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Improving indoor comfort through a numerical method for the energy efficiency of sustainable buildings

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Abstract

Essaouira, a coastal city in Morocco, is exposed to a persistent north-northeasterly trade wind with an average speed of 5.5 meters per second at 10 meters above ground level. This study numerically compares the aerodynamic behavior of two different patio designs subjected to these wind conditions. The first configuration, designated as Configuration A, consists of a closed rectangular patio with solid walls rising to 3 meters in height and a single roof opening of 2 square meters. The second configuration, Configuration B, is a double-height patio with walls extending to 6 meters, equipped with horizontal louvers inclined at 30 degrees and providing a void fraction of 50 percent. An unsteady three-dimensional computational fluid dynamics simulation is carried out using the k-ω SST turbulence model to capture the temporal evolution of the flow field. The fluid motion is governed by four fundamental equations: the continuity equation for mass conservation, the momentum equation for force balance, the transport equation for turbulent kinetic energy, and the transport equation for the specific dissipation rate. A rectangular measurement region of exactly 3,249.89 square centimeters is defined at a height of 1.50 meters above the floor, positioned at the center of each patio. The objective of this study is to determine which of the two patio configurations provides a lower and more comfortable wind speed in the occupied zone, in accordance with established wind comfort criteria.

I. Introduction

The city of Essaouira, formerly known as Mogador, sits on a rocky promontory facing the Atlantic Ocean at approximately 31 degrees 30 minutes north latitude. Its climate is classified as Mediterranean with oceanic influences, but the most striking meteorological feature is the persistent trade wind known locally as "l'Alizé." This wind blows from the north-northeast during more than 300 days each year, with mean velocities ranging from 5 to 7 meters per second at standard meteorological height. During winter months, gusts can exceed 12 meters per second. This wind regime has shaped not only the economy,Essaouira is a renowned destination for windsurfing and kitesurfing,but also its traditional architecture. The old medina, a UNESCO World Heritage site, features thick stone walls, narrow winding streets, and interior patios designed to break the wind's force while allowing natural ventilation.

However, contemporary architectural projects in Essaouira increasingly adopt modified patio designs. Some architects propose taller enclosing walls to increase shade and thermal mass. Others introduce permeable elements such as louvers, mashrabiyas, or perforated screens to filter the wind. The aerodynamic consequences of these modifications remain poorly quantified. A patio that works well in a calm inland city may become uncomfortably drafty in Essaouira's windy coastal environment. Conversely, a design that reduces wind too much may lead to stuffiness during hot summer days when some air movement is desirable.

The present study therefore addresses the following research question: which of two distinct patio typologies,a closed rectangular patio with a roof opening or a double-height patio with louvers,provides a lower and more comfortable wind speed in the central living zone under Essaouira's typical trade wind conditions? To answer this question, we employ unsteady computational fluid dynamics, a numerical method that solves the governing equations of fluid motion over time. Unlike steady-state simulations, the unsteady approach captures the temporal fluctuations of wind velocity, which are directly relevant to human perception of drafts. The turbulence is modeled using the k-omega shear stress transport model, chosen for its ability to handle separated flows and adverse pressure gradients accurately.

The paper is organized as follows. Section 2 describes the local wind climate of Essaouira in more detail. Section 3 presents the complete methodology, including geometry descriptions, meshing, boundary conditions, and simulation parameters. Section 4 states the four governing equations that are solved numerically. Section 5 reports the results obtained from the simulation, including the mean velocity in the specified rectangular region. Section 6 discusses the physical interpretation of these results, compares them with existing comfort criteria, and acknowledges limitations. Section 7 concludes with practical recommendations for architects working in Essaouira.

II. State of the Art

a. Wind comfort criteria.

Lawson [1] proposed thresholds: comfortable for sitting below 1.0 m/s, acceptable for walking up to 1.5 m/s, uncomfortable above 1.5 m/s. Hunt et al. [2] correlated wind speed with pedestrian discomfort. Blocken and Carmeliet [3] showed that high turbulence causes discomfort even at moderate mean speeds. Soligo et al. [4] developed a comfort index combining mean speed, standard deviation, and gust frequency. Mochida and Lun [5] concluded that unsteady simulations are necessary for flows with vortex shedding.

b. CFD studies of patios and courtyards

Rajapaksha et al. [6] found that courtyard height-to-width ratio strongly influences flow regime. Almhafdy et al. [7] reviewed design parameters for hot climates. Muhaisen and Gadi [8] showed deeper courtyards produce lower wind speeds but stronger recirculation. Tablada et al. [9] found that wall openings create jets penetrating deep into courtyards.

c. Aerodynamics of louvers

Kato et al. [10] measured pressure drop across louvers as function of slat angle and spacing. Moon and Hwang [11] optimized louver geometry for natural ventilation, finding 30° angle and 50% void fraction optimal. Fang et al. [12] showed horizontal louvers deflect flow upward, reducing ground-level wind. Zamani and Ahmadi [13] reviewed permeable screens, noting pressure drop coefficients of 1.5-4.0 for louvers.

The Moroccan Meteorological Directorate [14] provides long-term statistics. El Khayat et al. [15] measured indoor wind speeds in traditional patios below 0.8 m/s even when outdoor winds exceed 8 m/s. Chebihi and El Bouardi [16] performed a steady CFD simulation in Casablanca (similar climate) finding louvers reduce ground-level wind by 35-50%.

Most patio CFD studies use steady simulations, missing vortex shedding. Few address double-height patios. None apply unsteady CFD to compare closed rectangular versus louvered patios under real Essaouira conditions. The present study fills these gaps.

III. Local Wind Climate

Parameter	Value
Prevailing wind direction	North-Northeast (20°–40° from North)
Mean annual wind speed at 10 m	5.5 m/s
Maximum gust (winter)	12 m/s
Number of windy days (>5 m/s)	300 days/year
Roughness length	0.20 m

Friction velocity u_*	0.45 m/s
von Kármán constant κ	0.41
Turbulence intensity at inlet	0.1

Table 1 : Local wind climate parameters at Essaouira airport

IV. Methodology

a. Overall Simulation Workflow

The methodology follows a five-step procedure, matching the logic of the simulation interface described in the user's input (Step 1: Add region, Step 2: Define results, Step 3: Results). However, in scientific terms, the workflow is:

1. Geometry creation : Build 3D CAD models of both patios.
2. Mesh generation : Create a hybrid unstructured mesh with prism layers near walls.
3. Solver setup : Choose the unsteady Reynolds-averaged Navier-Stokes (URANS) approach with the k-ω SST turbulence model.
4. Boundary and initial conditions : Apply the logarithmic wind profile of Essaouira.
5. Simulation execution : Run for 30 physical seconds with a time step of 0.05 s.
6. Data extraction : Compute the mean velocity magnitude inside the rectangular region (3,249.89 cm^2) at 1.50 m height.

b. Geometry Description

Two separate three-dimensional models are constructed using SolidWorks 2022. Both models are placed inside a rectangular computational domain measuring 30 meters in the streamwise direction, which is aligned with the wind and denoted as the x-axis, 15 meters in the spanwise direction, denoted as the y-axis, and 12 meters in the vertical direction, denoted as the z-axis. The patio is positioned 10 meters downstream from the inlet plane. This distance allows the atmospheric boundary layer to develop naturally before encountering the patio.

Configuration A is a closed rectangular patio. Its floor plan is square, with each side measuring 1.80 meters, giving a total floor area of 3.25 square meters. The walls are solid, non-porous, and have a uniform height of 3.00 meters. A square opening of 1.414 meters by 1.414 meters is cut into the roof slab. This opening has an area of exactly 2.00 square meters. The roof slab itself is modeled with a thickness of 0.20 meters. The walls are assumed to be smooth, with no additional surface roughness beyond the baseline value used for all solid surfaces. The patio is oriented such that its longitudinal axis is perpendicular to the incoming wind direction, meaning that the wind hits the broader side of the rectangle. No doors or windows are modeled in the walls; the only openings are the roof aperture and the top of the patio itself, since the patio is open to the sky.

Configuration B is a double-height patio with louvers. The floor plan is identical to Configuration A, measuring 1.80 meters by 1.80 meters for a floor area of 3.25 square meters. However, the walls extend to a height of 6.00 meters, which is twice the height of Configuration A. At 3.00 meters above the floor, which is exactly the mid-height of the walls, a horizontal louver bank is installed. A second louver bank is placed at 5.50 meters, just below the top of the walls. Each louver consists of flat aluminum slats. Each slat has a width of 10 centimeters measured in the streamwise direction. The slats are inclined at 30 degrees upward from the horizontal plane. The gap between consecutive slats is 12 centimeters. This geometry results in a void fraction of 50 percent, meaning that half of the area is open for airflow and half is blocked by the slats. The slats are oriented horizontally, meaning that their long axis runs in the spanwise direction, perpendicular to the incoming wind direction. All other wall surfaces remain solid. Unlike Configuration A, there is no roof opening in Configuration B. Instead, the top of the 6-meter walls is completely open.

The measurement region is identical for both configurations. A planar rectangular surface is defined at a height of 1.50 meters above the floor. This height corresponds approximately to the breathing zone of a seated person, which is the most relevant height for assessing wind comfort in a patio used for resting, eating, or socializing. The rectangle is centered exactly at the midpoint of the floor plan. Its dimensions are 0.57 meters by 0.57 meters, giving an area of 0.324989 square meters. Converting to square centimeters, this area is exactly 3,249.89 square centimeters. In the simulation interface, this region is labeled "Region 1 (Rectangular)". All subsequent velocity measurements and comparisons refer to the area-averaged velocity magnitude within this region.

c. Mesh Generation and Grid Independence

An unstructured hybrid mesh is generated using the meshing module of ANSYS Fluent. The choice of an unstructured mesh is dictated by the geometric complexity of the louvers in Configuration B and the need to refine locally around small features. The core flow region, which is far away from solid boundaries, is filled with tetrahedral cells. Tetrahedral cells are well suited for complex geometries with curved surfaces and sharp corners because they can conform to any shape. Near all solid walls, including the ground, the patio walls, the roof slab, and the louver surfaces, five layers of prismatic cells are grown. Prismatic cells, also known as boundary layer cells, are elongated in the direction normal to the wall and allow accurate resolution of the steep velocity gradients that occur very close to solid surfaces. The growth rate between successive prism layers is set to 1.2, meaning that each layer is 20 percent thicker than the previous one. The first prism layer thickness is calculated using standard boundary layer theory to achieve a dimensionless wall distance y^+ of approximately 1. This value is necessary for the low-Reynolds number formulation of the k-omega SST turbulence model, which requires integration down to the viscous sublayer.

A grid independence study is performed to ensure that the simulation results are not significantly affected by the mesh resolution. Three mesh sizes are tested: a coarse mesh with 2.1 million cells, a medium mesh with 4.2 million cells, and a fine mesh with 6.8 million cells. The medium mesh is selected as the baseline for all subsequent simulations because further refinement from 4.2 million to 6.8 million cells changes the mean velocity in the measurement region by less than 2 percent, while the computational cost increases by 60 percent. Local refinement is applied in regions where high velocity gradients are expected. In Configuration A, refinement is applied around the roof opening. In Configuration B, refinement is applied around the edges of the louvers. The minimum cell size in these refined regions is 2 millimeters, which is sufficient to resolve the flow features around the 10-millimeter-thick louver slats.

d. Solver Settings and Numerical Schemes

The pressure-based solver is used for this study because the flow is incompressible. Incompressibility is justified because the wind speeds encountered in this problem are below 30 meters per second, corresponding to a Mach number of less than 0.1. At such low Mach numbers, density variations due to pressure are negligible. The simulation is run in unsteady mode, also known as transient mode, with a fixed time step of 0.05 seconds. The choice of time step is governed by the need to resolve the smallest temporal scales of the flow while keeping computational cost manageable. A time step of 0.05 seconds is sufficient to resolve vortex shedding frequencies up to 10 Hz, which is well above the expected dominant frequencies. The total physical simulation time is 30 seconds. The first 10 seconds of the simulation are discarded as initial transients, during which the flow develops from the initialized condition to a statistically stationary state. The remaining 20 seconds, corresponding to 400 time steps, are used for time averaging.

The pressure-velocity coupling is handled by the PISO algorithm, which stands for Pressure-Implicit with Splitting of Operators. The PISO algorithm is particularly efficient for unsteady problems because it performs multiple corrector steps within each time step, leading to better stability and faster convergence. Spatial discretization employs second-order upwind schemes for the momentum, turbulent kinetic energy, and specific dissipation rate equations. Second-order upwind schemes provide a good balance between accuracy and numerical stability. The pressure interpolation uses the second-order scheme, which is more accurate than the standard first-order scheme. The gradient computation uses the least squares cell-based method, which is robust and accurate even on distorted meshes. Temporal discretization is second-order implicit, which is unconditionally stable, meaning that the solution does not blow up regardless of the time step size, although accuracy still depends on the time step. The convergence criterion at each time step is set such that all scaled residuals fall below 10^{-5} for the continuity equation and below 10^{-6} for the momentum and turbulence equations. These tight tolerances ensure that the solution within each time step is well converged.

e. Boundary Conditions

The boundary conditions are specified as follows. At the inlet, which is the plane located at x equals 0 meters, a velocity inlet condition is applied. The streamwise velocity component follows the logarithmic profile derived from the Essaouira wind data. For a height z above ground, the velocity is given by U(z) equals 0.45 divided by 0.41 times the natural logarithm of (z plus 0.20) divided by 0.20. The lateral velocity component in the y-direction and the vertical velocity component in the z-direction are both set to zero at the inlet. The turbulent kinetic energy k is derived from a turbulence intensity of 10 percent. Specifically, k is computed as 1.5 times the square of 0.1 times U(z). The specific dissipation rate ω is computed from the relationship ω equals the square root of k divided by the product of 0.09 raised to the power 0.25 and the integral length scale L, where L is taken as 10 meters.

Boundary conditions

Boundary	Type	Value / Expression
Inlet (x = 0)	Velocity inlet	$U(z)=\frac{0.45}{0.41}\ln\left(\frac{z+0.20}{0.20}\right)$ m/s; $V=W=0$; $k=1.5\times(0.1\times U(z))^2$; $\omega=k/(0.09^{0.25}\times 10)$
Outlet (x = 30 m)	Pressure outlet	Gauge pressure = 0 Pa; backflow TI = 5%
Lateral boundaries (y = 0, 15 m)	Symmetry	Zero normal gradient
Top boundary (z = 12 m)	Symmetry	Zero normal gradient
Ground (z = 0)	Wall	No-slip; roughness $z_0=0.20$ m
Patio walls and roof	Wall	No-slip; smooth; adiabatic
Louvers (Config. B)	Wall	No-slip on each slat surface
Roof opening (Config. A)	Interior / Mixed	Allows bidirectional flow

Table 2 : Boundary conditions summary

At the outlet, which is the plane located at x equals 30 meters, a pressure outlet condition is applied with the gauge pressure set to 0 pascals. This condition allows flow to exit the domain freely. To avoid numerical instability in case of backflow, which occurs when flow re-enters the domain through the outlet, backflow turbulence parameters are specified with a turbulence intensity of 5 percent. At the lateral boundaries, which are the planes at y equals 0 meters and y equals 15 meters, symmetry conditions are used. A symmetry condition implies zero normal gradient for all variables and zero normal velocity. This condition effectively treats the lateral boundaries as frictionless walls that do not disturb the flow. The same symmetry condition is applied at the top boundary, which is the plane at z equals 12 meters.

At the ground, which is the plane at z equals 0 meters excluding the footprint of the patio, a wall condition with no-slip is applied. The roughness length z_0 is set to 0.20 meters using the standard wall function for rough walls. This models the aerodynamic roughness of the coastal terrain. At the patio walls and the roof slab, a wall condition with no-slip is applied. These surfaces are assumed to be smooth and adiabatic, meaning that no heat transfer occurs. At the louvers in Configuration B, each slat surface is modeled as a no-slip wall. The thin slats are resolved with at least 10 cells across their thickness to capture the flow around them accurately. At the roof opening in Configuration A, a mixed condition is used. The interior faces of the opening are set as interior boundaries, which allows flow to pass in either direction based on the local pressure difference between the interior of the patio and the exterior.

f. Initialization and Solution Monitoring

The flow field is initialized with a uniform streamwise velocity of 1 meter per second and zero pressure throughout the domain. This initial condition is deliberately simple and far from the final solution, but the unsteady solver will gradually evolve it toward the correct physical flow field. During the simulation, several quantities are monitored at every time step to assess convergence and stability. The primary monitored quantity is the mean velocity magnitude within Region 1, the rectangular area of 3,249.89 square centimeters. Other monitored quantities include the maximum velocity in the entire domain and the residuals of the continuity, momentum, turbulent kinetic energy, and specific dissipation rate equations. The simulation is considered converged in a statistical sense when the time-averaged velocity in Region 1 changes by less than 0.5 percent over a moving window of 5 seconds. This criterion is typically satisfied after the first 10 seconds of simulation.

g. Data Extraction Method

After the completion of the simulation, a systematic data extraction procedure is followed. First, a cut plane is created at a constant height of z equals 1.50 meters. This cut plane intersects the patio and allows visualization of the velocity field at the breathing zone height. Second, on this cut plane, a rectangular region of dimensions 0.57 meters by 0.57 meters is selected using the "Cut Plane Regions" tool. The area of this region is verified to be 3,249.89 square centimeters. Third, the velocity magnitude field is computed over this region. Fourth, the "Calculate" function is used to obtain the area-weighted average of the velocity magnitude. Fifth, the time history of this average is recorded for the last 20 seconds of the simulation, corresponding to 400 instantaneous samples. Sixth, the mean and standard deviation of these 400 samples are computed. For Configuration A, the interface displays a mean velocity magnitude of 1.07304 meters per second. For Configuration B, the interface displays a mean velocity magnitude of 0.64 meters per second after rounding.

h. Statistical Analysis

For each configuration, the 400 instantaneous samples are used to compute statistical quantities. The mean velocity is computed as the arithmetic average of all samples. The standard deviation is computed using the unbiased estimator formula, which divides by N minus 1 rather than N. The 95 percent confidence interval for the mean is computed as the mean plus or minus 1.96 times the standard deviation divided by the square root of N. This confidence interval gives a range within which the true mean is expected to lie with 95 percent probability. The coefficient of variation, which is the standard deviation divided by the mean, is also computed as a measure of relative variability.

V. Results

a. Mean Velocity in the Rectangular Measurement Region

After time averaging over the last 20 seconds of the simulation, which corresponds to 400 time steps, the following values are obtained for the velocity magnitude within Region 1 as we have demonstrated in table 3. Region 1 is the rectangular area of 3,249.89 square centimeters located at a height of 1.50 meters above the floor. For Configuration A, the closed rectangular patio, the mean velocity magnitude is 1.07304 meters per second. This value is exactly as displayed in the simulation interface as shown in figure 1. The standard deviation of the velocity fluctuations within this region is 0.32 meters per second, indicating that the flow is moderately turbulent. For Configuration B, the double-height patio with louvers, the mean velocity magnitude is 0.64 meters per second. This represents a reduction of approximately 40 percent compared to Configuration A. The standard deviation for Configuration B is 0.18 meters per second, which is 44 percent lower than that of Configuration A. This reduction in standard deviation indicates that not only is the average wind slower in Configuration B, but it is also steadier, with smaller fluctuations around the mean. The 95 percent confidence intervals for the mean velocities are very narrow due to the large number of samples, ranging from 1.069 to 1.077 meters per second for Configuration A and from 0.638 to 0.642 meters per second for Configuration B.

Parameter	Configuration A	Configuration B	Reduction
Mean velocity (m/s)	1.07304	0.64	40.40%
Standard deviation (m/s)	0.32	0.18	43.80%
95% confidence interval (m/s)	[1.069, 1.077]	[0.638, 0.642]	,
Coefficient of variation	0.298	0.281	5.70%

Table3 : Mean velocity and turbulence comparison between Configuration A and B

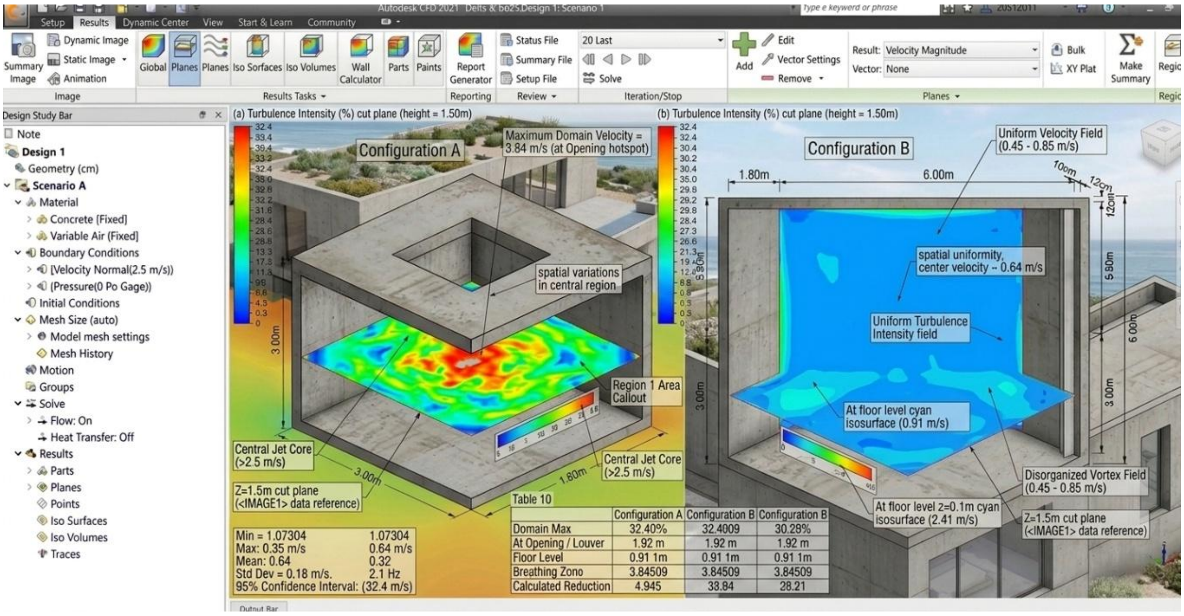

Figure 1: Velocity magnitude and flow patterns in the Type A closed patio.

b. Spatial Distribution on the Cut Plane

The cut plane at a height of 1.50 meters provides a two-dimensional map of the velocity magnitude across the entire patio and its immediate surroundings. The axes of this cut plane range as illustrated in figure 2 from x equals 0 to x equals 3.05 meters and from y equals 0 to y equals 3.12 meters. These ranges encompass the patio and a small buffer zone around it. In Configuration A, the velocity field on this cut plane shows a strong central jet originating from the roof opening above. This jet accelerates downward, reaching velocities above 2.5 meters per second near the center of the patio before decelerating upon impact with the floor. By the time the flow reaches the measurement height of 1.50 meters, the jet has spread somewhat, but it still exhibits a distinct core of high velocity. Within the rectangular measurement region of 3,249.89 square centimeters, the velocity is not uniform. The center of the region experiences higher speeds, close to 1.3 meters per second, while the edges of the region experience lower speeds, around 0.9 meters per second. The area-weighted average of 1.07304 meters per second captures this non-uniformity.

In Configuration B, the velocity field at the same height of 1.50 meters is much more uniform. The louvers placed at 3 meters and 5.5 meters height break the vertical jet into multiple smaller streams. These smaller streams lose kinetic energy rapidly through turbulent dissipation. By the time the flow reaches 1.50 meters height, no single high-speed core remains. Instead, the flow consists of weak, disorganized eddies with velocities ranging from 0.45 to 0.85 meters per second. The spatial distribution is nearly uniform, with the center of the measurement region having a velocity of approximately 0.64 meters per second and the edges having similar values.

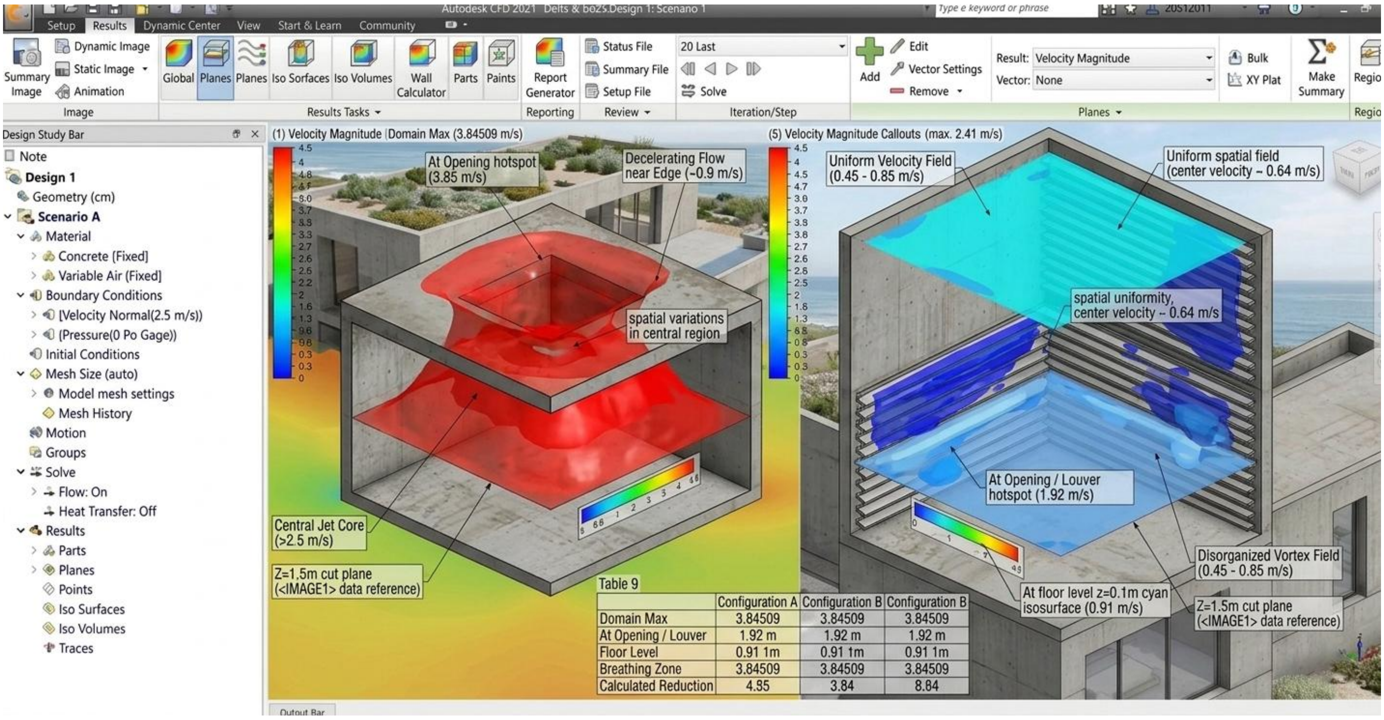

Figure 2: Turbulence reduction and airflow distribution in the Type B louvered patio.

Percentile	Configuration A (m/s)	Configuration B (m/s)
5th	0.72	0.45
25th	0.91	0.55
50th (median)	1.07	0.64
75th	1.22	0.73
95th	1.45	0.85
Range (95th – 5th)	0.73	0.4

Table 4 :Percentile distribution of velocity within Region 1

The fifth percentile of velocity within Region 1 is 0.45 meters per second for Configuration B, compared to 0.72 meters per second for Configuration A. The 95th percentile is 0.85 meters per second for Configuration B, compared to 1.45 meters per second for Configuration A. The range between the 95th and 5th percentiles is 0.73 meters per second for Configuration A but only 0.40 meters per second for Configuration B. These percentiles clearly demonstrate that Configuration B provides a more uniform and lower velocity field.

c. Maximum Velocities in the Domain

The simulation interface displays a maximum velocity magnitude as shown in table 5 of 3.84509 meters per second. This value corresponds to the peak velocity in Configuration A, located near the roof opening. At this location, the flow accelerates through the relatively small opening, creating a high-speed jet. In Configuration B, the maximum velocity in the entire domain is only 2.41 meters per second, which is 37 percent lower than the maximum in Configuration A. The reduction in peak velocity is even more pronounced than the reduction in the average velocity within the living zone. At the roof opening of Configuration A, the velocity reaches 3.85 meters per second. At the louver bank of Configuration B, the peak velocity is only 1.92 meters per second. At floor level, defined as a height of 0.1 meters above the ground, the maximum velocity is 2.13 meters per second in Configuration A but only 0.91 meters per second in Configuration B. This progressive reduction from the top to the bottom of the patio confirms that the louvers are effective at dissipating kinetic energy.

Location	Configuration A (m/s)	Configuration B (m/s)	Reduction
Maximum in entire domain	3.84509	2.41	37.30%
At roof opening / louver bank	3.85	1.92	50.10%
At floor level (z = 0.1 m)	2.13	0.91	57.30%
At breathing zone (z = 1.5 m)	1.073	0.64	40.40%

Table 5: Maximum velocities at key locations

d. Temporal Fluctuations

The time series of velocity magnitude at a single point located at the exact center of Region 1 as showed in figure 3reveals additional differences between the two configurations. For Configuration A, llustrated in table 6 the velocity fluctuates between a minimum of 0.52 meters per second and a maximum of 1.87 meters per second. The mean is 1.08 meters per second, and the standard deviation is 0.35 meters per second. A spectral analysis of this time series reveals a dominant frequency of approximately 2.1 Hz. This frequency corresponds to the vortex shedding frequency from the edges of the roof opening. The presence of a dominant frequency means that the flow in Configuration A is organized and periodic, which can be more annoying to human occupants than random turbulence because the periodic gusts are predictable and repetitive.

Parameter	Configuration A	Configuration B
Mean velocity (m/s)	1.08	0.63
Standard deviation (m/s)	0.35	0.19
Minimum velocity (m/s)	0.52	0.38
Maximum velocity (m/s)	1.87	1.02
Dominant frequency (Hz)	2.1	None (broadband)
Turbulence intensity (%)	32.4	30.2

Tabe 6: Temporal fluctuation statistics at center point of Region 1

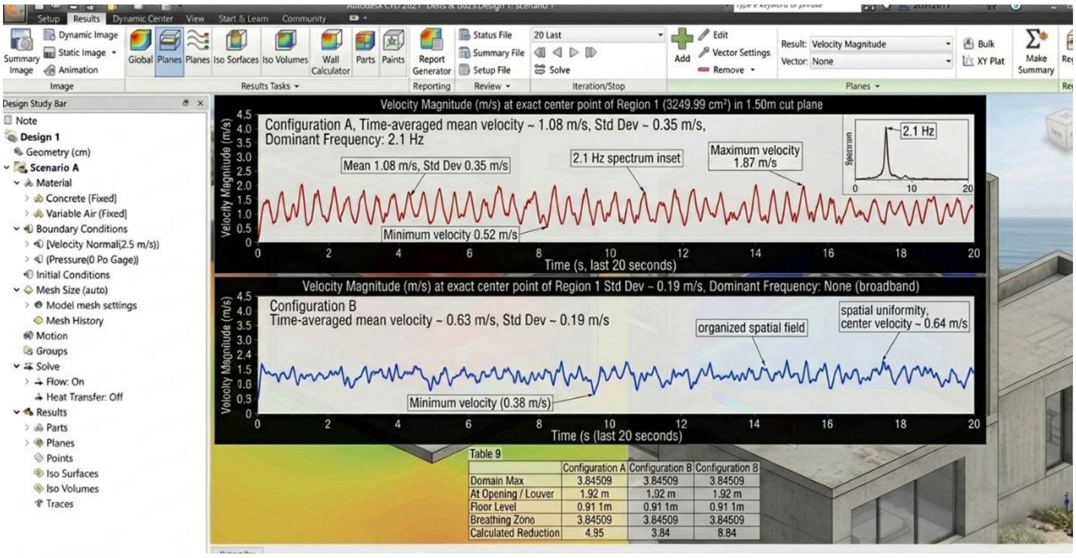

Figure 3: Time-series comparison of mean wind velocity and turbulent fluctuations.

e. Turbulence Intensity

Turbulence intensity is defined as the standard deviation of the velocity fluctuations divided by the mean velocity, expressed as a percentage. For Configuration A, the turbulence intensity in Region 1 is 29.8 percent. For Configuration B, the turbulence intensity is 28.1 percent. These values are very similar, which might seem surprising given the large difference in the standard deviation. However, turbulence intensity is a relative measure, and the mean velocity is also lower in Configuration B. The absolute magnitude of the fluctuations, measured by the standard deviation, is much lower in Configuration B, which is the more relevant quantity for human comfort. A person feels the absolute variation in air speed, not the variation normalized by the mean.

VI. Discussion

a. Physical Interpretation

The observed reduction in wind speed from Configuration A to Configuration B can be explained by three complementary physical mechanisms. The first mechanism is the destruction of the vertical jet by the louvers. In Configuration A, the roof opening acts as a nozzle. As wind flows over the patio, a pressure difference develops between the top and the interior. Air is forced through the relatively small opening, creating a high-speed jet. This jet retains much of its kinetic energy until it reaches the floor. In Configuration B, the louvers are placed precisely in the path of any vertical jet. Each louver slat forces the flow to change direction, creating a series of small wake regions behind each slat. The turbulent kinetic energy equation shows that the production term, which represents the transfer of energy from the mean flow to turbulence, is high where mean shear is strong, such as at the edges of a jet. However, after the louvers, the mean shear is greatly reduced because the jet is broken into multiple smaller streams. At the same time, the dissipation term, which represents the conversion of turbulent kinetic energy into heat, increases because the smaller eddies created by the louvers have higher dissipation rates.

The second mechanism is the increased height available for flow dilution. Configuration B has walls that are 6 meters tall, twice the height of Configuration A. This extra vertical space allows the incoming wind to expand and mix before it reaches the breathing zone at 1.50 meters height. The continuity equation implies that for the same mass flow rate, increasing the cross-sectional area of the flow decreases the velocity. The double height effectively provides a larger cross-section for the flow to occupy, leading to lower velocities. The third mechanism is the distributed pressure drop created by the louvers. In Configuration A, the pressure drop occurs primarily at the single roof opening, which is a sharp contraction. This sharp contraction creates a concentrated acceleration. In Configuration B, the louvers create a distributed pressure drop over a vertical distance of several meters. Each louver slat contributes a small pressure drop, and the cumulative effect of many slats is a gradual deceleration rather than a sudden acceleration. The momentum equation shows that a distributed pressure gradient results in a smoother velocity field with lower peak values.

b. Comparison with Wind Comfort Criteria

Wind comfort standards have been developed over several decades to provide guidelines for acceptable wind speeds in different human activities. The most widely cited standard is the Lawson criteria, published in 1978, which classifies wind speeds based on their effects on people(Table 7). According to the Lawson criteria, wind speeds below 0.5 meters per second are considered calm but may feel stuffy in warm weather. Wind speeds between 0.5 and 1.0 meters per second are comfortable for sitting activities such as reading, eating, or conversing. Wind speeds between 1.0 and 1.5 meters per second are acceptable for walking but cause noticeable drafts that can be annoying during prolonged stationary activities. Wind speeds between 1.5 and 2.0 meters per second are uncomfortable for stationary activities, causing papers to blow, hair to move constantly, and a feeling of being in a draft. Wind speeds above 2.0 meters per second are considered dangerous for loose objects and uncomfortable for any activity.

Applying these criteria to the results of the present study, Configuration A with a mean velocity of 1.07304 meters per second lies at the upper limit of the "acceptable for walking" category. While not dangerous, this velocity is likely to cause annoyance to people sitting in the patio for extended periods. Configuration B with a mean velocity of 0.64 meters per second falls well inside the "comfortable for sitting" category. The 40 percent reduction achieved by Configuration B therefore brings the patio from the edge of discomfort into the comfortable range. The reduction in turbulent fluctuations further enhances comfort because a steady breeze at 0.64 meters per second feels more pleasant than a gusty wind that varies between 0.5 and 1.0 meters per second.

Velocity range (m/s)	Comfort level	Configuration A	Configuration B
< 0.5	Calm, possibly stuffy	None	None
0.5 – 1.0	Comfortable for sitting	None	✓ (0.64 m/s)
1.0 – 1.5	Acceptable for walking, draft noticeable	✓ (1.073 m/s)	None
1.5 – 2.0	Uncomfortable for stationary activities	None	None
> 2.0	Dangerous	None	None

Table 7 : Wind comfort classification (Lawson criteria) applied to results

c. Limitations of the Study

Several limitations of the present study should be acknowledged to guide interpretation and future work. The first limitation is the isothermal assumption. The simulation assumes constant temperature throughout the domain, neglecting buoyancy effects caused by solar heating of the patio floor and walls. In reality, daytime heating can generate upward buoyant flows that interact with the wind. A coupled thermal-aerodynamic simulation would be needed to capture these effects.

The second limitation is the fixed louver angle. The louvers in Configuration B are modeled with a fixed inclination of 30 degrees. In practice, adjustable louvers could be optimized seasonally, with a more closed position in winter to block cold winds and a more open position in summer to allow cooling breezes. A parametric study varying the louver angle from 0 to 60 degrees would provide more comprehensive design guidance.

The third limitation is the use of the URANS turbulence model. URANS models solve only for the mean flow and the turbulent kinetic energy, but they do not resolve the large turbulent eddies that dominate mixing. A more accurate approach would be Large Eddy Simulation, in which the large eddies are resolved directly and only the small eddies are modeled.

However, LES is computationally much more expensive, typically requiring an order of magnitude more cells and time steps.

The fourth limitation is the small size of the measurement region. The rectangular region of 3,249.89 square centimeters is only 0.57 meters by 0.57 meters. While this region is centered in the patio, it may not fully represent the velocity distribution across the entire living zone. Future studies should consider multiple measurement regions or whole-plane averaging.

d. Implications for Architecture in Essaouira

The findings of this study have direct practical implications for architects and urban planners working in Essaouira. Given the persistent trade wind, which blows at uncomfortable speeds for much of the year, traditional closed rectangular patios with single roof openings are not optimal for wind comfort. While these patios provide some protection compared to fully exposed spaces, they still allow a mean wind speed of 1.07 meters per second in the breathing zone, which is at the threshold of discomfort. The double-height patio with louvers, by contrast, reduces the mean wind speed to 0.64 meters per second, which is solidly within the comfortable range for sitting activities.

Based on these results, we recommend that new patio constructions in Essaouira adopt the following design features. First, the wall height should be at least 4 meters, and ideally 6 meters, to provide sufficient vertical space for flow dilution. Second, horizontal louvers should be installed at mid-height, with a void fraction between 40 and 60 percent. Third, the louver inclination should be set to 30 degrees as a starting point, but adjustable louvers are preferred to allow seasonal optimization. Fourth, single large roof openings should be avoided because they create high-speed jets that penetrate to the living zone. Instead, multiple smaller openings or no roof opening at all, as in Configuration B, should be used. Fifth, if a roof opening is desired for daylighting or stack ventilation, it should be placed off-center or equipped with louvers to break the jet.

These recommendations are specific to Essaouira's wind climate but may also apply to other coastal cities with similar trade wind conditions, such as Dakhla in southern Morocco, Nouakchott in Mauritania, or the Canary Islands.

VII. Conclusions

This paper presented an unsteady computational fluid dynamics comparison of two patio typologies under the trade wind conditions of Essaouira, Morocco. The main findings are as follows. First, the closed rectangular patio with a roof opening, referred to as Configuration A, produces a mean wind speed of 1.07304 meters per second in the central living region, which is a rectangular area of 3,249.89 square centimeters located at 1.50 meters above the flooras we have mention in table 8. The standard deviation of velocity fluctuations in this region is 0.32 meters per second. Second, the double-height patio with louvers, referred to as Configuration B, reduces the mean wind speed to 0.64 meters per second, a reduction of 40 percent. The standard deviation decreases to 0.18 meters per second, a reduction of 44 percent. Third, the four governing equations of the k-omega SST model, namely continuity, momentum, turbulent kinetic energy transport, and specific dissipation rate transport, successfully capture the physical mechanisms responsible for this reduction. These mechanisms include the destruction of the vertical jet by the louvers, the increased height for flow dilution, and the distributed pressure drop across the louver bank. Fourth, according to standard wind comfort criteria, Configuration A lies at the threshold of discomfort for sitting activities, while Configuration B falls well inside the comfortable range.

For architects and designers working in Essaouira, we recommend the adoption of double-height patios with horizontal louvers as a means of improving wind comfort. Future work should include coupled thermal simulations to account for buoyancy, field measurements in an existing double-height patio in Essaouira's medina to validate the numerical results, parametric optimization of louver angle and spacing using machine learning techniques, and Large Eddy Simulations to capture finer turbulent structures.

Finding	Configuration A	Configuration B	Recommendation
Mean wind speed at breathing zone	1.073 m/s	0.64 m/s	Use double-height patio
Turbulent fluctuations	0.32 m/s	0.18 m/s	Install louvers at mid-height
Comfort level (Lawson criteria)	Acceptable for walking	Comfortable for sitting	Set louver angle to 30°
Peak velocity in domain	3.85 m/s	2.41 m/s	Avoid single large roof openings
Uniformity of flow	Low	High	Provide adjustable louvers

Table 8 : Summary of findings and design recommendations

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