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Numerical Simulation of air Temperature and air flow Distribution in a Cabinet tray Dryer

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Abstract*: *The quality of dried product can be enhanced in cabinet tray dryers through a uniform distribution of drying air flow and temperature. In this work, a numerical investigation is conducted to examine the consequence of air movement on the quality of product dried in a convective tray dryer. The temperature and velocity contours of air in the drying chamber are numerically determined for three different geometries of cabinet tray dryer and are compared. A good harmony is found between the predicted data from CFD and experimental data from the literature. This work will enable us to optimize the drying chamber design for uniform dispersal of air flow and temperature and to improve quality of dried product for large scale applications.

Keywords*: *Cabinet tray dryer, Drying uniformity, Dried product quality, Numerical simulation.

I. INTRODUCTION

Cabinet tray drying is the conventional drying technique and most preferred in farmhouses for fruit drying because of its mature status and familiarity. In cabinet dryers, generally, air first passes from bottom to top tray as shown in Figure 1. Due to this, product in bottom tray will be over dried when compared to that of top tray during the process [1]. So, dried product from these dryers possesses uneven moisture content and hence quality of end products are low. The reason for this can be attributed to uneven air movement and temperature dispersal in the cabinet. Hence now a days, these dryers are not being utilized [2-4]. Therefore, consideration of steady air flow and temperature diffusion inside the cabinet is of prime importance. Study of air movements and temperature variation within a dryer experimentally need a lot of time and monotonous efforts, as it requires several sensors to be placed at different locations. Hence, mathematical modelling and computational fluid techniques are accurate and appropriate replacements to experimental procedures [5-7]. With the advent of fast workstations and software tools like Fluent, computational fluid dynamics has been progressively gaining importance in every aspect of food engineering [8-11]. Simulation can act as indirect sensors of dampness, rate and temperature of air. Simulation is sensitive to any minor fluctuations and has no restrictions in investigating different drying ambience. In addition, there is no need of large spaces and skilled operators. In spite of these advantages, we cannot completely rely on CFD in the field of food industry, due to shortfall of enough data of physiochemical, mechanical and thermal properties of foodstuffs [12].

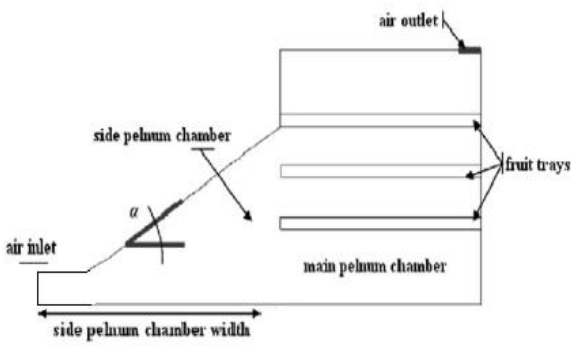

Fig. 1. Cabinet tray dryer

CFD is an advanced numerical tool to solve governing PDEs of mass, momentum and energy conservation in fluid flow, food engineering, heat and mass transfer problems [13]. CFD was first used in early 1950s and since then it has been gaining importance day to-day in every field of engineering and technology [14]. Animations of simulated results from CFD helps us in interpreting the occurrence of physical phenomena very easily, which enables us to enhance the overall process and product quality [15]. The obtained CFD simulated results may be compared with actual drying experiments and if there is an agreement between the projected and experimental data, then this numerical procedure may be reapplied for other drying conditions to optimize the drying performance of the cabinet tray dryer. In the literature, CFD works have not been validated. So, projected data by such studies can hardly be used in a large scale [16]. There have been some studies on optimization of cabinet drying chamber design for uniform air flow and temperature distribution. D. P. Margaris and A – G Ghiaus [17] numerically optimized the design of the dryer and predicted the parameters of air flow using PHOENICS CFD code and validated the results from experimental investigation. The nonexistence of homogeneousness of the air velocities above the product in drying chamber was found and an attempt is done numerically to decrease the degree of non-uniformity in air movement [18]. Two different geometrical configurations of drying chambers are designed and analysed using CFD. The most appropriated sketch for uniform air flow in cabinet is selected and fabricated. The predicted values are compared with those of experimental data and found good agreement [19-20]. Air velocities and temperature distribution in cabinet of dryer can be determined using CFD in short span of time [9,21].

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Installation of guide vanes and deflectors within the drying chamber reduces low – velocity region and increases the spatial consistency of the velocity over the product [22-23].

Air velocity and temperature dispersal in the chambers of cabinet dryers has not been studied broadly. Hence, the present work objective is to examine the impact of different geometries of cabinet drying chamber on the distribution of air flow and temperature and to propose the best design for the uniform air movement and temperature distribution profiles.

II. GEOMETRICAL MODELLING

Generally, hot dry air is injected into the cabinet chamber at the bottom. The ability of drying air flow progressively decreases as it passes through the cabinet. Three different designs of chamber of cabinet dryer has been made to analyze the distribution of air velocity and temperature. Air outlet shape, size and its location, addition of deflectors are the important parameters that are varied in the different geometries of the dryer but depth of drying cabinets is kept same in all cases. All the three different geometries designed are displayed in Figure 2.

Reynolds number calculated from geometrical dimensions and fluid viscosity is higher than 2000 at the dryer entrance for the three geometries. Thus, turbulent flow model is taken inside the cabinet dryer. Hence, the standard $k-\varepsilon$ model is considered for the present analysis, as its positive applications are stated in recent literature [17-18]. Eq. [1-2] denotes turbulent kinetic energy and its rate of dissipation. Eq. [3] helps in finding convective heat and mass transport in $k-\varepsilon$ models.

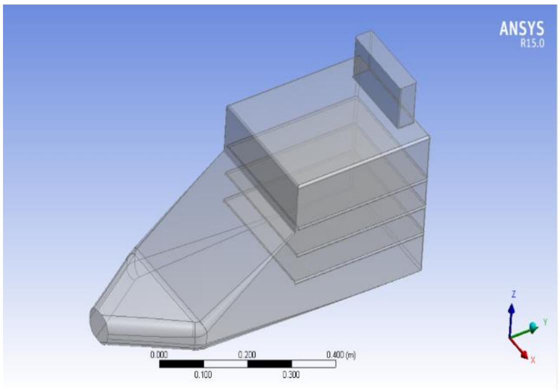
$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_i}(\rho k u_i)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right]+ U_k+U_b-\rho\varepsilon-F_M+S_k \quad (1)$$

$$\frac{\partial}{\partial t}(\rho \varepsilon)+\frac{\partial}{\partial x_i}(\rho \varepsilon u_i)=\frac{\partial}{\partial x_j}\left[\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial k}{\partial x_j}\right]+ C_{1\varepsilon}\frac{\varepsilon}{k}(U_k+C_{3\varepsilon}U_b)-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k}+S_\varepsilon \quad (2)$$

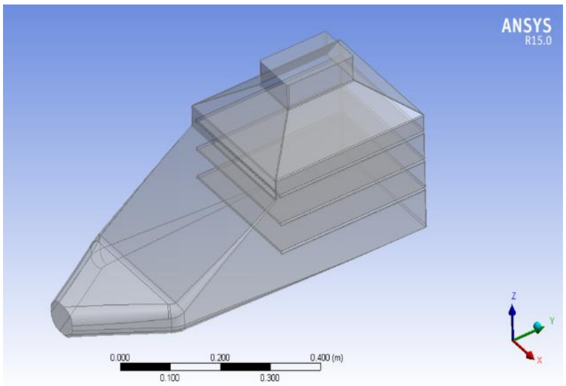
$$\frac{\partial}{\partial t}(\rho E)+\frac{\partial}{\partial x_i}\left[u_i(\rho E+p)\right]= \frac{\partial}{\partial x_i}\left[\left(k+\frac{c_p\mu_t}{\Pr_t}\right)\frac{\partial T}{\partial x_i}+u_i(\tau_{ij})_{eff}\right]+S_h \quad (3)$$

Trays are generally permeable media for air flow. Hence, standard fluid transport equations are added with momentum term. This term composed of inertial losses and fluid friction losses.

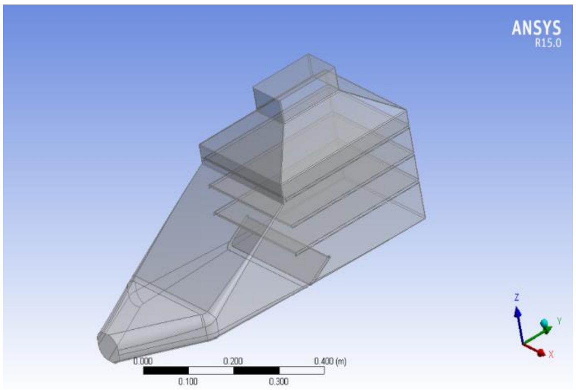
$$S_i=-\left(\sum_{j=1}^{3}D_{ij}\mu v_j+\sum_{j=1}^{3}C_{ij}\frac{1}{2}\rho v_{mag}v_i\right) \quad (4)$$



(a) Simple type cabinet tray dryer



(b) Hood type cabinet tray dryer



(c) Hood type with deflector cabinet tray dryer

Fig. 2. Three geometries of cabinet tray dryer considered for present investigation

III. NUMERICAL SIMULATION

The basic equations in the domain can be solved using boundary conditions. Since these are nonlinear and can't be solved analytically, numerical FVM technique has been applied using ANSYS workbench 15.0. Mesh details and Meshed view are represented in Table 1. and Fig.3. In the present work, segregated double precision solver is chosen in the analysis. Precise surface conditions of the domain to be mentioned for flow – simulation.

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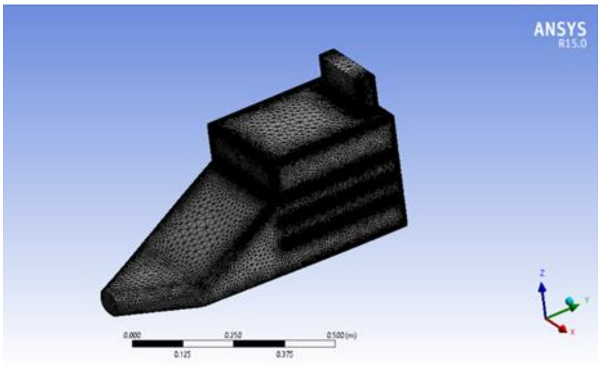
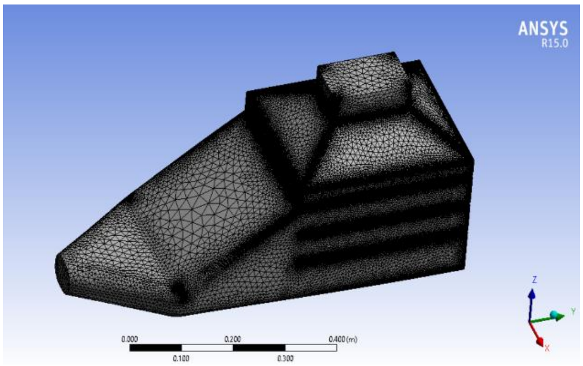
In the present investigation, the movement of air during the drying process is of prime consideration and all the cases simulated here are taken as steady state condition.

A. Simulation Details

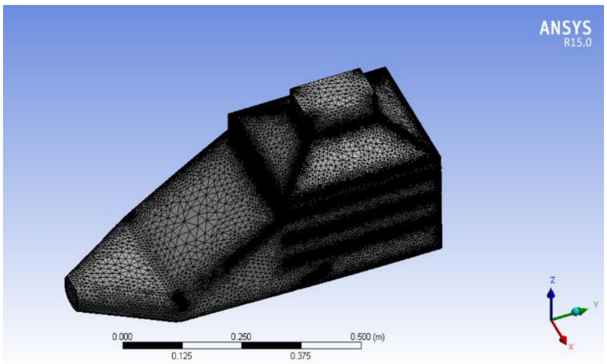
- Inlet**:** Drying air velocities 1-4 m/s and temperatures 30-50°C is selected. Air flow direction is normal to the air inlet.
- Outlet: Gauge pressure is assumed to be atmospheric pressure (= 0) at the outlet.
- Permeable media**:** Tray porosity, experimental parameters of pressure drop equation and aluminum net are defined.
- Wall: Atmospheric conditions and heat transfer coefficients of cabinet walls are defined.



(a) Simple type



(b) Hood type



(c) Hood type with deflector

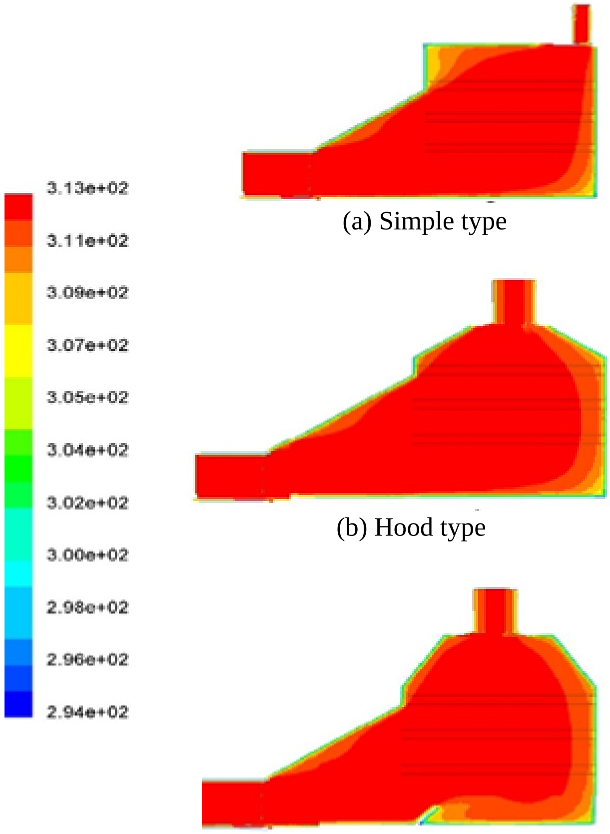
Fig. 3. Meshed view of three geometries of cabinet tray dryer

Table- I: Mesh details for the three geometries of tray dryer

Geometry	Simple type	Hood type	Hood with deflector type
Inflation layers	4	4	4
Nodes	21422	22569	23658
Elelments	56559	57859	59867
Element shape	Tetrahedron	Tetrahedron	Tetrahedron
Orthogonal quality	0.8667	0.7553	0.7341
Orthogonal skew	0.2743	0.2932	0.3324

B. Simulation results

- Temperature distribution



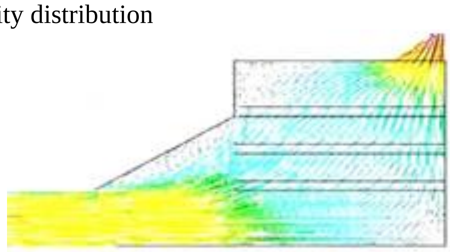
(a) Simple type

(b) Hood type

(c) Hood type with deflector

Fig. 4. Temperature distribution patterns of drying air at inlet temperature of 40°C

- Air velocity distribution



(a) Simple type

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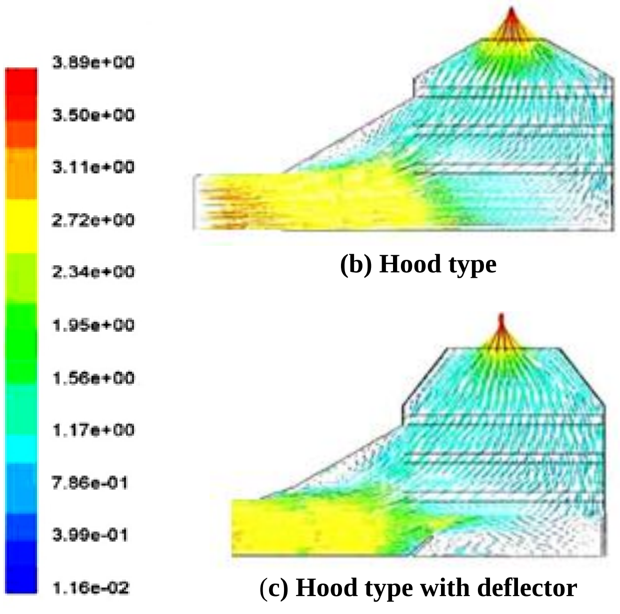

(b) Hood type

(c) Hood type with deflector

Fig. 5. Velocity dispersal patterns for the three designs of cabinet tray dryer at air velocity 3 m/s

IV. RESULT AND DISCUSSION

Temperature profiles and movement of air flow are predicted numerically inside the cabinet of dryer for three different designs. The evenness of air movement and temperature distribution in the three geometries are compared through the simulated results.

Fig.4 illustrates the air temperature distributions for three different geometries. Temperature profiles are uneven in simple type dryer design when compared to other two designs. The reason for this can be attributed to size of the drying air outlet in simple type cabinet design which is less in compared with the width of the tray. More uniformity in the distribution of air temperature in designs (b) and (c) are found, which can be accredited with their cabinet design modifications like hood – type ceilings in (b) and (c) and inserting a deflector in design (c). Among all the three geometries hood type ceiling with deflector cabinet design has shown appreciable uniformity in distribution of air temperature. Drying air temperatures in simple design cabinet type are higher than that of other geometries.

Air velocity is more influenced with the geometrical changes of drying chambers when compared to temperature variation. Figure 5 illustrates the air velocity patterns in three cabinet designs. Air flow at the corners of drying chambers are scarce. Design (b) and (c)'s hood – type air outlets enhanced the velocity dispersals in the cabinet. Air drag is created due to the deflector in design (c) which triggered a diminution in velocity of air at the right bottommost region of the cabinet. From the above results, the hood type ceiling with deflector design is best for the uniform air movement and temperature distribution of a cabinet tray dryer. The data from reference [3] is considered for comparison of predicted data from CFD simulation at various regions of the cabinet for both air temperatures and velocities. The predicted results are in good harmony with that of data in reference [3] and is illustrated in Figures 6 and 7.

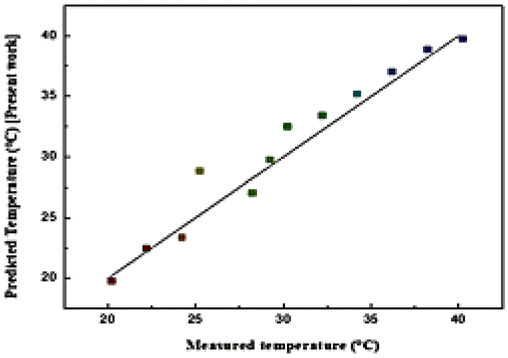

Fig. 6. Validation of predicted air temperature with data from literature

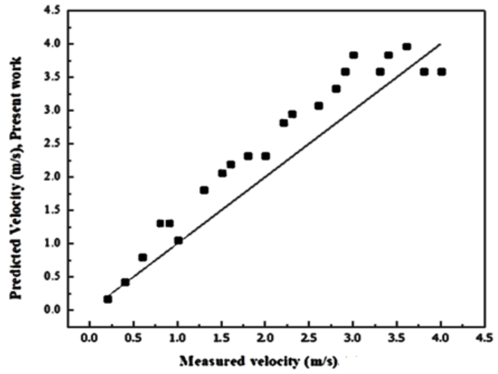

Fig. 7. Validation of predicted air velocity with data from literature

V. CONCLUSION

From the present work these conclusions can be drawn

- Patterns of air velocity and temperature within the cabinet of tray dryer is analyzed numerically using ANSYS Fluent 15.0.
- Drying air temperatures in simple type are higher than that of other geometries.
- Introducing hood – type ceilings and deflectors into the design of dryer cabinet lead to reduce the non - uniformity of air temperature and velocity past the trays.
- The hood type with deflector design reasonably best among the three designs, for steady movement of air and temperature dispersals in the cabinet fruit dryer.
- A good agreement has been found between reference [3] data and predicted results from current work.

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NOMENCLATURE

c_p	:	constant pressure specific heat
C_{ij}	:	prescribed matrices
C_0, C_1	:	empirical coefficients
D_{ij}	:	mass diffusion coefficient
E	:	total energy
U_k	:	turbulent kinetic energy due to velocity
U_b	:	turbulent kinetic energy due to buoyancy
k	:	turbulent kinetic energy
p	:	Pressure
Pr_t	:	Prandtl number
S_i	:	i^{th} momentum equation source term
S_k, S_e, S_h	:	source terms defined by user
T	:	Temperature
t	:	Time
u	:	velocity magnitude in x
F_M	:	fluctuating dilatation
σ_k	:	turbulent Prandtl numbers for k
σ_e	:	turbulent Prandtl numbers for ε
ε	:	rate of dissipation
ρ	:	density of fluid
μ_t	:	turbulent viscosity
μ	:	dynamic viscosity
v_i	:	velocity vector
v_{mag}	:	velocity magnitude
τ_{ij}	:	deviatoric stress tensor

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