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Research Article

Determining Infiltration Rates and Predicting Building Occupancy Using CO_2 Concentration Curves

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Demand controlled ventilation (DCV) reduces energy loss by reducing the air exchange flow rate to the minimum required to maintain acceptable indoor air quality (IAQ). DCV commonly uses carbon dioxide (CO_2) as a proxy for human activity and increases the ventilation rate once a preset CO_2 threshold is exceeded. Significant improvements over threshold based ODV strategies are possible if the natural infiltration rate of the building is measured and the occupancy schedule determined by analysing the CO_2 concentration continuously. These calculated parameters allow mathematical modeling of the ventilated space and the determination of future CO_2 concentrations and allow prediction of future ventilation demands. The natural infiltration rate and the onset and duration of vacancy periods in a residential dwelling were determined by analysing CO_2 concentration data. Concentration declines which fit an exponential decay curve with a correlation coefficient >0.90 identified all vacancy periods. The measured natural infiltration rate was found statistically correlated with average wind speed. A dynamic predicted occupancy map was constructed that has the potential to facilitate significant energy savings via deferred ventilation and intelligent cooling and heating strategies.

1. Introduction

The energy required for heating, ventilation, and air conditioning (HVAC) of buildings can be reduced by minimizing uncontrolled air infiltration through leaks in the building envelop. The natural air infiltration rate of older North American residential structures is large enough that IAQ is seldom a problem. However, the continuous air and vapour barrier installed in new construction has necessitated the introduction of mechanical ventilation systems to remove excess moisture and maintain acceptable IAQ. This mechanical ventilation is often provided by a heat or energy recovery ventilator (HRV, ERV) which is sized based on the number and types of rooms and provides a fixed quantity of air exchanges per hour (ACH). This static approach results in excessive ventilation and energy waste during periods of low occupancy.

DCV systems reduce these losses by varying the ventilation rate as needed to maintain a minimum acceptable IAQ. These systems typically use CO_2 as a proxy for IAQ and trigger additional ventilation once a threshold is exceeded. Unfortunately, using a gas sensor as a demand switch wastes the opportunity to derive additional information from the continuous analysis of CO_2 concentration, including the natural infiltration of the space being ventilated and its patterns of occupancy. In order to enable intelligent DCV strategies that can reduce energy waste by supplying heating and cooling only when necessary and eliminate overventilation, the characteristics of the building and its usage patterns are required. The natural infiltration rate is required to determine the current CO_2 generation rate and to predict future CO_2 concentrations. Decisions to defer ventilation or plan a heating and cooling schedule require a knowledge of upcoming occupancy patterns. While the occupancy schedule could be entered manually by occupants similar to programming a thermostat, the infiltration rate would require a gas diffusion study. The ideal control system would learn by analysing real-time CO_2 concentration data and require minimal user setup. Currently available control systems for residential use do none of this, using simple on and off controls and a humidistat. Unfortunately, humidity is a poor proxy for human generated pollutants because it varies slowly as weather patterns change and with the seasons except for short periodic spikes driven by bathroom showers. Furthermore, natural infiltration rates are seldom known and the standard blower door tests provide leakage data at 50 Pa which far exceeds normal conditions.

To confirm the assumption that an HVAC control system can learn building occupancy and calculate the natural infiltration rate from an analysis of CO_2 concentration data, the author equipped a residential dwelling with a modified ventilation system and instrumentation for the continuous recording of CO_2. The data was used to generate a weekly occupancy map and the natural infiltration rate was calculated every time the dwelling became vacant.

This paper presents the results of analysing the CO_2 concentration curves, the generated vacancy map, and the correlation between natural infiltration and wind speeds and its implication for improved HVAC control systems.

2. Background

Occupant comfort is affected by temperature, humidity, odours, and CO_2. The permissible exposure limit for CO_2 is 5000 ppm [1] which far exceeds levels that will be encountered in a home. Yawning is not caused by CO_2 even at concentrations of 30,000 ppm [2, p.384]; however, 20% of visitors are dissatisfied with body odours at CO_2 concentrations of 1880 ppm [3]. CO_2 generation is a function of the quantity and size of the occupants and their activity levels. CO_2 also correlates proportionally with pollutants such as body odour and in a more general manner with cooking, cleaning, or smoking that produce volatile organic compounds (VOC), moisture, and particles. This makes CO_2 a useful proxy for IAQ and for controlling ventilation systems.

Since CO_2 is nonreactive in the indoor environment and the dwelling volume is a constant, the total mass of CO_2 and therefore its concentration can change only if more is added by human activity or if it is diluted via air exchange from outside. The portion of CO_2 concentration change over time within the dwelling due to human activity is the CO_2 generation rate divided by the total volume of the ventilated area. Assuming that the indoor air is well mixed and therefore the concentration throughout the building is a constant at any instant, the rate of concentration change due to outgoing exhaust air is the mechanical ventilation rate times the indoor concentration divided by the room volume. Similarly since the outdoor concentration is approximately a constant, the change due to incoming fresh air is the mechanical ventilation rate times the outdoor CO_2 concentration divided by the room volume. This is expressed as a differential equation:

$$\frac{dC(t)}{dt} = \frac{R}{V}\left(C_a - C(t)\right) + \frac{G}{V}, \tag{1}$$

where $C(t)$ is indoor concentration of CO_2 at time t (mass/volume), R is mechanical ventilation rate (volume/time), V is dwelling volume, C_a is ambient atmospheric CO_2 concentration (mass/volume), and G is CO_2 generation rate by occupants (mass/time).

Separating the variables and integrating dt from zero to t and $dC(t)$ from $C(0)$ to $C(t)$ we obtain:

$$C(t) = C_a + \frac{G}{R} + \left(C(0) - C_a - \frac{G}{R}\right)e^{-(R/V)t}, \tag{2}$$

Figure 1: Canadian home built in 2003.

where $C(t)$ is indoor concentration of CO_2 at time t (mass/volume) and $C(0)$ is initial indoor CO_2 concentration (mass/volume).

When all occupants vacate a dwelling, the remaining CO_2 can be used as a tracer gas to measure the natural infiltration rate. When the house is vacant, G is zero and the CO_2 concentration is a decaying exponential asymptotic to C_a. The beginning of the exponential decay marks the onset of vacancy and the natural infiltration rate of the dwelling is its volume divided by the time constant of the decaying exponential.

The CO_2 generation rate of twenty adults between 21 and 28 years of age, standing and sitting at a desk, was found to average 0.24 L/min and 0.18 L/min, respectively [4]. Assuming that household activities such as standing at a kitchen counter or watching television require similar effort, the CO_2 generation rate for three adults, (3), would be 79.1 g/hr. Substituting this into (2) with large t and a natural infiltration rate of 80 m^3/hr yields (4). Therefore, the maximum CO_2 concentration in a well-mixed home with leakage of 80 m^3/hr and three low activity adults would be 1175 ppm:

$$G(t) = 3 \times 0.24 \times 60 \times \frac{41.01}{22.4} = 79.1\ \text{g/hr}, \tag{3}$$

$$C(\infty) = 400 + \frac{79.1}{80 \times 1.2754} \times 1000 = 1175\ \text{ppm}. \tag{4}$$

3. Methodology

Testing was performed on an occupied two-story, 650 m^3, wood-framed home, Figure 1, built to Canadian residential standards in 2003. The air change rate with 50 Pa depressurization, η_{50}, was 2.55 air changes per hour (ACH). The maximum flow rate of the HRV was 385 m^3/hr with fresh air ducts into bedrooms and living areas and return ducts in bathrooms and kitchen. The kitchen and bathrooms were equipped with dedicated exhaust fans and operable windows.

The HRV unit was modified for computer control of recirculation and fan speed. A Figaro K30 nondispersive infrared (NDIR) CO_2 sensor was installed in a central sampling device for differential measurements between the indoor and outdoor air streams. Figure 2 shows the HRV unit with the

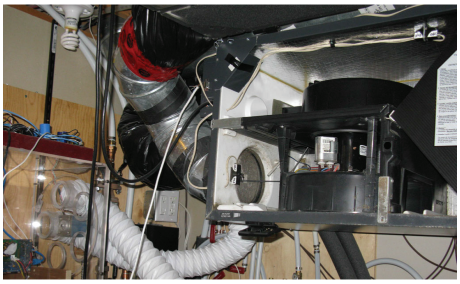

Figure 2: HRV and air sampler.

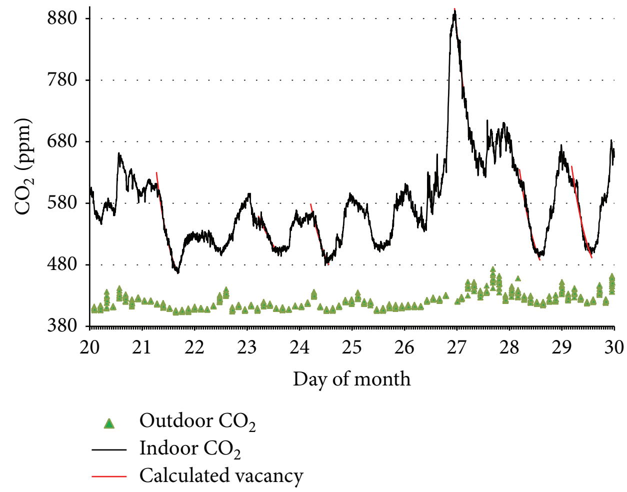

Figure 3: Estimated vacancy periods overlaid on actual data.

access door open. The translucent box to the left of the HRV is the air source selector which also contains the NDIR sensor.

The CO_2 concentration was measured at the return duct every 180 seconds while the HRV recirculated air at 153 m^3/hr. Every 2.5 hours recirculation was disabled and fresh air was pumped into the building at 385 m^3/hr. Once the fresh air readings stabilized the CO_2 concentration was recorded and the system reverted to recirculation at 153 m^3/hr. All measurements were logged into a database.

A moving window of 200 CO_2 concentration values, corresponding to 8.3 hours, was curve-fit to a theoretical decay by subtracting the background CO_2 concentration from each datum and then taking its natural logarithm. The linearised data were then fit to a straight line using the least squares method. The window was advanced one data point at a time until the correlation coefficient R^2, calculated as per (5), peaked at a value ≥0.90 marking the beginning of a vacancy period. The window was further advanced sequentially until R^2 dropped below 0.50, marking the end of the vacancy period. Each exponential decay meeting the criteria $R^2 > 0.90$ was then mapped into one-hour time slots to produce an occupancy map. The map was then compared with personal notes from the occupants for verification:

$$\begin{aligned}\text{slope} &= \frac{\sum xy - \sum x \sum y}{\sum x^2 - \sum x \sum x},\\ \text{intercept} &= \frac{\sum y}{n} - s\frac{\sum x}{n},\\ \text{correlation} &= 1 - \frac{\sum (y - i - xs)^2}{\sum (y - \sum y/n)^2},\end{aligned} \tag{5}$$

where x is seconds elapsed from start of window, y is natural log of CO_2 concentration, and n is number of measurements in window period.

A Davis Vantage Pro 2 weather station positioned 4 m above ground level and 5 m from the home was used to record local meteorological data.

4. Results

Sequences of exponential CO_2 decline were identified and the curves they were fit to, shown as red segments in Figure 3, were superimposed on a graph of actual indoor and outdoor CO_2 concentrations. These overlays were generated using the equation calculated when the correlation coefficient was maximal and used to visually verify the fit.

Table 1 lists the start and end of potential vacancy periods, correlation with a pure exponential decay, decay time constant, lowest CO_2, and whether the identification of vacancy was correct.

The vacancy map in Table 2 shows a weekly calendar with 24 hourly time slots. Each period shows the CO_2 concentration at the end of the period. Cells with multiple values represent multiple vacancies during the same time slot, over the five-week observation period.

5. Discussion

Setting the threshold for correlation to $R^2 \geq 0.90$ identified all true vacancies and included three false positives.

Using decays where $R^2 \geq 0.95$, the 95% confidence interval for the mean of the decay constant during vacancies is (8.5, 11.5) hours with a standard deviation of 2.3 and mean of 10 hours.

Low wind speeds of 4 kmh yielded an infiltration rate of 650 m^3/12.2 = 53 m^3/hr. The mean time constant of 10 hours represents an infiltration rate of 650 m^3/10 = 65 m^3/hr.

The infiltration rate was too low to return the indoor CO_2 concentration to background levels for short vacancy periods so some vacancies would have been missed had the identification been based on absolute levels.

Table 3 shows a variation in infiltration rate with wind speed. The correlation between decay constants and average wind speed during the measurement period was significant with a Pearson correlation coefficient of −0.833 and a P value of 0.001. Figure 4 shows a negative correlation between the time constants and average wind speed which is expected. Wind direction is also a factor in asymmetrical houses as is turbulence [5–7]. The low end of the infiltration rate range can be used to conservatively predict CO_2 and the end of a vacancy period, although if a wind sensor was installed the correlation could provide a better guess.

Table 1: Vacancy periods identified via CO_2 analysis.

Fit R^2	TC (h)	Start (m-d hh:mm)	End (m-d hh:mm)	Low CO_2 (ppm)	Wind (kmh)
0.9811	6.0	Jan-21 07:24	Jan-21 16:43	466	15.2
0.9178	15.3	Jan-23 05:10	Jan-23 14:41	495	9.7
0.9460	7.6	Jan-24 05:46	Jan-24 13:16	479	9.0
0.9817	12.2	Jan-26 22:55	Jan-27 06:33	676	4.1
0.9614	7.8	Jan-28 04:34	Jan-28 13:52	493	9.7
0.9330	7.9	Jan-29 04:27	Jan-29 13:40	497	8.7
0.9593	9.9	Jan-30 05:00	Jan-30 14:23	531	3.0
0.9291	6.3	Jan-31 02:40	Jan-31 12:26	489	18.7
0.9586	7.0	Feb-01 06:04	Feb-01 15:29	502	15.6
0.9800	7.4	Feb-03 21:13	Feb-04 06:26	483	16.1
0.9804	7.1	Feb-05 04:58	Feb-05 13:59	470	15.9
0.9560	17.9	Feb-06 06:47	Feb-06 16:25	517	4.7
0.9473	13.6	Feb-07 05:23	Feb-07 14:27	527	3.1
0.9451	9.0	Feb-07 19:38	Feb-08 04:48	475	19.1
0.9617	3.4	Feb-11 04:21	Feb-11 13:54	432	8.5
0.9625	9.8	Feb-12 06:06	Feb-12 15:14	488	5.7
0.9341	8.6	Feb-14 05:06	Feb-14 13:43	470	12.4
0.9373	11.6	Feb-15 04:34	Feb-15 14:44	474	9.2
0.9460	06.7	Feb-18 05:48	Feb-18 15:10	452	11.6
0.9482	15.8	Feb-21 02:50	Feb-21 12:15	522	10.4
0.9631	13.2	Feb-22 04:39	Feb-22 14:29	498	4.5
0.9714	12.5	Feb-25 06:42	Feb-25 15:53	498	3.5
0.9532	09.6	Feb-26 04:42	Feb-26 13:49	471	5.5
0.9486	16.6	Mar-05 02:46	Mar-05 12:35	475	18.6
0.9795	12.7	Mar-06 07:21	Mar-06 16:24	456	5.9
0.9791	11.4	Mar-07 05:51	Mar-07 15:02	468	4.0
0.9336	31.5	Mar-09 22:52	Mar-10 09:25	568	10.1

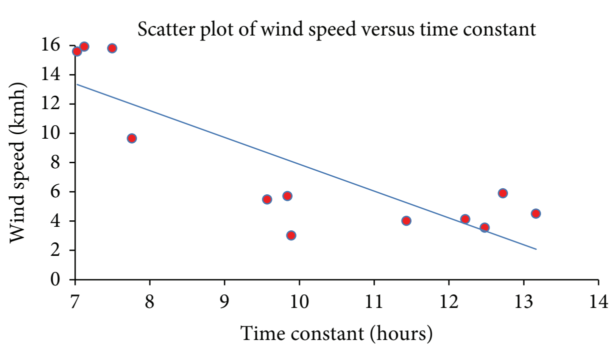

Figure 4: Correlation between wind speed and natural infiltration rate.

The maximum mechanical ventilation rate of the HRV was 384 m^3/hr; therefore, natural infiltration was approximately 17% of what the HRV was capable of providing. This natural leakage rate prevented interior CO_2 levels from exceeding 710 ppm during the observation period with one exception during a gathering of many people where it reached 880 ppm. Three adults engaged in light activity would have been expected to ultimately produce CO_2 concentrations levels of approximately 650 ppm.

Periodic variation in outside CO_2 concentrations, **Figure 3** lower green line, was correlated with changes in indoor concentrations. The intake and exhaust vents from the HRV were installed as per building code but this resulted in mixing of the air streams that varied with atmospheric conditions. To improve the accuracy of outdoor readings, an extension duct was added to the exhaust vent which greatly reduced mixing. Random mixing made differential measurements inaccurate and resulted in missing most vacancy periods because of lower R^2 values. Since the NDIR sensor drift was negligible, the analysis was based solely on absolute indoor concentrations.

During the observation period, CO_2 concentrations never exceeded 710 ppm with three occupants indicating that the greatest saving from DCV would come from disabling fresh air intake most of the time.

A control system which has learned the occupancy map and average infiltration rate over a period of a few weeks could be implemented as follows.

If the CO_2 rises above a threshold then look ahead to the next hourly time slot. If the probability of vacancy exceeds 50%, calculate the CO_2 concentration at the end of the projected vacancy using the average infiltration rate. If this is less than the threshold, then do not introduce fresh air.

Table 2: Vacancy map for $R^2 \geq 0.93$.

Hour	Sun.	Mon.	Tue.	Wed.	Thu.	Fri.	Sat.
1	13	0	0	0	14	0	29
2	13	0	0	0	14	0	29
3	13	0	13	0	29	0	29
4	13	0	13	0	29	0	29
5	13	25	**50**	0	29	29	29
6	13	38	**50**	13	**71**	29	29
7	13	**50**	**63**	25	**71**	43	29
8	0	**63**	**63**	38	**71**	43	14
9	0	**63**	**63**	38	**71**	43	14
10	0	**63**	**63**	38	**71**	43	14
11	0	**63**	**63**	38	**71**	43	0
12	0	**63**	**63**	38	**71**	43	0
13	0	**63**	**63**	38	**71**	43	0
14	0	**63**	**50**	38	**57**	43	0
15	0	38	13	38	29	43	0
16	0	38	13	25	14	14	0
17	0	13	0	25	0	0	0
18	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0
20	0	0	0	0	14	0	0
21	0	0	0	0	14	0	0
22	13	0	0	0	14	0	0
23	13	0	0	0	14	0	29
24	13	0	0	0	14	0	29

The bold values indicated the periods of vacancy.

Table 3: Wind speed versus time constant.

Wind (kmh)	TC (h)	R^2	Infiltration (m^3/h)
4.1	12.2	0.982	53
9.7	7.8	0.961	84
3.0	9.9	0.959	66
15.6	7.0	0.957	92
15.8	7.5	0.979	87
15.9	7.1	0.979	91
5.7	9.8	0.963	66
4.5	13.2	0.963	49
3.5	12.5	0.971	52
5.3	9.6	0.953	68
5.9	12.7	0.979	51
4.0	11.4	0.979	57

Scenario 1. The CO_2 concentration is 800 ppm above outdoor levels at 7:30 a.m. Monday morning, and the threshold for ventilation is 600 ppm above background levels. Should mechanical ventilation be used to bring this down by 200 ppm?

The Monday 8 a.m. to 1 p.m. time slot was vacant the last five weeks without exception; the probability of vacancy is estimated at 100%. Anticipating 5 hours of vacancy and time constant of 2.6 hours, CO_2 should decayed to $800 * e - (5/2.6) = 117$ ppm above outdoor levels. This is negligible and well below the 600 ppm threshold. Therefore, fresh air ventilation at 7:30 is not necessary and will not be required until some time after 1 p.m.

Scenario 2. Assume there will be a 1 hour vacancy, and that the probability is 75% that it will occur between 8 a.m to 9 a.m, otherwise conditions are identical to Scenario 1.

Since there is a greater than 50% chance of upcoming vacancy the system expects CO_2 should decay to $800 * e - (1/2.6) = 544$ ppm above outdoor levels. This is just below the threshold, so ventilation can be deferred.

Had this been a newer home with a tighter building envelop and a time constant of 12 hours, the system would expect CO_2 to decay to $800 * e - (1/12) = 736$ ppm above outdoor levels. In this case, fresh air would be provided until CO_2 levels returned to a concentration that could be reduced to 600 ppm by natural infiltration during the remainder of the vacancy period. Alternatively, the fan could be run at a lower speed sufficient to augment natural infiltration such that 600 ppm was reached just as occupants were expected to return.

The major energy savings for such a control strategy would come from the following:

(1) automatically setting occupied and unoccupied temperatures based on the vacancy probability map;

(2) disabling fresh air ventilation when not needed, which in this case, for a threshold of 1000 ppm, would have been all the time;

(3) disabling fresh air ventilation before vacancy periods, which for a 9–5 work schedule might eliminate an hour of fresh air each work day depending on the initial concentrations.

6. Conclusion

Periods of vacancy in residential homes were successfully detected using occupant generated CO_2 as a tracer gas and following the decay in concentration. An accurate occupancy map was generated, indicating the probability and duration of future vacancies. The upper and lower limits of natural infiltration were determined from the time constant of the decay and statistically correlated with wind speed as expected.

The control system for a residential DCV system could be enhanced to use these parameters to optimize energy losses by minimizing excess ventilation while maintaining IAQ. The vacancy map could also be used to automatically program heating and cool systems.

Conflict of Interests

The author declares that there is no conflict of interests regarding the publication of this paper.

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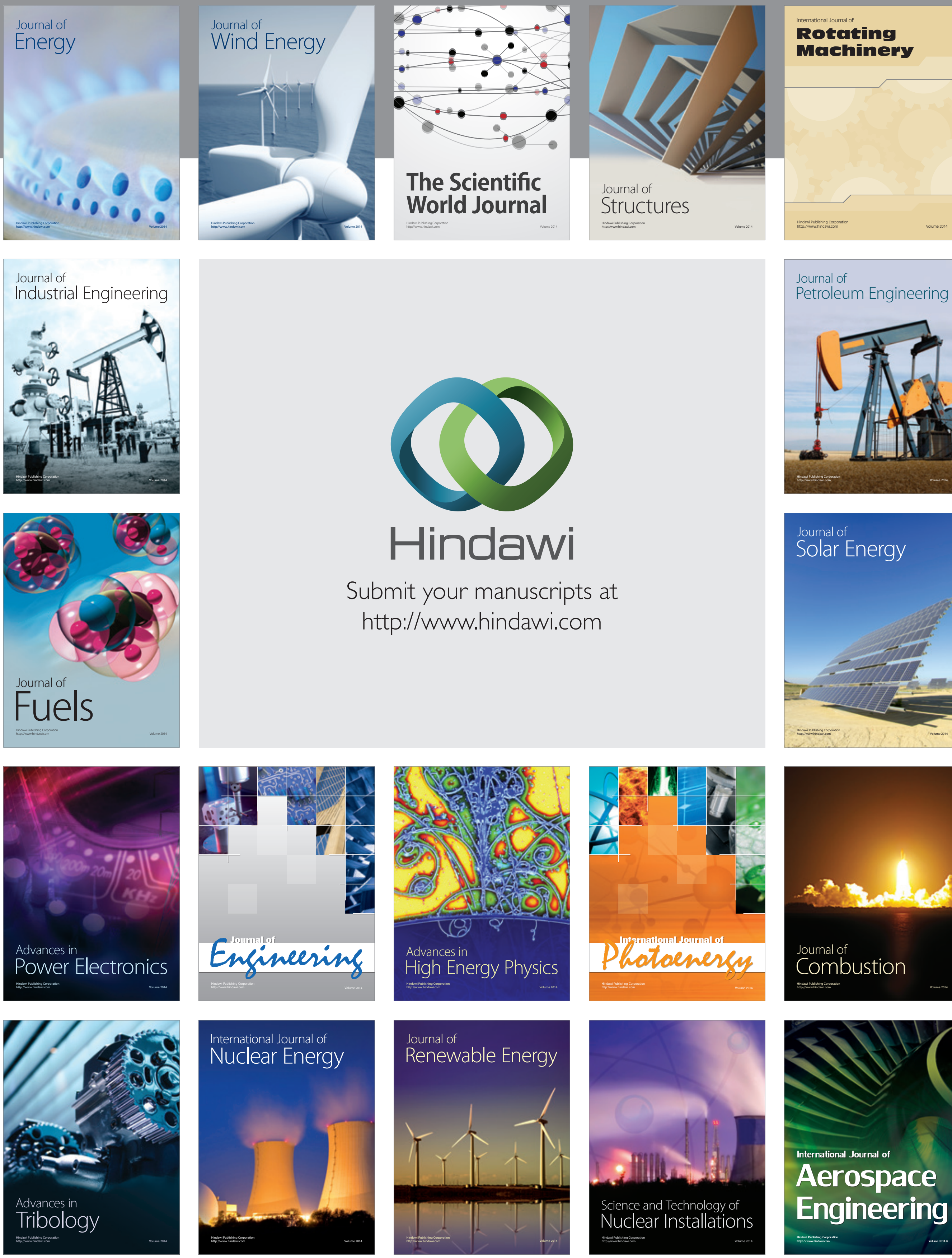
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