Numerical Study of the Effect of a Turbulent Airflow on the Heat Transfer on Cuboid Food

E. Martínez-Espinosa, M. Salinas-Vázquez, W. Vicente, C. Lara-Guzman

Abstract - A numerical simulation is conducted to study the effect of a turbulent airflow on heat transfer on cuboid food. The simulation is carried out with the Large Eddy Simulation approach. Periodic boundary conditions are implemented to represent a drying chamber as a single isolated zone where the phenomenon is conserved. Conjugate modelling is performed by coupling air-food phases by boundary conditions of continuity at the food interface. Numerical code is validated with empirical correlations of Nusselt number. Results show that low stream wise separations (0.25) present the best and worst heat transfer. Therefore, the best heat transfer on the cuboid food is found at span wise distances higher than 0.5 and stream wise separations higher than 0.25. These separations are recommended to have a reasonable food drying control.

Keywords: Numerical simulation, LES, periodic boundary conditions, turbulent flow, heat transfer, food drying.

I. INTRODUCTION

Conjugate simulations on food drying reported in the open literature have been conducted in laminar flow, or turbulent flow with the Reynolds Averaged Navier-Stokes (RANS) approach. For instance, laminar flow simulations have been conducted in one-dimensional (Tang and Min [1]), two-dimensional (Kaya et al. [2-4], De Bonis and Ruocco [5], Kim et al. [6], and Silva Júnior et al. [7], and Selimefendigil et al. [8]), and three-dimensional cases (Ateeque et al. [9], Chandra Mohan and Talukdar [10], Chandramohan [11-12], Curcio et al. [13], and Khan and Straatman [14]). Turbulent simulations have developed in two-dimensional (Sabarez [15], Kurnia et al. [16], Tzempelikos et al. [17], and Defraeye and Radu [18]) and three-dimensional studies Caccavale et al. [19], and Curcio et al. [20].

LES simulations allow a statistical study of flow and turbulence because instantaneous, fluctuating, and mean variables are available. Then Reynolds stresses, turbulent heat flows, and many other statistical variables can be obtained. Therefore, a conjugate heat and mass transfer simulation to model vegetable cuboids drying with the Large Eddy Simulation (LES) is performed. The implementation of periodic boundary conditions represents a cuboid vegetable (potato) inside an in-line arrangement. A potato cuboid, turbulent airstream (Re=4200), and air temperature of 60 °C are injected into the chamber. The main objective is to study the effect of turbulent airflow on heat transfer of cuboid food, which can be applied to industrial drying chambers.

II. PHENOMENON FORMULATION

The phenomenon representation of heat and mass transfer in food drying is shown in Fig. 1. Conjugate modelling simultaneously solves heat and mass transport equations in external flow and inside the food. The external flow is modelled as a turbulent regime through the LES approach. Then governing equations of continuity, momentum, and energy are solved. Moisture concentration inside the food is represented by Fick law (pure diffusion). Mathematical conditions on the food interface are imposed by the complete continuity of the heat and mass fluxes. Energy flux considers the effect of moisture evaporation as studies performed by Ateeque et al. [9], Aversa et al. [21], and Curcio et al. [20]. Simulation represents a drying chamber by periodic boundary conditions in all directions of the computational domain. In these boundary conditions, the walls did not influence any direction. Then a drying chamber can be reduced to a single isolated zone (fraction of inline arrangement) in the fully developed zone where the phenomenon is conserved and calculation times are finite.

III. NUMERICAL SIMULATION

The work simulates a cuboid potato of Dx0.5Dx0.5D (04x0.02x0.02 m, D=0.04 m) in the x, y, and z directions, as shown in Fig. 2. Simulations consider a mainstream velocity U0= 2.5 m/s (Re=4200) and inlet air temperature (T0=333.15K). The representation of the inline food array in a
cuboid food is done by periodic boundary conditions, as shown in Fig. 2.

![Figure 2: Geometrical characteristics in the computational domain](image)

### 3.1 Study case

The geometrical characteristics of the computational domain and the location of the cuboid food are represented in Fig. 2. The stream wise and span wise spacing between solid body and walls of the computational domain is pointed out as $S_1/D$ and $S_2/D$, $S_3/D$ (the two transversal directions $S_1/D=S_2/D$ and $L_2/D$ in x, y, and z directions. A combination of two sizes of the computational domain and spacing between bodies are presented in Table 1. Then twelve simulations are conducted to study the effect of turbulence on heat and mass transfer.

<table>
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<tr>
<th>Case</th>
<th>$L_1/D$</th>
<th>$L_2/D$</th>
<th>$S_1/D$</th>
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<td>0.5</td>
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<td>0.75</td>
<td>0.25</td>
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<tr>
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<td>0.25</td>
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<tr>
<td>7</td>
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<td>1.5</td>
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<tr>
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<td>1.0</td>
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<tr>
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<td>0.25</td>
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<tr>
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<td>3.0</td>
<td>2.0</td>
<td>1.0</td>
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<td></td>
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</tbody>
</table>

### 3.2 Numerical details

The simulation is performed in a homemade numerical code with the LES approach for turbulent airflow. The homemade code has been validated in different studies as Cubos-Ramírez et al. [22], Salinas-Vázquez et al. [23-24], Salinas-Vázquez and Métais [25].LES solves large grid scales and models the small scales, which are isotropic. The heat and mass diffusion inside cuboid food is modelled by Fick law, which is solved by a three-level fully-implicit finite difference scheme. The heat diffusion coefficient is constant, but the mass diffusion coefficient is temperature-dependent, calculated as a temperature function (Chandramohan [12]). The implementation of boundaries conditions is based on Poinosot and Lele [26]. Then initial conditions used in the simulation are velocity null, pressure, and temperature equal to the atmospheric values (reference values). Periodic boundary conditions are imposed in all directions (x, y, z).

The grid resolution used in all simulations has a resolution of 200,100,100 computational points in the x, y, and z directions, see Fig. 2. Finally, simulation is validated in heat transfer with the experimental correlations of a global Nusselt number proposed by Iguarashi [27-28] for a square cylinder case. Numerical predictions show a global Nusselt number of $Nub=74$, which agrees with values of Nub between 71-101.

### IV. RESULTS

Discussion is focused on the turbulence kinetic energy and fluctuation velocities, which are related to heat and mass transfer by the turbulence, in dimensionless form. Fig. 3 presents turbulent kinetic energy $k = \frac{1}{2}((u'u') + (v'v') + w'w')$ contours, where $u'$, $v'$, and $w'$ are the fluctuation velocities in the x, y, z directions. The maximum k values are located near the body’s front vertices, where separation of the boundary layers occurs. This separation promotes high stream wise velocity gradients, and heat and mass transfer could be favorable for food drying. Turbulent kinetic energy is high on the lateral walls (1-1.3$U_0$ for $S_2/D<0.75$ and 1-1.5$U_0$ for $S_2/D<0.75$) and around the wake, as shown in Fig 3. Then heat and mass transfer are intense at high k values. Contour shows that as $S_2/D$ decreases, $k$ increases, and the flow’s stream wise velocity between the bodies enhance. Heat transfer is more intense at $S_2/D$ separations less than 0.75, but the drying process is more homogeneous at $S_2/D=0.75$, as seen in the heat transfer discussion.

![Figure 3: Dimensionless turbulent kinetic energy](image)
The root-mean-square streamwise velocity fluctuation \( (u'_{rms}) \) measures the turbulence intensity in any direction. Fig. 4 shows a similar streamwise component \( (u_{rms}) \) behaviour as the turbulent kinetic energy contours (Fig. 3). The main source of \( k \) is related to the streamwise velocity fluctuation by the separation of the boundary layer, which generates strong velocity gradients in the streamwise direction. High gradients of fluctuation velocities promote heat and mass transfer, but the cuboid food's heating could be non-homogeneous, which affects food drying. Other velocity fluctuation components as spanwise velocities \( (v'_{rms}, w'_{rms}) \) contours in \( x-y \) planes are similar to \( w'_{rms} \) contours in \( x-z \) planes give additional information about the flow, especially from the body downstream where maximum values are found.

The contours of spanwise velocity fluctuation \( (v'_{rms}) \) in the middle of the \( x-y \) plane are presented in Fig. 5, which shows the \( v'_{rms} \) values are lower than \( u'_{rms} \). This component’s behavior changes behind the solid body, as a function of the spanwise and streamwise separations. Streamwise distance \( S/D=0.25 \) (cases 1, 5, and 9) presents almost null values of this component because the wake is weak and small. Intermediate distances \( S/D>0.25 \) and \( S/D<0.5D \) for cases 2-4, 6, and 7), exhibit an elongated contour around the wake as the \( u'_{rms} \) contour and a central contour between the precedents. Due to the proximity between bodies, the wake’s movement is limited. The highest values of the spanwise component are presented in the region of maximal streamwise velocity gradients (similar for the streamwise component). Cases at \( S/D=0.25 \) and \( S/D<0.5 \) (8 and 10-12) present a behavior similar to a flow around a single body. The wake core moves freely, generating high values of spanwise \( (v'_{rms}, w'_{rms}) \) as shown in two blue zones. The second zone of high \( (v'_{rms}, w'_{rms}) \) is found in the body’s front by boundary layer separation.

The effect of \( k \) and fluctuation velocities on heat transfer is presented in Fig. 6. The graph shows food cuboid heating (transient temperature difference between the bulk \( T_a(t) \) and the solid body \( T_s(t) \)) at different drying times. Results show the best food cuboid heating \( (\Delta T_{d}) \) corresponds to cases 1-4 and 10-12. The best and worst heating \( (\Delta T_{d}) \) is found at streamwise distances \( S/D=0.25 \) (cases 1, 5, and 9). The heating is sensible by a blocking effect in the wake zone that affects heat transfer. Cases 10-12 present similar heating, which support the heat transfer tend to be homogeneous. So, these cases are the best option for food drying control.
V. CONCLUSIONS

Results show that the highest values of turbulent kinetic energy and velocities fluctuation are located on the body’s front vertices, lateral walls, and around the wake. The heat and mass transfer could be favorable for food drying in these zones. The best cuboid food heating ($\Delta T_{in}$) is presented incases 1-4 and 10-12. In cases 10-12, heating is high, and heat transfer tends to be more homogeneous than in other cases. Therefore, spanwise separations $S_z/2D<0.5$ and streamwise separations $S_x/D>0.25$ are recommended for better food drying control.

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