Build Tight, Ventilate Right: Air-Sealing Relationship to Indoor Air Quality for Healthy Resilient Homes that Use Less Energy

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ABSTRACT

You've heard it before: "build tight, ventilate right", but what about older homes that don't have mechanical ventilation? Won't the air in my home be unhealthy if my home doesn't "breathe"?

We tested the air tightness of 21 homes in California with normalized leakage ranging from 0.4 to 1.3. We also monitored $PM_{2.5}$ at 19 of these homes, investigating the relationship between envelope leakage and the transport of indoor and outdoor particulate pollutants using continuous passive sensors from Purple Air.

We calculated the infiltration factor during steady state periods of elevated outdoor $PM_{2.5}$: wildfire smoke, rush hour, agricultural activities, and other poor outdoor air quality events. Additionally calculating the particle decay rate at the end of elevated indoor $PM_{2.5}$ periods.

The study found no consistent relationship between blower-door-derived air exchange rates and $PM_{2.5}$ infiltration factor or decay rate, underscoring the complexity of pollutant transport and the influence of short-term environmental and operational factors in natural air infiltration. While tighter building envelopes can reduce particulate ingress during poor outdoor air quality events, minimum ventilation guidelines must be observed for safety. Overall results were inconclusive, emphasizing the complex relationship between envelope tightness and indoor air quality. Further study should consider short time-scale variability of the air infiltration and pollutant transport metrics.

Introduction

Fine particulate matter ($PM_{2.5}$) is a significant public health concern due to its ability to penetrate the respiratory tract and enter the bloodstream, where it can induce systemic inflammation and oxidative stress. Epidemiological studies have shown that short-term exposure to $PM_{2.5}$ is associated with respiratory irritation, asthma exacerbation, and acute cardiovascular events, while long-term exposure contributes to chronic respiratory disease, cardiovascular disease, lung cancer, cognitive decline, and increased premature mortality (State of Global Air 2024; U.S. EPA 2019). Susceptible populations—including children, older adults, pregnant individuals, and those with pre-existing cardiopulmonary conditions—experience disproportionately greater health risks from $PM_{2.5}$ exposure (CARB 2023). These established health impacts indicate the importance of limiting indoor exposure to outdoor-generated $PM_{2.5}$, particularly during episodic air pollution events such as wildfires.

The intent of this study, funded by the California Energy Commission (CEC), was to characterize fireplaces in the California residential building stock and understand the contribution of air leakage through the fireplace chimney to the overall building shell air leakage.

In addition, CEC was interested in the extent to which polluted outdoor air contaminates indoor air during poor air quality events such as wildfires or rush-hour traffic.

We conducted a comprehensive survey of single- and multi- family occupants across the state of California, building on CEC's Residential Appliance Saturation Survey (RASS). At each of the 21 sites we performed multi-point blower-door tests (using the ASTM E1827 procedure) under successive fireplace configurations—from fully open to sealed with a chimney plug—to isolate air leakage attributable to the fireplace. We monitored $PM_{2.5}$ and NO_x inside and outside the house for one year by installing paired indoor/outdoor low-cost sensors. Data were corrected for PurpleAir biases, as shown below. This paper focuses on the air leakage testing and pollutant monitoring portion of the CEC study.

Methods

Below we describe the methods used to characterize the building envelope leakage using a blower door, and those used for long-term pollutant monitoring.

Site Visit Methods

The field measurements involved blower door tests to characterize envelope leakage with the fireplace in multiple configurations, from completely open to completely sealed. At each site visit we performed initial diagnostic tests, collected contextual data, conducted NO_2 spot measurements, and installed the air quality monitors for long term observation of $PM_{2.5}$. We performed a multi-point air tightness test (per ASTM E1827-11) using a Minneapolis Blower Door and DG-700 differential pressure gauge. An initial battery of blower door tests was conducted with differential pressures ranging from 25 to 50 Pascals in 5 pascal increments. This allowed the construction of a regression relationship between the observed pressure differential and corresponding flow rate that is specific to each tested location. Doing so increases the reliability of transposing leakage flow rates tested at 25 and 50 Pascals down to smaller pressure differentials that more accurately represent natural ventilation rates

Pollutant Monitoring Methods

To examine the relationship between envelope leakage and the transport of indoor and outdoor particulate pollutants, we monitored $PM_{2.5}$ concentrations both outdoors and indoors at 19 of the 21 field measurement sites using continuous passive sensors from Purple Air. Each test home was continuously monitored for at least six months covering both summer and winter seasons. The collected data was regularly uploaded to a central database.

Due to the identified discrepancies between PurpleAir data and reference instrument data, which are especially obvious during extreme events like wildfires or (for sensors deployed indoors) when the concentrations are below the limit of detection (LoD), we applied correction methods to address nonlinearity (Barkjohn 2022) and LoD (Wallace 2021) issues. Details of the deployed sensors are provided in Table 1.

Table 1: Details of deployed air-quality sensors

Sensor	Usage	Specs
PurpleAir Touch - Indoor Air Quality Monitor	Indoor $PM_{2.5}$, temperature, pressure, humidity	Laser particle counters: Manufacturer: Plantower Effective range: 0 to 500 µg/m³ Maximum consistency error: ±10% at 100 to 500µg/m³ & ±10µg/m³ at 0 to 100µg/m³ Pressure, temperature, humidity sensor: Manufacture: BOSCH Temperature range: -40°F to 185°F Pressure range: 300 to 1100 hPa Humidity: Accuracy tolerance: ±3% RH
PurpleAir Flex - Air Quality Monitor	Outdoor $PM_{2.5}$, temperature, pressure, humidity	
Attune air quality sensor	Indoor and outdoor NO_x	Nitrogen Dioxide (NO_2) sensor: range: 0-5/50/100ppm, accuracy:± 5%

The analysis used established research methods to understand how outdoor air pollution moves into homes. By comparing indoor and outdoor particle levels during periods when outdoor pollution was high, and indoor pollution sources were minimal, the analysis estimated the amount of outdoor pollution that typically enters indoors and remains suspended: the infiltration factor. When outdoor pollution levels were low, the analysis instead looked at how quickly indoor particle levels declined after events such as cooking by calculating the particle decay rate. This provided insight into how efficiently particles are removed from the indoor environment through a combination of air movement and natural settling.

Indoor and outdoor pollution measurements alone do not distinguish among the various processes that remove particles from indoor air. Consequently, the pollutant analysis could not separately quantify removal attributable to air exchange versus particle deposition onto surfaces. To address this limitation, building air leakage measurements were used to estimate the typical rate of outdoor air entering each home by applying standardized methods and weather adjustment factors. This estimate allowed the calculation of particle deposition rate at each home.

The methods described below were drawn from a 2013 literature review study (Diapouli 2013). Indoor particulate concentration profiles are governed by the mass balance equation:

$$\frac{dC_{in}(t)}{dt} = a \cdot P \cdot C_{out}(t) - (a + k) \cdot C_{in}(t) + \frac{G}{V}$$

Where C_{out} and C_{in} are the outdoor and indoor concentrations respectively (µg/m^3), *a* is the air exchange rate (hr^{-1}), k is the deposition rate (hr^{-1}), P is the dimensionless penetration efficiency, G is the indoor particle generation rate (µg/hr) and V is the volume of the indoor area (m^3). The fraction of outdoor particles that enter an indoor environment and remain suspended is defined by the following infiltration factor (F_{INF}) equation:

$$F_{INF} = \frac{a \cdot P}{a + k}$$

We used the indoor and outdoor $PM_{2.5}$ concentration measurements during steady state periods when outdoor pollutant levels are high, and indoor pollutant generation is negligible to determine F_{INF} which is (by definition) equal to the indoor to outdoor concentration ratio during those periods:

$$\frac{C_{in}}{C_{out}} = F_{INF}$$

We used three criteria to identify steady state periods and eliminate time periods with indoor source events. First, the indoor and outdoor concentration rate of change must both be lower than 0.005. Second, the indoor concentration must be lower than outdoor concentration, removing the top of indoor spikes. The front of an indoor spike is very steep, so the second criterium removes almost all points at the beginning of an indoor spike, but the tail decreases much more gradually so the third criterium requires the indoor concentration rate of change to be greater or equal to zero. This criterium removes some extra points that are just part of indoor concentration fluctuations, and we perhaps should have allowed slight negative indoor concentration rates of change.

Because indoor–outdoor concentration data and time-lag (decay) observations constrain only the combined removal rate (a+k) and the infiltration factor $\left(\frac{a \cdot P}{a+k}\right)$, the penetration efficiency P and deposition rate k are not separately identifiable without additional independent information. Having used a blower door to measure building shell leakage, We used standard formulas and ASHRAE 62.2 Weather and Shielding Factors (WSF) to estimate effective annual infiltration rate from the blower door data, using this as a proxy for the natural air infiltration, or air exchange rate (a). We refer to this as the blower-door-derived infiltration rate.

When outdoor $PM_{2.5}$ concentrations were low, We used the indoor concentration decay (after indoor source events) to determine the combined removal rate of $PM_{2.5}$ due to infiltration and particle deposition. The governing equation after the indoor source stops is:

$$C_{in}(t) = C_f + (C_{in,0} - C_f)e^{-\lambda t}$$

Where $C_{in,0}$ is the indoor concentration at the start of decay, C_f is the equilibrium indoor concentration and t is the elapsed time. During periods of indoor pollutant decay, we solved for the decay constant, λ, which equals a + k.

Results

Characteristics of Field-Testing Homes

The onsite sample consisted of 21 homes built between 1900 to 2000, as shown in Table 2. A slightly higher number of homes in our sample were constructed during the 1950's, 1960's and 1970's compared to earlier and later decades. Approximately half of the homes built after 1960 had crawlspace foundations, while none of the earlier-built homes featured them. This trend aligns with California construction practices, which have begun favoring less expensive slab foundations in housing developments. Homes with slab foundations typically exhibit lower building shell leakage, as there is no air leakage through a concrete slab. All the homes were heated using ducted forced-air furnaces, and 76 percent of the homes were equipped with central air conditioning.

Table 2: Home construction characteristics by decade built

Decade built	No air conditioning	Air conditioning present	Slab foundation	Unconditioned basement/ vented crawlspace	Total number of homes	Percent of homes
1900	0	1	0	1	1	4.8%
1920	1	0	0	1	1	4.8%
1930	1	1	0	2	2	9.5%
1940	0	2	0	2	2	9.5%
1950	0	4	0	4	4	19.0%
1960	1	2	1	2	3	14.3%
1970	1	4	2	3	5	23.8%
1980	1	1	1	1	2	9.5%
2000	0	1	1	0	1	4.8%
Total	24%	76%	24%	76%	21	100%

Leakage Testing Results

Prior research and this project's tests show that an unsealed fireplace can be a source of uncontrolled air exchange. A Lawrence Berkeley Lab study (1982) found that fireplaces without inserts accounted for 9 percent (with damper closed) up to 24 percent (damper open) of a home's total air leakage. In other words, even a closed metal damper is often not airtight. Total home leakage and fireplace leakage reduction testing results by site are presented in Table 3 and additional discussion is below. For each home tested, the table contains the following values measured with the fireplace damper and doors in the 'as found' configuration.

- The Equivalent Leakage Area (ELA), in square meters, of the home tested with the fireplace as found configuration.
- The Normalized Leakage (NL), a dimensionless value, which attempts to reduce the influence of the house size (area) and height on the leakage estimate.
- The annual average natural infiltration airflow in cubic feet per minute (CFM) and air changes per hour (ACH).[1]

[1] Estimated from blower door test results using ASHRAE Standard 62.2 methods and a Weather and Shielding Factor (WSF), which adjusts for local wind and temperature conditions

Table 3: Air leakage testing results by site

Site	Year built	Total area of home (ft2)	ELA [m^2]	NL	$Q_{natural}$ [CFM]	$Q_{natural}$ [ACH]
1	1925	1,934	0.448	0.347	97	0.4
2	1948	1,606	0.392	0.348	53	0.2
3	1956	4,200	1.102	0.375	271	0.5
4	1967	1,742	0.802	0.658	86	0.4
5	1979	1,948	1.009	0.825	143	0.5
6	1978	4,107	1.270	0.453	209	0.4
7	1982	1,224	0.775	1.099	95	0.6
8	1984	3,127	0.997	0.456	175	0.4
9	1978	1,325	0.774	0.835	77	0.4
10	1950	2,574	1.147	0.667	120	0.4
11	1906	2,535	1.146	0.706	149	0.4
12	1975	1,894	0.966	0.827	71	0.3
13	1952	1,401	0.805	0.821	62	0.3
14	1977	1,271	0.807	0.951	63	0.4
15	1939	1,726	0.901	0.755	65	0.3
16	1944	1,020	0.775	1.137	56	0.4
17	1939	1,439	0.866	0.977	79	0.4
18	1965	1,320	0.827	0.895	77	0.3
19	2001	2,196	0.791	0.563	88	0.3
20	1961	2,584	0.882	0.488	97	0.4
21	1952	1,244	0.803	0.922	53	0.2
Average			0.871	0.72	107	0.4
Standard deviation			0.209	0.24	58.24	0.10
Coefficient of Variation			24%	34%	54%	25%

The average equivalent leakage area (ELA) of the tested homes in their as-found configuration was 0.871 square meters with a standard deviation of 0.209 square meters. The calculated average normalized leakage (NL), which normalizes the measured leakage by the home's floor area and relative height, was 0.72. According to LBNL's leakage database, the average NL in single-family homes across the U.S. is 0.61 with a 2.5 standard deviation.[2] The

2 homes.lbl.gov/residential-leakage-database

homes in our study were slightly less airtight than the average home, but well within the expected distribution.

The natural air changes per hour were calculated using the blower door test results, and the wind shielding factors from ASHRAE 62.2. For this set of homes there was no correlation between the age of the home (Figure 1) or the size of the home (Figure 2) and the natural air change rate.

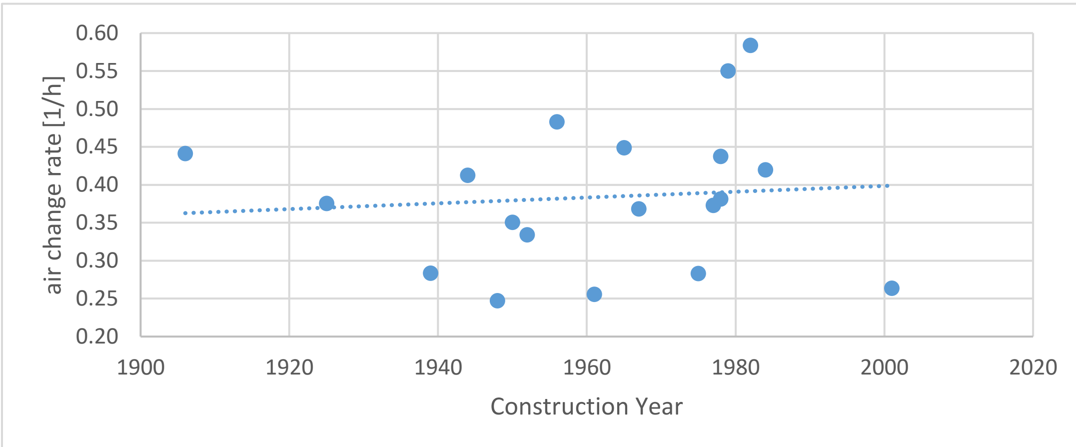

Figure 1: Blower-door-derived natural air change rate by year of home construction

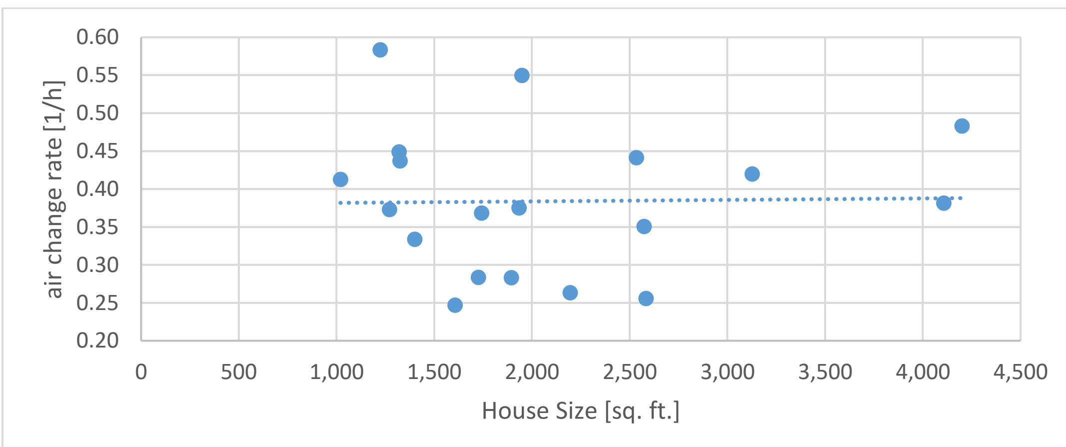

Figure 2: Blower-door-derived natural air change rate by house size

Air Quality Testing Results

The homes in our study had average indoor $PM_{2.5}$ levels that varied from 1.9 to 17.1 mg/m3, and average outdoor $PM_{2.5}$ that varied from 2.5 to 13.5 mg/m3. The three homes with the highest average outdoor $PM_{2.5}$ were in the Los Angeles area, and the two homes with the lowest average outdoor $PM_{2.5}$ were in Santa Rosa. Although there were short periods of exposure that were unhealthy, the 24-hour value never landed in the unhealthy range (greater than 55.5 ug/m^3), as defined by the U.S. Air Quality Index. The average indoor and outdoor $PM_{2.5}$ concentrations for each site are shown in Table 4 along with the average steady-state infiltration factor values.

The mean infiltration factor for these homes was 0.578, aligning with values reported in previous studies. According to the literature review results reported by Diapouli et al (2013), $PM_{2.5}$ infiltration factors across occupied residences generally cluster between 0.6 and 0.7, regardless of whether steady-state, dynamic, or surrogate methods are used. A summary of these comparative studies is provided in the Appendix.

Table 4: Average indoor and outdoor $PM_{2.5}$ concentrations and F_{INF} values

Site ID	Average C_{in} [μg/m^3]	Average C_{out} [μg/m^3]	F_{INF} values
1	2.9	4.8	0.612
2	17.1	4.2	0.690
3	3.1	5.5	0.496
4	3.6	4.4	0.519
5	2.9	5.2	0.498
6	5.6	7.0	0.719
7	5.9	6.3	0.399
8	4.4	3.6	0.646
9	1.9	2.2	0.600
10	14.8	12.6	0.558
11	8.1	13.5	0.662
12	5.9	7.8	0.576
13	5.9	4.8	0.610
14	5.2	5.2	0.498
15	5.4	9.9	0.550
16	5.0	12.8	0.460
18	7.5	6.7	0.700
19	9.6	8.1	0.786
20	3.3	9.9	0.406

Sites 2 and 10 exhibited unusually high indoor $PM_{2.5}$ concentrations, attributed to frequent indoor events. At site 10, the events displayed a steep incline and decay pattern characteristic of indoor cooking activities (see Figure 3). Site 20 presented a distinct signature of fireplace combustion during December (Figure 4), with outdoor concentrations closely tracking indoor levels. Frequent use of the fireplace for heating at this site was confirmed by survey results. Elevated outdoor background concentrations may indicate the effect of this fireplace on surrounding outdoor air, and/or neighboring residences may also have had active fireplace fires.

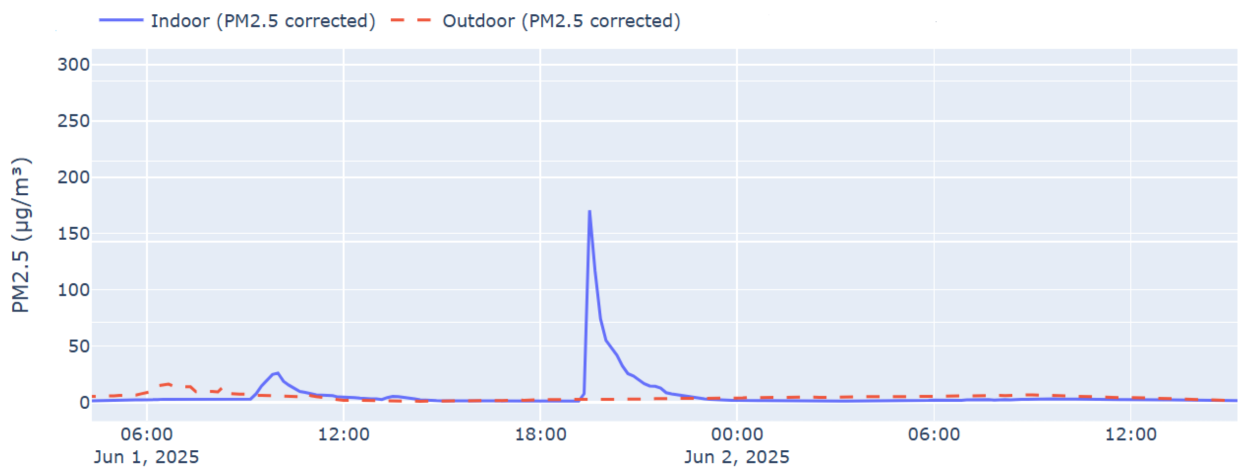

Figure 3: Indoor cooking activity observed at 7:30 pm

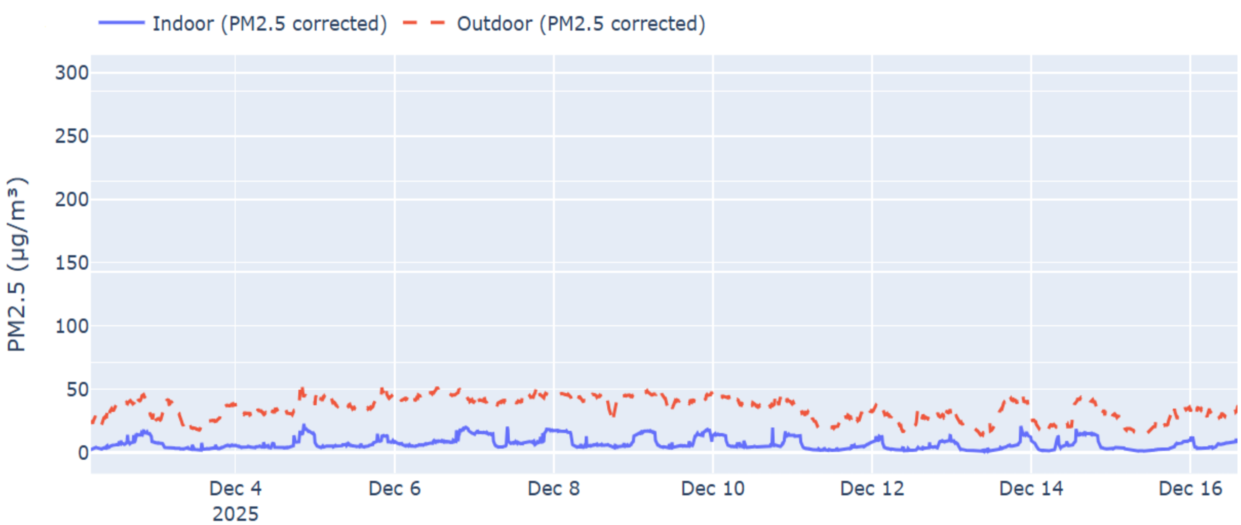

Figure 4: Indoor fireplace combustion events observed throughout early December

As discussed in the methods, the infiltration factor (F_{INF}), defined as the ratio of indoor to outdoor pollutant concentration, was estimated using long-term $PM_{2.5}$ measurements at each site, as presented previously in Table 4. Infiltration factors were determined during steady-state periods when outdoor concentrations significantly exceeded indoor concentrations. The calculated infiltration factors were highly variable throughout the year, with more variation in the winter, and higher values in the summer. This may have been due to more frequent window opening activity during the summer. Although this study did not measure real-time infiltration, we expect it to be higher in the winter due to stack effect (California climates have larger indoor/outdoor temperature differences in the winter), and in fall/spring windy periods, but not higher in the summer as we see in the infiltration factor time series data. It is likely that the higher summer infiltration factor is due to occupant behavior of opening windows. Figure 5 shows a full year of measured data along with the calculated infiltration factor for one representative home.

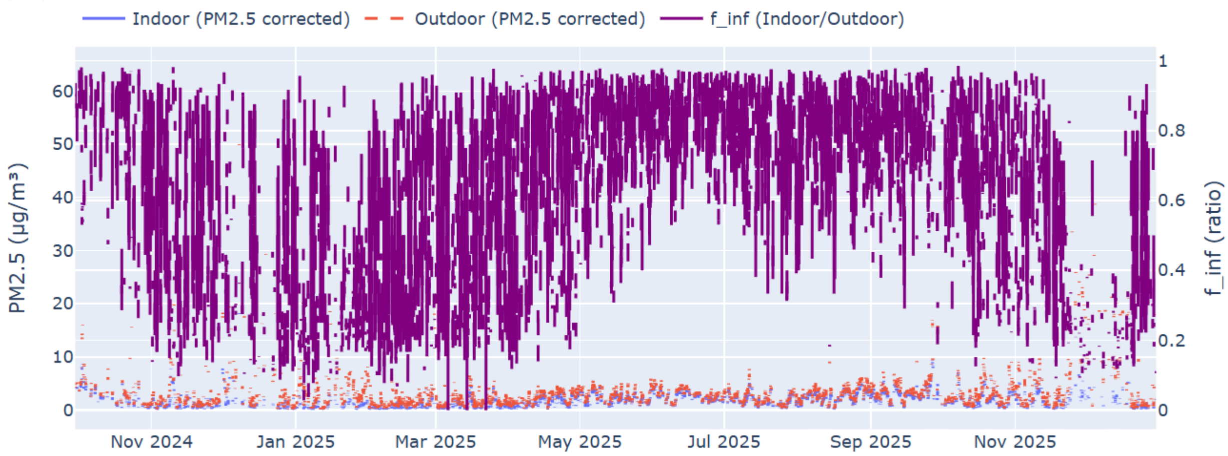

Figure 5: Seasonal variation of steady-state $PM_{2.5}$ measurements and calculated infiltration factor in one representative home

We expected to see a correlation between infiltration factor and blower-door-derived air change rate, but we did not see any strong correlation, see Figure 6. The slight negative trend line through the data is counter intuitive.

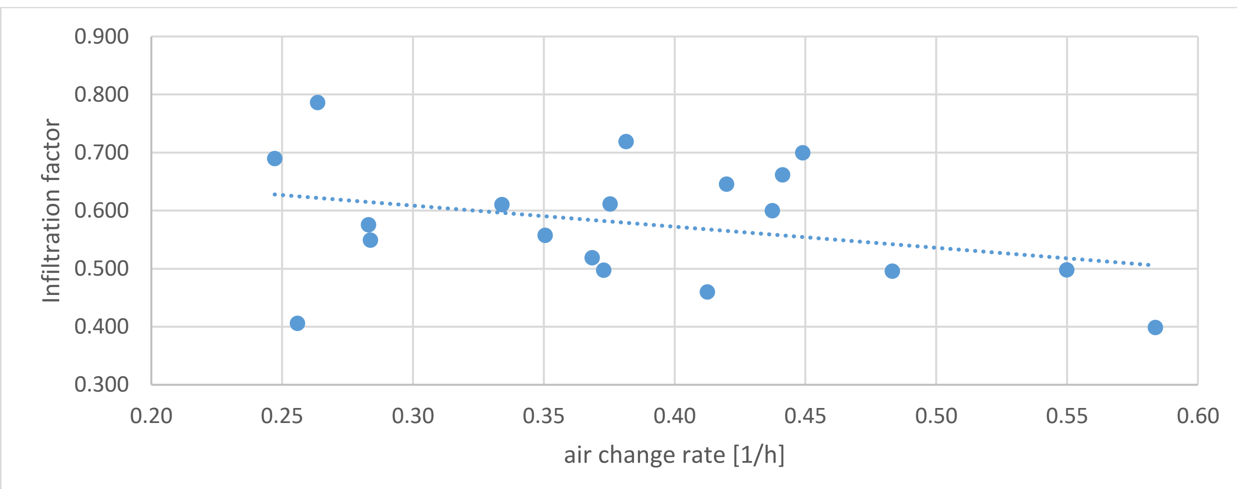

Figure 6: Infiltration factor by blower-door-derived average air change rate

Despite the lack of correlation between infiltration factor and average air change rate, at Site 15, the data showed a distinct increase in indoor $PM_{2.5}$ concentration just before 10:00 am during an outdoor wildfire smoke event. We presume a window was opened when the indoor concentration quickly rose to meet the outdoor concentration. The indoor and outdoor concentrations tracked each other until approximately 8:00 pm when the window was presumably closed and indoor concentration began to fall below the outdoor concentration, see Figure 7.

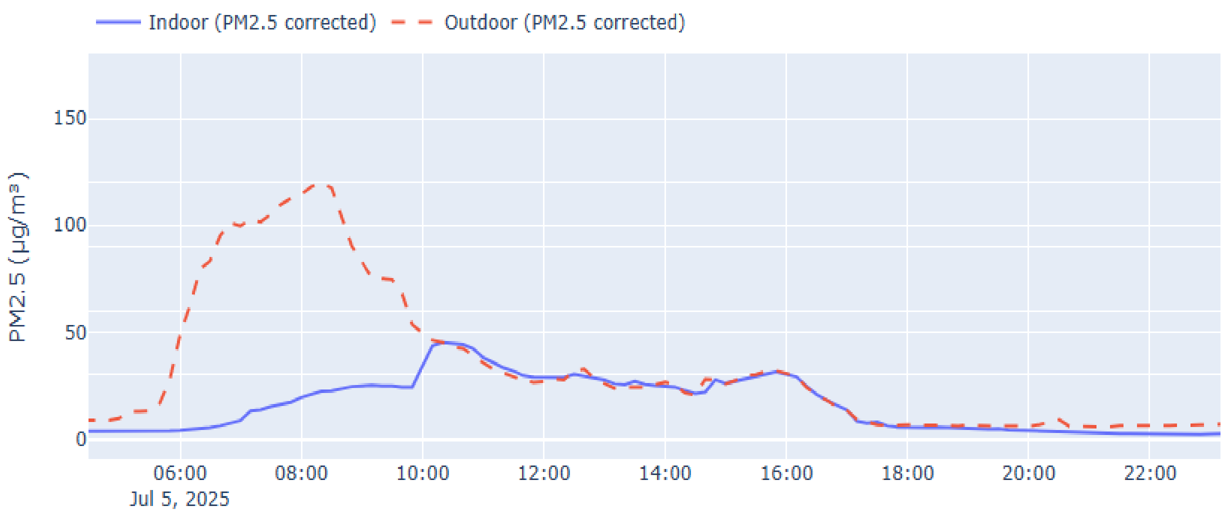

Figure 7: Indoor and outdoor $PM_{2.5}$ concentration at site 15 on July 5, 2025

We analyzed the data to determine the particle decay rate (λ) as described in the methods section, and the results are shown in Table 5. Also shown in the table are the air infiltration rate (a), the calculated particle deposition rate (k = λ - a), the number of decay events used to calculate the particle decay rate and the standard deviation of the set of decay rates per site. The standard deviation is surprisingly consistent, between 0.7 and 1.2, and not correlated with the number of decay events, suggesting that even the smaller number of decay events captured the variation in particle decay rate and that it is driven by random fluctuations that affect all homes similarly rather than house specific.

Table 5: Blower-door-derived air infiltration (a), particle decay rate (λ), calculated particle deposition rate (k), number of decay events, and standard deviation of the particle decay rate for each site

Site ID	a [1/h]	λ [1/h]	k [1/h]	Number of decay events	Standard deviation of λ
1	0.4	1.1	0.7	54	1.1
2	0.2	1.0	0.8	605	1.0
3	0.5	1.9	1.4	31	1.0
4	0.4	1.8	1.5	161	1.1
5	0.5	1.5	1.0	88	0.9
6	0.4	2.0	1.6	64	1.2
7	0.6	1.1	0.5	102	0.7
8	0.4	1.7	1.3	204	1.2
9	0.4	1.9	1.5	29	1.2
10	0.4	2.0	1.6	347	1.1
11	0.4	1.8	1.4	108	1.0
12	0.3	1.5	1.2	61	1.2
13	0.3	1.7	1.4	42	1.1
14	0.4	1.6	1.3	176	1.2
15	0.3	1.4	1.1	49	1.2
16	0.4	1.5	1.1	50	1.2
18	0.4	2.3	1.9	175	1.2
19	0.3	1.5	1.2	87	1.0
20	0.3	2.2	1.9	39	1.2
Average	0.4	1.7	1.3	130	1.1

We found the calculated values for the particle deposition rate (k) are high compared to those cited in literature; values between 0.5 and 0.05 were expected, while an average value of 1.3 was calculated by subtracting the air infiltration rate (a) from the particle decay rate (λ). All the homes in this study had forced air furnaces that cause higher decay rates due to air filtration when the system is running. All homes also had fireplaces, which cause increased infiltration when they are actively being used. In addition, 25% of the homes were pressurized (3 homes) or depressurized (2 homes) by more than one pascal when the HVAC system fan was running. This causes increased infiltration during periods when the HVAC system is running. The values are shown by site in Figure 8 with standard deviation plotted as the uncertainty in particle decay rate. Though air leakage rates are highly variable throughout the year given the variation in outdoor temperature and wind conditions that drive infiltration, the consistent bias in this data indicates that particle decay rates for this set of homes may be high or the average inferred natural air change rate values may be lower than the actual average.

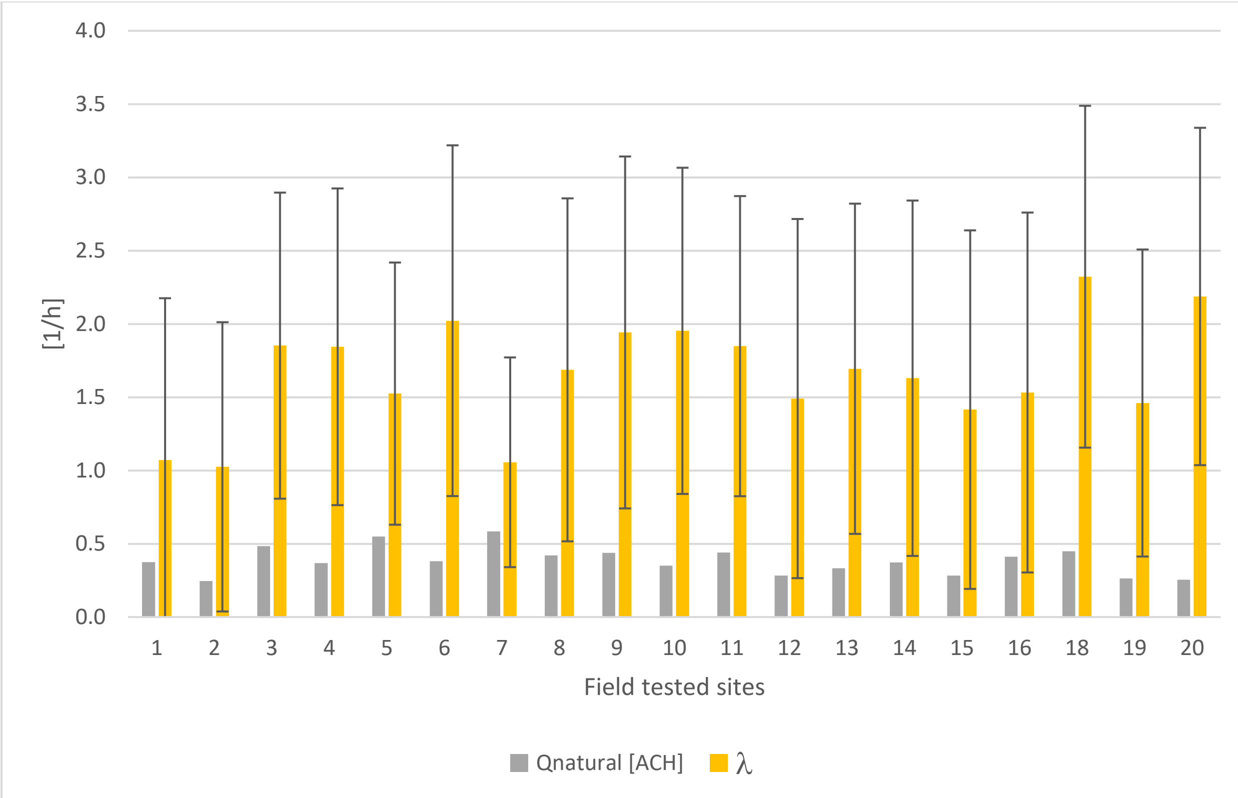

Figure 8: Particle decay rate (λ) with its standard deviation and blower-door-derived natural air change rate (a) by site

Conclusions

The lack of a clear correlation between blower-door-derived air exchange rates and $PM_{2.5}$ infiltration factors highlights the complexity of pollutant transport; governed not only by air infiltration but also by leakage pathways, occupant activities, indoor surface properties, and building operation (*i.e.* opening windows). Averaging the infiltration factor over a year and comparing it to blower-door-derived average infiltration estimates did not yield conclusive results.

Similarly, we did not find a correlation between indoor particle decay rate and the average blower-door-derived average infiltration estimate, probably because of short time-duration infiltration variation driven by wind and indoor/outdoor temperature differentials.

However, the observation of rapid increase in indoor $PM_{2.5}$ when a window was opened during a smoke event, reinforces the importance of controlling unintended air pathways. During periods of poor outdoor air quality homes with tighter building envelopes can provide meaningful protection by limiting the ingress of particulate pollution.

It is important to note that pollutants not only come from outside but are also generated inside the building envelope (*i.e.* when cooking). Reducing outdoor air infiltration without adding mechanical ventilation can negatively impact indoor air quality due to indoor pollutant sources.

Ultimately, the results of this study were inconclusive, demonstrating that the nuanced relationship between building envelope tightness and indoor air quality. is strongly influenced by short time-scale events. Further study should consider these temporal aspects, rendering air infiltration and pollutant transport metrics over a short time-scale rather than averaging over a year.

Acknowledgments

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Appendix

Table 6 shows a summary of infiltration factors from the literature review performed by Diapouli (2013). Across occupied residences, $PM_{2.5}$ infiltration factors (F_{INF}) generally cluster between 0.6 and 0.7, regardless of whether steady-state, dynamic, or surrogate methods are used. When applied to the same dataset, dynamic and surrogate approaches often yield closely aligned results, providing confidence in the use of simplified methods when long-term continuous monitoring data are unavailable.

Table 6: Reported $PM_{2.5}$ infiltration factors (F_{INF}) from residential studies

Study (year)	Location / setting	F_{INF} ($PM_{2.5}$)	Method	Description of test home(s)
Dockery & Spengler (1981)	Harvard Six-City Study (U.S.)	0.7	Steady-state	Occupied residences; long averaging periods
Koutrakis et al. (1992)	New York State ERDA	0.49	Steady-state	Occupied residences; AER measured
Ozkaynak et al. (1996)	Riverside, CA (PTEAM)	0.71	Steady-state	178 single-family homes; 12-h samples
Williams et al. (2003)	North Carolina (RTP Panel)	0.45	Steady-state	37 occupied residences
Meng et al. (2005b)	RIOPA (3 U.S. cities)	0.35–0.69	Steady-state	212 residences; multiple model forms
Wichmann et al. (2010)	Stockholm residences	0.42	Steady-state	Homes only; 2-week mean PM2.5
Allen et al. (2003)	Seattle, WA	0.65 ± 0.21	Dynamic	44 occupied residences; hourly data

Polidori et al. (2007)	Los Angeles retirement homes	0.47	Dynamic	Elder-care residences
Diapouli (2008)	Athens, Greece	0.71	Dynamic	7 homes and 1 office; warm/cold seasons
Kopperud et al. (2004)	Redwood City, CA	0.47–0.70	Experimental	Single residence; 5-day campaign
Sarnat et al. (2002)	Boston, MA	0.84	Surrogate (sulfate)	6 residences; sulfate tracer
Hänninen et al. (2004)	Four European cities	0.59–0.70	Surrogate	290 residences; one sample per home
Noullett et al. (2010)	Prince George, Canada	0.53–0.57	Surrogate	Children's personal exposure