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Analysis of the Effects of a Swing Door Opening on Indoor Airflow Fields - An Experimental Study

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Abstract:	The interaction between the occupants and the built environments is known to influence the indoor airflow patterns significantly. Door opening, being one of the most common modes of human-introduced disturbances in a controlled environment, affects the flow fields, which can be attributable to the dispersion of airborne contaminants. The wakes, originated from the alterations in the airflow patterns, contribute to the transport of the pollutants. These wakes need to be carefully considered for system design in clean rooms, operating rooms, and healthcare environments. Therefore, the knowledge about the movement patterns of these wakes is crucial in the context of indoor air quality. A series of experiments were conducted in a controlled chamber under two different schemes of a swing door opening and three different flow regimes. These experiments were designed to study the turbulent vortices produced from door openings and their spatiotemporal propagation. The results suggest a significant effect of a door opening on the indoor airflow fields. The velocity fields demonstrate that consecutive openings under different ventilation conditions have a prolonged impact on the propagation of door-opening induced wakes farther into the test chamber. The quantification of the change in kinetic energy from door opening also shows that the level of ventilation governs the flow patterns that result from human-induced perturbation of the steady-state flow fields.
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Dear Prof. Domingo, September 11, 2021

A paper titled 'Analysis of the Effects of a Swing Door Opening on Indoor Airflow Fields - An Experimental Study' has been submitted to the Environmental Research journal. This paper highlights a series of experiments conducted in a controlled environment chamber to study the effects of a swing door movement on steady-state airflow fields under three different ventilation conditions.

Results suggest that a swing door motion significantly impacts the airflow patterns under a range of air supply rates. The transient change of the flow fields originated from the door opening and was spatially correlated as well – the door tip was associated with the greatest changes in velocity magnitude. The secondary velocity fields penetrate further into the experiment chamber when a swing door is operated for consecutive two times.

To the best of the authors' knowledge, this paper is unique and contribute to the state-of-the-art at least in three ways:

1. Using on-field experimental data, it analyses the transient patterns of alterations of velocity fields and their spatial variation as effects of a door-opening – a ubiquitous interaction between the built environment and the occupant.
2. It evaluates, insignificant detail, the effects of three different ventilation rates on the occupant induced perturbations, studying the changes in flow velocity against time.
3. It compares the kinetic energy changes resulting from the two standardized door openings under three different initial conditions in the test chamber.

As the corresponding author of this research, I attest to its originality and accuracy and do hereby certify that the author(s) have no known conflict of interest and are in full compliance with the submission declaration. I also confirm that this study did not involve human subjects.

With Warm Regards,

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Analysis of the Effects of a Swing Door Opening on Indoor Airflow Fields - An Experimental Study

Highlights:

- Significant impacts are found on the indoor air flow fields from a swing door opening.
- Spatiotemporal transient changes in the flow fields from door motion are location specific - the vicinity of the door tip was associated with the most disturbances.
- With multiple door openings, the transient effects penetrate further into the room and takes more time to return to initial condition.
- The presence of a boundary (e.g. - room wall) results in higher turbulent interaction.
- It takes more kinetic energy to overcome higher pressure differential resulting from high air supply.

Analysis of the Effects of a Swing Door Opening on Indoor Airflow Fields - An Experimental Study

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Abstract

The interaction between the occupants and the built environments is known to influence the indoor airflow patterns significantly. Door opening, being one of the most common modes of human-introduced disturbances in a controlled environment, affects the flow fields, which can be attributable to the dispersion of airborne contaminants. The wakes, originated from the alterations in the airflow patterns, contribute to the transport of the pollutants. They need to be carefully considered for system design in clean rooms, operating rooms, and healthcare environments. Therefore, the knowledge about the movement patterns of these wakes is crucial in the context of indoor air quality. A series of experiments were conducted in a controlled chamber under two different schemes of a swing door opening and three different flow regimes. These experiments were designed to study the turbulent vortices produced from door openings and their spatiotemporal propagation. The results suggest a significant effect of a door opening on the indoor airflow fields. The velocity fields demonstrate that consecutive openings under different ventilation conditions have a prolonged impact on the propagation of door-opening induced wakes farther into the test chamber. The quantification of the change in kinetic energy from door opening also shows that the level of ventilation governs the flow patterns that result from human-induced perturbation of the steady-state flow fields.

Keywords: door opening, velocity profiles, temporal patterns, indoor airflow; human-induced contamination

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1 Introduction

The emphasis on maintaining clean and healthy indoor air quality now is more important than ever when our world is plagued by a virulent pandemic. Given the fact that on average, people spend about 90% of their whole life indoors [1, 2], while the National Safety Council and the US Environmental Protection Agency (EPA) warns about indoor quality potentially getting 100 times worse than outside air [3], occupant health outcome depends largely on contaminant-free indoor air. In addition to the occupant health, the controlled environments in application, particularly in healthcare (e.g., isolation rooms, operating rooms, etc.) are very sensitive to contamination. To be specific, the effects of airborne infection due to a system malfunction is disastrous in healthcare facilities [4]. Airborne contamination is a principal source of such contamination, and hence, controlling the dispersion of airborne contaminants is invaluable to maintain the requisite level of sterility.

Contaminated airborne particles, depending on their sizes, can stay afloat for a long duration or travel a short distance with flowing air currents [5]. Thus, the engineering solution to control their spread, is to control the airflow. In recent times, the airborne pollutants, their spread, and the methods to control such spread have received renewed interests as the entire community of scientists have reoriented their focus on controlling the COVID-19 outbreak. Even though there are contradictory opinions regarding the process of COVID-19 transmission, it's largely claimed that the main route of infection dispersion is through close contact. Still, there are sufficient scientific evidences to suspect that the SARS-CoV-2 can be aerosolized in small enough sizes to travel through air, as did its closest known relative SARS-CoV-1, shown through the review of previous studies by Morawska and Cao (2020) [6]. Researchers have already established that aerosolized droplets of SARS-CoV-2 can be passive, i.e., capable of being carried by moving air [7, 8]. The on-field studies inside Wuhan Hospitals in China has demonstrated the virus's capability to diffuse indoors and travel upto 10 m airborne [9]. Thus, in order to understand the dispersion patterns of airborne microbes, and to implement ways to curb airborne contamination, it is important to understand the flow characteristics and the factors that affect indoor airflow [10, 11].

In an indoor environment, the HVAC system is designed to govern the flow, and depending on the room attributes (geometry, cleanliness requirement, etc.), the air flow fields reach a steady state, when the supply and exhaust air quantities are balanced to determine the differential pressure and directional airflow. The flow fields undergo changes under interventions from occupants like occupant movements and door opening. Researchers have been studying the effects of such intervention on indoor flow fields since a long time [12, 13, 14, 15, 16, 17, 18]. Even though the direction of airstreams are controlled generally through (de)pressurizing the chambers with respect to adjacent spaces and/or by controlling the inlets/outlets [19, 20, 21], it was shown that door opening has adverse impacts on pressurized spaces as it disrupts the isolation condition [22, 23, 24]. Kiel and Wilson (1989) demonstrated the pumping effect of a swing door that contributed to the mass exchange at both sides separated by the door [25]. Ahmed et al. (1993) studied a laboratory pressurization and demonstrated the influence of door opening on the pressurization scheme of a laboratory environment [26]. The findings form the study by Hitchings (1994) corroborate these results [27]. A study by Gustavsson (2010) revealed the creation and propagation of vortices due to door opening, altering the indoor flow fields [28]. Balocco et al. (2012) studied an ISO 5 class laminar flow operating room (OR) with a sliding door using Computational Fluid Dynamics (CFD) simulation to conclude that the opening of the door and passage of people and stretcher had significant and complex effects on the operating room flow fields. They demonstrated that the changes in the static pressure from opening the door resulted in varied energy consumption for the HVAC system [29]. Smith et al. (2013) studied another laminar flow operating room and they associated increased contamination with increased infection [30]. Frequent door openings have been related to interruption and even reversal of differential pressure leading to increased contamination rate [21]. In a computational simulation study, Mousavi et al. (2016) showed that the opening and closing of the door an isolation room can transport 5% of the isolation chamber air to the cleaner environment [24]. Bhattacharya et al. (2021) demonstrated 10% of the room air can escape through opening the door for 5s from a positively pressurized room [31]. So, it is crucial to understand the transient changes in the flow fields that leads to such outcomes from door opening, which is one of the most common interaction between the built environment and the occupants.

Now that it is established that door openings have profound impacts on the indoor flow fields, how different door openings impact the the air movements are also worth careful consideration - as Mousavi et al. (2018) showed that the impacts are different depending on the type of door, opening speed and frequency [32]. There is a debate on whether the type of door - swing or sliding, have significantly different effect on the steady state flow fields. Lee and colleagues (2016) measured interzonal volume exchange due to door opening using tracer gas and CFD to assert that in isothermal conditions, there is not much difference in terms of air exchange volume due to opening a swing door and a sliding door [33]. In another study, the results indicated reduced impact of sliding doors on the airflow pattern compared to swinging door [34]. So, to critically and holistically evaluate the effects of door opening on indoor air fields, importance should also be given to the type of door selected for the study. A study in an OR illustrated that the air flow across the door during closing a swing door was different than during opening the door, indicating a difference in flow patterns for the two movements of a swing door [35]. Eames et al. (2009) indicated the generation of a vortex at the door tip during swing motion and moving of that vortex through the middle of the room, measuring dye concentrations in a model room [17]. It was also shown in that study that a significant structure of airflow moved along the wall, implying a difference in flow behavior near wall. Mazumdar and team (2010) simulated an inpatient ward using CFD to study the effects of moving objects on airflow pattern to find that contaminant concentration was higher near the moving objects [36]. In an experimental study in office rooms and laboratories, it was found that with longer period of keeping the door ajar, the swept volume is close to being equal to that of exchange volume [11]. The incoming traffic movement to a chamber followed by a door opening has higher impacts on the door movement generated flow field, as demonstrated through experimental study by both Villafruela et al. (2016) and Bhattacharya et al. (2020) [37, 38]. Opening of doors not only affects the pressurization scheme, but can also change the thermal boundary condition of indoor space, aiding in the generation of lateral airflow movement, specifically found as the effect on displacement ventilation [39]. Using 3-dimensional velocity measurements near the door, Papakonstantis and colleagues (2018) demonstrated the movement of flow vectors during door opening and closing and explained the advection of flow vortex along the wall during opening [40]. In a two-dimensional numerical simulation study of door opening, Bhattacharya et al. (2020), showed that the opening and closing movement of the door has profound impacts on the velocity profiles and the direction of streamlines, even after the door became stationary [38]. As demonstrated through that study, the region close to the door tip was associated with the highest velocity magnitude during the door motion. It was also discussed that the flow field recorded higher speed during the closing motion compared to the opening, owing to the residual flow from the opening motion.

Barring a few, most of the published studies focused on studying door opening to assess volumetric exchange across the door to understand the contaminant transfer. Some of them provided the results combining the effects of door opening and inbound/outbound traffics. In spite of studying the door movement through different quantitative and simulation approaches (e.g. numerical simulation, tracer gas method etc.), there is a dearth of work that analyzed the door movement induced flow patterns in the space into which the door is opening using actual experimental data. Addressing that, this study has aimed to analyze the transient airflow patterns under the influence of two different movement settings of a swing door in a controlled environment. This study has used the real-time experimental data, obtained under three distinct initial conditions. The novelty of this study lies in the holistic analysis and quantification of the changes in flow properties introduced by two different door opening scenarios and the penetration of wakes from door opening.

2 Methodology

2.1 Chamber Geometry

The controlled environment chamber in UC Berkeley's Center for Built Environment was available to conduct experiments during Summer 2019. This 5.48m x 5.44m x 2.5m experiment facility, with a door of 1.98m x 0.98m at one corner had capabilities to supply air at altering rates from floor mounted grilles, overhead supply diffusers or wall mounted grille. For the experiments, air was supplied through the 0.3m x 0.3m grille mounted on wall at a height of 0.3 m from the ceiling (Figure 1) with the exfiltration arrangement through the gap around the door, which created positive pressure inside the chamber compared to the outside corridor when supply fans were on.

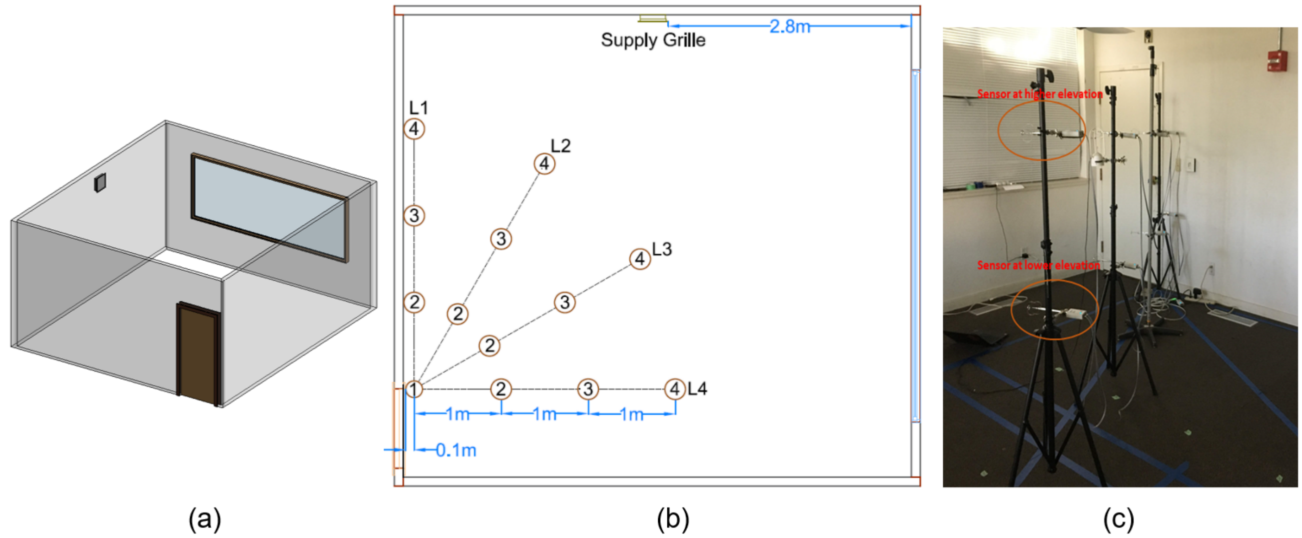


Figure 1: **(a) Chamber geometry – 3D (b) Peripheral Configuration of Sensors (c) Radial Configuration of Sensors (d) Actual Photograph from Test Chamber**

2.2 Test Setup

A series of experiments involving opening and closing of the door were conducted to obtain data on the effects of a swing door movement on the steady state indoor airflow characteristics. The planned experimental design required at least 32 sensors to collect the flow velocity through the entire room; but due to the availability of only 8 sets of sensing system, the tests were conducted in sets. The sensors were arranged along four imaginary rows, designated as L1 to L4 in Figure 1 (b). The row L1 was parallel to the closed door with a distance of 0.1 m from the wall, whereas row L4 was perpendicular to the closed door, with row L2 and L3 at angles 30 degrees and 60 degrees with row L1. Each row consisted four distinct locations where tripod-mounted sensors were placed at locations designated as 1 through 4 at two separate elevations. The first set of sensing systems were closest to the door tip being 0.1 m away from it. The following sets of sensors were placed at 1 m subsequent distances. At every location, one sensor was at the lower level, at 0.66 m above the ground, covering 1/3rd of the door height, whereas another sensor was at an additional 0.66m high from the lower level sensor elevation, covering a total 2/3rd of the door height (Figure 1 c). For ease of nomenclature, the sensing stations are designated according to their locations. For example, at row L1, the lower level sensor at the first position is identified as LL11 (the first 'L' is to indicate the lower elevation) and at row L3, the sensor at the higher elevation at position 2 is called UL3 (the letter 'U' to indicate upper elevation).

To understand the three-dimensional flow fields generated from the swing door movement, this tiered arrangement of sensors provided the possible understanding at at least two altitudes. Given the restricted availability of sensing systems, the arrangement of sensors provided an opportunity to study the evolution of wakes from the door movement until the middle of the room.

2.3 Inlet Conditions and Door Opening Events

A set of different experiments were carried out based on the door movement and steady state condition inside the chamber, depending on the supplied airflow through the inlet. Three different flow regimes were defined, as described below:

1. Still air – during this scenario, the initial steady state condition inside the experiment chamber was quiescent as the fan and the Air Handling Unit (AHU) responsible for air supply to the chamber were not operating, and the supply diffuser was shut off.

2. 70% fan – for the second type of flow regime, the supply fan and the AHU were o throttled to operate at 70% of the full capacity. After steady state condition was reached inside the chamber, the manometer reading indicated a positive pressure differential of 10 Pa between the experiment chamber and the outside.

3. 100% fan – for this inlet condition, the supply fan and AHU operated at full capacity. With 190 cfm (90 L/s)[41] air supplied through the inlet during this flow setting, the positive differential pressure between the chamber and outside was measured to be 20 Pa at steady state.

Two different door operation were used for conducting the experiments:

- Door opening and closing once - the door is opened at the first second during every repetition of each experiment for 2 seconds, held ajar for a second, followed by the closing movement for 2 seconds. The total time for a complete cycle of door opening-closing was $\sim$ 5 seconds.

- Door opening and closing twice – with the first cycle identical as opening once, the door was kept shut for two seconds before performing a second cycle of door opening and closing as before (2s opening, remained open for 1s, and closing for another 2s). The total time required for this scenario was $\sim$ 12 seconds.

As the opening and closing of the swing door, as well as the time keeping were conducted manually , the duration was generally higher than 5 s for operating the door once and higher than 12 s for operating the the door twice. Table 1 presents the average door opening time for each of the six experiment arrangements. Every experiment was repeated 30 times and each time the velocity sensors recorded the data for 60 seconds. This way, a large number of observations were obtained to ascertain statistical consistency of the measurements.

Table 1: **Experiment Setups**

	Average Door Operation Time (Std. Dev.)	
Door Opening Once	Still Air (Test 1)	5.38 ($\sigma = 0.21$)
	70% Fan (Test 2)	5.52 ($\sigma = 0.82$)
	100% Fan (Test 3)	5.42 ($\sigma = 0.39$)
Door Opening Twice	Still Air (Test 4)	12.33 ($\sigma = 1.14$)
	70% Fan (Test 5)	12.49 ($\sigma = 0.24$)
	100% Fan (Test 6)	12.48 ($\sigma = 0.19$)

2.4 Sensing Instruments

During the experiments, omnidirectional hotwire anemometer air speed sensing systems AirDistSys 5000 manufactured by Sensor Electronic, Poland were utilized. These sensors consist of a transducer, a converter and a transmitter. SensoAnemo5100LSF is a transducer with omnidirectional (spherical) sensor with a diameter of 2mm, measurement speed range of 0.05 to 5 m/s, 0.02 m/s or 1.5% of reading accuracy of measurement, directional sensitivity error for v> 2 m/s of 2.5% of the actual value. The data logging frequency of these sensors was one data point every two second. The sensor, designed for low speed velocity measurement at indoor conditions, has wide range of frequency response and high sensitivity. The transducer measures instantaneous mean air speed and standard deviation of air

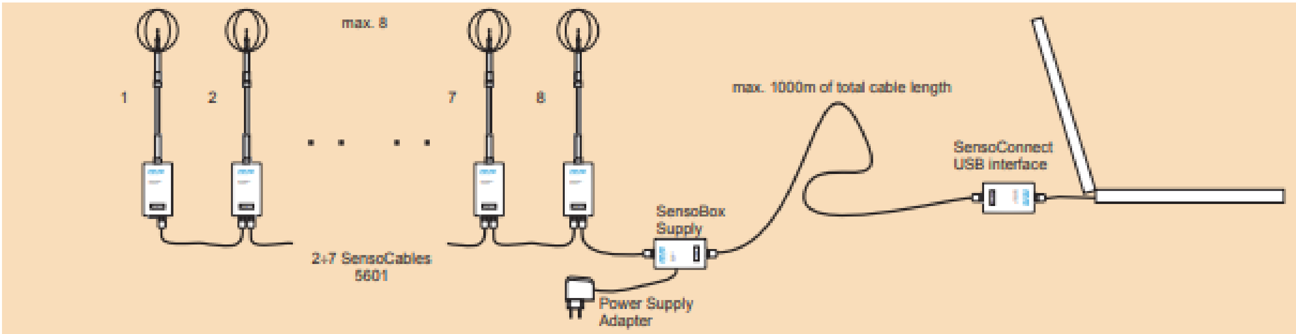


Figure 2: **Omnidirectional Sensing System Schematic**

speed. The probes in all the sensors are connected to SensoDACon series 5400 converter which allows to convert a digital signal with Sensoanemo transducer to the analog signal of velocity as output which is recorded in the system through wireless connection using SensoBee transmitter and receiver. Figure 2 shows an example configuration of the measurement units, as provided in the user manual (`http://www.sensor-electronic.pl/pdf/KAT_AirDistSys5000.pdf`). A number of previous studies have used these sensors [42, 43, 44, 45, 46], and thus, their use has been validated.

This experimental study was designed to analyze the air movement originated from opening and closing a swing door to a chamber, and the effects of those air movements on the steady state conditions inside the chamber. As temperature fluctuations are associated with buoyancy driven airflow, to control that the temperature fluctuations were measured using the omnidirectional sensors as well. Our data indicates that the temperature fluctuations were negligible (mean temperature across all experiments = 23.7 degree Celsius, with a standard deviation of 0.025). Thus, an isothermal condition was assumed inside the chamber.

2.5 Statistical Consistency

The time averaged outputs of the omnidirectional sensors for each test case was collected for 60 seconds which generated 30 data points for each of the 30 repetition. For all the sensing systems, those 30 data points were averaged to obtain a transient velocity profile. The data indicated fair consistency at each point in time, for all the measuring units. To assess the consistency of measurements, all the spatial and temporal data points were combined in one array (V). The Relative Standard Errors (RSE) was defined as the data standard error (SE) of V divided by its average. Since the RSEs were normalized by average velocity, it was reasonable to present the data in percentage (Table 2). RSE was largest for quiescent air, perhaps due to the low average value of data points.

Table 2: **Data consistency**

Experiment	**Average RSE**
Test 1	11.56%
Test 2	10.09%
Test 3	7.67%
Test 4	11.43%
Test 5	10.23%
Test 6	8.19%

3 Results and Discussion

The velocity magnitude data obtained for 60 seconds at every location during different experiment setups were analyzed to understand the alterations in indoor airflow characteristics, influenced by the door movement. These findings are discussed in this section according to the measuring system locations.

3.1 Door Opening Once – Still Air

As explained in the method section, the door was opened at the first second of the tests, and there was considerable delay after which an increase in the flow velocity were measured, meaning all the sensors recorded values of changing velocity after the airflow had already passed them. The increase in air velocity was logged quicker at sensor location 1 for all four rows (L11, L21, L31 and L41) at both the elevations compared to sensors located further from the door. The observations are further broken down according to the elevations where the sensors were mounted.

3.1.1 Sensing systems at lower elevation

The temporal characteristics of flow velocity as captured by sensors at the lower level, displayed location-specific trends, according to the arrangement in the imaginary rows (Figure 1). As can be seen from

Figure 3, at the first row, LL11 was the first sensing station recording an increase at second 3, as it was the closest to the tip of the door. LL12 recorded the first instance of air speed increase at second 5 whereas L13 and L14 started to log higher velocity values from second 11. The first and second sensing stations had recorded the same highest magnitude of air speed of 0.51 m/s at 15 second and 19 second, respectively. It is also apparent that the drop after attaining the highest velocity was steeper for sensor LL11 and LL12, whereas for LL13 and LL14, the change in the velocity magnitudes were smoother. The senors located farther from the door, i.e., LL13 and LL14, recorded velocity greater than 0.1m/s until almost 50 seconds, when velocity magnitude dropped to near zero by second 40 for LL11 and LL12. These finding suggests temporal propagation of velocity fields.

At row L2, a significant change was observed – the highest recorded velocity at LL22 (0.29 m/s), was nearly 45% of the max value recorded at LL21. At this row, LL23 and LL24 had mostly similar velocity magnitude values compared to LL13 and LL14, respectively. At the next row, L3, the first and second sensors recorded similar peak velocity as of row L2 (0.51 m/s and 0.29 m/s, respectively). Whereas LL31 logged the highest velocity at time equivalent to that of LL11 and LL21, the sensor LL32 reached the maximum velocity quicker than that of the second sensors at rows L1 and L2. A similar trend was observed for the sensing station LL33, which had the highest velocity of 0.12 m/s at second 19. The farthest sensor, LL34 did not record much change in terms of air velocity from the door motion, but a small change in velocity magnitude is apparent around 23 second. The next set of sensor locations had some unique observations - the sensing stations in row L4 recorded the change of velocity at similar time frame, unlike previous rows which has distinguishable lag corresponding to the increasing distance of sensors from the door. LL41 and LL42 logged slightly reduced highest speed as compared to L2 and L3, but at the same time – second 15, which is 4 second quicker for LL42 than the highest recorded velocity by LL12. Likewise, LL43 and LL44 also peaked at least 5 second and 6 second earlier than the sensors at the same locations for the other three rows.

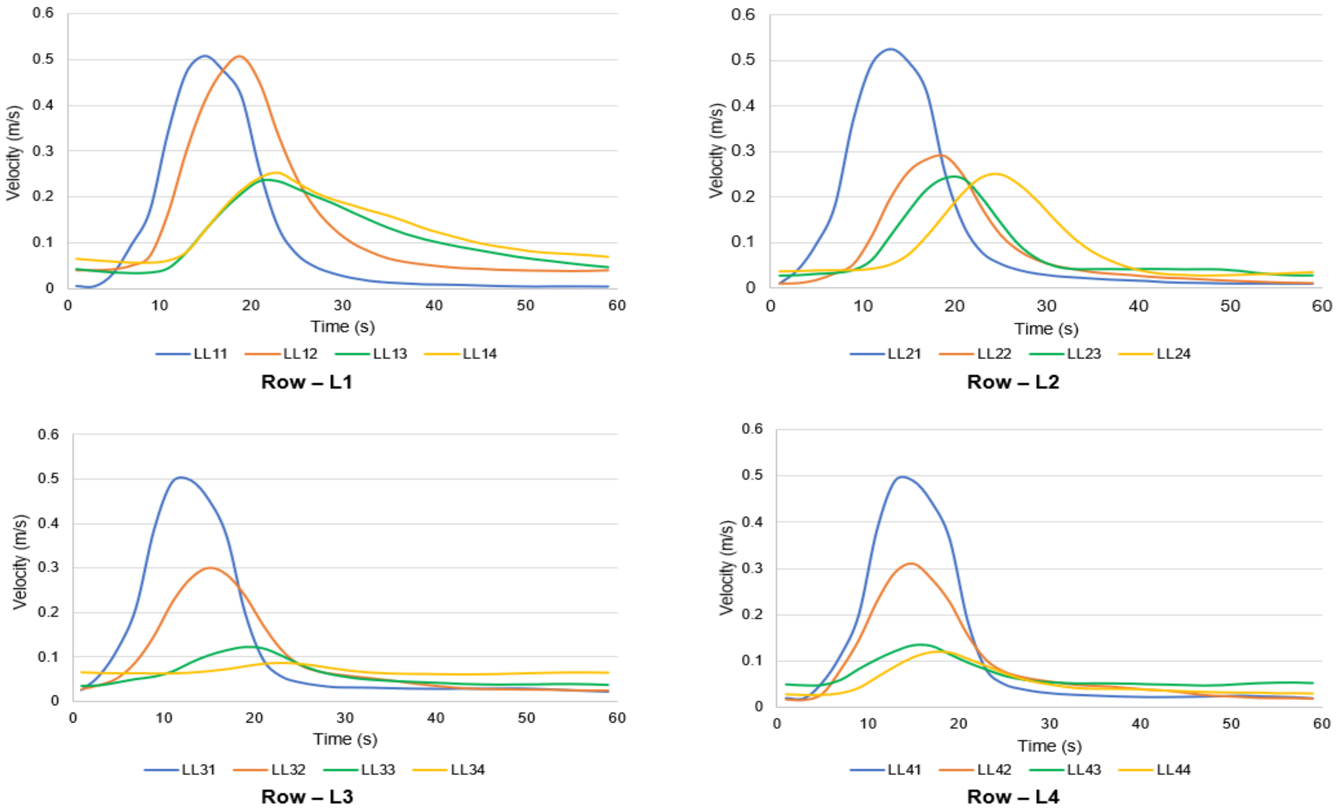


Figure 3: **Temporal velocity trends for lower elevation sensors - door-opening once**

3.1.2 Sensing systems at higher elevation

With the initial condition of quiescent air inside the chamber, Figure 4 dispalys the temporal changes in the velocity profile for the sensors at the higher elevations. The sensing stations located closest to the door i.e. UL11, UL21, UL31 and UL41, had logged the changes in air velocity with minimum lags and they had recorded peak velocity in the order of ~ 0.49 m/s. Apart from these sensors at location 1 for all four rows, the sensors at locations 2, 3, and 4 in all the rows recorded the surge in velocity after some time (i.e., with a comprehensible lag), which could be correlated to the distance of these sensors from the door. The measuring units closest to the door and the following ones (sensors at locations 1 and 2) recorded an identifiable change in speed at all four rows of measurement stations, whereas, sensors 3 and 4 recorded airspeed more than 0.1 m/s only at row L1. The time of the highest observed velocity at row L4 was quicker than at row L1. Another noteworthy observation was that peak velocity magnitudes were recorded two second earlier in all the rows, when compared to the sensors at the lower elevation. Table 3, that compares the velocity profiles at the two different altitudes of sensor mounting, describes that only the values recorded by the sensors close to the door tip (location 1) were comparable between two different elevations, whereas other sensors (i.e, sensors at location 2, 3, and 4) at the higher elevation registered almost half of what the lower elevation sensors had recorded.

3.2 Opening Twice – Still Air

The observed temporal trends for air movement characteristics corresponding to opening the door twice with still air was comparable to that of opening the door once with quiescent conditions inside the test chamber, albeit door opening twice resulted in higher velocity magnitudes and greater area under the curve of velocity plotted against time. It was found that the omnidirectional sensing systems used for the experiments, did not record any drop in velocity magnitude at any position due to the 2 s recess time between the two consecutive door opening activity. Even though both sets of door operations are completed close to second 12 and presumably the wakes carried by moving air hovered past the sensors

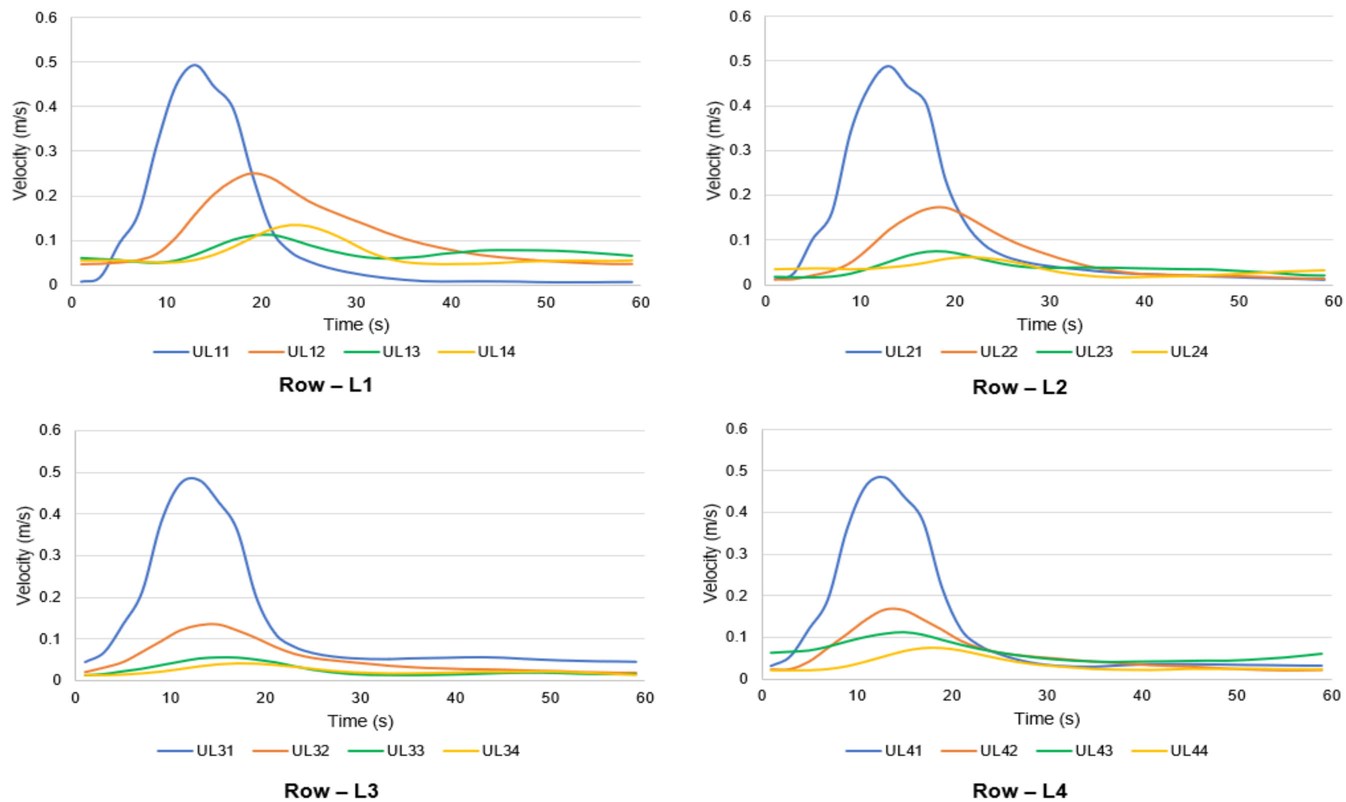


Figure 4: **Temporal velocity trends for higher elevation sensors - door-opening once**

Table 3: **The maximum velocity associated to the sensing stations and the time it occurred - door opening once**

Sensors at low elevation				Sensors at high elevation			
Sensor ID	Range of non-zero entries (s)	lag(s)	Maximum Velocity [Time it occurred] (s)	Sensor ID	Range of non-zero entries (s)	lag(s)	Maximum Velocity [Time it occurred] (s)
LL11	26	2	0.51 [15]	UL11	22	2	0.49 [13]
LL12	34	6	0.51 [19]	UL12	34	6	0.25 [19]
LL13	35	8	0.23 [21]	UL13	20	10	0.11 [21]
LL14	40	10	0.25 [23]	UL14	23	12	0.13 [23]
LL21	26	<1	0.53 [13]	UL21	26	<1	0.49 [13]
LL22	28	6	0.29 [19]	UL22	33	2	0.17 [19]
LL23	26	8	0.24 [19]	UL23	20	6	0.07 [19]
LL24	30	10	0.25 [25]	UL24	20	10	0.06 [21]
LL31	24	<1	0.5 [13]	UL31	24	<1	0.48 [13]
LL32	26	2	0.29 [15]	UL32	22	2	0.13 [15]
LL33	28	2	0.12 [19]	UL33	24	2	0.05 [15]
LL34	19	11	0.087 [23]	UL34	20	6	0.04 [17]
LL41	22	2	0.49 [13]	UL41	26	<1	0.48 [13]
LL42	30	2	0.31 [15]	UL42	26	2	0.17 [13]
LL43	24	4	0.14 [15]	UL43	24	4	0.11 [15]
LL44	26	6	0.12 [17]	UL44	22	6	0.08 [17]

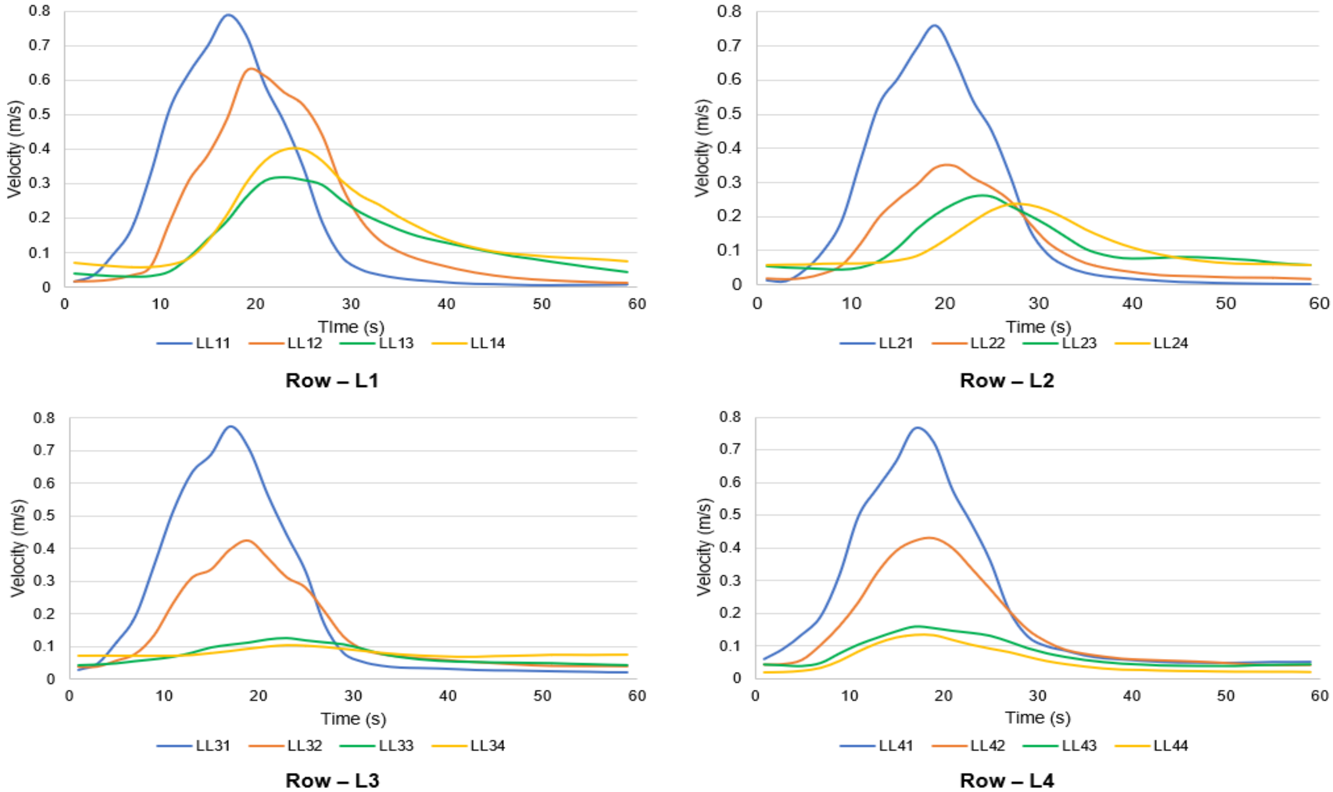


Figure 5: **Temporal velocity trends at lower elevation sensors - door-opening twice**

sometime close to that, a lag of at least 5 s was observed. Assuming the highest velocity was obtained from consecutive door openings, the earliest recorded maximum velocity magnitude was at the first sensors located the closest to the door at the corresponding time of second 17.

3.2.1 Sensing systems at lower elevation

As already witnessed during door opening once, the measuring units at the beginning of the rows (i.e., at location 1), being at the closest proximity to the door, recorded the highest magnitude of the air flow speed which was 0.79 m/s for L1 and 0.76 for the other three rows - L2, L3, and L4. The measuring units located at the second spot in terms of greater distance from the door tip, i.e. LL12, LL22, LL32 and LL42, also captured substantial changes in air movement.

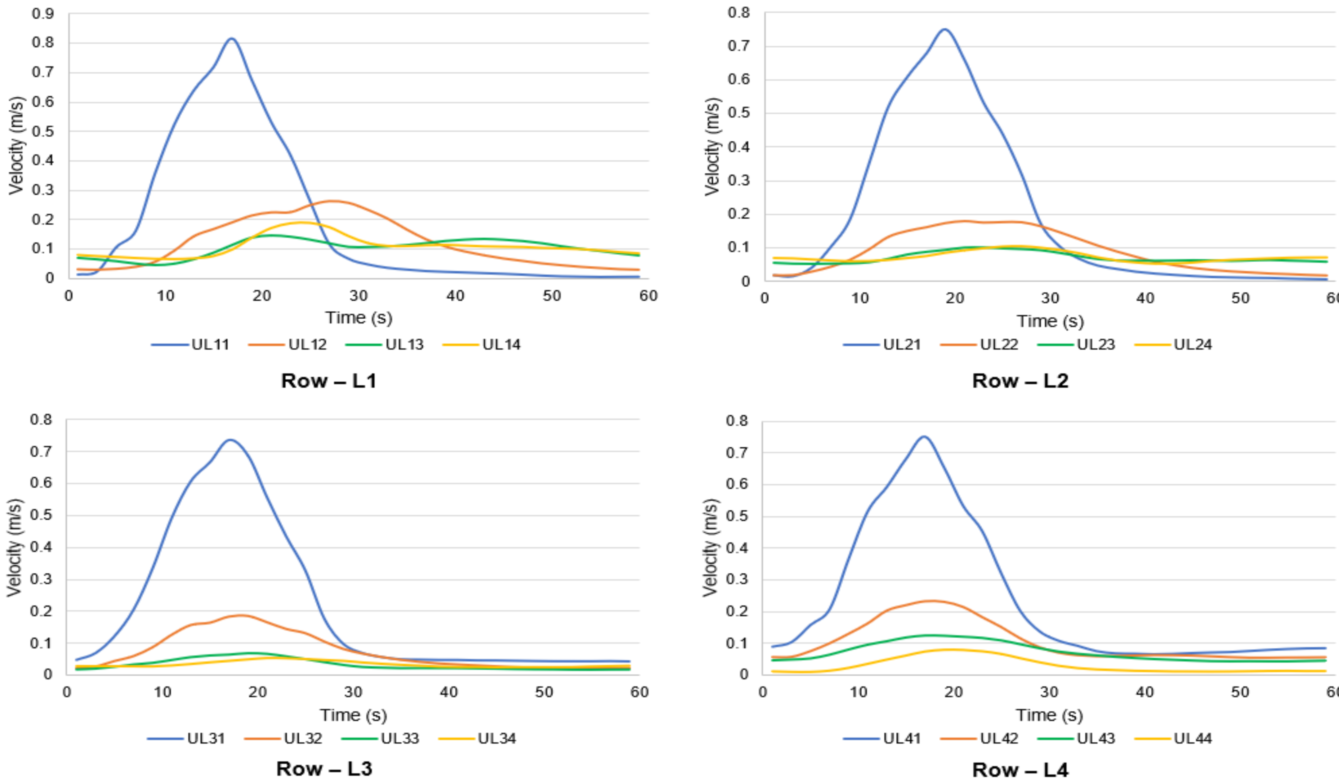


Figure 6: **Temporal velocity trends at upper elevation sensors - door-opening twice**

For row L2, sensors at position 3 and 4 also had recorded significant changes in the temporal velocity profile, whereas, at row L3 and L4, sensors at those positions did not record notable change in the velocity magnitude. For row L1, the difference between the maximum speed readings at LL11 (0.79 m/s) was 25% higher than that of LL12. This was unlike door opening once, where recorded airspeed was equal for these sensors. Analogous to the readings of bottom layer sensors in door opening once, the time difference between sensors attaining the highest magnitude of velocity reduced from row L1 to L4, meaning the sensors at L4 logged the highest velocity in time quicker than at L3, and so on. In row L1, and more vividly observed in L2 (Figure 5), the sensors logged the highest velocity in a sequence, when the closest sensors were the earliest to record the peak velocity and the farthest units to be the last, i.e., as a function of distance, providing additional evidence of a temporal pattern in the propagation of the velocity fields through the indoor airfield.

3.2.2 Sensing systems at higher elevation

Analogous to the results for test 1 (door opening once - no air supply), when the trends in the change in velocity were comparable between the two altitudes of sensors with different magnitude, the data from test 4 (door opening twice - no air supply) also showed that the change in velocity magnitudes at the upper elevation was commensurable with that of the lower elevation units, with decreased velocity magnitude.

Table 4: **Change in velocity proportion from opening once to twice at all sensor locations**

Sensor ID	**Door Opening Once**	**Door Opening Twice**	**Velocity Proportions**	**Sensor ID**	**Door Opening Once**	**Door Opening Twice**	**Velocity Proportions**
Column	A	B	B/A	Column	A	B	B/A
LL11	0.1504	0.1962	1.3	UL11	0.1431	0.268	1.87
LL12	0.1824	0.1821	1	UL12	0.1318	0.1518	1.15
LL13	0.1258	0.1342	1.07	UL13	0.0739	0.1012	1.37
LL14	0.1426	0.1629	1.14	UL14	0.0753	0.1137	1.51
LL21	0.1597	0.1911	1.2	UL21	0.1547	0.2731	1.77
LL22	0.1029	0.1103	1.07	UL22	0.0766	0.1125	1.47
LL23	0.0932	0.1122	1.2	UL23	0.0404	0.0744	1.84
LL24	0.1063	0.1088	1.02	UL24	0.0376	0.0769	2.05
LL31	0.1556	0.2033	1.31	UL31	0.1645	0.2808	1.71
LL32	0.116	0.1401	1.21	UL32	0.0634	0.0929	1.47
LL33	0.0683	0.0715	1.05	UL33	0.0282	0.0404	1.43
LL34	0.0694	0.0789	1.14	UL34	0.0238	0.0364	1.53
LL41	0.1495	0.2218	1.48	UL41	0.1563	0.2971	1.9
LL42	0.112	0.1485	1.33	UL42	0.0753	0.1242	1.65
LL43	0.0745	0.0758	1.02	UL43	0.0695	0.0832	1.2
LL44	0.0613	0.0546	0.89	UL44	0.0395	0.0397	1.01

As mentioned earlier, the instantaneous increase was logged by the sensors closest to the door and the lag between when the wakes crossed the sensors and when the increased velocity was recorded were higher for sensors located further along the row, which can be presumed to be a function of distance from the door. An interesting fact, as observed from (Figure 6), is that similar to the units at the lower level, the peak velocity recorded at row L4, was concurrent at all four sensing stations. To compare between the air velocity values originated from door opening once and twice, time averaged velocity magnitude ($\bar{v}$) at each location are showed in Table 4. Since, for most of the experiment scenarios, there was no significant change in velocities after 40s, the time-averaged calculation was done using the following equation:

$$\bar{v} = \frac{\sum_{t=1s}^{40} v}{N} \tag{1}$$

Here v is the velocity magnitude, recorded at each timestep (2 s), and N is the total no. of data points from second 1 to 40. As expected, the largest differences in the velocity profile from opening the door once and twice were corresponding to the sensors closest to the door tip, nearly a maximum of 1.5 times at the lower elevation and more than 2 times at the higher elevation, while the least proportions corresponded to the farthest sensors.

3.3 Discussion

The steady state condition before operating the door was quiescent air and the door movement was the only physical movement present in the test chamber. With no other motion than the swinging door movement, there were changes in the air velocity, clearly attributable to door movements. It is observed in the previous figures that the first sensors in every row recorded higher magnitude of air velocity that resulted from the door opening and closing, compared to the sensors located farther into the room. According to the sensing station arrangement scheme, sensors in row L1 was along the wall parallel to the closed door. When the door started to open, the moving door provided a thrust that gets the air moving and the subsequent movement transferred the momentum to the air, generating wakes in the air over background. The recorded movement of the airflow wakes were mostly associated with the leading door tip with other weaker wakes following. When the door was completely open and remained ajar for a second, the wakes started to dissipate further into the chamber, but then the closing movement started, providing another motion to generate vortices in the already moving air. During the closing movement, the flow field had residual velocities moving along the direction of the opening movement. The closing operation forced the air to move in a contrasting direction, generating turbulent vortices, raising the magnitude of air velocity in the flow field.

The frequency of the sensing system, that recorded one data point every two seconds, was not responsive enough to record and reflect all the fluctuations of the air velocity. From what can be observed in the previous figures (Figure 3 to Figure 5, the location-specific fluctuations in the flow velocity represents the cumulative flow field resulted from the cyclic door motion – consisting of opening and closing. At row L1, the velocity magnitude recorded through sensors located further from the door were higher than the other rows as the wakes propagated further in presence of the stationary wall. In the proximity to the wall with higher velocity gradients present, the flow field was unable to dissipate, instead, the boundary acted as a surface that aided in the wakes' translation along its length. Also, after the door was closed, there was no other movement to alter the flow of moving air and it continued to propagate. One can see that maximum velocity magnitude and the time of logging by the sensors were functions of distance from the door. It is also noteworthy that in row L4, the temporal distribution of maximum air speed was almost concurrent for all the sensors. At the end of door opening, the air was moving forward along that row, but the sudden movement for the closing the door got the air moving again, in altering directions, drawing the air streams back towards the sensors, hence all of them peaked with negligible intervals between them.

The sensing stations at the lower elevation were found to have logged higher velocity magnitude than that of the higher-level ones. This phenomenon was attributable to the increased interaction between the moving air and the floor – which could be presumed to as a stationary wall with zero-slip condition. The presence of a boundary (the floor) restricted the quick dissipation of flow fields, aided by the resurfacing of settled particles during the closing motion raised turbulence which affected the flow plane captured by the sensors at lower elevation. The absence of any such boundary near the sensors at the higher elevation but was an additional testament of the fact that presence of a boundary has profound impacts on the indoor flow fields.

Higher magnitude of velocity was recorded for operating the door twice compared to a single opening and closing of the door. Understandably, the residual movements in the air inside the test chamber from the opening and closing of the door first time was the initial condition for the second cycle of door operation. Physical movements with residual movements present resulted in increased turbulence and faster moving vortices, which in turn, was captured as higher speeds in Figure 5 and Figure 6.

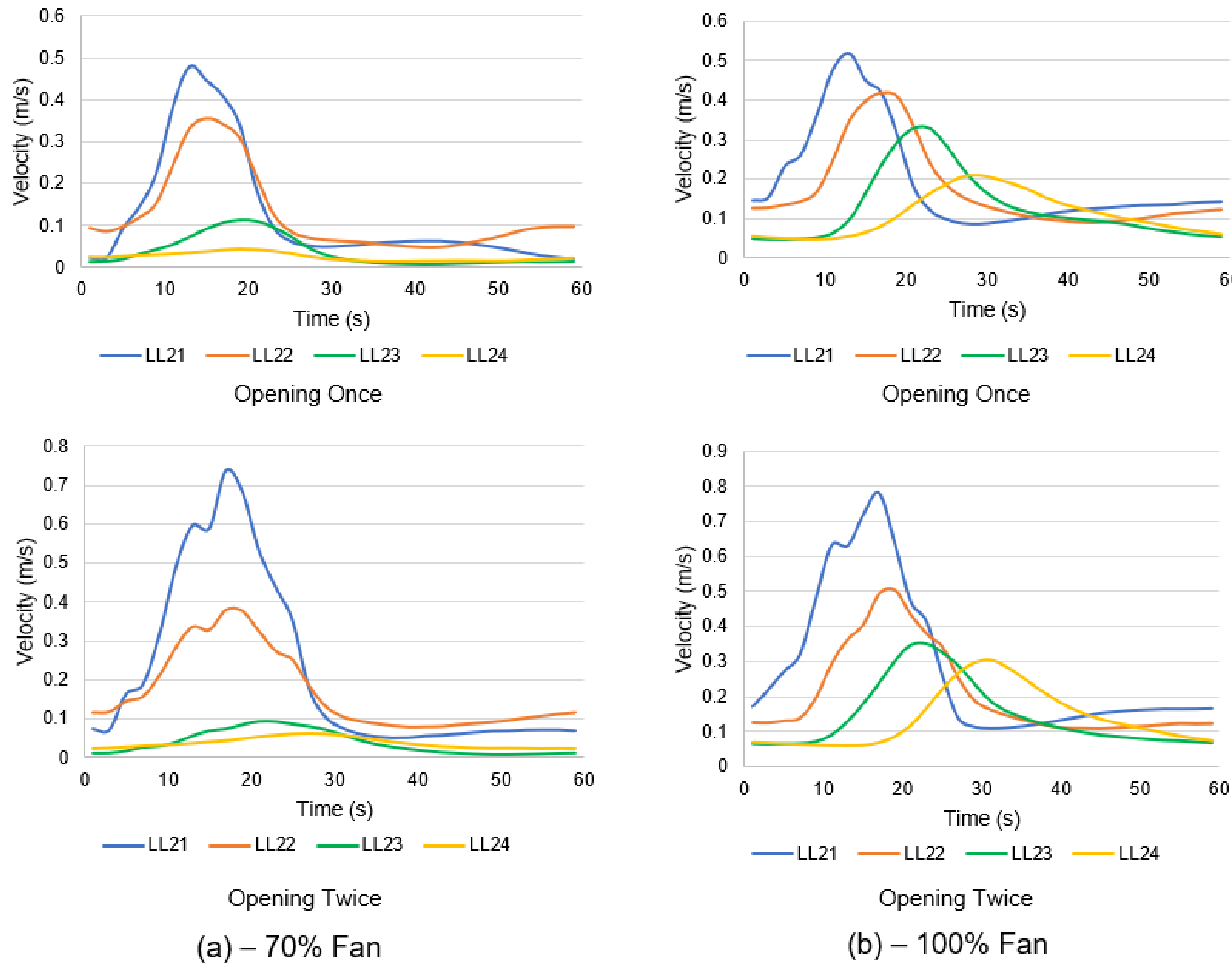


Figure 7: **Velocity Magnitude in sensors at row L2 for (a) 70% fan and (b) 100% fan**

3.4 Effect of Initial Conditions

The velocity magnitudes obtained from both the door opening exercises, i.e., opening once and twice for the two separate airflow regimes when the supply fan and AHU were operating - 70% air and 100% air, were compared to the spatiotemporal trends as obtained from the still air initial condition. The results revealed that the trends, specific to the row of sensor arrangement, and their positions on the row (the location and the elevation), were comparable to that obtained from tests conducted under the initial condition of quiescent air. An example case has been shown in Figure 7, where the temporal trends for both door opening once and twice under 70% air and 100% air, as captured by the lower elevation sensors at row L2. It is noteworthy that two distinct differences were observed between the quiescent air initial condition and the other initial conditions (70% fan and 100% fan). One can see from Figure 7 that with more air supplied to the indoor environment, the disturbances introduced through door opening, were subdued quickly by the pressure differential generated from the large quantity of supplied air. This is observable by the dip in the velocity around second 17, logged by the sensors at first two locations for door opening twice, which reflects the 2-second pause after the first cycle of door opening-closing. After the first cycle of door opening, the air velocity generated from the door movement, that was moving away from the door, was found to be dropping as the air already present in the chamber was flowing in the opposite direction. The second cycle of door opening forced the turbulent air to move again, aiding in subsequent increase as measured by the sensors. This phenomenon substantiates the claim that during door opening twice, the interaction between supply airflow and airflow from the second cycle of door opening creates more vortices, increasing the intensity of turbulence, captured as increased velocity. It is also noteworthy that with more air supply, the sensors farther from the door, which did not record significant changes for either quiescent air or 70% fan, showed significant changes in the velocity profile when the fan was operating at full capacity. This can be attributed to the fact that with 100% air, moving the door meant displacing a very large quantity of air, working against a high pressure differential, that led to the generation of higher turbulence compared to the other initial condition. This high turbulence, in turn, resulted in high velocity wakes travelling inside the room, as captured by sensors located in position 3 and 4.

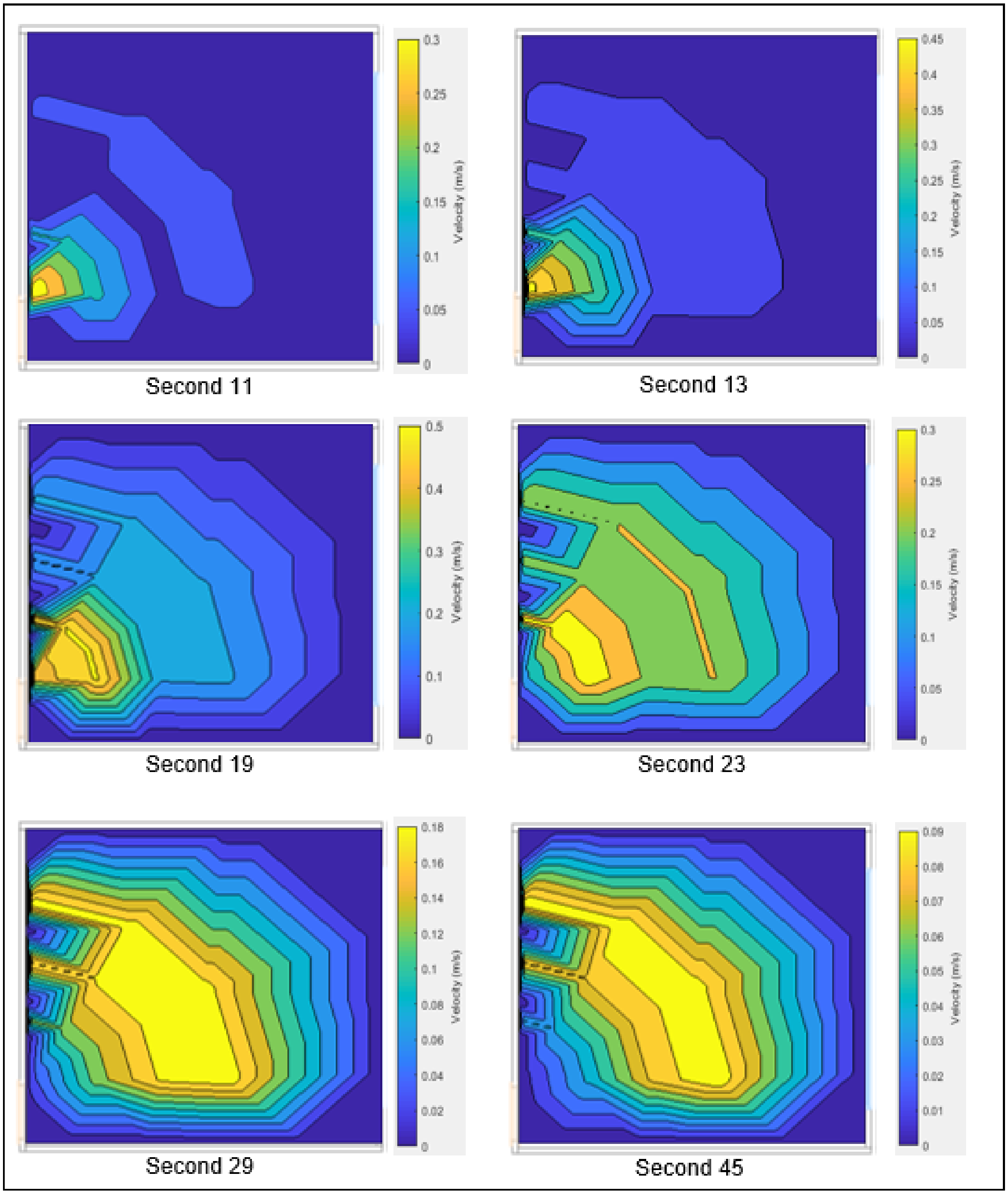
3.5 Spatial Distribution

For both door opening once and twice with the quiescent air initial condition (Test 1 and Test 4), the distribution of velocity fields are depicted through Figure 8. For door opening twice, the iso lines were associated with higher magnitudes of velocity and iso lines with higher speeds were found deeper inside the test chamber when compared to door opening once. It is worth noting that the highest velocity flow fields were located near the door movement zone quickly after the door movement were stopped, and with time as these wakes expanded deeper into the room, velocity values dropped gradually.

For the experiments involving door opening once with no fan, until second 11, the areas with significant velocity values ($\simeq$ 0.3 m/s) were found to be within 1.5 m from the door. By second 19, the velocity values of the range $\simeq$ 0.5 m/s were to found further into the room. At second 23, iso lines of $\simeq$ 0.3 m/s could be found at the middle of the room, which started to drop down from second 29. But, it is interesting to observe, that even though the velocity values have decreased to $\leq$ 0.1 m/s, the highest velocity magnitudes correspond to a location at the middle of the room; suggesting that the absence of ventilation, the wakes become stagnant.

For door opening twice, the flow fields containing higher velocity magnitude, in the range of $\simeq$ 0.7 m/s, are found to be in close proximity to the door movement region until late, compared to opening once, as seen from the surface plots at time 19 second (Figure 8), due to additional motion generated by opening the door a second time. At second 29, velocity values close to 0.3 m/s were still found close to the middle of the chamber. By second 45, wakes with ranges $\simeq$ 0.1 m/s was observable at a distance of $\simeq$ 2.5 m from the door. The presence of higher velocity wakes deeper into the experiment chamber is due to the interaction between already moving air with the wakes generated from opening and closing the door for a second time. It is important to note about the different ranges of velocity associated with the surface plots for two cases, represented by the color bars in each plot. It may also be noted that these surface plots were approximated using the data from the lower elevation sensors only, considering zero velocity values at the walls.

The surface plots in Figure 8, showing temporal distribution of airspeed across the chamber, demonstrates that initially, the wakes were closely knit around the door for both opening the door once and twice; as, at the beginning of door movement, the air started to move at the proximity to the door. Like explained earlier, the highest velocity magnitude was always associated with the swing edge of the door. With time, the flow fields dissipated inside the chamber in the absence of any perturbation (the door was already closed) to alter the direction of the wakes. The momentum generated from the door movement was transferred to the air inside chamber at different times, depending on how many times the door was operated, and the initial condition inside the chamber. The movement of air molecules was dictated by the door while still in motion and once the door movement stopped, the air started to move in the direction of residual velocity. As the velocity fields were distributed throughout the chamber by means



Test 1

Figure 8: **Spatial Distribution of flow fields for door-opening once (Test 1), and twice (Test 4)**

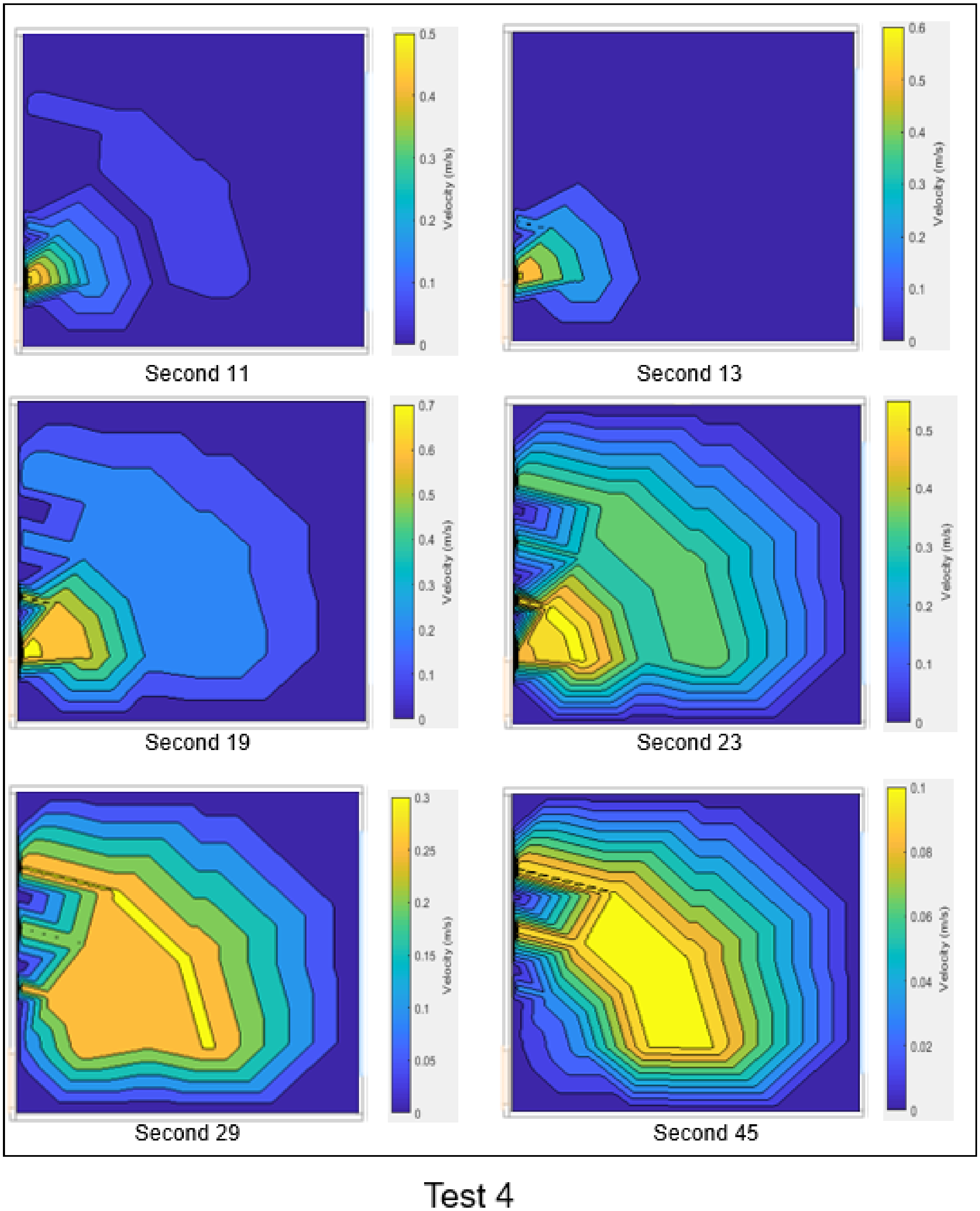


Figure 8: **Spatial Distribution of flow fields for door-opening once (Test 1), and twice (Test 4) (cont.)**

of momentum transfer between air molecules, some parts of that momentum was lost during the process - evident from the decreased maximum speed as the velocity fields spread out. The area close to the walls was not surrounded by as many molecules as in the middle of the chamber, hence the momentum transfer was slower with reduced loss. As the flow fields dissipated, the abrupt changes in the velocity fields along the wall could be attributed to this reason.

3.6 Kinetic Energy

The movement of the door imparted the kinetic energy into the moving air, which is proportional to the velocity, raised to the second power (Equation 2). Additionally, the time averaged kinetic energy of door opening (K_{do}) and background kinetic energy (K_{bg}) are defined as follows:

$$K = \int mv.dv \tag{2}$$

$$K_{do} = \frac{\int_{t=3s}^{23s} v^2}{(23 - 3)} \tag{3}$$

$$K_{bg} = \frac{\int_{t=40s}^{60s} v^2}{(60 - 40)} \tag{4}$$

As negligible changes in the air velocity was recorded by any of the sensing stations after second 40, the duration from 40 s to 60 s indicated the background kinetic energy (i.e. - the kinetic energy of the air without the impacts of the door movement), which in turn helps to demonstrate the change in kinetic energy due to the door movement. The kinetic energy at the onset of door opening initiation was comparable for both the test scenarios, but admittedly, door opening twice was associated to higher amount of kinetic energy transfer involved for longer duration (Figure 9). The ratio of kinetic energy between the two door opening scenarios were $\simeq 2$ for the three different initial conditions, as shown in Table 5. It can be noted that for zero initial condition (i.e. - no fan operating) and 70% air, the kinetic energy for door opening is > 2 times that of the steady state condition without any interference in terms

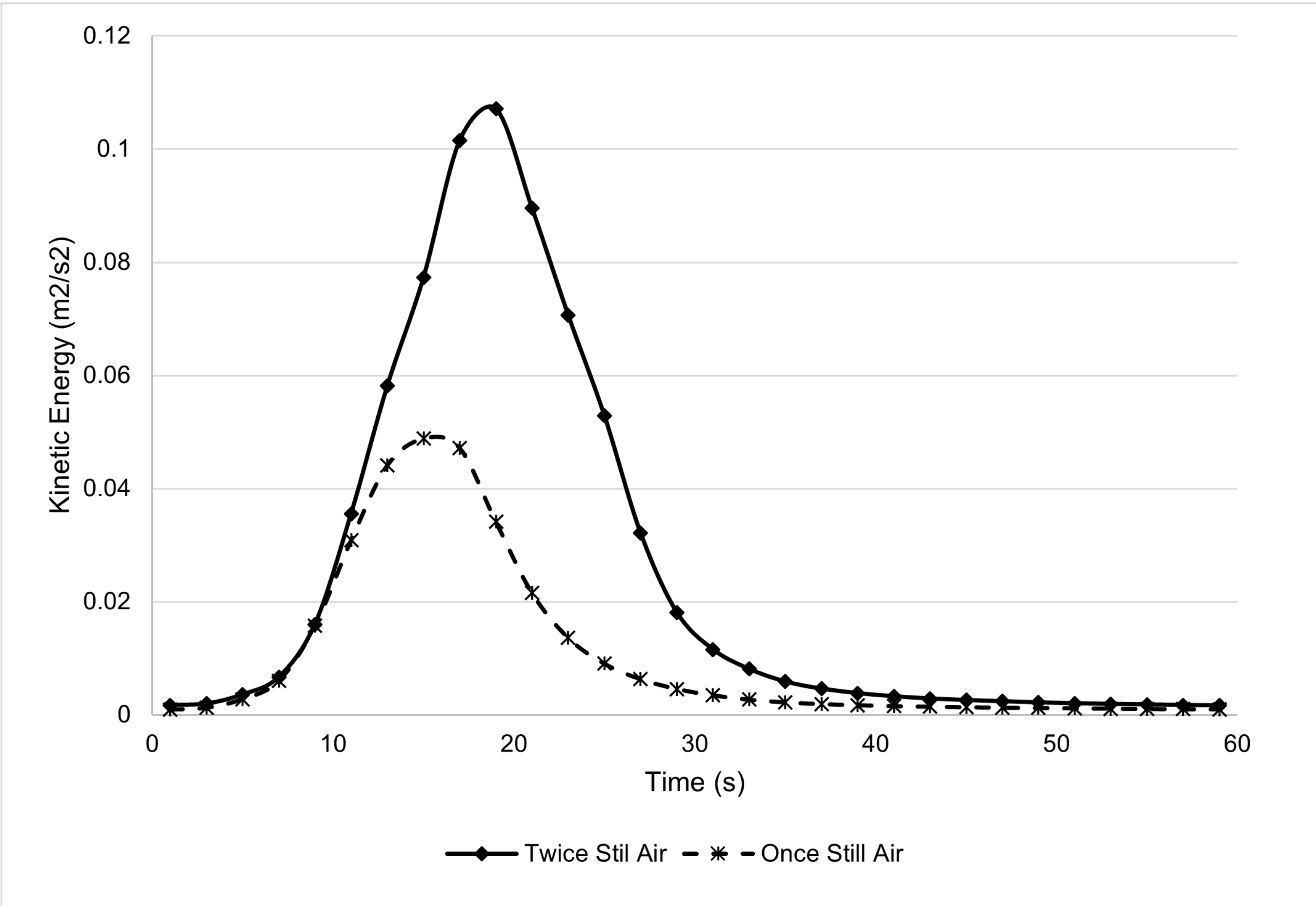


Figure 9: **Total Kinetic Energy of Still Air for two door opening schemes; sum over all sensor locations**

of door operation. But, with the maximum air supply (i.e., the 100% fan), a part of the energy is spent to overcome the heavy resistance provided by the air mass inside the test chamber when opening the door, taking the proportion below 2.

4 Conclusions and Limitations

The study was aimed at analyzing the alterations in the resultant indoor airflow fields from two probable operations of a swing-door. The experiment chamber, initial conditions, and the door operations

Table 5: **Time Averaged Kinetic Energy for Two Door Opening Schemes**

Initial Condition	**Still Air**		**70% Fan**		**100% Fan**	
Door Opening Scheme	Opening Once	Opening Twice	Opening Once	Opening Twice	Opening Once	Opening Twice
K_{do}	0.0242	0.0516	0.0249	0.0483	0.0411	0.0682
K_{bg}	0.0012	0.0022	0.0042	0.0052	0.0129	0.0145
$\Delta K(K_{do} - K_{bg})$	0.023	0.0494	0.0206	0.0431	0.0281	0.0537
$\Delta K(Twice)/\Delta K(Once)$	2.15		2.09		1.91	

represented a critical environment chamber (e.g. - an operating room, a laboratory, etc.), even though the chamber was smaller and the initial conditions were not recommended by standards. A umber of previous studies have studied the door opening phenomena in a variety of different indoor environment using methods such as numerical simulation [33, 39, 36, 24], experimental [23, 31, 34, 40, 47] and passive measurement [26, 27, 17] (e.g., tracer gas, dye concentration measurement etc.). These studies had shed lights on the volumetric air exchange across the door and sometimes studied the flow fields, depending on the door position, type and proposed use of the chamber, type of door, specific ventilation system, etc. With the insights from these previous researches, this work had investigated the flow characteristics at steady-state and under the occupant-introduced disturbances by means of a door opening, aiming for a broader understanding, in part by measuring flow characteristics at different heights of the chamber. This study had utilized the real-time experimental data to analyze the effects a swing door opening can have on the steady state indoor airflow. The restricted access to the test chamber, and the limited availability of sensors constrained the experiments to be conducted under three initial conditions, with only two scenarios of door openings defined as the source of occupant-induced perturbation. Access to a deficient number of sensors, restricted the data collection could be done at sparse locations; sensors could only be placed one ft apart to maximize the area of data gathering inside the chamber. It is acknowledged that there can be several occupant-introduced motions having effects on the indoor airflow, studying them experimentally is difficult due to time and monetary constraints.

The two-second opening and two-second closing movement of the door after a pause of one-second resulted in a sustained airflow that showed strong velocity components in the close vicinity of the door - indicating that the effects of door opening were location specific. Emulating the opening and closing movement twice resulted in further increase of the flow velocity. This increase in air velocity was due to the wakes carried by the moving door in the quiescent air before being dissipated through the chamber. As these dissipated wakes penetrated further through the chamber, the flow velocity continued to decrease, due to the lost momentum during transfer between air molecules. The location closest to the movement periphery, logged the changes quickly whereas, change in flow patterns was recorded with a lag at distant locations, which could be correlated to the distance from the door. This study also revealed that the presence of stationary boundaries has profound impacts on the propagation of flow fields. Limited dissipation of velocity wakes at zones close to walls resulted in higher turbulent interaction between a stationary surface and moving velocity fields, causing increased gradients. Similarly, the lower elevation sensors had to record the moving air that did not have the free space to move like the flow captured at the higher elevation had. Instead, moving air at locations close to the floor had an enhanced association to the re-suspension of settled particles on the floor. Under different initial conditions, the flow profiles demonstrated equivalence to door-movement generated flow under still air. It was evident that a strong inlet air aids in achieving equilibrium quicker, even though the turbulence associated during door movement was higher.

This study also looked at the kinetic energy distribution in the chamber. Operating the door for two consecutive opening and closing cycles yields almost double kinetic energy when compared to opening and closing the door once. This increase was dependent on the initial condition, as the highest amount of supply air reduced the difference marginally. The higher differential pressure across the door with supply air flow is the probable reason behind this. Presumably, a substantial amount of the kinetic energy was used to overcome the resistance from higher pressure differential and move the air. Also, higher positive pressure in the room meant outflow of air through the door when opened. As the airflow was going out through the door instead of moving the wakes from door operation, there kinetic energy decreased.

Despite the limited availability of the experiment chamber and number of different experiments conducted during the narrow time-frame, 30 sets of data for every set of experiments were collected to ensure repeatability and consistency of the obtained results. As this study concludes that the presence of stationary boundary impacts the flow fields as well as the propagation of wakes in time, the future research would seek a more detailed understanding of near wall phenomena, using both experimental and numerical simulation data. Studies to find out the effect of a wide range of initial conditions on the dispersion of wakes inside the chamber with time, is also another direction the research team wants to steer the efforts in future.

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Conflicts of Interest Statement

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