p.p.m. at the wall fan during flushing (Fig. 9). The concentration at the chimneys increased rapidly during heating and reached 1313 p.p.m. at 22:35. The concentration at the wall fan increased only slightly to 587 p.p.m. by the end of the heating period. Concentrations of CO$_2$ at both sampling locations remained quite constant 1 h after heating with that at the chimneys (663 ± 11 p.p.m.) about 100 p.p.m. higher than at the wall fan (565 ± 7 p.p.m.). The mean CO$_2$ release rate at 1 h after heating was 4.0 ± 0.3 kg/h (Table 3).

3.3. Gas concentrations and release rates in occupied buildings

Building 3A had 858 ± 0.3 pigs weighing 88.1 ± 2.1 kg and Building 3B had 870 ± 0.2 pigs weighing 84.2 ± 2.1 kg during the 44 h of measurement selected in March and April (Table 4). The mean ventilation rate and temperature in Building 3A were 21,000 ± 330 m$^3$/h and 19.9 ± 0.1°C, respectively, which were similar to the conditions before heating during the first test in the same building (Table 2). A lower mean ventilation rate of 15,200 ± 240 m$^3$/h was measured in Building 3B although the mean temperature was the same as in Building 3A. The mean NH$_3$ concentration in the pit chimneys was 2 p.p.m. higher in 3A than in Building 3B. Concentrations of H$_2$S and CO$_2$ in the pit chimneys were very similar in both buildings. Gas concentrations at the wall fans and at the centre of the room were not measured. The NH$_3$ release rates were 255 ± 7 and 186 ± 5 g/h and the H$_2$S release rates were 120 ± 19 and 75 ± 0.6 g/h for Buildings 3A and 3B, respectively.

### Table 4

Mean values of measurements and calculations at ‘tranquil time’ in the two buildings (Building 3A and Building 3B) when they were occupied from 18 March to 17 April

<table>
<thead>
<tr>
<th></th>
<th>First test in 3A</th>
<th>Second test in 3B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of hours</td>
<td>44</td>
<td>44</td>
</tr>
<tr>
<td>Pigs, head</td>
<td>858 ± 0.3</td>
<td>870 ± 0.2</td>
</tr>
<tr>
<td>Pig weight, kg</td>
<td>88.1 ± 2.1</td>
<td>84.2 ± 2.1</td>
</tr>
<tr>
<td>Outdoor temperature, °C</td>
<td>−1.0 ± 0.5</td>
<td>−1.0 ± 0.5</td>
</tr>
<tr>
<td>Indoor temperature, °C</td>
<td>19.9 ± 0.1</td>
<td>19.9 ± 0.2</td>
</tr>
<tr>
<td>Ventilation, m$^3$/h</td>
<td>21,000 ± 330</td>
<td>15,200 ± 240</td>
</tr>
<tr>
<td>NH$_3$ Chimney concentration, p.p.m.</td>
<td>17.2 ± 0.6</td>
<td>15.2 ± 1.7</td>
</tr>
<tr>
<td>Release rate, g/h</td>
<td>255 ± 7</td>
<td>186 ± 5</td>
</tr>
<tr>
<td>Release flux, mg/m$^2$h</td>
<td>319 ± 9</td>
<td>233 ± 6</td>
</tr>
<tr>
<td>H$_2$S Chimney concentration, p.p.b.</td>
<td>425 ± 62</td>
<td>423 ± 33</td>
</tr>
<tr>
<td>Release rate, g/h</td>
<td>12 ± 1.9</td>
<td>7.5 ± 0.6</td>
</tr>
<tr>
<td>Release flux, mg/m$^2$h</td>
<td>15 ± 2.4</td>
<td>9.4 ± 0.7</td>
</tr>
<tr>
<td>CO$_2$ Chimney concentration, p.p.m.</td>
<td>3189 ± 89</td>
<td>3131 ± 87</td>
</tr>
</tbody>
</table>

4. Discussion

4.1. Quantities of gas release

Gas release rates varied considerably at different periods of the empty building tests (Tables 2 and 3). They were related to differences in temperature and ventilation. The highest release rates are used here to discuss the potentials of gas releases from the pit, except for those during the flushing of the second test.

4.1.1. Ammonia

Ammonia release rates were the highest during heating, 167 ± 11 g/h for the first test and 46 ± 2 g/h for the second test. They were about 65% and 24.9% of the fully occupied buildings, respectively. The average ratio of both tests was 45.2% of the full buildings. The ratio in the first test agreed with the estimation of Hoeksma et al. (1992), who stated that NH$_3$ released from the pit accounted for about 60–70% of the total NH$_3$ emission from a pig house. However, the ratio in the second test was much lower than the first test. This appeared to be the result of the different ventilation mode than the first test, which is discussed in Section 4.2.

The NH$_3$ release fluxes of fully occupied buildings listed in Table 4 were within the range of reported NH$_3$ release fluxes and were therefore representative. Aarnink et al. (1996) reported a mean NH$_3$ emission rate of 6.2 g/d from an experimental house in the Netherlands with a floor area of 0.73 m$^2$ (50% slatted) per fattening pig.
(weight 28.1–105.8 kg) at a mean temperature of 23.6°C. This is equivalent to an NH₃ release flux of 350 mg/m² h. In a test in Sweden, Andersson (1995) obtained a release flux of 103 mg/m² h at a temperature of 16.2°C. The release flux from a 135 day test in a commercial pig house in Belgium was 449 mg/m² h at a mean temperature of 16.6°C (Ni, 1998).

The high quantity of NH₃ release from the pits suggested that the pits were an important source of NH₃ release. However, NH₃ released from the floor might have been equally important when the building was occupied. Higher NH₃ emission rates were directly correlated with larger floor areas that were covered with wet manure (Ni et al., 1999b). When a manure additive is used to reduce NH₃ emission from pig houses, it may be beneficial to consider applying it on the floor as well.

4.1.2. Hydrogen sulphide

The mean H₂S release rate during heating in the first test was 6.1 ± 0.8 g/h, which was 51% of the H₂S release (120 ± 19 g/h) in the same building when it was fully occupied (Table 4). The mean H₂S release rate 1 h after heating (1.7 ± 0.1 g/h) was higher than that during heating in the second test, and was about 23% of that in the same building when it was fully occupied (7.5 ± 0.6 g/h). Because of the burst of H₂S concentrations after heating in the two tests (Figs 4 and 7), the maximum H₂S release rates 1 h after heating (96 g/h in the first test and 31 g/h in the second test) were higher than the mean release rates. They were equivalent to 80 and 41% of the full buildings, respectively.

There is little information available about the quantity of H₂S release. Avery et al. (1975) presented the results of 80 samples in six pig units, where measured H₂S concentration ranged from 120 to 2174 p.p.b. The daily production of H₂S ranged from 0.07 to 2.95 mg/d per 100 kg of pig weight. Assuming 100 kg of pig weight per m² of pit surface, the H₂S release fluxes would be between 0.003 and 0.01 mg/m² h. These values were only tiny fractions of our values obtained in this work. The daily ‘H₂S production’ in Avery et al. (1975) was calculated as the average daily concentration of H₂S multiplied by the total daily airflow. This technique may have resulted in lower calculated emission rates.

Heber et al. (1997) reported mean H₂S emission rates of 150 mg/d pig from two naturally ventilated, pig fattening houses starting with an average number of 893 pigs during a 63 day continuous measurement. The buildings had pit surfaces of 670 m² each. The building ventilation rates were calculated with the heat balance method. The estimated release flux would be about 8.3 mg/m² h and was slightly lower than the release fluxes in this study. There might be an underestimation of the ventilation rate in Heber et al. (1997) because of the inadequacy of the heat balance technique.

Ni et al. (1998) reported a mean H₂S emission rate of 24.3 ± 2.4 g/h during 89 days of warm weather from the same building, in which the second empty building test was conducted for this study. The release flux was 30.4 mg/m² h and was much higher compared with the release fluxes in fully occupied buildings in this work. The main reason of higher release in Ni et al. (1998) was probably the much higher ventilation rate, which was 158 800 ± 9700 m³/h, 7.5–10.4 times as much as the ventilation rates presented in Table 4.

4.1.3. Carbon dioxide

The CO₂ release flux was 41 ± 0.2 g/m² h before heating. The average ventilation rate during that time was 26.3 m³/h m² of floor surface. In the second test, the CO₂ release flux was only available 1 h after heating with a mean of 5.0 ± 0.4 g/m² h and the maximum of 8.8 g/m² h. The mean ventilation rate 1 h after heating was 28.5 m³/h m² of floor. These CO₂ release values were within the range reported by Ni et al. (1999c) who conducted experiments in a partly (50%) slatted fattening pig house both when it was emptied and when it was occupied. In the emptied house, the CO₂ release fluxes were 0.8, 25.8 and 118.4 g/m² h at ventilation rates of 160, 3350 and 5100 m³/h (2.2, 46.5 and 70.8 m³/h m² of floor surface), respectively. When it was occupied during a 128 day test, the calculated mean CO₂ release flux of 42.1 g/m² h (ranged from 1.1 to 116.7 g/m² h) accounted for 37.5% of that exhaled by pigs. The influence of ventilation rate on the CO₂ release rate was demonstrated in both empty room tests, the one reported by Ni et al. (1999c) and this research.

Sneath et al. (1997) measured the CO₂ production of 300, 25 kg pigs for 17 days in a fattening pig house with a fully slatted floor. The house had a slurry pit surface area of 100.1 m². The mean CO₂ production rate was 18 kg/d per 500 kg of pig weight. It was 20% higher than the CO₂ exhalation rate calculated with the model of Pedersen et al. (1998). It was still 15% higher if the CO₂ released from manure (4.2% of that exhaled by the pigs) were included. Since there was no direct-fired heating in the house, this direct measurement implied that a higher percentage of CO₂ from manure was released than predicted by the model of Pedersen et al. (1998).

One of the main difficulties of investigating the CO₂ release from manure in an occupied building is estimating the source of CO₂, whether from the manure decomposition or from pig respiration. The emptied building test eliminated pig respiration so the CO₂ production from the manure pit could be evaluated. It was useful for verifying the potential of CO₂ release from manure. The CO₂ release rate was related to the ventilation rate, pig
weight and manure temperature (Ni et al., 1999c). When the buildings were occupied, there were usually higher ventilation rates and temperatures. There was also continual fresh manure loading which provided new substrates for biological decomposition. Although CO₂ release from the emptied buildings in this work could not compare directly with that when the buildings were occupied, CO₂ release from the manure pit was expected to be higher in the occupied buildings than when they were emptied.

4.2. Influences of heating and ventilation on gas concentrations and releases

Heating and ventilation had significant influences on gas concentrations and releases in the tests. Heating and ventilation were used as controlled inputs into the emptied pig building systems. Heating was pulse input in both tests. Different ventilation rates were imposed during and after heating in the first test. Different ventilation modes were used in the two tests. Gas release responded to both heating and ventilation inputs.

Gas concentration was a state variable measured during the tests. Gas concentration in a building is affected by gas release rate, gas emission rate and building air volume. Mean gas concentration in a pig building can be expressed by Eqn (7) using a mass balance

\[
\frac{dC_g}{dt} = \frac{Q_{ge} - Q_{ge}}{V_B}
\]

where \(C_g\) is the building gas concentration in g/m⁶ and \(V_B\) the building air volume in m³.

In an animal building with a given air volume, when the gas release rate is higher than the emission rate, the gas concentration in the building increases, otherwise, it decreases. There is also interaction between gas concentration and gas release. The gas concentration gradient between the gases in the surface manure and in the free air stream affects the convective mass transfer of the gas from the manure. Two other important variables affecting the mass transfer are temperature and air velocity. These are generally accepted principles that explain the process of NH₃ release from liquid manure (Ni, 1999).

4.2.1. Influence of heating

It can be seen from Figs 3 and 4 and Figs 7 and 8 that heating with the propane heaters had an immediate influence on the NH₃ and H₂S concentrations in the under-floor pit in both tests. The rapid increase of CO₂ concentration in the pit during heating in the first test might have been influenced by the transport of CO₂ gas from the heater to the pit, since there were only pit fans used at that time (Fig. 5). However, it was unlikely that the rapid increase of CO₂ concentration in the pit was caused by the CO₂ generation from the heaters in the second test, in which a tunnel ventilation fan was used (Fig. 9). The concentration increase of all three gases in the pit ventilation chimneys appeared to be directly related to the increase of gas release rates during heating, except for CO₂ in the first test. The increases in gas concentrations were detected in the gas samples right after the start of the heaters. Since the gas-sampling interval was 10 min, it was expected that the response of gas release in the pit chimneys to the heating was less than 10 min. Heating apparently raised the surface manure temperature and accelerated the gas release process. In the second test, heat transfer from the heaters to the manure was most probably due to radiation through the floor slats. Because of the large heat capacity of the liquid manure, the downward heat transfer and the short response time gas release, only a slight temperature increase in a thin layer of surface manure was to be expected.

4.2.2. Influence of ventilation

Pit ventilation was used in the first test. Downward air movement was expected since the air inlets consisted of 13 baffles in the flat ceiling of the building and the air outlets consisted of four openings in the pit sidewalls. There was a concentration decrease for NH₃ and H₂S in the room centre with a higher ventilation rate during heating (Figs 1–3). This might have been caused by the dilution of fresh air at the microzone surrounded by the sampling location, where it was only about 1·8 m from one of the ceiling air inlets. The indoor air in the pig buildings was imperfectly mixed and gas concentration gradients existed in the buildings. It could be expected that, inside ventilated buildings, lower pollutant concentration occurred at locations with more fresh air.

At a lower rate of pit ventilation after heating in the same test, there was little air movement and air mixing inside the building. The more rapid increase of NH₃ concentration in the room centre, which reached 18 p.p.m. at about 04:00 as compared with 12.5 p.p.m. in the pit chimney, might have been caused by the rising of the NH₃ due to its lower density than air. The concentrations of H₂S and CO₂ did not show the same impressive differences between the room and the pit after heating in this test (Figs 4 and 5). This was probably due to the higher densities of these two gases compared with air. At 0°C, the densities of air, NH₃, H₂S and CO₂ are 1·29, 0·77, 1·54 and 1·98 kg/m³, respectively.

Tunnel ventilation was used in the second test. Air was expected to descend from the ceiling, enter into the room, and move out horizontally through the tunnel fan. Less air movement and exchange in the pit headspace was
expected as compared with the pit ventilation mode. Concentrations of all three gases in the pit were higher compared with those in the room. The \( \text{NH}_3 \) concentration ranged from 1.7 to 2.6 p.p.m. in the room centre 1 h after heating while the pit concentration remained at about 13 p.p.m. (Fig. 7). The difference of \( \text{H}_2\text{S} \) between the two locations was equally significant. The maximum \( \text{H}_2\text{S} \) concentration in the room still remained below 120 p.p.b. when a peak concentration of 1492 p.p.b. was detected in the pit at 04:55 (Fig. 8). The mean concentration difference for \( \text{CO}_2 \) between the two locations was about 100 p.p.m. from 1 h after heating (Fig. 9). More fresh air dilution in the room and less air exchange between the pit and the room was the probable cause of low gas concentrations in the room. The tunnel ventilation mode in this test appeared more effective in reducing gas concentrations in the room, thus creating better air quality for the occupants. However, animals might alter the airflow patterns in the building and influence the tunnel ventilation effectiveness.

The effect of ventilation rate on gas release rate can be discussed by comparing the gas releases before heating and after heating in the first test. To reduce the effect of indoor temperature, the gas release from 22:42 to 23:32 (after heating) was calculated. During that time, the mean ventilation rate and indoor temperature were 9563 ± 749 m³/h and 19.9 ± 0.1°C, respectively. The \( \text{NH}_3 \), \( \text{H}_2\text{S} \) and \( \text{CO}_2 \) release rates were 53.7 ± 2.7, 1.8 ± 0.3 g/h and 1.8 ± 0.1 kg/h, respectively, which were only 58, 37 and 55% of those before heating. Although the indoor temperature from 22:42 to 23:32 was 0.8°C lower than before heating, the ventilation rate during that time was only 46% of that before heating. The decreased gas release rates are assumed to be largely attributed to the decrease of the ventilation rate.

4.3. Behaviour of hydrogen sulphide release

The behaviour of \( \text{H}_2\text{S} \) release was different to that of \( \text{NH}_3 \) and \( \text{CO}_2 \) in both tests (Figs 4 and 8). The release peak during the first test reached 9.6 g/h at 04:32, about four times higher than it was between 22:42 and 01:22 (Fig. 4). In Fig. 8, although the highest peak release rate was only 3.1 g/h, the peak concentration in the pit
Fig. 8. Hydrogen sulphide release rate and hydrogen sulphide concentrations at the pit chimneys and at the wall fans during the second test.

Fig. 9. Carbon dioxide release rate and carbon dioxide concentrations at the pit chimneys and at the wall fans during the second test.

chimneys reached 1500 p.p.b. at 04:45. These release and concentration peaks could be related neither to air temperature nor ventilation rate. No other known factors in the emptied buildings could have caused these peaks. Sudden increases of H\textsubscript{2}S concentration caused by manure agitation in animal facilities has been reported (Muehling, 1970; Patni & Clarke, 1991). However, H\textsubscript{2}S burst release behaviour without manure agitation has not been reported in the literature.

Hydrogen sulphide arises from the anaerobic bacterial decomposition of sulphur-containing amino acids in the dung/urine mixture (Hartung & Phillips, 1994). It was unlikely that the production of H\textsubscript{2}S inside the manure pits by anaerobic decomposition had gone through a sudden increase during the tests. It was more likely that H\textsubscript{2}S burst release, possibly a chain reaction, was triggered by some unknown factor(s). This particular behaviour of H\textsubscript{2}S in animal houses deserves more investigation.

Burst releases of H\textsubscript{2}S, which lasted from 2 to 6 h during the tests, might be related to some accidents involving H\textsubscript{2}S. It has been reported that accidents including fatalities sometimes occurred under operational procedures and ventilation conditions, which had often been used successfully before. Subsequent measurement of gas concentrations under conditions similar to those under which the accidents occurred indicated non-lethal concentrations (Patni & Clarke, 1991). If burst releases of H\textsubscript{2}S are a common phenomenon in animal farm facilities, they might be related to the causes of these unexplained accidents. Since the average H\textsubscript{2}S release rate was higher in the occupied than in the emptied buildings, as discussed in Section 4.1.2, the burst H\textsubscript{2}S releases in the occupied buildings, if they exist, might also be higher than was detected in the emptied buildings.

4.4. Effect of manure additive spray

The building in the first test received a 4 min spray of the manure additive at 09:00, 01:00 and 05:00 from an automatic chemical application system. During a comparison study of 94 days when both buildings were fully occupied (Heber et al., 1998), the NH\textsubscript{3} emission was 17-6% lower and the H\textsubscript{2}S emission was 12-4% higher from this treated building than the control building, where the second test was conducted (CO\textsubscript{2} was not studied). However, both NH\textsubscript{3} and H\textsubscript{2}S releases in the emptied buildings were higher in the first test than in the second test. This might have been caused by different procedures (e.g. ventilation modes) in the two tests. The burst releases of H\textsubscript{2}S in the empty buildings did not seem to be related to the manure additive spray either, because they occurred in both buildings.

5. Conclusions

(1) Tests in emptied room pig buildings were shown to be an effective way to study the potential and behaviour of gas release from manure pits, and the effects of temperature and ventilation on gas release.

(2) There were significant gas releases from the manure pits in the emptied buildings. Ammonia release rates during heating were 167 ± 11 g/h in the first test and 46 ± 2 g/h in the second test, equivalent to 65-5 and 24-9% of the fully occupied buildings, respectively. The NH\textsubscript{3} release fluxes in the fully occupied buildings were comparable to the literature. The maximum H\textsubscript{2}S release rates 1 h after heating were 9-6 g/h in the first test and 3-1 g/h in the second test, equivalent to 80 and 41% of the full buildings, respectively. The maximum CO\textsubscript{2} release rates after heating were 3-4 kg/h in the first test and 7-0 kg/h in the second test. The CO\textsubscript{2} release fluxes were within the range of previously reported releases in an emptied pig house.

(3) The operation of the propane space heaters located in the room had an immediate and positive influence on
NH₃, H₂S and CO₂ concentrations in the under-floor pit in both tests. The response of gas concentration increase occurred in less than 10 min. It is anticipated that the heating likely raised the surface manure temperature through radiation which accelerated gas release processes that increased the gas concentrations. Only a slight temperature increase in a thin layer of surface manure was to be expected during the heating period.

(4) Ventilation modes and rates had impressive effects on gas concentrations at different locations. Pit ventilation with an airflow rate of 21 000 m³/h provided effective downward airflow that diluted gas concentration in the room centre. At low pit ventilation of about 9100 m³/h, NH₃ concentration was higher in the room than in the pit due to the lower NH₃ density compared with air. The tunnel ventilation mode appeared to be more effective for diluting pollutant gas concentrations in the room. At a tunnel ventilation rate of about 22 200 m³/h, concentrations for all three gases in the room were lower than in the pit.

(5) Ventilation rates had significant effects on the gas release rates in the first test. At a ventilation rate of 9600 ± 750 m³/h after heating, the NH₃, H₂S and CO₂ release rates were 58, 37 and 55% of those before heating, when the ventilation rate was 21 000 ± 1400 m³/h.

(6) A peculiar behaviour consisting of H₂S burst releases without manure agitation occurred in both tests. This was a phenomenon that had not yet been reported in the literature. It could not be related to any known factors in the tests and deserves further investigation. The burst releases of H₂S might be related to some unexpected accidents involving acute H₂S concentrations in animal facilities.

(7) No evident effects of manure additive spray were found in the building during the first test.

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