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Bed-level ventilation conditions in daycare centers

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ABSTRACT

In Dutch daycare centers, most often, semi-enclosed beds are used in bedrooms. Given that air usually does not mix completely in a ventilated room, there are concerns about whether room-level ventilation would be enough to keep the air clean inside semi-enclosed beds. No studies into the bed-level ventilation conditions in daycare centers have been identified. Therefore, a field survey was performed in 17 Dutch daycare centers to collect bedroom ventilation conditions and occupants' characteristics. Based on that information, a full-scale bedroom identical to that of typical daycare centers was constructed in a climate chamber. The bed-level ventilation conditions were investigated by examining the dispersion and inhalation of CO_2 gas exhaled by a breathing thermal baby model while sleeping in a bed. The effect of three variables, i.e., sleep positions (supine, lateral-to-wall, lateral-to-corridor), baby ages (12- and 30-month-old), and ventilation rates (55 and 250 m^3/h), were studied. The results showed that excess exhaled CO_2 concentration was accumulated inside the semi-enclosed bed in most cases. This indicates that bed-level ventilation conditions are not sufficient enough when only relying on the room-level mixing ventilation mode. The inhaled CO_2 concentration of infants sleeping inside the bed was remarkably high, on average, three times higher than the measured values in the room exhaust. The study provides knowledge on the bed-level ventilation conditions in miniature semi-enclosed sleeping spaces under a mixing ventilation mode at room level and highlights the need to improve the air quality inside the baby bed.

1. Introduction

Daycare centers (DCCs) or early childhood educational institutions are typically designed to support infants and toddlers in their early cognitive, physical, social, emotional, and educational development before primary school [1]. The majority of young children in modern society spend most of their daily time in DCCs, besides being at their homes, since their parents need to return to work a few months after their birth [2]. For example, in the Netherlands, most children aged from 8 weeks to 4 years spend up to 11 h per day in DCCs [3]. Similarly, the substantial amount of time that young children spend in DCCs was also reported globally, such as in Finland [4], America [5], Poland [6], China [7], Denmark [8], Germany [9], Korea [10], Singapore [11], and Iran [12].

During the daytime, taking a nap is one of the essential daily activities for young children [10,13], which distinguishes daycare centers from other educational facilities like schools [14]. Therefore, DCCs typically have bedrooms with a high density of baby occupants, as reported in the studies on the indoor environment quality in DCCs around the world [6,9,15,16]. In particular, there is a type of semi-enclosed bed, called a baby bunk bed (see Fig. A1 in Appendix A of the Supplementary material, and Fig. 1b), intended for children aged 0–4 years [17]. In terms of practicality, the closure of the bed can prevent an infant from falling off the bed, which provides a safe sleeping space for children. In addition to that, psychologically, some infants and toddlers may also enjoy the feeling of being in a shelter that looks separate from the outside world [18]. Furthermore, the baby beds have compact features that allow their use in nearly any small space. As a result, these types of miniature semi-enclosed beds are popular around the world. For instance, over 95,000 beds are being used in most of the bedrooms in more than 9000 Dutch DCCs, according to feedback from one of the manufacturers [17].

As the main occupants in DCCs, infants and toddlers, are in a period of rapid physiological development, characterized by the developing organ systems, incomplete metabolic systems, immature host defense mechanisms, etc., which makes them highly sensitive to chemical and particulate matter exposures [19]. Also, compared to older children and adults, young children have higher inhalation rates per unit of body

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weight, much smaller airways, and greater surface-to-volume ratios, which increases their vulnerability and susceptibility to exposure to air pollutants [20–22]. Consequently, there are growing concerns about the potential negative effects of indoor air pollutants on children's health, thus raising interest in research on the air quality in the indoor environments they are exposed to, especially in DCCs [23]. Unsatisfactory IAQ issues in DCCs were unanimously identified in most recent studies in many parts of the world, such as France [24], South Korea [10,13], Iran [12], Malaysia [25], Singapore [11], Canada [26], Poland [6], Portugal [27,28], Slovenia [29], China [7], USA [30], and Spain [31]. It should be emphasized that, as compared with the awake state in most indoor environments, a sleeping person is a "passive recipient" who is unable to actively control the sleeping environment [32], particularly when referring to young babies. Even worse, in the sleep microenvironment, the source-proximity effect may become dominant. That is, pollutant concentrations such as volatile organic compounds (VOCs) emitted by beddings within the crib mattress are much greater than those in the bulk room air [33–36]. Regrettably, to the best of our knowledge, there is no study investigating the IAQ conditions inside these semi-enclosed baby beds in DCCs yet.

Improved outdoor air ventilation is one of the approaches to improve indoor air quality and lower the concentrations of indoor air pollutants, apart from source control and use of air cleaners [37,38]. The primary reason for ventilation is to supply clean air to the space or room and extract contaminants as efficiently as possible. In reality, however, the fully mixed assumption of room air seldom occurs and in turn, often is non-uniformly distributed. Such an inhomogeneity of the air in space in a fully-mixed assumption generally will cause lower ventilation effectiveness, which is a measure of representing the ability of a ventilation system to exchange the air in the room and to remove airborne contaminants [39]. It is important to note that what really counts for the building occupants is the air quality in their breathing zones. That is, "inhaled air quality" should be given more attention than "indoor air quality".

The breathing zone is defined as the immediate space around the mouth or nose from which the air is inhaled [40]. There are three airflows complexly interacting in the breathing zone: the breathing flow, free convective flow around the human body (including the thermal plume above the body), and ventilation-induced air flow toward the face. All of these can affect personal exposure to air contaminants and CO_2 dispersion of the exhaled air [41–43]. More specifically, the breathing flow is related to individuals' physical features, such as age (respiratory rate and tidal volume), metabolic conditions (activity patterns), the posture of the head, and geometry of the face (particularly nose and mouth), etc. The free convective flow around the body is affected by body heat generation, body posture, body shape, clothing, ambient air temperature, etc. Ventilation flow depends on room ventilation modes and thermal conditions [40,44,45]. All the aforementioned factors will make personal exposure and CO_2 dispersion different from person to person, especially in indoor environment settings with occupants' various activities [44,45].

In previous studies, Pantelic et al. [45] measured the metabolic CO_2 concentrations in the inhalation zone of 41 subjects sitting in a typical office environment. They found that the median CO_2 inhalation zone concentrations were between 200 and 500 ppm above the room-level concentrations, which confirmed that room-level CO_2 concentrations could not be regarded as those in the inhalation zone. In practice, it is not possible to control the breathing mode of a person or perform measurements in the inhalation zone, as sensors placed in front of the mouth and nose will hinder the occupants' activities. Therefore, the use of a breathing thermal manikin for studying personal exposure in the breathing zone can enable to study the effect of different environment settings by the control variable method. For example, Melikov and Markov [46] used a breathing thermal manikin to measure the CO_2 levels in the inhaled air in a meeting room with mixing air ventilation mode. They reported the inhaled CO_2 concentration to be 255 ppm

higher than the room exhaust air. Kiera et al. [42] utilized a breathing thermal manikin to simulate a room occupant in a seated mode using two types of tracer gases, that is, CO_2 and N_2O, released at armpits and groin to simulate bio-effluents. Their findings revealed that obtaining an accurate exposure assessment in the inhalation zone required measurements to be performed during the inhalation period, which was re-confirmed by the study of Kierat et al. [44]. Instead of an experimental study, recently, Kuga et al. [40] used steady-state computational fluid dynamic (CFD) and a computationally simulated person to quantitatively identify the breathing zone for various postures (standing, sitting, and supinate positions) and breathing conditions in transient conditions. They highlighted that the human body's thermal plume strongly influenced the breathing zone formation. In general, there is scanty information about the human exhalation and inhalation in literature, as stated by Xu et al. [47] and Melikov and Kaczmarczyk [48]. To the extent of our knowledge, there is no available study about the ventilation conditions in the breathing zone of a sleeping baby inside a semi-enclosed baby bed.

The objective of this study, therefore, is to understand how bed-level ventilation conditions are affected by its parameters, such as the room-level ventilation rates, and CO_2 source characteristics (including baby age and sleep position). More specifically, the aim is to investigate the effect of different room ventilation rates, baby ages, and sleep positions on personal exposure and CO_2 dispersion within the sleep microenvironment inside a semi-enclosed baby bed. In terms of novelty, this study is the first, in a full-scale setup, to research the bed-level ventilation conditions in the bedroom of Dutch daycare centers under a controlled indoor environment. For the research, a baby model with the respiratory system and thermal simulation was designed to study the personal exposure and CO_2 dispersion in the sleep microenvironment within a typical semi-enclosed baby bed.

2. Methodology

2.1. Field research

In light of the infeasibility of performing measurements and experiments inside baby beds in actual DCCs, a full-scale setup, representing the real situation as much as possible, is regarded an effective alternative. In order to design a representative experimental situation, a field survey was performed in Dutch DCCs in April and May of 2022 to obtain a true picture of bedroom characteristics and occupant information in DCCs. The study was approved by the Ethical Review Board of the Eindhoven University of Technology before the field survey (reference No. ERB2020BE8).

The results from the field study were used as input to the full-scale laboratory setup (see Section 2.2) and the experimental conditions (see Section 2.5). In terms of bedroom information, the mean area per baby is 1.5 m^2 with a range of 0.8–2.8 m^2; the mean room height is 2.6 m with a range of 2.2–5.3 m; the mean bed number per bedroom is 3.5 with the range of 2–12 beds. There are 3 typical bed layouts in the bedroom, including bilateral layout (38%), unilateral layout (40%), and right-angle layout (19%). Regarding ventilation information, 41% and 59% of bedrooms were equipped with natural and mechanical ventilation, respectively. Among the 40 bedrooms with mechanical ventilation systems, 25 bedrooms (62.5%) met the requirement of the Dutch Building Code [49], with an average airflow rate of 17.3 m^3/h per person (range: 2.0–42.9 m^3/h per person).

In terms of baby information, DCCs normally divide young children into two groups by age: one is called the baby group with the age of 7 weeks to 2 years old; another one is called the toddler group with the age of 2–4 years old. These two groups of babies have different sleeping habits and durations, according to the feedback of most pedagogical staff. For the baby group, babies sleep multiple times per day, with a total duration of 3–5 h which varied greatly across individuals. For the toddler group, they sleep relatively shorter and more regularly, with

1–2 h per day. For this reason, normally, DCCs provide separate bedrooms for the two groups.

2.2. Full-scale bedroom setup

All experiments were conducted in a full-scale bedroom setup, which was built based on the results of the field survey, as follows:

(a) As shown in Fig. 1a and b, the bedroom had a dimension of L*W*H (4.2*2.7*2.5 m).
(b) In the bedroom, there were six baby bunk beds that were purchased from one of the investigated Dutch DCCs.
(c) Each bed was equipped with a mattress (POLYCLEAN baby mattress), all of which were used mattresses provided by one of the investigated DCCs.
(d) The 6 baby bunk beds (12 beds; 0.95 m^2 floor area per baby) were placed in a bilateral layout, a common layout in Dutch DCCs.
(e) The bedroom was equipped with a mechanical ventilation system which can be adjusted for the ventilation rate. A mixing air distribution, the most common ventilation mode in bedrooms of Dutch DCCs, was created in the bedroom by installing ceiling-mounted perforated type air supply and exhaust diffusers (face size: 600mmx600mm), both of which were symmetrically positioned in the space above the corridor.

Concerning the bedroom construction, plastic films, combined with wooden frames, were used as the materials for envelope enclosure. The envelope enclosure of the bedroom setup was assumed adiabatic, due to the fact that the full-scale setting was built inside a well-controlled climate chamber. The bedroom was well airtight, with an infiltration air exchange rate (AER) of 0.1/h, measured by an Innova instrument using Sulphur Hexafluoride (SF$_6$) tracer gas (see Section 2.4).

2.3. Baby model

A baby mock-up with heat generation and respiration, called a breathing thermal baby model (BTBM), was designed to simulate a baby body sleeping inside the bed, and its related airflows, namely, breathing flow and free convective flow [50]. The BTBM used in the experiments resembled a baby aged 12 and 30 months, though with equivalent body and head size and shape. The difference was found in the breathing flow rate. The thermal simulation was realized by wrapping the baby's torso with an electric heating layer, which was controlled by adjusting the supply voltage and current. The heat generated by the electric heating layer was 45 W/m^2, similar to the mean sleeping metabolic rate of infants and toddlers [51,52]. Consequently, as shown in the infrared

image (taken by the infrared camera: ThermaCAM™ S65) of Fig. 2, the steady-state surface temperature in the baby trunk part of the BTBM was around 36.5 °C, which was consistent with the results of the study [53] for the skin temperature of 3–24 months old toddlers in an asleep status.

The breathing simulation of the BTBM contained two systems, i.e., the inhalation system and the exhalation system. Both functioned independently and alternately at intervals controlled by a digital timer through switching two electric two-way valves. Both systems were set to provide the same amount of air volume for the tidal volume, which is the air volume exhaled or inhaled in each normal breath. The BTBM exhaled through the mouth and inhaled through the nose. The size and shape of both the mouth and nose openings were simplified to a polytetrafluoroethylene (PTFE) tube with a diameter of 1 cm. The exhalation system is represented in Fig. 2 by the blue colored lines. Depending on the age of the baby, the specific amount of air was supplied by mixing pure CO_2 gas with compressed air, each controlled by an independent mass flow controller (MFC) (Model 5850S, Brooks® Instrument; Model EF-203AV, Bronkhorst® High-Tech B.V.). To ensure complete mixing, the supplied air was fed through a three-way valve into a stainless steel sealed mixing tank. Two different brands of CO_2 sensors, i.e., Innova and SBA (for the specifications, see Section 2.4), were used prior to each experiment to ensure that the CO_2 concentration in the provided air was stable at ca. 50,000 ppm [44], which is also stated in ISO 8996:2021 [54]. Ultimately, the supplied air was delivered to the BTBM mouth and released as an exhaled jet, which was tilted 70º toward the chest when
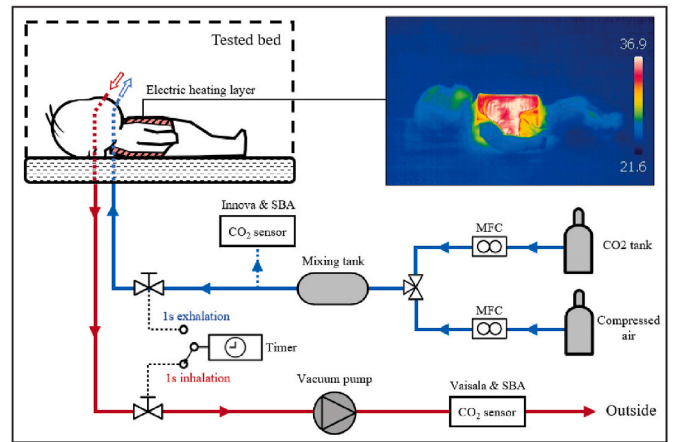

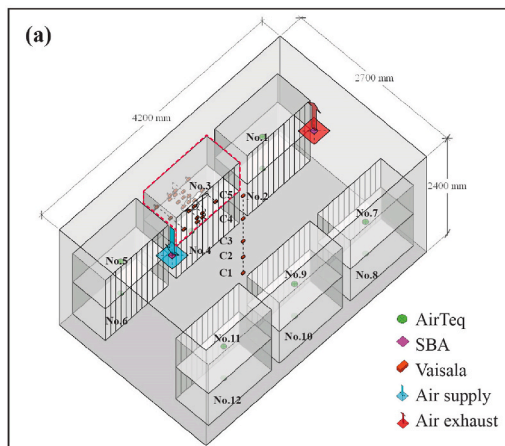**Fig. 2.** A schematic of the thermal and breathing simulation system of a baby model (BTBM).

Fig. 1. Experimental setup. **(a)** Axonometric schematic of the full-scale bedroom, including 12 beds (from No.1 to No.12) and sensor placement. **(b)** A picture of the on-site bedroom.

the BTBM was in a sleeping position. Due to practical restrictions, the exhalation air was untreated and assumed at ambient temperature. The inhalation system is indicated by the red colored lines in Fig. 2. The air was inhaled through the tip of the nose, which was inclined toward the chest at 70° from a horizontal plane. The inhalation was controlled by a pump. Notably, in order to ensure an accurate measurement of the inhaled CO_2 values, two CO_2 sensors, i.e., Vaisala and SBA (for the specifications, see Section 2.4), were used together to continually measure the CO_2 concentration of the inhaled air. Both sensors were able to measure the CO_2 concentration of every air stream of inhalation in real time before it was discharged into the ambient air.

In this study, a simulation of the respiration of two different ages (12 and 30 months old) was performed (see Section 2.5). The median respiratory rates of babies aged from 12 to 30 months old range from 36 to 28 breaths per minute [55]. The respiratory rate was set to 30 breathing cycles per minute for both ages due to the fact that the available digital timer could only be set to the minimum interval of 1 s. Each cycle was composed of two phases: 1-s inhalation and 1-s exhalation. The tidal volume was set at 61 ml and 123 ml for a 12-month-old and 30-month-old baby, respectively [56].

2.4. Instrumentation's specifications and placement

To characterize the bed-level and room-level ventilation conditions, two performance indicators were characterized in the bed and room level: air velocity and CO_2 concentration. The measurements of air velocity were mainly used to identify large velocity variations in the experimental setup. The CO_2 measurements provided insight into the exhaled CO_2 values, inhaled CO_2 levels, and CO_2 dispersion in the bed and room level. In total, ten units of air velocity sensors and 43 units of CO_2 sensors were used and placed in different locations.

Regarding the air velocity instruments, ten units of omnidirectional hot-sphere sensors, namely, AirDistSys 5000 (Sensor Electronic, Gliwice, Poland), were employed. The accuracy of the air velocity instruments was ± 0.02 m/s $\pm 2\%$ of reading in the range of 0.05–5 m/s. In the pre-tests of the study, as shown in Fig. B1 in Appendix B of the Supplementary material, three units of air velocity instruments were placed inside the No.3 bed at the height of 31 cm above the mattress; five units of air velocity instruments were placed in a vertical line in the middle of the room; two units were deployed directly below the supply and exhaust diffusers, respectively.

For the CO_2 sensors, due to the requirement of measurement range, conditions, and accuracy in this study, four types of instruments were utilized:

(a) One unit of Photoacoustic Gas Monitor (INNOVA 1512, LumaSense Technologies A/S, Ballerup, Denmark) in conjunction with a Multipoint Sampler and Dozer (INNOVA 1403, LumaSense Technologies A/S, Ballerup, Denmark) [57] was used. Hereafter, this instrument is named *Innova* for short. The accuracy of Innova was reported as $\pm 1.5\%$ of the measurement. As shown in Fig. 2, the Innova was used, at a ca. 42-second interval when being set to the one channel mode, to examine if the CO_2 concentration in the designed exhaled air was 50,000 ppm before each experiment. Besides, the Innova was also used by dosing and sampling SF_6 gas (constant concentration), combined with two mechanical fans insides, to test the real-time air exchange rate before the experiments, including no ventilation (only infiltration), 55 m³/h, and 250 m³/h ventilation rate.

(b) Four units of SBA-5 CO_2 gas analyzer (PP Systems, Amesbury, USA) [58], abbreviated as *SBA*, were employed. The accuracy of SBA sensors was stated as within 1% of span concentration over calibrated range (0–100000 ppm). SBA has a built-in pump with a gas flow rate of 500 cc/min. The sampling rate of SBA was 10 Hz and had a 1-s output. As shown in Fig. 2, one unit of SBA was used to detect if the CO_2 concentration in the designed exhaled air was

50,000 ppm prior to each case; one unit of SBA was employed to measure the CO_2 concentration in the inhaled air throughout the experiments; As shown in Fig. 1a, the other two units of SBA were placed in the bedroom supply and exhaust air duct to continuously monitor the CO_2 levels in the supply (background) and exhaust air during the experiments.

(c) 29 units of Vaisala Carbon Dioxide Probe GMP252 (Vaisala Oyj, Helsinki, Finland) were used, and this instrument is referred to as *Vaisala.* The accuracy of Vaisala was documented as ± 40 ppm in the range of 0–3000 ppm, $\pm 2\%$ of reading in the range of 3000–10000 ppm, and $\pm 3.5\%$ of reading in the range of 10,000–30,000 ppm. In this study, the Vaisala took measurements every 1 s. As shown in Fig. 1a, five units of Vaisala sensors (C1, C2, C3, C4, C5) were placed in a vertical line in the middle of the corridor of the room, located in front of the No.3 bed. These five units were deployed at different vertical heights above the floor: 38 cm (C1), 78 cm (C2), 118 cm (C3, corresponding to the height of a selection of CO_2 sensors placed inside the upper beds), 175 cm (C4), and 233 cm (C5). As shown in Fig. 2, One unit of Vaisala, together with one unit of SBA (SBA2), was used to measure the CO_2 concentration in the inhaled air throughout the experiments. In order to get a comprehensive understanding of the CO_2 concentration distribution in the sleeping microenvironment inside the bed, the other 23 units of Vaisala were placed inside the No.3 bed. As shown in Fig. 3a and b, and Fig. 3c, the Vaisala CO_2 sensors network was centered around the BTBM's mouth and distributed in four sections inside the No.3 bed.

(d) 11 units of AirTeq Pro Aero (AirTeq, the Netherlands), called below as *AirTeq* for short, were utilized. The AirTeq monitor integrated the Sensirion SCD41 CO_2 sensor, and its accuracy and stability was confirmed in our previous study [3], with an accuracy of $\pm(40$ ppm + 5% of reading) in the range of 400–5000 ppm. The AirTeq recorded data at a 1-min interval during the measurement. As shown in Fig. 1a, each AirTeq sensor was placed in the center of all the beds except for the No.3 bed.

All the CO_2 sensors were factory-calibrated before the study to ensure they complied with the corresponding specifications. Additionally, Vaisala sensors were laboratory-calibrated by using two-point calibration (500 ppm and 2000 ppm standard CO_2 calibration gas) right before the experiments. The results of two-point calibration reported an accuracy of ± 5 ppm at two standard CO_2 gas concentrations (500 ppm and 2000 ppm). In the end, cross-calibration among all of the CO_2 sensors was performed to ensure that the CO_2 measurements by these four different instruments were consistent. For that, they were all placed in the center of an airtight room where two mechanical fans facing the wall side were turned on at low speed to enhance the homogeneous distribution of indoor air. A mixture of CO_2 gas was injected into the room at a low dosing rate (0.175 L/min) lasting for 6 h, and then the CO_2 concentration was maintained at ca. 2000 ppm for half an hour, followed by a slow decay (lasting for 15 h) of the CO_2 concentration until it dropped to the background level. The results showed that all the sensors agreed within 50 ppm, which was in line with their reported specifications. Therefore, in this study, we considered the CO_2 measurement to have an uncertainty of 50 ppm.

2.5. Experimental conditions

Three factors influencing the microenvironment were included in this study:

(a) Baby age (12-month-old and 30-month-old), expressed in a different breathing flow rate. The ages refer to the two groups identified in Dutch DCCs, namely, infants (7 weeks-2 years) and toddlers (2–4 years), as shown in Section 2.1.
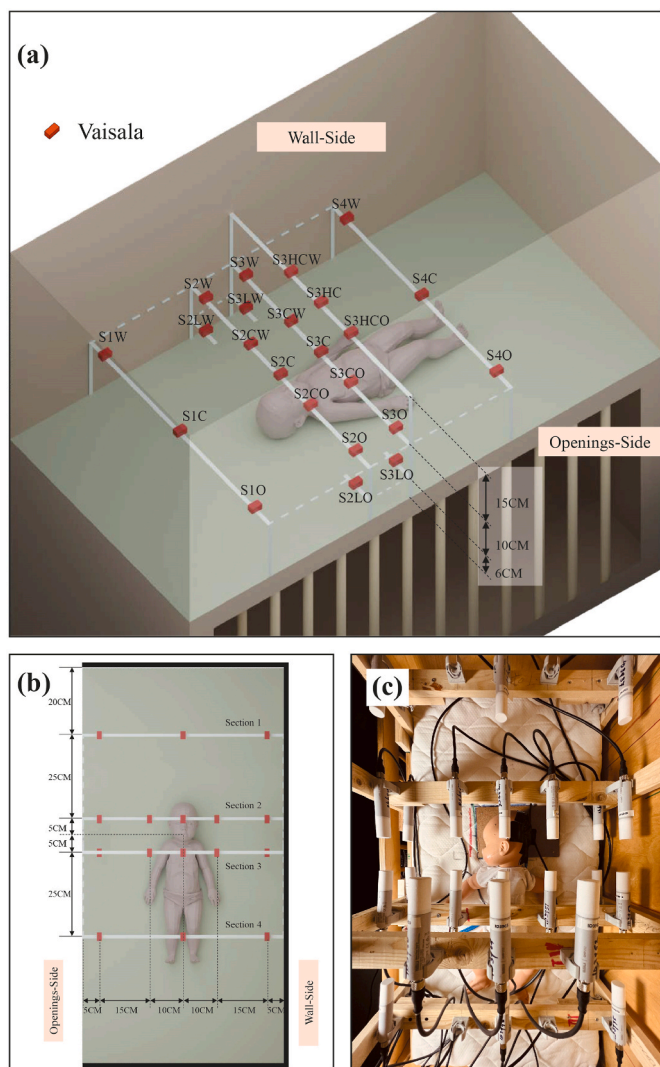
Fig. 3. The placement of sensors inside the No.3 bed. **(a)** An axonometric schematic of the No.3 bed with the sensors inside. **(b)** The top view of the schematic of the No.3 bed. **(c)** An on-site (top-down) photo of the setup inside the No.3 bed where the baby model was sleeping in the lateral-to-corridor position and Vaisala sensors were placed inside.

(b) Sleep position (supine, lateral-to-corridor, and lateral-to-wall), all of which are common sleep positions of young children according to the feedback from the pedagogical staff during the field survey (see Section 2.1).

(c) Room ventilation rate (55 m³/h [15 l/s] and 250 m³/h [70 l/s]), corresponding to a bedroom air exchange rate of 2.0 h⁻¹ and 9.3 h⁻¹, respectively. The selection of 55 m³/h was based on the suggestions from the Dutch Building Code [49] and ANSI/ASHRAE 62.1–2019 [59] when one person occupies the bedroom. For the selection of 250 m³/h, it was intended to investigate the effect of a high ventilation rate on the bed-level microenvironment, and compare this with the case at 55 m³/h. The temperature and relative humidity of the supplied air was in the range of 21–22 °C and 40%–60% throughout the experiments, respectively.

As shown in Table 1, a total of 12 cases were investigated, combining the setting for the three parameters discussed above. Among them, eight combinations (cases) were repeated once to examine the experimental reproductivity. Assessment of the case reproductivity was not conducted consecutively but at intervals.

Additionally, to provide insight into the air velocity field, pre-tests

Table 1

Overview of the experiments (cases) performed. Run times indicate whether the same case was conducted only once or twice. Both ventilation rates in this study are set for one baby occupying one bed in the room.

Case (No.) name	Sleep positions	Baby ages	Ventilation rates	Duration/ case (ca.)	Run times
(F01) Supine-30m-55	Supine	30 months	55 m³/h	2 h	2
(F02) Supine-30m-250	Supine	30 months	250 m³/h	1 h	2
(F03) Supine-12m-55	Supine	12 months	55 m³/h	2 h	1
(F04) Supine-12m-250	Supine	12 months	250 m³/h	1 h	1
(F05) LCorridor-30m-55	Lateral-to-corridor	30 months	55 m³/h	2 h	2
(F06) LCorridor-30m-250	Lateral-to-corridor	30 months	250 m³/h	1 h	2
(F07) LCorridor-12m-55	Lateral-to-corridor	12 months	55 m³/h	2 h	2
(F08) LCorridor-12m-250	Lateral-to-corridor	12 months	250 m³/h	1 h	2
(F09) LWall-30m-55	Lateral-to-wall	30 months	55 m³/h	2 h	2
(F10) LWall-30m-250	Lateral-to-wall	30 months	250 m³/h	1 h	2
(F11) LWall-12m-55	Lateral-to-wall	12 months	55 m³/h	2 h	1
(F12) LWall-12m-250	Lateral-to-wall	12 months	250 m³/h	1 h	1

were conducted right before the formal experiments (cases). The pre-tests focused on the air velocity at the ventilation inlet and outlet, in the room corridor, and inside the No.3 bed. The performed pre-tests are shown in Tab. B1 in Appendix B of the Supplementary material. The results (see Tab. B2) showed that the velocity in the room corridor and the bed generally was below the measurement range of the sensors (0.05 m/s). Apart from that, the mean air velocity in the inlet and outlet was 0.14 m/s and 0.13 m/s under the conditions at the ventilation rate of 55 m³/h, and 0.29 m/s and 0.31 m/s at the ventilation rate of 250 m³/h, respectively, as shown in Fig. B2.

2.6. Experiment procedure

Before each case, all the instruments used were placed in the predetermined locations, as shown in Figs. 1 and 3, and they were ensured to function properly. The baby's sleep position, respiration rate, tidal volume, and room ventilation rate were configured accordingly prior to each case. The duration of each case was well commissioned to ensure a steady state for the CO₂ dispersion or air velocity conditions inside. To be more specific, for the formal cases (see Table 1) at the room ventilation rate of 55 m³/h and 250 m³/h, the duration was about 2 h and 1 h, respectively. The specific method for assessing equilibrium is presented in Section 2.7.

2.7. Data processing and analysis

The data processing and analyses were performed via python 3.8.8. For that, the following steps were applied:

(a) Considering the different time intervals of recording data by the used instruments, the measurement results of all sensors were converted into 1-min average values by the Resample method (pandas.DataFrame.resample.mean) to align all the data.

(b) The results collected from all sensors at 1-min interval of the final 10 min in each case were analyzed by comparing them with each

other. One-way ANOVA was used to determine whether they had reached a steady state. The statistical significance was set at 0.05 as the threshold value.

(c) If cases had achieved equilibrium, the experimental replicability between two repeated cases was examined by (i) first averaging the 10-min results at equilibrium for each sensor used in each case, producing one dataset per case; (ii) and then using paired samples *t*-test to compare the differences between two datasets (two repeated cases).

(d) For the repeated cases that met the threshold of reproductivity, the average was taken between two repeated cases for each sensor. As a result, a total of 12 cases were obtained (see Table 1). Then, in order to exclude the influence of the supply (background) CO_2 concentration to better compare the differences among different cases, CO_2 concentrations reported by sensors were subtracted by the corresponding CO_2 values in the room supply air. In the end, these results (above the background level) were the main focus of this study.

(e) The descriptive statistics, namely, mean and standard deviation, were used and visualized by line charts and histograms to analyze the 10-min mean CO_2 values of different sensors under the equilibrium state for each case.

(f) To get a better understanding of CO_2 dispersion inside the sleeping microenvironment, all the 10-min mean values of CO_2 sensors inside the No.3 bed were visualized by using CO_2 concentration bubbles [60], rendered by Blender software [61].

(g) One-way ANOVA was used to compare the difference in CO_2 distribution among cases under 3 sleep positions, and the Bonferroni post-hoc tests was conducted to determine whether CO_2 distribution in each two sleep positions differed when the significant differences were observed. When comparing the difference in mean CO_2 values between cases under two ventilation rates, or with two different ages, the paired samples *t*-test was used, with p < 0.05 as the significance threshold.

3. Results

3.1. General results

Concerning the assessment of whether a steady state has been achieved in each case, all of the one-way ANOVA tests reported statistically insignificant differences (p-value >0.05) in results (CO_2 concentration) among the last 10-min measurements. Therefore, it was regarded that all cases had achieved a steady state in the last 10 min, at which point data was retrieved for the further analyses.

In terms of the case reproductivity test, as shown in Tab. A1, the results of paired samples t-tests indicated insignificant differences in mean values between most repeated cases. Only two cases (F02, F06) reported a statistically significant difference in CO_2 concentrations. A further analysis was conducted to examine the absolute difference in CO_2 concentration between two repeated cases for each sensor. The results (see Fig. A2) demonstrated that the median values of CO_2 differences in these two cases (F02, F06) were less than 50 ppm (the uncertainty of CO_2 measurements). Consequently, it was concluded that good experimental reproducibility was achieved, and thus the results of repeated cases were converted into one case by averaging the data of each sensor, as mentioned in Section 2.7.

With regard to CO_2 concentration in the air supply during 12 cases, the average background CO_2 concentration was 393 ppm, with a small mean standard deviation (1 ppm) among all cases, which means CO_2 levels in the background hardly changed. More details are illustrated in Tab. A2 in the Supplementary material.

In this study, as shown in Fig. 2, the inhaled CO_2 concentration was measured by two different types of CO_2 sensors, i.e., one Vaisala and one SBA, during 12 cases. The absolute differences (median: 28 ppm) in measured CO_2 concentration between these two sensors in all cases was less than 50 ppm (the uncertainty of CO_2 measurements), as illustrated in Fig. A3. Therefore, the average of these two sensors was used to indicate the inhaled CO_2 concentration in this study.

3.2. CO_2 dispersion at room level and other 11 beds

Based on the results in Section 3.1, it was concluded that all 12 cases have reached a steady state. Therefore, the subsequent analysis of the impact of experimental variables (room ventilation rate, age, sleep position) is based on the average CO_2 value of the 10-min results of each sensor at equilibrium for each case. Additionally, the time-series plots of the monitored CO_2 concentration (in-bed spots, inhalation, and the difference between air inlet and exhaust) for all cases have been added to the Supplementary materials (see Fig. A8 to Fig. A27).

Fig. 4 plots the CO_2 dispersion in the corridor (at 5 different heights) of the room center and inside 11 beds for the 12 cases investigated. Five observations based on this figure are presented below:

(a) Overall, sensors in room level reported relatively low CO_2 concentration, with a mean value of 107 ppm above the background level among all cases.

(b) The average CO_2 values of all room-level and 11 in-bed sensors measured at the higher room ventilation rates (250 m^3/h) were lower than those measured at the lower rates (55 m^3/h) for the same sleeping position and age conditions, with a mean difference of 70 ppm for each point.

(c) Under the same conditions of ventilation rate and age, similar CO_2 concentrations at each point (at room level and inside 11 beds) among 3 different sleep positions were reported, with a low mean standard deviation of 14 ppm among all cases.

(d) Slightly higher CO_2 levels were observed in cases with an older baby (30 months) than a younger baby (12 months) when the conditions of room ventilation rates were the same.

(e) In addition, among five points in a vertical height in the center of the room, for each case, the sensor at the lowest point (C1) recorded the lowest CO_2 concentration while the sensor at the highest point (C5) measured the highest values.

3.3. Bed-level CO_2 spatial distribution

Fig. 5 presents five illustrative examples of the CO_2 spatial distribution at bed level (all results are shown in Fig. A4, and Fig. A5). Based on Fig. 5a, b, and Fig. 5c, the CO_2 distribution can be visually compared in 3 different sleep positions (supine & lateral-to-corridor & lateral-to-wall position) for the same baby age (30 months) and room ventilation rate (55 m^3/h). Combined Fig. 5a with Fig. 5d, the difference in CO_2 distribution in two different ventilation rates (55 & 250 m^3/h) can be compared under the same baby age (30 months) and sleep position (supine). Similarly, both Fig. 5a and e depict the difference in CO_2 distribution for two different baby ages (12 & 30 months) under the same room ventilation rate (55 m^3/h) and sleep position (supine). Last but not least, Fig. 5f integrates the results of all CO_2 distribution for the above five cases. Five features of Fig. 5 that are generally true for most tested cases are highlighted, as follows:

(a) Across three different sleep positions, a relatively high CO_2 concentration (up to 7996 ppm, see Fig. 5c) was reported in the point through which the exhaled airstream passed. To be more specific, these locations inside the No.3 bed included three points (S3C, S3HC, S3HCW, see Fig. 3a for detailed placement) for the supine position, two points (S2LO, S3LO) for the lateral-to-corridor position, and two points (S2LW, S3LW) for the lateral-to-wall position. In the subsequent analysis, the results of these aforementioned spatial points in the specific sleep positions were excluded, considering that these measurements almost were the direct CO_2 concentration of the exhaled air stream, which can
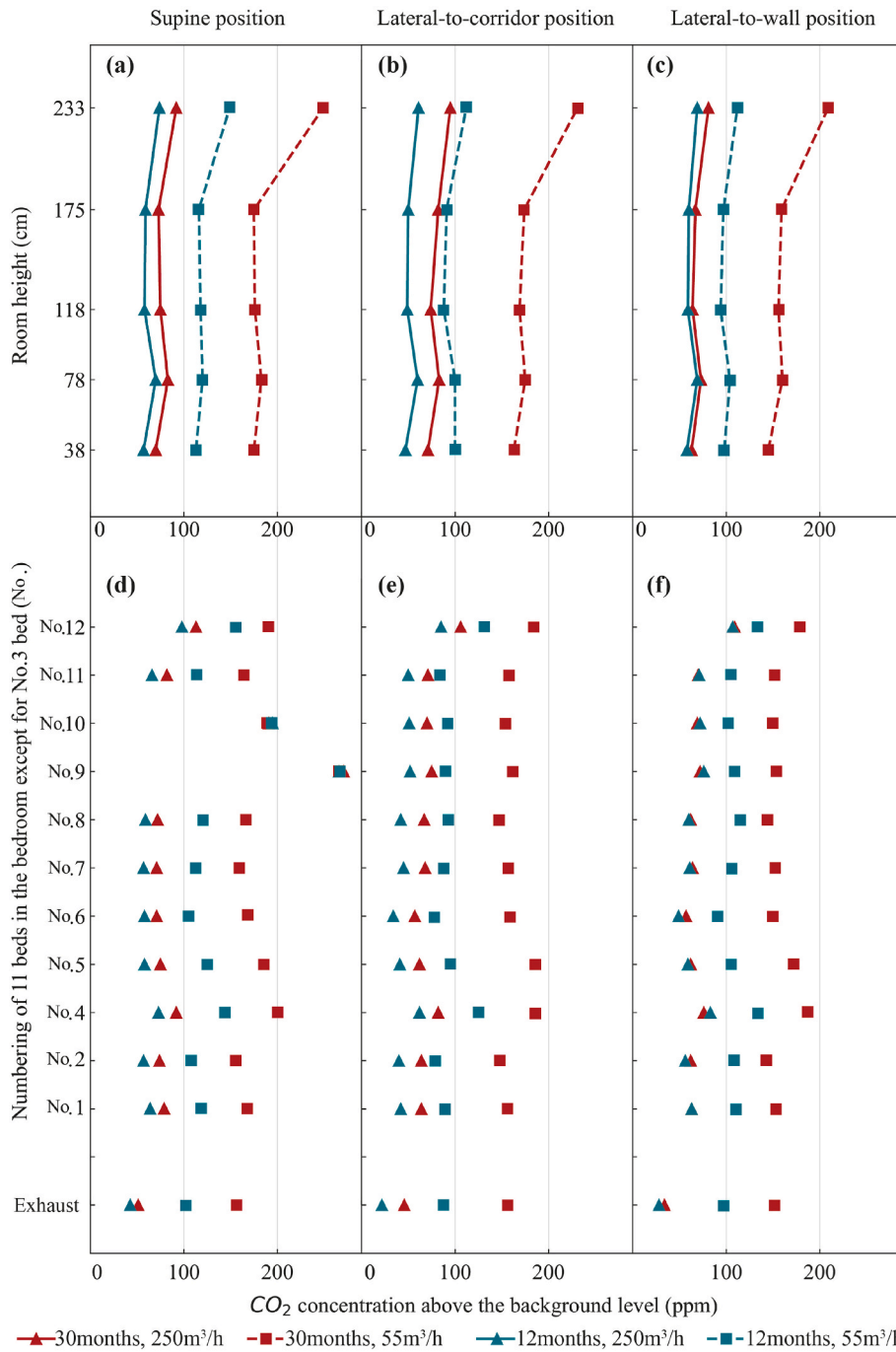
Fig. 4. Measured mean CO_2 concentration above the background level at room level (corridor at 5 different heights, exhaust air) and inside 11 beds (except for the No.3 bed) in 12 cases. Each subplot contains four cases under the same sleep position. For example, **(d)** shows the CO_2 levels in four cases [(Supine-30m-250), (Supine-30m-55), (Supine-12m-250), and (Supine-12m-55)].

distort the final insight and interpretation of the CO_2 dispersion inside the bed. The difference in mean in-bed CO_2 concentration with and without removing some of the sensors for each case is shown in Fig. A6.

(b) All the sensors placed inside the No.3 bed detected at least 50 ppm higher CO_2 concentration levels above the background level in five cases (see Fig. 5a–e), with mean CO_2 values of all the in-bed sensors, apart from the sensors excluded as described in **(a)**, being up to 495 ppm above the background level in a case (see Fig. 5b), and with a standard deviation of mean CO_2 values of all in-bed sensors being up to 294 ppm in a case (see Fig. 5c). Among the five cases presented in Fig. 5, mean CO_2 concentration

in the wall-side space of the No.3 bed (S1W, S2W, S2LW, S3W, S3LW, S4W) was 124 ppm higher than that in the openings-side space of the No.3 bed (S1O, S2O, S2LO, S3O, S3LO, S4O), with a difference being up to 453 ppm in the case LWall-30m-55 (see Fig. 5c).

(c) A statistically significant difference in CO_2 spatial distribution inside the No.3 bed among three different sleep positions (F (2, 59) = 8.34], p < 0.001) was found, by performing a one-way ANOVA analysis among the cases of Fig. 5a, b and c. The Bonferroni post-hoc tests for multiple comparisons found that the mean value of CO_2 concentration was significantly different between supine and lateral-to-corridor positions (p = 0.000) and
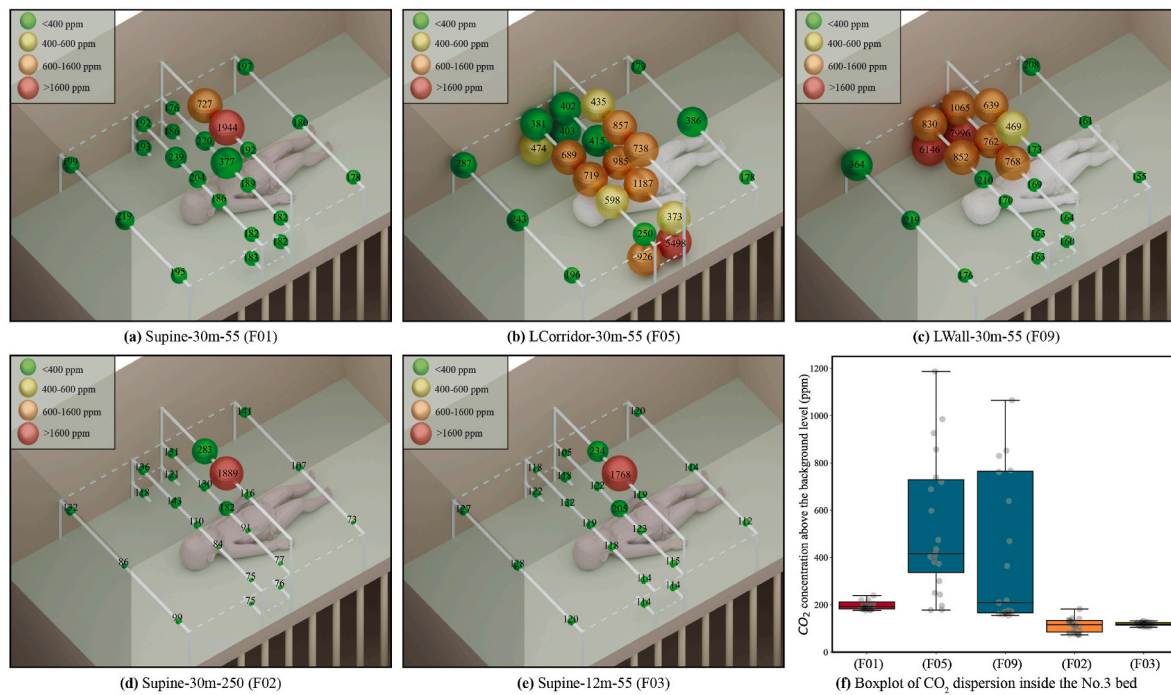
Fig. 5. CO_2 dispersion (values above the background level) inside the No.3 bed under five combinations (cases) of experimental conditions. **(a)** Supine-30m-55; **(b)** LCorridor-30m-55; **(c)** LWall-30m-55; **(d)** Supine-30m-55; **(e)** Supine-12m-55; **(f)** A boxplot of CO_2 values inside the No.3 bed, where outliers were not illustrated for better visualization. The legends in the five subplots [**(a)**–**(e)**] have the same scale. Specifically, there are four colors of bubbles in each legend, corresponding to four different CO_2 levels above the background level: green, yellow, orange, and red colored bubbles indicate CO_2 concentration ranging from 0 to 400 ppm, 400–600 ppm, 600–1600 ppm, and >1600 ppm, respectively. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

between supine and lateral-to-wall position (p = 0.041). For the lateral-to-corridor and lateral-to-wall sleep position, the difference was not significant (p = 0.4). However, the difference in mean CO_2 concentration between these two sleeping positions was 112 ppm, which is more than the uncertainty of CO_2 measurement (50 ppm). In addition, Fig. 5f shows a much larger variety of CO_2 concentration in these two conditions [SD = 276 ppm for the lateral-to-corridor position (F05), SD = 301 ppm for the lateral-to-wall position (F09)] compared to the case "supine-30-55 (F01)" (SD = 16 ppm).

(d) Both Fig. 5a and d show a similar CO_2 distribution pattern under the same sleep position (supine), though there was a statistically significant difference in mean CO_2 concentration [t (19) = 17.48 (p = 0.000)] between the case at the room ventilation rate of 55 m^3/h (M = 194 ppm, SD = 16 ppm) and the case at the room ventilation rate of 250 m^3/h (M = 106 ppm, SD = 25 ppm) by using a paired samples *t*-test analysis.

(e) There was a statistically significant difference in mean CO_2 concentrations [paired samples *t*-test, t (19) = 29.252, p = 0.000] between the cases with a BTBM aged 30 months (M = 194 ppm, SD = 16 ppm) and the cases with a BTBM aged 12 months (M = 119 ppm, SD = 20 ppm), which corresponds to Fig. 5a and e.

3.4. Inhalation, bed-level, and room-level CO_2 concentration

Fig. 6 shows mean CO_2 values above the background level for inhalation, bed level, room center, and exhaust air from the 12 cases. For the mean CO_2 values at bed level, sensors directly facing the exhaled airstream were excluded from the dataset that consists of the mean CO_2 values of each sensor in each case (see Fig. A6), as mentioned in Section 3.3. The error bars present the standard deviation across the mean values of each sensor selected in a case. For the CO_2 concentration at room level, results of the sensor (C3) at a height of 118 cm in the

corridor are presented in Fig. 6, taking into account that this sensor was located directly in front of the No.3 bed (centrally in the room), which is in compliance with the CO_2 measurement protocol from ISO16000-26 [62] and ANSI/ASHRAE 62.1–2019 [59]. Five main aspects that are generally applicable to most cases in Fig. 6 are pointed out as follows:

(a) The inhaled CO_2 concentration in all cases was the highest among all the measured locations, with a mean positive difference in the CO_2 value of 1010 ppm, 1150 ppm, and 1165 ppm, relative to the bed level, the room center, and the exhaust air, respectively. Across all cases, the inhaled CO_2 concentration inside a semi-closed baby bed is, on average, three times higher than the CO_2 concentration in the exhaust, with one case even being up to 10 times higher than the value in exhaust air (see Fig. 6f).

(b) Across all cases under three sleep positions, the highest mean inhaled CO_2 concentration was found in lateral-to-wall sleep positions (2243 ppm above the background level), followed by the lateral-to-corridor positions (1039 ppm), and the supine sleep positions (462 ppm). In particular, in two cases (LWall-30m-55, LWall-30m-250), inhaled CO_2 levels were as high as 3971 ppm and 3910 ppm above the background level, respectively (see Fig. 6e and f).

(c) There is no statistically significant difference in CO_2 inhalation between cases under two room ventilation rates [paired samples *t*-test, t (5) = −0.997, p = 0.365]. Slightly higher mean CO_2 inhalation was recorded in the cases under the high room ventilation rates (250 m^3/h) as compared to the low room ventilation rate (55 m^3/h), with a mean value of 1336 ppm and 1161 ppm above the background level, respectively.

(d) An apparent difference in mean CO_2 inhalation between cases with different baby ages was found [paired samples *t*-test, t (5) = −2.594, p = 0.049], with a mean value of 475 ppm and 2021 ppm
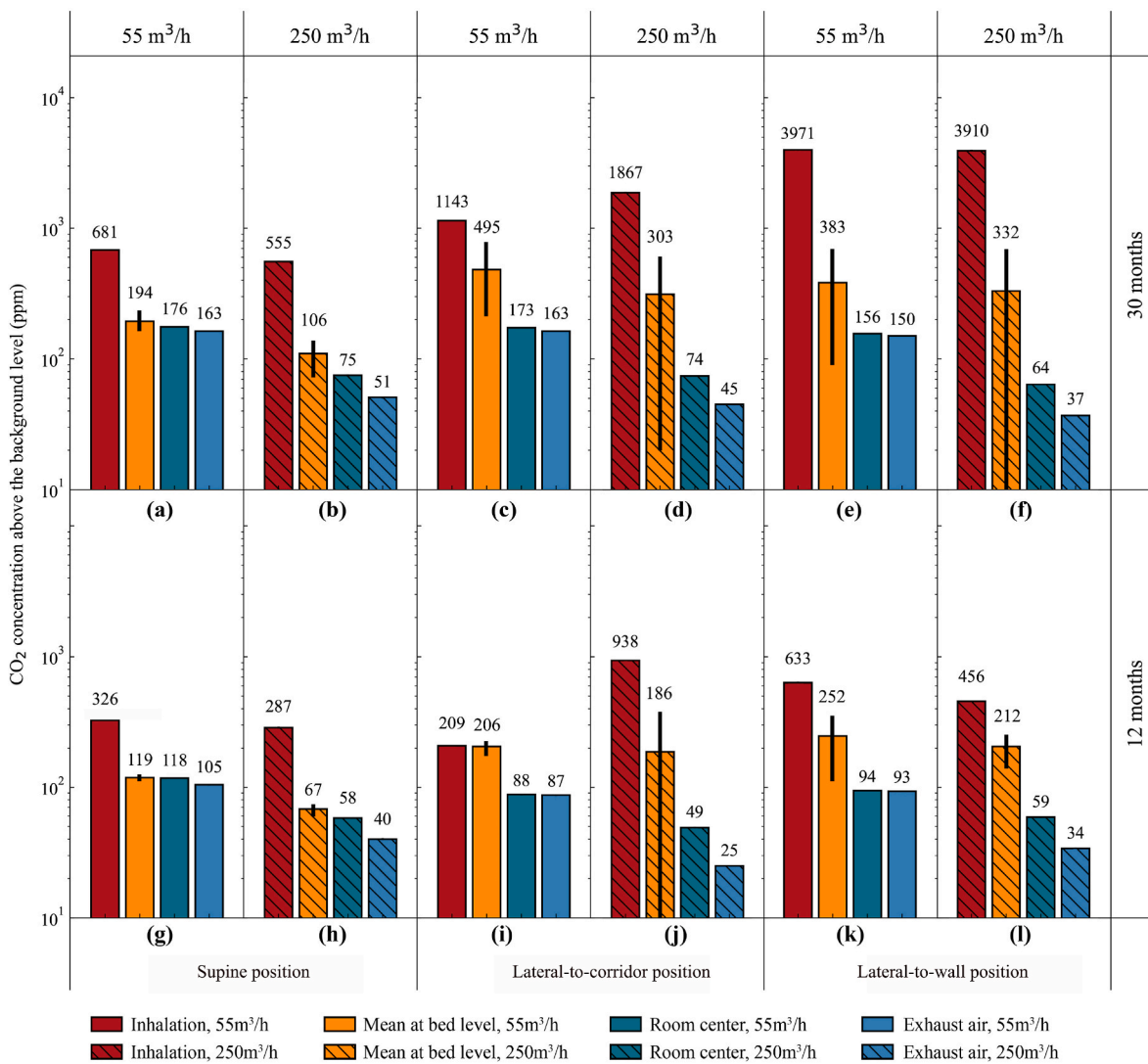
Fig. 6. Mean CO$_2$ concentrations (above the background level) in inhalation, bed level, room center, and exhaust air under 12 combinations of different conditions (ventilation rate [55 m³/h & 250 m³/h], sleep position [lateral-to-wall & supine & lateral-to-corridor], ages [12 months & 30 months]). Y-axis uses a logarithmic scale due to the large difference in CO$_2$ values between inhalation and other locations.

above the background level for the cases with a BTBM aged 12 months and 30 months, respectively.

(e) In addition, among all cases, the mean CO$_2$ values at bed level (sensors directly facing the exhaled air were excluded) were 155 ppm higher than that in the exhaust air, with a statistically significant difference between them [paired samples *t*-test, t (11) = 4.923, p = 0.000]. Although there was a statistically significant difference [t (11) = 5.496, p = 0.000] in mean CO$_2$ values between the corridor sensor (C3) and the air exhaust among 12 cases, both populations mean values were almost the same (98 & 83 ppm).

4. Discussion

4.1. CO$_2$ dispersion from a semi-enclosed baby bed

In this study, the extent to which the emissions constantly generated by a sleeping baby can be removed out of a semi-enclosed baby bed via room-level ventilation was explored. Scenarios that realistically mimic regular bedroom conditions in Dutch daycare centers were used. In order to present a more realistic context with more credibility, three types of variables in our cases were added, including different sleeping

positions, the ages of the baby, and room ventilation flow rates. Results showed that all three factors, i.e., sleep position, ventilation rate, and baby age, significantly affected the CO$_2$ distribution inside the baby bed by using the control variate method. More specifically, the mean CO$_2$ concentration inside the No.3 bed was remarkably high, with a case being up to 495 ppm above the background level (see Section 3.3), and mean CO$_2$ concentration among all cases was higher than that in the exhaust air, in one case by as much as 332 ppm (see Fig. 5c). This demonstrates the existence of excess CO$_2$ concentration inside a semi-enclosed bed while a baby is sleeping. Also, the difference between the concentration of CO$_2$ in the corridor and the exhaust was not significant. It is, therefore, reasonable to state that the air, especially inside a semi-enclosed bed, is not well-mixed under the room-level ventilation. Notably, in the case of a semi-enclosed bed, the CO$_2$ accumulation and inhomogeneity in space appears even higher when compared to other scenarios, such as classroom and office settings [45,60].

4.2. Inhalation exposure to CO$_2$ concentration inside a semi-enclosed baby bed

The CO$_2$ inhalation of a baby sleeping inside the bed was investigated by using a designed breathing system in our study. It was well-

acknowledged that the breathing thermal baby model only has one facial profile geometry and a fixed breathing pattern, while real-life human individuals differ from each other [45,50]. However, in light of the infeasibility of investigating the CO_2 inhalation of a real baby, a BTBM is regarded an effective alternative. According to the results of this study, it is a concern that the concentrations of CO_2 inhaled by infants are very high, on average, 3 times higher than the values in the exhaust air. As CO_2 exhalation rates applied were realistic and well commissioned in the current study, the absolute values are also of interest. The mean inhaled CO_2 concentration was 1647 ppm (absolute values) among all cases, and in two cases (see Fig. 6e and f), the inhaled CO_2 concentration was even more than 4300 ppm (absolute values) when sleeping inside a baby bed. It was found that different sleeping positions had an effect on the CO_2 uptake, with the worst being sleeping in a lateral-to-wall position, which was 1781 ppm higher than a supine position. Unexpectedly, the mean CO_2 inhalation in a lateral-to-corridor position was generally higher than that in a supine position, possibly due to room draft-induced air flow from the corridor toward the face. Furthermore, the airflow may be responsible for the higher CO_2 inhalation at higher ventilation rate (250 m^3/h), compared to the cases at lower ventilation rate (55 m^3/h), especially in the case where the BTBM was positioned in a lateral-to-corridor position (see Fig. 6c and d, i and j). The phenomenon that the personal exposure may, paradoxically, be elevated when multiple airflow interacts in the breathing zone was confirmed by Bivolarova et al. [41]. The current study demonstrated that older babies (30 months) inhaled much more CO_2 than young ones (12 months) due to a higher CO_2 exhalation. The higher tidal volume (from the 30-month-old BTBM) apparently was not able to dilute the exhaled CO_2 sufficiently to arrive at conditions experienced by a 12-month-old baby. In summary, the study shows that CO_2 distribution inside a semi-enclosed baby bed is affected by various factors and highlights the importance of considering personal exposure differences (namely, sleep positions, and infants' ages) when configuring room- and/or bed-level ventilation.

In comparison to other similar studies that investigated the CO_2 inhalation [44,46,63,64] of occupants inside the room, higher levels of CO_2 inhalation inside a semi-enclosed bed were found in the current study. For example, Kierat et al. [44] reported around 1000 ppm CO_2 inhalation in absolute values by using a breathing thermal manikin to simulate an adult in a sitting position in the center of a room. With regard to health outcomes, the impact of CO_2 exposure on human health, comfort, and sleep quality remains a contentious topic in the contemporary scientific literature [65–68]. Delving into the physiological effects of CO_2 on individuals [69], it is important to highlight a study [70] that conducted experiments with human subjects to examine the influence of CO_2 concentrations in inhaled air on CO_2 emission rates. The study discovered that elevated CO_2 concentrations in the inhaled air resulted in a reduction of respiratory excreted CO_2. While existing evidence is limited, it suggests that CO_2 levels below 5000 ppm may have minimal influence on adults' acute health symptoms and physiological outcomes. It is critical to note, however, that current research has not yet explored the implications of high CO_2 concentrations on children, particularly babies and toddlers [65]. Furthermore, several studies [71–73] found, inside the crib, much higher concentrations of adverse chemicals released from beddings, mattresses, and diapers worn by infants, compared to the bulk bedroom air. Combined with these findings, the excess CO_2 inhalation potentially raises a real issue for infants' health. In fact, in contemporary society, there are many scenarios which are similar to the sleeping environment in a semi-enclosed baby bunk bed, such as airport sleeping boxes, train soft sleeper compartments, and capsule hotels. The outcomes, therefore, also indicate a concern about personal exposure to air contaminants in all of these "miniature sleeping spaces" [74].

4.3. Is it possible to assess the inhaled CO_2 concentration by using sensors at fixed locations?

As stated in Section 4.1, the assumption of complete mixing of room air rarely occurs and is usually unevenly distributed. This appears to be exaggerated in bedrooms in DCCs. When CO_2 is used as an indicator of indoor air distribution, it is more reliable to assess the concentration of CO_2 in the air inhaled by occupants by measuring as close as possible to the breathing zone [44]. However, in reality, it is not feasible to take measurements of the inhaled CO_2 of occupants, not even in the vicinity of the breathing zone, especially for infants sleeping inside beds. Based on the results of this study, a further analysis was performed to investigate whether it would be possible to find a proper location where the measured CO_2 concentration is representative for the inhaled CO_2 concentration of a baby sleeping inside the bed. Pearson Correlation Coefficient (ρ) was used to analyze the linear relationship between the CO_2 values measured in the different locations and the inhaled air in the cases under the same sleep positions. Also, the ratio of CO_2 levels measured at a certain point to the inhaled CO_2 levels in each case was computed. Fig. 7 elucidates the qualitative and quantitative relationship between all sensors and inhalation and reinforces several of the results found in the preceding Section 3.4. As shown in Fig. 7, the markers (circle, triangle, or square) with green color indicate a strong correlation under a specific sleep position; the marker close to 1 (X-axis value) means the CO_2 values measured by a sensor are close to the inhaled CO_2 concentration for a specific case.

First, it shows that all the sensors at the room level (C1, C2, C3, C4, C5, Exhaust) do not reliably assess the inhaled CO_2 values. The correlation is weak, and most sensors have quantitative ratios of less than 0.5 to the CO_2 inhalation. Second, all the sensors inside the bed have better correlations with the CO_2 inhalation under the supine sleep position, followed by the lateral-to-corridor position, and the lateral-to-wall position. The third key finding is that there is one sensor (S2CO) that reports a good correlation ($\rho > 0.7$) with the inhaled CO_2 values under all sleep positions, with a ratio higher than 0.5 in most cases. This demonstrates that it is possible to qualitatively assess the inhaled CO_2 concentration by using sensors at fixed locations inside the bed, but not at the room level. But it should be noted that this finding is based on the limited number of cases for which the breathing thermal baby model was used. In reality, various factors such as multiple sleeping positions, different ventilation flows in the room, and individual differences in infants can affect the results.

In comparison to the results of previous studies [44,45,75], for instance, Kierat et al. [44] measured CO_2 concentration at nine locations close to the face of a breathing adult manikin in a sitting position. They found that it would be possible to accurately assess CO_2 exposure by placing sensors at locations, such as, between the center of the chin and the mouth, or at the left (or right) corner of the mouth, or next to and above the nostrils. Similarly, Pantelic [45] tested six different locations close to the face of a subject, and they concluded that the sampling location at 0.5 cm from the tip of the nose would be suitable for measuring CO_2 exposure. This implies that CO_2 measurements at the room level cannot be equivalent to the breathing zone. However, the standard ISO16000-26 [62] states that the sampling location for CO_2 monitoring should be in the center of the room, 1.0–1.5 m above the ground, which can represent the breathing zone of the occupants. Also, ANSI/ASHRAE 62.1–2019 [59] defines the breathing zone as the region within an occupied space between planes (0.75 and 1.8 m) above the floor and more than 0.6 m from the walls or fixed air-conditioning equipment. These inconsistent conclusions raise the need to clarify the definition of the occupants' breathing zone and monitoring protocols in different scenarios whenever using CO_2 concentration as an indicator of outdoor air ventilation rates, perceived air quality, ventilation performance, or infection risks in the future [60,76–79]. Most importantly, the current results demonstrate that all our previous knowledge with respect to CO_2 monitoring, which assumes a high correlation between what we
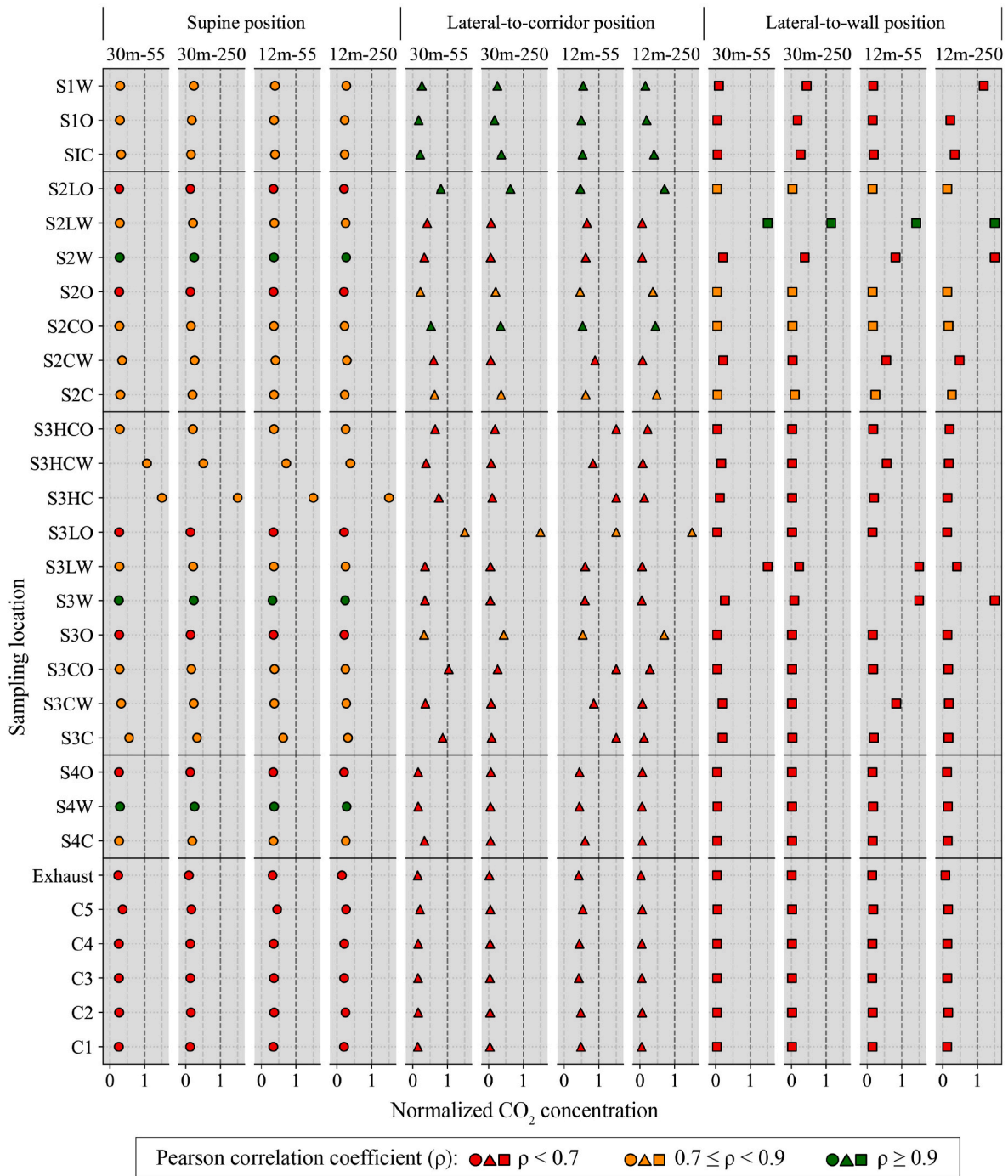
Fig. 7. Correlation of CO_2 concentration measured by all sensors related to CO_2 inhalation under the same sleep position. The Pearson Correlation Coefficient (ρ) of each sensor with the corresponding inhalation value is indicated by the color. The marker identifies the sleep position. The normalized CO_2 concentration is the ratio of CO_2 concentration (above the background level) measured at a certain point to the CO_2 concentration in the inhaled air. A ratio of 1.5 or greater is plotted at 1.5 (X-axis). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

measure in the room and what we inhale, may be invalid. Different situations (such as room features, ventilation configurations, occupants' activities, etc.) will have different correlations and therefore one should always be aware of that and try to reveal that relation [80–82].

4.4. Limitation & outlooks

In addition to some of the considerations mentioned in the discussion above, some limitations of this study should be taken into account.

(a) In terms of the baby model, first, the simulation of baby respiration assumes a mean stable breathing airflow in two phases, i. e., inhalation and exhalation. In reality, the process of one inhalation or exhalation has the characteristics of gradual increase, achieving peak, subsequently gradual decrease, and finally a short pause [83,84]. Also, inhalation through the nose has only one nostril, which affects the realistic inhalation of air, and therefore, CO_2 concentration. Third, because of practical limitations, the temperature of the exhaled air was set to the ambient air temperature (around 25 °C), rather than being heated

to the core temperature (around 36.5 °C) [53]. But it is worth mentioning that based on the study [48], the humidity and temperature treatment of exhaled air might increase the amount of air re-inhaled by the manikin. Additionally, a comparative analysis was conducted between the CO_2 levels inhaled by the infant model in the room and those reported in existing literature, revealing similar CO_2 inhalation levels (see Fig. A7 and Tab. A3).

(b) In order to take a high spatial-resolution measurement of CO_2 dispersion, a number of CO_2 sensors (23 units) and the rack of sensors were placed inside the bed, which may affect the realistic CO_2 inhalation. Therefore, after the formal cases, four additional tests were performed to check the extent to which the sensors placed inside the bed affect the CO_2 dispersion and inhaled CO_2 concentration. During the additional cases, 17 out of 23 Vaisala CO_2 sensors were removed from the No.3 bed, as shown in Fig. C1 in Appendix C of the Supplementary material, and the rest of experimental conditions were the same as that in the formal cases (see Tab. C1). The results from these four additional cases showed no statistically significant differences to the corresponding formal cases (see Tab. C2), which means that there was no significant effect of the large number of sensors inside the No.3 bed on CO_2 dispersion. However, as shown in Fig. C2, slightly lower mean inhaled CO_2 values in all additional tests were observed than that in the corresponding formal cases, with an average difference of 74 ppm among the four tests (higher than 50 ppm). This demonstrated that, still, there was a slight effect of a large number of sensors inside the No.3 bed on the inhaled CO_2 values.

(c) Additionally, in this study, it was mainly intended to investigate the dispersion of CO_2 emitted by a baby sleeping in a semi-enclosed bed, taking into account different conditions in three variables, i.e., three different sleep positions, two different ventilation rates, and two types of ages, respectively, but the interaction effect of these three factors on the CO_2 dispersion was not explored in the current study due to the limited number of cases, and the fact that the baby model used was the only subject. However, it can be visually observed that different sleeping positions and infant ages have more pronounced effects on CO_2 inhalation relative to different ventilation rates, based on the limited cases, as shown in Fig. 6.

(d) The research verified poor ventilation conditions at the bed-level within a semi-enclosed baby bed, highlighting the necessity to enhance the design of such baby beds. However, this study only examined a single baby sleeping in the bedroom under one air distribution approach, specifically, mixing ventilation. Additionally, a higher CO_2 concentration was observed in Bed No. 9 (situated opposite Bed No. 3) in four cases, as detailed in Section 3.2 and Fig. 4d, which suggests the potential for CO_2 cross-contamination between beds. Consequently, more investigation is required to examine CO_2 exposure and dispersion when multiple infants sleep in bedrooms with varying ventilation systems, as well as to identify appropriate solutions.

5. Conclusion

This study applied a full-scale bedroom setup based on a field survey in 17 Dutch daycare centers to investigate the CO_2 dispersion and exposure from a breathing thermal baby model sleeping inside a semi-enclosed baby bed. The main findings are as follows:

(a) Excess exhaled CO_2 concentration was found to accumulate inside a semi-enclosed bed in most cases, and to be unevenly distributed in beds under mixing ventilation mode, which indicates that the bed-level ventilation conditions are insufficient and cannot be maintained by using a mixing ventilation mode at the room level only.

(b) Across all cases, the concentration of CO_2 inhaled by infants was high, on average, with a factor of three of the measured values in the room exhaust, which potentially poses a health issue, or affect other outcomes, to infants sleeping in the beds.

(c) The sleep positions had a significant impact on the CO_2 accumulation and inhalation inside the bed, with the worst being sleeping in a lateral-to-wall position, followed by the lateral-to-corridor, and the supine position. A high ventilation rate (250 m³/h) contributes to removal of the CO_2 emissions from the bed but can also lead to elevated CO_2 inhalation, compared to the cases of 55 m³/h. Older babies emit more amount of CO_2, which causes more CO_2 to be inhaled and accumulated inside the bed.

(d) It is possible to qualitatively assess the CO_2 exposure of babies by placing sensors inside the bed. This is not possible at room level. For the current study, the location (S2CO) which was parallel to the baby's head and close to the opening side of the bed can well qualitatively monitor the inhaled CO_2 concentration even under different sleep positions, ventilation rates, and baby ages.

(e) To conclude, the current study confirms the unfavorable status of the ventilation conditions inside a semi-enclosed baby bed and highlights the need to improve the air quality inside the baby bed.

CRediT authorship contribution statement

Hailin Zheng: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Zhijian Wang:** Writing – review & editing, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Marcel Loomans:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Shalika Walker:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Wim Zeiler:** Writing – review & editing, Supervision, Resources, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.buildenv.2023.110638.

References

[1] UNESCO-UIS, ISCED 2011 Operational Manual: Guidelines for Classifying National Education Programmes and Related Qualifications, The United Nations Educational, Scientific and Cultural Organization (UNESCO), Institute for Statistics (UIS), 2015.

[2] H. Zheng, et al., Response of Low-Cost Environmental Monitors to Typical Emission Events in Daycare Centers, CLIMA 2022 conference, 2022.

[3] H. Zheng, et al., Laboratory evaluation of low-cost air quality monitors and single sensors for monitoring typical indoor emission events in Dutch daycare centers, Environ. Int. 166 (2022), 107372.

[4] R. Ruotsalainen, N. Jaakkola, J.J.K. Jaakkola, Ventilation and indoor air quality in Finnish daycare centers, Environ. Int. 19 (2) (1993) 109–119.

[5] L. Quirós-Alcalá, et al., Volatile organic compounds and particulate matter in child care facilities in the District of Columbia: results from a pilot study, Environ. Res. 146 (2016) 116–124.

[6] M. Basinska, M. Michalkiewicz, K. Ratajczak, Impact of physical and microbiological parameters on proper indoor air quality in nursery, Environ. Int. 132 (2019), 105098.

[7] W.J. Deng, et al., Measurement and health risk assessment of PM2.5, flame retardants, carbonyls and black carbon in indoor and outdoor air in kindergartens in Hong Kong, Environ. Int. 96 (2016) 65–74.

[8] B. Kolarik, et al., Ventilation in day care centers and sick leave among nursery children, Indoor Air 26 (2) (2016) 157–167.

[9] I. Sander, et al., Allergen quantification in surface dust samples from German day care centers, J. Toxicol. Environ. Health 79 (22–23) (2016) 1094–1105.

[10] C. Kim, et al., Diagnosis of Indoor Air Contaminants in a Daycare Center Using a Long-Term Monitoring, vol. 204, Building and Environment, 2021, 108124.

[11] S. Jia, et al., Exposure and risk assessment of volatile organic compounds and airborne phthalates in Singapore's Child Care Centers, Chemosphere 224 (2019) 85–92.

[12] F.M. Chegini, et al., Indoor and Outdoor Airborne Bacterial and Fungal Air Quality in Kindergartens: Seasonal Distribution, Genera, Levels, and Factors Influencing Their Concentration, Building and Environment, 2020.

[13] C.Y. Um, et al., Occupant behavior and indoor particulate concentrations in daycare centers, Sci. Total Environ. 824 (2022) 153206.

[14] Y. Zhang, P.K. Hopke, C. Mandin, Handbook of Indoor Air Quality, Springer Nature Singapore Pte Ltd, 2022.

[15] C. Roda, et al., Assessment of indoor environment in Paris child day care centers, Environ. Res. 111 (8) (2011) 1010–1017.

[16] A. Onishchenko, et al., Radon measurements in kindergartens in ural region (Russia), Radiat. Protect. Dosim. 177 (1–2) (2017) 112–115.

[17] B.V. Capi Education, Capi education for bed, Available from: https://www.capi-education.com/?s=bed&post_type=product, 2022.

[18] S. Lester, W. Russell, Children's right to play: an examination of the importance of play in the lives of children worldwide, in: Working Papers In Early Childhood Development, No. 57, Bernard van Leer Foundation, The Hague, the Netherlands, 2010.

[19] World Health Organization, WHO Global Air Quality Guidelines: Particulate Matter (PM2. 5 and PM10), Ozone, Nitrogen Dioxide, Sulfur Dioxide and Carbon Monoxide, World Health Organization, 2021.

[20] EPA, U.S., Exposure Factors Handbook 2011 Edition (Final Report), U.S. Environmental Protection Agency, Washington, DC, 2011.

[21] C.F. Bearer, How are children different from adults? Environ. Health Perspect. 103 (suppl 6) (1995) 7–12.

[22] P.J. Landrigan, et al., Pollution and children's health, Sci. Total Environ. 650 (2019) 2389–2394.

[23] S. Zhang, et al., What do we know about indoor air quality of nurseries? A review of the literature, Build. Serv. Eng. Res. Tecnol. 42 (5) (2021) 603–632.

[24] O. Ramalho, et al., Association of carbon dioxide with indoor air pollutants and exceedance of health guideline values, Build. Environ. 93 (2015) 115–124.

[25] N.M. Salleh, et al., A quantitative evaluation of indoor environmental quality in refurbished kindergarten buildings: a Malaysian case study, Build. Environ. 94 (2015) 723–733.

[26] M. St-Jean, et al., Indoor air quality in Montreal area day-care centres, Canada, Environ. Res. 118 (2012) 1–7.

[27] P.T.B.S. Branco, et al., Quantifying Indoor Air Quality Determinants in Urban and Rural Nursery and Primary Schools, Environmental Research, 2019, p. 176.

[28] P.T.B.S. Branco, et al., Impact of indoor air pollution in nursery and primary schools on childhood asthma, Sci. Total Environ. 745 (2020), 140982.

[29] T. Rejc, et al., Microbiological and chemical quality of indoor air in kindergartens in Slovenia, Int. J. Environ. Health Res. 30 (1) (2020) 49–62.

[30] G. Zheng, et al., Exposure to melamine and its derivatives in childcare facilities, Chemosphere (2020) 244.

[31] F. Villanueva, et al., Indoor and outdoor air concentrations of volatile organic compounds and NO2 in schools of urban, industrial and rural areas in Central-Southern Spain, Sci. Total Environ. 622–623 (2018) 222–235.

[32] Ventilation Ashrae, IEQ and sleep quality in bedrooms, in: Residential Buildings Committee (RBC) Residential Issue Brief, 2022.

[33] B.E. Boor, et al., Human exposure to indoor air pollutants in sleep microenvironments: a literature review, Build. Environ. 125 (2017) 528–555.

[34] Y. Liang, Y. Xu, Emission of phthalates and phthalate alternatives from vinyl flooring and crib mattress covers: the influence of temperature, Environ. Sci. Technol. 48 (24) (2014) 14228–14237.

[35] E.J.F. Jr, et al., Modeling indoor air concentrations near emission sources in imperfectly mixed rooms, J. Air Waste Manag. Assoc. 46 (9) (1996) 861–868.

[36] K.-H. Kim, et al., Emissions of amides (N, N-dimethylformamide and formamide) and other obnoxious volatile organic compounds from different mattress textile products, Ecotoxicol. Environ. Saf. 114 (2015) 350–356.

[37] EPA, U.S, Improving indoor air quality, Available from: https://www.epa.gov/indoor-air-quality-iaq/improving-indoor-air-quality, 2022.

[38] G. Cao, et al., A review of the performance of different ventilation and airflow distribution systems in buildings, Build. Environ. 73 (2014) 171–186.

[39] E. Mundt, et al., Ventilation Effectiveness, Rehva, 2004.

[40] K. Kuga, P. Wargocki, K. Ito, Breathing zone and exhaled air re-inhalation rate under transient conditions assessed with a computer-simulated person, Indoor Air 32 (2) (2022).

[41] M. Bivolarova, et al., Effect of airflow interaction in the breathing zone on exposure to bio-effluents, Build. Environ. 125 (2017) 216–226.

[42] W. Kierat, et al., Accurate assessment of exposure using tracer gas measurements, Build. Environ. 131 (2018) 163–173.

[43] A.K. Melikov, Human body micro-environment: the benefits of controlling airflow interaction, Build. Environ. 91 (2015) 70–77.

[44] W. Kierat, et al., Towards enabling accurate measurements of CO2 exposure indoors, Build. Environ. 213 (2022), 108883.

[45] J. Pantelic, et al., Personal CO2 cloud: laboratory measurements of metabolic CO2 inhalation zone concentration and dispersion in a typical office desk setting, J. Expo. Sci. Environ. Epidemiol. 30 (2) (2020) 328–337.

[46] A.K. Melikov, D.G. Markov, Validity of CO2 based ventilation design, in: E3S Web of Conferences, EDP Sciences, 2019.

[47] C. Xu, et al., Measuring the exhaled breath of a manikin and human subjects, Indoor Air 25 (2) (2015) 188–197.

[48] A. Melikov, J. Kaczmarczyk, Measurement and prediction of indoor air quality using a breathing thermal manikin, Indoor Air 17 (1) (2007) 50–59.

[49] M.v.B.Z.e. Koninkrijksrelaties, Dutch building Code (in Dutch) [2023/01/03]; Available from: https://rijksoverheid.bouwbesluit.com/(X(1)S(dnpkjd45yn0fjj55b1h0gr45))/Inhoud/docs/wet/bb2012, 2023.

[50] A. Melikov, Breathing thermal manikins for indoor environment assessment: important characteristics and requirements, Eur. J. Appl. Physiol. 92 (6) (2004) 710–713.

[51] D. Hull, et al., Individual variation in sleeping metabolic rates in infants, Arch. Dis. Child. 75 (4) (1996) 288–291.

[52] D. Hull, et al., Metabolic rate of sleeping infants, Arch. Dis. Child. 75 (4) (1996) 282–287.

[53] M. Garcia-Souto, P. Dabnichki, Core and local skin temperature: 3–24 months old toddlers and comparison to adults, Build. Environ. 104 (2016) 286–295.

[54] ISO, ISO 8996:2021, Ergonomics of the Thermal Environment — Determination of Metabolic Rate, ISO, 2021.

[55] S. Fleming, et al., Normal ranges of heart rate and respiratory rate in children from birth to 18 years of age: a systematic review of observational studies, Lancet 377 (9770) (2011) 1011–1018.

[56] P. Kumar, et al., Normative data of infant pulmonary function testing: a prospective birth cohort study from India, Indian Pediatr. 57 (1) (2020) 25–33.

[57] Advanced Energy Industries Inc, Innova 1512 specifications [2023/01/03]; Available from: https://www.advancedenergy.com/products/gas-sensors/gas-monitors/innova-1512/, 2023.

[58] P.P. Systems, SBA-5 CO2 gas analyzer specifications [2023/01/03]; Available from: https://ppsystems.com/wp-content/uploads/EDSSBA5.pdf, 2023.

[59] ANSI/ASHRAE, ANSI/ASHRAE standard 62.1-2019 – ventilation for acceptable indoor air quality, Am. Soc. Heat. Refrig. Air Cond. Eng. (ASHRAE) (2019).

[60] D. Zhang, E. Ding, P.M. Bluyssen, Guidance to assess ventilation performance of a classroom based on CO2 monitoring, Indoor Built Environ. 31 (4) (2022) 1107–1126.

[61] The Blender Foundation, Blender is free and open source software, forever [2023/01/14]; Available from: https://www.blender.org/about/, 2023.

[62] ISO, ISO 16000-26-*Indoor Air Part 26: Sampling Strategy for Carbon Dioxide (CO₂)*, ISO, 2012.

[63] O. Geiss, Effect of wearing face masks on the carbon dioxide concentration in the breathing zone, Aerosol Air Qual. Res. 21 (2) (2021) 200403.

[64] A. Ghahramani, et al., Personal CO2 bubble: context-dependent variations and wearable sensors usability, J. Build. Eng. 22 (2019) 295–304.

[65] W. Fisk, P. Wargocki, X. Zhang, Do indoor CO2 levels directly affect perceived air quality, health, or work performance? ASHRAE J. 61 (9) (2019) 70–74, 76-77.

[66] X. Zhang, et al., Effects of exposure to carbon dioxide and bioeffluents on perceived air quality, self-assessed acute health symptoms, and cognitive performance, Indoor Air 27 (1) (2017) 47–64.

[67] C. Sekhar, et al., Bedroom Ventilation: Review of Existing Evidence and Current Standards, vol. 184, Building and Environment, 2020, 107229.

[68] S. Sadrizadeh, et al., Indoor air quality and health in schools: a critical review for developing the roadmap for the future school environment, J. Build. Eng. 57 (2022), 104908.

[69] E.P. Cummins, M.J. Strowitzki, C.T. Taylor, Mechanisms and consequences of Oxygen and carbon dioxide sensing in mammals, Physiol. Rev. 100 (1) (2020) 463–488.

[70] D. Markov, et al., On the impact of CO2 concentration in the inhaled air on the CO2 emission rate by people, in: Proceedings of the ROOMVENT, 2020.

[71] B.E. Boor, et al., Infant exposure to emissions of volatile organic compounds from crib mattresses, Environ. Sci. Technol. 48 (6) (2014) 3541–3549.

[72] K. Hoffman, et al., High exposure to Organophosphate flame retardants in infants: associations with baby products, Environ. Sci. Technol. 49 (24) (2015) 14554–14559.

[73] K. Oz, et al., Volatile organic compound emissions from polyurethane mattresses under variable environmental conditions, Environ. Sci. Technol. 53 (15) (2019) 9171–9180.

[74] H. Yin, et al., Performance evaluation of three attached ventilation scenarios for tiny sleeping spaces, Build. Environ. 186 (2020), 107363.

[75] S. Yun, et al., Proxy methods for detection of inhalation exposure in simulated office environments, J. Expo. Sci. Environ. Epidemiol. 33 (3) (2023) 396–406.

[76] K.P. Andrew, P. Brian, Indoor carbon dioxide metric analysis Tool, Tech. Note (NIST TN), Natl. Inst. Stand. Technol. (2022). https://doi.org/10.6028/NIST.TN.2213.

[77] Z. Peng, J.L. Jimenez, Exhaled CO2 as a COVID-19 infection risk proxy for different indoor environments and activities, Environ. Sci. Technol. Lett. 8 (5) (2021) 392–397.

[78] D. Zhang, P.M. Bluyssen, Exploring the Possibility of Using CO2 as a Proxy for Exhaled Particles to Predict the Risk of Indoor Exposure to Pathogens, Indoor and Built Environment, 2022.

[79] M.R. Laurent, J. Frans, Monitors to improve indoor air carbon dioxide concentrations in the hospital: a randomized crossover trial, Sci. Total Environ. 806 (2022), 151349.

[80] M.P. Bivolarova, et al., Can CO2 be used as an indicator of the probability of cross-infection?, in: 17th International Conference on Indoor Air Quality and Climate, INDOOR AIR, 2022, p. 2022.

[81] A. Lipczynska, et al., Airborne infection probability in relation of room air distribution: an experimental investigation, in: E3S Web of Conferences, EDP Sciences, 2022.

[82] A. Lipczynska, et al., Experimental evaluation of the airborne infection probability in ventilated office room at different supply airflow rates, in: E3S Web of Conferences, EDP Sciences, 2022.

[83] M.J. Tobin, Breathing pattern analysis, Intensive Care Med. 18 (4) (1992) 193–201.

[84] F.A. Berlanga, et al., Influence of the geometry of the airways on the characterization of exhalation flows. Comparison between two different airway complexity levels performing two different breathing functions, Sustain. Cities Soc. 53 (2020), 101874.