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Stratification effects on flow and scalar transport through a deep cavity: A bioinspired examination

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ABSTRACT

This study investigates the effect of thermal stratification and boundary layer wind on the transport phenomena within a deep cavity. The study is inspired by the ventilation and gas-exchange process within the chimneys of open-vent termite mounds. Large-eddy simulations are conducted over an idealized termite mound subject to different thermal stratifications that are formed based on the observed mean day and night-time air and mound nest temperatures reported in the literature. A thorough analysis of the flow, temperature, and scalar fields indicates that the dynamics of the flow and the ventilation process within the cavity are controlled by the combined effects of the cavity entrance vortex and the stability condition within the lower regions of the cavity. The results show that, despite the small differences in the imposed stratification condition, the ventilation capacity is significantly higher in unstable conditions, owing to the stronger suction at the cavity entrance, together with the positive buoyant forces at the lower sections of the cavity. The results are in agreement with experimental observations of termite mounds in nature.

I. INTRODUCTION

The atmospheric boundary layer turbulence and the state of the atmospheric stratification determine the complex transport phenomena at the interface of the earth and atmosphere. The diurnal solar cycle is responsible for heating and cooling of the earth’s surface and, thus, for the thermal stratification in the lower atmosphere, resulting in an unstable boundary layer during the day and a stable one at night (e.g., Stull, 2012; Garratt, 1994).

There are several animal species in nature that use the diurnal solar heating, atmospheric wind flow, their own metabolic heat, and the principles of thermal stratification to create controlled microclimates in their nests. Eciton burchelli ants create temporary underground nests that, despite large temperature fluctuations of the ambient air, can maintain a constant internal temperature throughout the day. This climate-control process is done through the creation or closing-up of ventilation channels that extend deep into the ants’ nest (Franks, 1989). A similar ventilation mechanism is also seen in different species of bees and wasps (Ishay and Ruttnier, 1971; Ishay and Barenholz-Paniry, 1995; and Jones and Oldroyd, 2006). Among different animals, mound-building termites are known for their ability in building structures that can effectively use solar and wind energies and energy from the colony’s metabolic activities to maintain the necessary condition for termites’ survival (for a review, see, for example, Abou-Houly, 2010; Worall, 2011). The microclimate-controlling function of termite mounds and their efficient ventilation mechanisms have been the subject of several studies since the 1940s and have inspired the creation of several massive architectures around the world [e.g., the Eastgate Center in Zimbabwe, Davis Alpine House in England, and the Council House 2 in Australia (Turner and Soar, 2008; Zari, 2015)].

Termites are social insects that live on every continent. Termites are one of the only two soil organisms (the other is ants) that modify the soil to create a habitable environment for their survival. They do this mainly by constructing massive mounds. Mounds that termites build are complex structures that are constructed from the local soil particles cemented together with termites’ saliva (Mermut et al., 1984). Construction of mounds [that in some
instances tower to 9 m (Wood, 1988) by miniature size (~1 cm) termites has been compared to humans creating mountains (Bölsche et al., 1993; Harris, 1956). While there are about 2400 species of termites with different needs and feeding behaviors spread around the world (Krisha et al., 1969), mound types are limited to only a few classes [i.e., conical, cathedral, dome, mushroom, and wedge shaped mounds (Claggett et al., 2018)]. The internal structure of termite mounds is diverse. Some are perforated with a complex, but systematic, network of tunnels and have one or several vents opened to the outside (known as open-vent mounds), while in others, the internal channels have no obvious openings to the exterior (Turner and Soar, 2008). In most classes, termites, themselves, do not reside within the mound structures, rather they live in compact nests that are located under the ground level, beneath the mound over-ground structure. Termites’ metabolic activities are confined to their nest, and they enter the over-ground part of the mound only for defending, construction, and repairing purposes (e.g., Turner, 2000; 2001). These nests interact with the outside fresh air, primarily, through a main channel (also known as chimney).

Ventilation mechanisms in termite mounds have been the subject of several experimental studies with measurements of local temperature, CO₂ concentrations, and tracer gas techniques aiding in identifying flow patterns and mixing behavior. Throughout the years based on the experimental results, various mechanisms have been proposed to explain the ventilation and gas exchange process in termite mounds. The earliest model that was offered by Lüscher (1961) suggested that closed-vent mounds use a thermosiphon mechanism in which the termites’ metabolism heat in the nest produces a buoyancy force in the mound conduits. The second model that was proposed by Weir (1973) and was based on an experiment over open-vent mounds of Macrotermes subhyalinus suggested that flow inside the mound conduits was induced by the wind passing over the open chimneys, drawing air in through the ground-level openings (stack effect). These hypotheses were questioned and refined in later studies Turner (2001), through direct measurements of air flows in termites’ subterranean nests and mounds over-ground structures, proposed a new model suggesting a tidal flow (rather than circulatory or unidirectional), driven by the interaction of the mound superstructure with the temporally variable atmospheric turbulent wind. In this mechanism that he observed in both open and closed-chimney mounds (e.g., Turner, 1994; 2001), mixing within the mound conduits is related to the fluctuating pressure field over and across the mound body. Due to the observation of the tidal flow, the gas exchange mechanism in mounds is, therefore, compared to the function of the mammalian lung (Turner, 2001; Turner and Soar, 2008). Analogous to the lung, where multiple airways (trachea, bronchi, and alveoli) are involved in the respiration process, the various parts of the complicated mound internal architecture (air channels, chimneys, and the nest) work together to provide adequate ventilation and gas-exchange to the nests. Other studies indicated that termite mounds function differently during the day and night-time. Korb and Linsenmair (2000) examined the cathedral- and dome-shaped mounds of Macrotermes bellicosus and discovered that thermal gradients created during the day give rise to convection currents. During the night, air was more stagnant with higher CO₂ concentrations in the air channels. King et al. (2015) assessed cathedral mounds of Odontotermes obesus in the humid environment of south Asia via direct measurements of flow inside the structure. With the sun heating up surfaces during the day, a rising flow in air channels close to the surfaces was observed and a downward flow in the central chimney, whereas at night, the opposite ensued. Thus, a cyclic pattern driven by the diurnal ambient temperature was concluded.

In a similar manner to King et al. (2015), dome- and cone-shaped closed-chimney mounds of Macrotermes michaelseni were investigated by Ocko et al. (2017). During the day, rising flow was noted in the channels that were directly heated by the sun, whereas channels on the shaded side had a downward flow. As a result, parallel to King et al. (2015), a cyclic flow pattern was observed; however, it was noted to be dependent upon the location of incident direct sunlight (azimuthal dependence).

A thorough review of the literature indicates that despite a long history of valuable experimental studies on the ventilation function of termite mounds, the underlying physics of the ventilation process is still under debate and continues to be elusive. The disputes are mainly due to the nature of the experimental methods that are performed over complex natural structures, as well as their limitations to particular mounds, located in particular geographical locations and climates. In this work, we are interested in developing a computational framework for assessing the fundamental physics of the natural ventilation mechanism and scalar (respiratory gas) transport within termite mounds. A numerical approach allows for a comprehensive investigation of the heat transfer and flow physics governing the intricate ventilation process in complex natural structures. In addition, in contrast to empirical approaches, computational studies can be expanded and examined over a wide range of parameters. The particular focus of the current computational study is on the ventilation mechanism of open-vent termite mounds under different thermal stratifications. The key component of the model is a large-eddy simulation (LES)-based approach. Understanding the physics of mass and heat transfer in such a multiphysics and multiscale problem is challenging and computationally expensive, which is why there is a scarcity of computational analyses in the field of termite biology. To the best of our knowledge, there has been only one computational effort in understanding the mound’s function (Abou-Holy, 2010), in which the simplifications forced by the numerical limitations prevented a comprehensive study.

Unlike closed-vent mounds, the internal structure of open-chimney mounds is simple and usually consists of a single tall central cavity, which opens to the atmosphere on one end and is connected to the underground termite nest on the other (Fig. 1). From the computational point of view, the flow pattern and passive respiratory gas ventilation within the open-vent mound chimney under the influence of atmospheric turbulent eddies can be seen as a problem of flow field and ventilation rate within a deep cavity that opens into the boundary layer wind.

There are several species of termites that build open-chimney mounds, among which M. bellicosus (Glover, 1967), Macrotermes jeanneli (Darlington et al., 1997), M. subhyalinus (Darlington, 1984), and Odontotermes transvaalensis (Turner, 1994) can be named. Both the height and base diameter of this mound type can range from 1 m to 5 m, with central chimneys of 0.1 m–0.3 m in diameter (e.g., Darlington, 1984; Glover, 1967). Termites reside in the nest that lies under the ground at the base of the chimney. The chimney is connected to the nest via numerous smaller and thinner air channels. At the base of the nest, the chimney branches out into thin foraging
tubes deep underneath the soil surface. These tubes are sometimes connected to the surface through foraging access holes. The access holes remain sealed when not in use (Darlington et al., 1997).

Although the current study focuses on passive ventilation and flow characteristics within a termite mound’s vertical chimney, the outcomes could be leveraged to the transport phenomena within any cavity-shape geometries/topographies found on the earth’s surface (for example, pollution ventilation in deep urban canyons and transport phenomena within natural canopies and mountain valleys). This paper is structured as follows: in Sec. II, we describe the main components of the computational modeling and simulation setup. Results and discussions are provided in Sec. III, followed by the conclusions in Sec. IV.

II. MODEL DESCRIPTION AND SIMULATION SETUP

The described problem of gas-exchange mechanism in single-vent open-chimney termite mounds is simplified to the examination of the ventilation rate of a passive scalar emitted from the base of a deep vertical cavity (representing the termite colony’s respiratory gas production from the underground nest) under the effect of the atmospheric turbulent wind flow (Fig. 2). The wind flow effect and the ventilation mechanism are examined under different atmospheric stratifications (i.e., representing average day and night conditions).

The problem under study is a multiscale problem, with a working flow representing local-scale atmospheric wind flow, while the focus is on the transport phenomena in a deep cavity of a smaller size. For the simulation of the atmospheric airflow field, the PArallelized Large-Eddy Simulation Model for Atmospheric and Oceanic Flows (PALM; Maronga et al., 2015) is used. PALM is a large-eddy simulation (LES)-based model that solves the nonhydrostatic, filtered, incompressible Navier-Stokes equations in Boussinesq-approximated form, along with the potential temperature and passive scalar equations. The advection terms are discretized using the fifth-order upwind Wicker-Skamarock scheme (Wicker and Skamarock, 2002), and a third-order Runge-Kutta scheme (Williamson, 1980) is used for time differencing with time steps...
A. Simulation setup

To characterize the underlying physics of the multiscale problem under study, the computational domain should be large enough to represent the physics of the atmospheric flow at the local scale over a bluff body, while the deep cavity within the body should be small enough to represent the transport phenomena in the mound chimney. The mound shape (Fig. 2) is approximated based on the geometry of open-chimney termite mounds, using a Gaussian shaped structure with a height of 2.0 m, a half-height diameter of 1.0 m, and a base diameter of 2.4 m. The model mound contains a chimney with a square cross section of side 0.3 m in the middle, extending from the bottom to the top, conforming to the Cartesian grids of the computational domain.

Considering computational efficiency and resources, the multiscale nature of the problem enforces a careful analysis of the size of the computational grid and domain. Therefore, several domain and grid size sensitivity analyses were conducted. The goal was to have a large enough domain that contains the most energetic eddies passing over the mound body with fine enough grids in the cavity to capture the transport phenomena within. To evaluate the domain size, the integral length scales of the turbulent eddies in the domain were analyzed. The integral length scale, which provides a measure of the extent of the region over which the velocities are correlated, is defined as \( \Lambda = \int_0^\infty \rho R_{uu}(r) \, dr \), where \( R_{uu} \) is the longitudinal velocity correlation function, \( r \) is the distance between two points in the flow, and \( x \) is the first zero crossing of the correlation curve (e.g., Pope, 2001; O’Neill et al., 2004). Four different cuboidal domain sizes with horizontal widths of 3.6, 4.8, 6.0, and 8.1 times the height of the mound structure (i.e., \( H = 2 \) m) were examined. The integral length scale increases with the increase in the domain size up to a point beyond which the increase in the domain size has little or no effect on the integral length scale. Based on the results, the energy-containing eddies of size \( \Lambda = 0.53 \), \( H = 1.07 \) m, associated with the domain size 4.8H \( \times 4.8H \), were chosen. The chosen domain size is nine times larger than the obtained integral length scale [larger than the minimum eight-times criteria required for isotropic turbulence (Pope, 2001)]. The vertical height of the domain (9.6H) was chosen large enough (over six times the roughness height) to ensure that the effect of the turbulent coherent structures within the inertial sublayer on the near-wall flow is considered (e.g., Finnigan, 2006; Watanabe, 2004; Coceal et al., 2007; Inagaki et al., 2012; and Yaghoubian et al., 2014).

Several tests were performed to ensure that the simulation results are independent of the grid resolution. Based on the comparison of time-averaged profiles of several parameters, including velocity components, temperature, turbulent kinetic energy (TKE), and eddy integral length scales, obtained from simulations with various grid sizes, it was found that a grid spacing of 0.025 m in each direction is fine enough to represent the flow characteristics in the whole domain, including the mound chimney. However, to ensure that the transport phenomena within the cavity are correctly captured, the computational resolution in the direction perpendicular to the flow direction in the cavity is doubled, resulting in a grid spacing of \( \Delta x = \Delta y = 0.0125 \) m, and \( \Delta z = 0.025 \) m. This grid spacing resolves the chimney with 24 grids in the horizontal directions and 80 grids in the vertical direction.

Periodic boundary conditions were used in the streamwise and spanwise directions considering that in reality, termite mounds are located in close proximity to each other (Grigg and Underwood, 1977; Turner, 2001; and Jacklyn and Munro, 2002) and the dynamics of one mound might affect those of others in the atmospheric flow conditions. For momentum, no-slip and Neumann boundary conditions were applied at the surface (mound walls and ground) and at the top boundary, respectively, while for temperature, Dirichlet conditions were imposed at the domain top and bottom.

B. Suite of simulations

Three production simulations were run using the selected domain and grid sizes with neutral, unstable, and stable thermal stratifications. The stratification conditions were established by varying the thermal boundary conditions in accordance with the information of the mean day and night-time air and mound nest (or chimney) temperatures reported in the literature for the locations of different mounds (e.g., Darlington et al., 1997; Turner, 1994; and 2001). Based on the collective information, a \pm 4^\circ C difference between the surface (ground and mound body) and air temperatures was considered. The surface temperature (including the chimney walls) was fixed at 17.38 \(^\circ C\) and 37.46 \(^\circ C\) for stable and unstable cases, respectively (Turner, 2001). In addition, the air temperature at the domain top was fixed at 21.38 \(^\circ C\) and 33.46 \(^\circ C\) to, respectively, generate stable and unstable stratifications in the simulation domain.

The rise of hot air from the warmer surface results in a low pressure system near the surface that extends to the top of the domain. Due to the negative buoyancy, the reverse takes place in the stable condition, resulting in a higher pressure system throughout the domain height. A constant wind of 2 m s\(^{-1}\) was imposed in the simulations to achieve wind speeds representing those observed by Turner (2001) at the mound location. Respiratory gas transport from the underground nest is investigated via introducing a passive scalar with a constant flux of 142.8 \(\mu\)mol m\(^{-2}\) h\(^{-1}\) (Konaté et al., 2003) at the base of the cavity. Due to the narrow geometry of the cavity, its perpendicular orientation with respect to the prevalent wind direction, the small amount of scalar flux, and the large volume of the simulation domain (representing the atmospheric flow condition) compared to the volume of the cavity (1681 m\(^3\)), the amount of recirculated scalar back into the cavity is assumed to be insignificant. Therefore, the dynamics of the passive scalar within the cavity will not be affected by the effect of the periodic boundary conditions in the simulations.

III. RESULTS AND DISCUSSION

A. Mean flow and temperature fields

To characterize the flow features resulting from the air-mound interaction and explore the external flow effect on the mass transport within the cavity, first, the mean velocity and pressure fields over the mound body were investigated. All simulations are allowed
to evolve for 1 h in physical time after stabilizing, and results are averaged over 300 s corresponding to over 30 eddy-turnover times in the domain. Figure 3(a) shows the mean streamwise velocity profiles over the mound body for all stability conditions, and Fig. 3(b) shows streamlines and a horizontal cross section of the neutral pressure field contours at the mound midheight. Due to the mound body shape, the overall mean flow features observed here are qualitatively similar to those observed in flow over hills (e.g., Ishihara and Hibi, 2002; Krajnović, 2008; García-Villalba et al., 2009, 2010; and Yang et al., 2015). A region of backflow \((u < 0)\) can be seen at the foot of the mound on the windward side (a zoomed-in figure is not shown) that correlates with the formation of a horseshoe vortex at this region. The approaching wind gives rise to pressure on the windward face due to the stagnation at the surface [Fig. 3(b)]. This is followed by low pressures at the peak of the mound with a corresponding increase in the velocity field [Fig. 3(a)]. As the flow separates from the mound, it forms a recirculation region and a descending flow in the leeward side of the mound. Further downstream \((x/H > 1.5)\), the mound effect on the flow field diminishes and the pressure recovers to the freestream pressure, accompanied by the wake recovery [Fig. 3(b)].

While the flow features are similar between the three cases, the effect of (the imposed weak) stratification can be seen in the velocity profiles [Fig. 3(a)], as well as in the turbulent kinetic energy (TKE) profiles (not shown), with the velocities and TKE being larger in unstable and smaller in stable conditions. The flux Richardson numbers \(\left( Ri_f \right)\) for statically unstable \((-0.017)\) and stable \((0.004)\) cases also indicate the difference in the thermal stabilities. The flux Richardson number is defined as

\[
Ri_f = \left( \frac{g}{\bar{T}} \right) \frac{\overline{u'w'}/\bar{T} + \overline{v'w'}/\bar{T}}{\partial \bar{u}/\partial z + \partial \bar{v}/\partial z},
\]

where \(g\) is the acceleration due to gravity, \(\bar{T}\) is the mean temperature, \(z\) is the height, \(\overline{u'}\) and \(\overline{v'}\) are mean streamwise and spanwise velocities, \(\overline{u'w'}\) and \(\overline{v'w'}\) are mean turbulent vertical momentum fluxes, and...
$\overline{w'T'}$ is the mean turbulent vertical heat flux. It should be noted that the imposed stratification is driven by the observed mean day and night conditions at the location of different mounds.

To investigate the flow condition within the cavity, velocity vectors together with velocity magnitude contours at a vertical cross section in the middle of the cavity ($y/H = 0$) are visualized in Fig. 4. Even though the velocity vectors in this vertical cross section mainly show upward flows, downwelling flow that keeps the flow conserved within this three-dimensional (3D) cavity mostly happens around the cavity corners and face of the windward wall. Due to the interaction of the cavity entrance with the overpassing flow, flow enters the cavity and creates a primary clockwise rotating vortex at the top right corner of the cavity ($z/H \sim 0.9$) in all cases. The similarity in the vortex size and location in all three cases is attributed to the dominant effect of the shear forces at the cavity entrance, which suppress the thermally driven differences between the three cases. It is noted that the shear production at the entrance region is two orders of magnitude larger than the buoyant production in this region. In the upper 25%, the velocity magnitude is an order of magnitude larger than that in the lower parts, and as the depth increases, the velocities reduce further (at $z/H = 0.25$, the magnitude becomes two orders smaller). Due to the high aspect ratio of the cavity ($H/W \sim 7$, where $W$ is the width of the cavity), the external flow does not penetrate deep into the cavity. Thus, prominent secondary vortices complementing the primary vortex at the entrance region are not seen. However, smaller and weaker secondary vortices can be observed in the lower cavity region. The higher velocity region at the top of the cavity in all cases creates a low pressure region, which is stronger in the unstable case (~1.3 N m$^{-2}$, in average, compared to ~0.4 N m$^{-2}$ and 0.6 N m$^{-2}$ for the neutral and stable cases, respectively) as a result of the greater external velocity. The stronger suction in the unstable case together with the positive buoyant forces due to the warm cavity walls in this case results in a larger mean upward velocity within the lower 75% of the cavity compared to the other two cases (Fig. 4).

To have a better insight into the 3D nature of the flow within the cavity, horizontal cross sections of the velocity magnitude and streamlines at four different heights throughout the cavity are visualized in Fig. 5. From Fig. 5, it can be observed that the secondary vortices seen at the bottom of the cavity in Fig. 4 are part of larger 3D structures, which are different in mean shape and strength among the three cases. This secondary vortex is larger and stronger for the unstable case.

Consistent with the profiles in the vertical cross section, contours of velocity magnitude in Fig. 5 show higher mean velocity throughout the cavity for the unstable case. In general, the neutral and stable cases show more similarities in flow patterns throughout the cavity height. Positive buoyancy in the unstable case and negative buoyancy in the stable case result in higher and lower velocity magnitudes, respectively, compared to the neutral case. The higher velocity leads to a more chaotic flow field (evident from the streamlines) and a better mixing for the unstable situation. In contrast, the stable case shows a lower velocity magnitude in the bottom region, marking a more stagnant flow field. As also seen in Fig. 5, the horizontal cross sections of flow at the cavity entrance show similar patterns for all three cases. The different flow fields within the
cavity determine the way the cavity controls the gas-exchange process under different stratification conditions that are discussed in more detail in Secs. III B–III D.

Contours of mean temperature within the cavity (not shown) follow the features of the velocity magnitude contours (Figs. 4 and 5), with temperatures being higher (lower) in the low-velocity regions and lower (higher) in the high-velocity regions in the unstable (stable) case. These temperature differences result in horizontal temperature gradients in the lower 75% of the cavity, which is one order of magnitude greater in the unstable case. The strong mixing at the entrance region pushes the external cooler (in unstable) or warmer (in stable) air into the cavity, but this shear driven effect remains confined to the upper 10%–15% of the cavity height [equivalent to the size of the primary vortex at the entrance region (Fig. 4)]. Vertically, a smaller temperature gradient (−0.012 °C) is observed in the stable case as compared to the unstable case (0.080 °C) between the bottom and top of the cavity.

B. Scalar concentration

The effect of the external and internal forces on the scalar transport within the cavity is investigated through comparing the mean scalar flux and mean concentration at each level throughout the cavity height (Figs. 6 and 7). Due to the stronger suction and positive buoyancy, the scalar flux throughout the cavity is consistently larger in the unstable case [Fig. 6(a)], which results in a lower mean scalar concentration throughout the cavity in this case [Figs. 6(b) and 7]. In order to be able to compare the cavity mean ventilation process between the different cases, the mean scalar concentration ($c$) in each case has been normalized by the total amount of scalar in the domain ($c_{total}$) since the time taken for the scalar to reach a steady state varies depending upon the stability condition in each case.

The contours of the normalized mean scalar concentration in Fig. 7 and their profiles in Fig. 6(b) show an enhanced mixing of the scalar throughout the cavity and, thus, a lower concentration at the lower region in the unstable case. However, in the neutral and stable cases, there is a higher accumulation in the bottom of the cavity as a result of the lower ventilation capacity in these cases. As discussed in more detail in Secs. III C and III D, the enhanced mixing and scalar flux in the unstable case are due to the higher buoyant production and an increase in the horizontal velocity variances, which lead to a better spreading of the scalar both vertically and horizontally. Our investigation of the two-point correlation coefficients between the turbulent transport of vertical heat and scalar fluxes throughout the cavity height also indicated a high correlation (reaching to 75% at the
lower cavity sections) in the unstable case while oscillations around zero for the stable case are shown.

To further investigate the ventilation rate in the mound chimney, the nondimensional residence time was calculated. Here, the residence time is defined as the time taken for the ratio of the scalar within the cavity to the total scalar in the domain to fall below 99%. This residence time is normalized by the time span of the mean flow in the domain, defined by $\frac{L}{U}$, where $L$ is the length of the domain and $U$ is the average velocity in the domain for each case. The dimensionless residence time was estimated to be the largest for the stable stratification (47.76), followed by that of the neutral (35.34) and unstable (20.95) cases, implying a significant high-efficient ventilation under the unstable situation (over twice that of the stable case, despite the small difference in the stratification condition). Investigation of the temporal variation of the mound ventilation (or breathing) shows that for the stable stratification, unlike the unstable case, the scalar slowly ventilates out of the cavity and accumulates in the lower regions of the chimney with momentum being its dominant mode of transport. The neutral case behavior lies in between those of the two non-neutral cases [A video of the instantaneous scalar field is shown in Fig. 8 (multimedia view).].

To evaluate different modes of the transport process, the relative importance of the free and forced convection throughout the cavity height under different stratifications is shown in Fig. 9(a) through comparing the Richardson numbers ($R_i$) at the cavity centerline. The Richardson number is defined as the ratio of the Grashof number [$Gr = \frac{g\beta \Delta T L^3}{\nu^2}$] to the square of the Reynolds number ($Re = \frac{uL}{\nu}$) throughout the cavity height, where $\Delta T$ is the temperature difference between the cavity walls and the air at the centerline, $\beta = 1/T$ is the coefficient of thermal expansion, $L$ is the cavity width, $u$ is the velocity magnitude at the cavity centerline, and $\nu$ is the kinematic viscosity of air. From Fig. 9(a), it is evident that in the unstable stratification, the transport process in the lower 70% of the cavity is due to the free convection driven by the higher (positive) temperature differences between the cavity air and walls (one order of magnitude higher than that in the stable case), whereas the negative buoyant forces in the stable stratification confine the free-convection zone to the lower 40% of the cavity while suppressing the transport process. The heated walls of the cavity in the unstable case lead to an increase in buoyant forces, resulting in assisting (upward) flow to the suction at the top of the cavity and a quicker escape of the scalar. As the external atmospheric flow starts to affect the cavity flow near the entrance region, both free and forced convections become of the same importance until the forced convection leads the process at the upper regions. This region develops at the upper 50% of the cavity in the stable case, while it is shorter (top 20%) in the unstable case. Comparison of the mass transfer Grashof number, defined by the concentration gradient of the scalar at the base of the cavity and those throughout the cavity height [Fig. 9(b)] illustrates higher spatial variations in the scalar concentration for the stable stratification and the lowest for the unstable, with the neutral in between the two, further indicating well-mixed scalar within the cavity in the unstable case.

![FIG. 8. Snapshots of the instantaneous scalar contours (normalized by the total scalar in the domain) ($c/c_{total}$) within the cavity for (a) unstable, (b) neutral, and (c) stable conditions. Multimedia view: https://doi.org/10.1063/1.5134096.](https://doi.org/10.1063/1.5134096)
**C. Flow characteristics within the cavity**

Figure 10 displays the horizontally averaged vertical profiles of mean turbulent kinetic energy (TKE) within the cavity and its contributing velocity variance components for different cases. From Fig. 10(a), it can be seen that the mean TKE for all cases is weak and nearly constant up to around \( z/H = 0.6 \), and it rapidly increases as the cavity flow mixes with the highly turbulent freestream flow at the top of the cavity. The magnitudes of the TKE (and its contributing components) within the lower 60% of the cavity suggest that the flow condition in this region, in neutral and stable cases, is close to the characteristics of laminar flows.

Figure 10(a’) [the inset within Fig. 10(a)] shows the increase in the mean TKE (by two orders of magnitude) within the upper 20% of the cavity compared to those within the cavity with all three cases revealing a similar behavior. The contributions of the horizontal and vertical velocities to the TKE in the top region of the cavity also bear similarities in magnitude [Figs. 10(b)–10(d)]. This behavior is due to the mechanically induced flow at the entrance region that suppresses the thermally driven differences between cases (as described in Sec. III A). Comparison of the vertical profiles of shear and buoyant productions within the cavity (not shown) illustrates that the shear production is two orders of magnitude larger than the buoyant production at the entrance region and vice versa at the bottom region.

In the lower 60% of the cavity, the greater magnitude of TKE for the unstable case suggests a higher level of instabilities and a more efficient mixing within the cavity that is due to the temperature gradient and buoyant production in this region. The larger thermal production in the unstable case is mainly due to the larger horizontal temperature gradient within the cavity (an order of magnitude larger than the stable case) that leads to increased \( u \) and \( v \) velocity variances.

Figures 10(b)–10(d) show that (as expected, due to the cavity geometry) the relative contribution of the vertical velocity variances to the local TKE is much larger than those of the horizontal velocities. The higher contribution of \( u'^2 \) and \( v'^2 \) to the TKE in the unstable case results in a lesser input from \( w'^2 \) to the local TKE, signifying more efficient local mixing within the cavity in this case. Even though the relative contribution of the vertical velocity variances to the TKE is less for the unstable case compared to the other two cases, its actual value throughout the cavity height (not shown) is greater, which contributes to the more efficient ventilation out of the cavity in this case. In general, stable and neutral cases show similar behaviors, indicating that the ventilation mechanism is alike for the two cases.

**D. Quadrant analysis**

To investigate the relative importance of short-lived events of large magnitude that contribute to the diffusion process, the conditional sampling or quadrant analysis is employed. Following Lu and Willmarth (1973), quadrants (Q) 1–4 are defined as follows: Q1: outward interactions \( (w' > 0, u' > 0) \), Q2: ejections \( (w' > 0, u' < 0) \), Q3: inward interactions \( (w' < 0, u' < 0) \), and Q4: sweeps \( (w' < 0, u' > 0) \), while \( u' \) and \( w' \) represent the streamwise and vertical velocity fluctuations, respectively, at every time step. Quadrants 1 and 3 represent upward transfer, while Q2 and Q4 characterize downward transfer [details of quadrant analysis are mentioned in several works, including Raupach and Thom (1981), Shaw et al. (1983), Smedman et al. (1999), and Kinzel et al. (2015)]. The strength of each event is represented by stress fraction \( S_i = \langle u' w' \rangle / u' w' \), defined as the...
relative contribution of each event (conditionally averaged over the stresses in each quadrant $i$) to the total Reynolds shear stress $\langle u'w' \rangle$. Figure 11 shows the absolute value of the stress fraction in each of the quadrants for the three (unstable, neutral, and stable) cases as a function of hole size $HS$ (defined as the strength of the turbulent fluctuations to the Reynolds stress; $HS = |\langle u'w' \rangle|/\langle u'w' \rangle$) at $z/H = 0.25, 0.5,$ and $0.8$ within the cavity. It can be seen that near the cavity entrance $(z/H = 0.8)$, inward interactions (Q3) account for most of the transport process for all three cases with hole sizes beyond 20, implying the dominance of the upward transport out of the cavity in all cases. Deeper within the cavity, in unstable and neutral cases, the contribution of the interaction terms (Q1 and Q3) is small and remains limited to the events less than 10 times the average flux ($HS < 10$), while around 20% of the total stress is due to the ejection and sweep events greater in magnitude than 10 (implying the dominance of downward diffusion of momentum). This behavior continues to $z/H = 0.25$, but it shows smaller contributions from all events near the cavity base. Within the cavity, in the stable case, the interaction quadrants are almost as large as the ejection and sweep quadrants, showing curves that are spread out. This behavior indicates intense and frequent events of fluxes of both positive and negative signs that result in nearly zero net flux. The slight greater contribution

FIG. 11. Absolute values of the stress fraction as a function of the hole size for unstable (left), neutral (center), and stable (right) conditions at $z/H = 0.25, 0.5,$ and $0.8$ within the cavity, where Q1: outward interactions ($u' > 0, w' > 0$), Q2: ejections ($u' > 0, w' < 0$), Q3: inward interactions ($u' < 0, w' < 0$), and Q4: sweeps ($u' < 0, w' > 0$).

FIG. 12. Snapshots of the instantaneous cavity flow contours for (a) unstable, (b) neutral, and (c) stable conditions. Multimedia view: https://doi.org/10.1063/1.5134096.2
of the interaction fluxes results in a weak upward transport in the midcavity region in the stable case. Our observation of the instantaneous flow within the cavity also marks the existence of the alternating events by sudden increases in the velocity field [a video of the instantaneous cavity flow is shown in Fig. 12 (multimedia view)].

A similar analysis following the definitions in Katul et al. (1997) was conducted for the scalar fluxes. In the stable case, most of the scalar flux in the middle of the cavity was found to be due to the events that result in upward movements of the concentration with large fluctuations. However, for the unstable and neutral cases, both upward and downward events contribute equally to the scalar transport with small fluctuations (plots are not shown).

IV. CONCLUSIONS

Using a computational framework, this study investigates the effect of thermal stratification and boundary layer wind on the transport phenomena within a narrow deep cavity. The study is inspired by the ventilation and gas-exchange process within the long upright chimneys of open-vent termite mounds. Large-eddy simulations are conducted under different thermal stratifications (stable, neutral, and unstable) that are formed based on the observed mean day and night-time air and mound nest (or chimney) temperatures reported in the literature.

The investigation of a deep cavity flow in this study revealed that the dynamics of the flow and the ventilation process within the cavity are controlled by the combined effects of the cavity entrance vortex and the stability condition within the lower regions of the cavity. While the shear-driven entrance vortex, whose strength depends on the external wind velocity defined by the atmospheric stability, controls the pressure gradient and the power of the suction at the upper 20%-25% of the cavity, deeper within the cavity temperature gradients between the cavity air and wall determine the general ventilation efficiency. The results show that, despite the small differences in the imposed stratification condition, the ventilation capacity is significantly higher in unstable conditions (over twice that of the stable case), owing to the stronger suction at the cavity entrance, together with the positive buoyant forces at the lower parts.

Variations in velocity magnitudes and gas concentration are important for termites’ survival, given that termites are highly sensitive to small changes in their habitat (Stuart, 1972; Nicolas and Sillans, 1989; Turner, 2001; and 2011). It should be noted that the low velocity magnitudes observed in the modeled cavity are found to be in the same range as the velocities observed experimentally in termite mound conduits [e.g., 0.01–0.05 m s⁻¹ at midcavity height (King et al., 2015; Ocko et al., 2017)]. In addition, the findings of higher scalar concentration during stable conditions (i.e., night-time) are aligned with the findings of experimental works (e.g., Korb and Linsenmair, 2000). It should also be noted that Turner, based on his field experiments over different types of termite mounds, related the mound ventilation process to the tidal air movements that he observed in chimneys of both open (Turner, 1994) and closed-vent mounds (Turner, 2001) (see Sec. 1). Our quadrant analysis indicated the dominance of sweep and ejection events of noticeable magnitudes in turbulent momentum fluxes within the cavity far from the entrance region. We speculate that the occurrences of these bursts and gusts were the events that have been interpreted as a tidal flow by Turner. However, based on our results, we cannot relate the gas-exchange process to the observed tidal flow; rather, as mentioned earlier, the ventilation process is a result of the combined effects of the cavity entrance vortex and the stability condition within the lower regions of the cavity, and the tidal flow is the secondary result of this combination.

Aligned with our findings, Turner concluded that “wind is a significant source of energy for powering nest ventilation” (Turner, 2001). However, his conclusion of the effect of the temporal variation of the atmospheric wind speed on the mound tidal flow cannot be supported by our findings. A two-point correlation study (not shown) between the cavity flow (at all heights) and three locations (before, after, and above the mound) in the external flow showed little or no correlation between the cavity flow and the turbulent eddies in the boundary layer wind. These results indicate that the flow in the cavity does not (directly) feel the turbulent flow fluctuations in the over-passing wind. Due to the size of the cavity, the time scale of the dynamics within the cavity is much smaller than that of the external flow. Therefore, due to this large gap between the scales of the cavity and atmospheric flows, the dynamics of the temporally variable turbulent eddies in the outside appear as those of a steady flow for the cavity (additional simulations that can confirm this point remain for future studies).

While constant thermal conditions throughout the mound body were imposed in this study, in reality, the internal and external mound surface temperatures might not be the same due to the thermal inertia and heat capacity of the mound material. This effect is not considered in this study, and the impact of the diurnally variable internal and external mound surface temperatures on the mound function is left for future studies. As a part of series of computational work, while this study is motivated by open-vent termite mounds, the ventilation mechanism in the more complex structures of closed mounds will also be investigated.

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