SENSOR AND ACTUATOR INFRASTRUCTURE FOR DEMAND-CONTROLLED VENTILATION AND INDOOR AIR QUALITY MANAGEMENT IN AN AUTOMATED HVAC SYSTEM

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Annotatsiya:

Ushbu maqolada ma'muriy bino HVAC tizimida talabga asoslangan ventilyatsiya (DCV) va ichki havo sifatini boshqarish uchun sensor va aktuator infratuzilmasi ilmiy tahlil qilingan. Muammo: sobiq belgilangan ventilyatsiya tezligi xona bandligidan qat'i nazar doimiy bo'lib, energiya isrofiga (bo'sh xonalar) yoki yetarsiz ventilyatsiyaga (to'la xonalar, CO_2 > 1400 ppm) olib keladi. Usul: Siemens QPA2062 NDIR CO_2 sensori, QAA2281 harorat/namlik sensori, PIR harakat sensorlari va Belimo VAV aktuatorlari asosida zona darajasidagi sensor tizimi loyihalandi; CO_2 massa balansi modeli orqali xona bandligi real vaqtda baholanadi. Natija: sensor tizimi bandlikni ±1 kishi aniqlikda baholadi, CO_2 darajasini 940 ppm da ushlab turdi (oldingi 1420 ppm). Xulosa: DCV algoritmi yillik ventilyatsiya energiyasini 18 600 kVt·soat (16,3%) tejadi, sensor signal ishonchliligi 98,4% ni tashkil etdi.

Kalit so'zlar: DCV, CO_2 sensori, NDIR, ichki havo sifati, VAV aktuator, bandlik aniqlash, HVAC sensorlari, Belimo, ASHRAE 62.1, energiya tejash.

Аннотация:

В данной статье научно анализируется инфраструктура датчиков и приводов для вентиляции по потребности (DCV) и управления качеством внутреннего воздуха в системе HVAC административного здания. Проблема: фиксированная скорость вентиляции независима от занятости помещений, что приводит к потерям энергии в пустых помещениях или недостаточной вентиляции в заполненных (CO_2 > 1400 ppm). Метод: спроектирована система датчиков на уровне зон на основе NDIR-датчика CO_2 Siemens QPA2062, датчика температуры/влажности QAA2281, PIR-датчиков движения и приводов VAV Belimo; занятость помещений оценивается в реальном времени через модель баланса массы CO_2. Результат: система оценивает занятость с точностью ±1 человек, поддерживает уровень CO_2 на 940 ppm (ранее 1420 ppm). Вывод: алгоритм DCV сэкономил 18 600 кВт·ч (16,3%) энергии вентиляции в год, надёжность сигналов датчиков составила 98,4%.

Ключевые слова: DCV, датчик CO_2, NDIR, качество воздуха, привод VAV, обнаружение занятости, датчики HVAC, Belimo, ASHRAE 62.1, энергосбережение.

Abstract:

This article presents a scientific analysis of the sensor and actuator infrastructure required for demand-controlled ventilation (DCV) and indoor air quality (IAQ) management in an automated HVAC system. Problem: fixed ventilation rates, independent of zone occupancy, cause either energy waste in unoccupied zones or inadequate ventilation in occupied zones (CO_2 exceeding 1400 ppm), both common in conventional administrative building HVAC systems. Method: a zone-level sensor system was designed based on the Siemens QPA2062 NDIR CO_2 sensor, QAA2281 temperature/humidity sensor, PIR motion sensors, and Belimo TSV24-SR VAV actuators; real-time occupancy is estimated from a CO_2 mass-balance model. Result: the sensor system estimated occupancy with ±1 person accuracy and maintained CO_2 at 940 ppm (down from 1420 ppm under fixed ventilation). Conclusion: the DCV algorithm saved 18,600 kWh (16.3%) of annual ventilation energy, with sensor signal reliability of 98.4%.

Keywords: demand-controlled ventilation, CO_2 sensor, NDIR, indoor air quality, VAV actuator, occupancy detection, HVAC sensors, Belimo, ASHRAE 62.1, energy savings.

Introduction

Demand-controlled ventilation (DCV) is among the most effective HVAC energy-saving strategies for buildings with variable occupancy — administrative buildings, conference centers, classrooms — where occupancy can vary from zero (nights, weekends, vacant offices) to full design capacity (all-hands meetings) within the same day. The effectiveness of DCV depends entirely on the accuracy, reliability, and response speed of the sensor infrastructure that estimates real-time occupancy and air quality [1].

Two sensing approaches dominate DCV implementations: direct occupancy detection (PIR motion sensors, door switches, badge readers) and indirect occupancy estimation via CO_2 concentration (since human respiration is the dominant indoor CO_2 source in office environments). Each approach has limitations when used alone: PIR sensors detect motion, not presence — a seated occupant working quietly may not trigger continued detection, leading to premature ventilation reduction; CO_2-based estimation has inherent time lag (CO_2 concentration changes gradually following occupancy changes, with response time constants of 10–30 minutes depending on zone volume and ventilation rate) [2].

This article presents the design and six-month field evaluation of a combined sensor infrastructure that fuses PIR motion detection (fast response, binary presence indication) with CO_2 mass-balance occupancy estimation (slower response, but quantitative occupant count), achieving both rapid response to occupancy changes and accurate ventilation rate calculation. The actuator infrastructure — VAV dampers and their control interfaces — is analyzed alongside the sensor system, as DCV performance depends on the combined sensor-actuator response chain.

Sensor and actuator requirements for DCV

ASHRAE Standard 62.1 specifies minimum ventilation rates as the sum of a per-person component (proportional to occupancy) and a per-area component (independent of occupancy, addressing material emissions): $V_{bz} = R_p \cdot P_z + R_a \cdot A_z$, where Rp is the per-person outdoor air rate (2.5 l/s/person for office spaces), Pz is zone population, Ra is the per-area outdoor air rate (0.3 l/s/m²), and Az is zone floor area. DCV implementation requires real-time estimation of Pz — the only variable component — with sufficient accuracy and response time to adjust ventilation before CO_2 exceeds the 1000 ppm guideline.

Sensor selection and characterization

CO_2 sensing — Siemens QPA2062

The QPA2062 uses non-dispersive infrared (NDIR) absorption spectroscopy: an infrared source emits light through a sample chamber, and a detector measures absorption at the CO_2 characteristic wavelength (4.26 μm). NDIR sensors offer ±50 ppm accuracy (0–2000 ppm range), long-term stability (drift < 5% over 5 years with auto-calibration), and immunity to humidity and most interfering gases — advantages over older electrochemical CO_2 sensors (±100–150 ppm, 2-year lifespan). Auto-calibration uses the assumption that the lowest CO_2 reading over a 7-day rolling window approximates outdoor CO_2 concentration (~420 ppm) — valid for buildings with regular unoccupied periods.

Response time consideration: the QPA2062's physical response time (T_{63} = 2 minutes for the sensor itself) is fast relative to the zone CO_2 dynamics (10–30 minute time constants), meaning the sensor is not the limiting factor in DCV response speed — the zone air volume and ventilation rate are. This justifies the combined PIR+CO_2 approach: PIR provides the fast initial response while CO_2 provides the accurate steady-state ventilation rate.

Occupancy detection — PIR sensors and door switches

Passive infrared (PIR) motion sensors integrated into the QPA2062 housing detect occupant movement within a 6m × 6m coverage pattern (typical single-office or small meeting room zone). PIR sensors provide near-instantaneous (< 1 s) detection of occupancy transitions but cannot distinguish a single seated occupant from an empty room during periods without movement — a known limitation addressed by combining PIR with CO_2 trend analysis: if PIR detects no motion for > 15 minutes but CO_2 continues rising, the algorithm infers continued occupancy by a stationary occupant. Door-position reed switches on meeting rooms provide a third independent occupancy signal — door closed + lights on is a strong indicator of an in-progress meeting.

VAV actuators — Belimo TSV24-SR

The Belimo TSV24-SR spring-return damper actuator (24V AC/DC, 0–10V or 4–20mA control signal, 0.5–1.5 s/° rotation speed, 5 Nm torque) positions the VAV box damper in proportion to the cooling/ventilation demand signal from the zone controller. The spring-return mechanism is a critical safety feature: on loss of control signal or power, the actuator returns to a pre-configured fail-safe position (typically minimum ventilation position) within 90 seconds — ensuring zones never lose all ventilation due to a control system fault. Actuator feedback (potentiometer position signal) is monitored by the zone controller to verify commanded vs actual damper position, detecting mechanical faults (stuck dampers, linkage failure) that would otherwise go unnoticed.

Occupancy estimation algorithm and zone airflow calculation

The combined occupancy estimate Pz_est is computed every 60 seconds as a weighted combination: when PIR indicates active motion, Pz_est is set to the zone's design occupancy (conservative assumption, since active motion typically indicates a meeting or active work, likely near-full occupancy); when PIR indicates no motion but CO_2 concentration is rising, Pz_est is computed from the CO_2 rate-of-rise using the mass balance $dC/dt = (G \cdot N - Q \cdot (C - C_{out}))/V$, solved for N given measured dC/dt, current C, outdoor concentration Cout (420 ppm), zone volume V, and current ventilation rate Q; when both PIR shows no motion and CO_2 is at or below outdoor-adjusted baseline for >

20 minutes, Pz_est = 0 (zone confirmed unoccupied) and ventilation reduces to the area-based minimum Ra·Az only.

Results

Table 1. Sensor system specifications and field-measured performance

Sensor	Parameter	Spec. accuracy	Field accuracy	Response time
QPA2062	CO_2 (ppm)	±50	±58	T63 = 2 min
QAA2281	Temp / RH	±0.3°C / ±2%	±0.32°C / ±2.4%	< 30 s
PIR (integr.)	Motion	6m×6m cov.	96.2% detect.	< 1 s
TSV24-SR	Damper pos.	±2%	±2.4%	0.5–1.5 s/°
Combined occupancy est.	**Person count**	**Target ±1**	**±1 person**	**60 s update**

Table 2. Comparison of occupancy estimation methods

Method	Response time	Occupancy count error	Energy savings (%)
PIR only	< 1 s	±3.4 persons	9.8
CO_2 mass-balance only	10–30 min	±1.2 persons	12.6

Combined PIR+CO_2	**< 1 s (initial), refined in 10 min**	**±1.0 person**	**16.3**

Discussion

PIR-only occupancy detection achieved only 9.8% energy savings with ±3.4 person count error — the binary present/absent signal cannot distinguish a single person from a full conference room, both registering identical PIR output, forcing the ventilation algorithm to assume worst-case (full design occupancy) whenever any motion is detected. CO_2 mass-balance alone achieved better accuracy (±1.2 persons) and higher savings (12.6%) but its 10–30 minute response lag means ventilation increase lags behind actual occupancy increase by the same period — during this lag, CO_2 continues rising above target, occasionally exceeding 1100–1200 ppm transiently before the algorithm catches up.

The combined PIR+CO_2 approach achieved the best results on all metrics: ±1.0 person count accuracy (best of all methods) and 16.3% energy savings (highest), while also achieving the fastest meaningful response — PIR immediately signals "occupancy increasing," prompting an immediate conservative ventilation increase to the design rate, while CO_2 mass-balance subsequently refines this to the actual occupancy-proportional rate over the following 10 minutes. This two-stage response (fast conservative response, followed by accurate refinement) avoids both the CO_2 overshoot of CO_2-only systems and the energy waste of PIR-only systems.

Sensor reliability of 98.4% (1.6% of readings flagged as out-of-range or sensor-fault during the six-month evaluation) was primarily attributable to two causes: temporary CO_2 sensor drift exceeding ±100 ppm before scheduled auto-calibration (0.9% of readings, resolved automatically within 24 hours), and PIR sensor false-negatives in zones with very still seated work (0.7% of readings, mitigated by the CO_2 backup as described above). No actuator failures occurred during the evaluation period, validating the Belimo TSV24-SR's suitability for continuous HVAC duty cycling.

A limitation identified is the 6m × 6m PIR coverage pattern's inadequacy for large open-plan office zones (>36 m²) — multiple PIR units would be required for full coverage, increasing per-zone sensor cost. For the evaluated building (predominantly individual offices and small meeting rooms ≤30 m²), single PIR-per-zone coverage was adequate; larger open-plan zones in other building types would require a zoned PIR array with logical OR combination of all units' outputs.

Conclusion

This article presented a scientific analysis of the sensor and actuator infrastructure for demand-controlled ventilation in an automated HVAC system. The following conclusions were drawn:

1. NDIR CO_2 sensing (Siemens QPA2062, ±50 ppm) combined with PIR motion detection provides both fast initial response (<1 s) and accurate steady-state occupancy estimation (±1 person), outperforming either method used alone.

2. The combined PIR+CO_2 occupancy estimation algorithm achieved 16.3% ventilation energy savings — 66% more than CO_2-only (12.6%) and 66% more than PIR-only (9.8%).

3. CO_2 concentration was maintained at 940 ppm average peak (down from 1,420 ppm under fixed ventilation), bringing indoor air quality within ASHRAE 62.1 limits while saving energy.

4. Sensor system reliability of 98.4% and zero actuator failures over six months confirm the suitability of the selected NDIR/PIR/spring-return actuator combination for continuous administrative building HVAC operation.

Future work will evaluate camera-based people-counting sensors for large open-plan zones, and investigate machine learning models trained on historical occupancy patterns to provide predictive (rather than purely reactive) ventilation pre-conditioning.

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