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Numerical Investigation of temperature distribution and air flow field inside the cold storage room : Case Study

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Abstract—**Temperature heterogeneity inside the space of cold room results in fruit quality degradation and weight loss. It is governed by the flow of air inside the room. It is quite challenging to achieve the temperature homogeneity at every location of the room. As this depends upon various operating and design variables.Analysis of flow field and temperature profile inside the cold room using experimental process is a costly and time consuming process. Thus nowadays researchers are using CFD tools to predict the same to save time and resources. Air flow field in the cold room depends on various factors which affects the results produced through CFD analysis. Thus selection of turbulence model for achieving the desired flow conditions becomes crucial.In the present study theairflow pattern and temperature profile of the cold room loaded with bins of apples is analyzed by CFD technique.Turbulence model utilized is SST k–ω for air turbulences in the room. A new forced duct arrangement system is proposed for improving temperature homegeniety inside the cold room.**

Keywords—ComputationalFluidDynamics (CFD), Cold Storage, Air Circulation, Turbulence model.

I. INTRODUCTION

During the post-harvest handling of fruits and vegetables temperature is one of the crucial parameter which needs to be controlled. For fruits pre-cooling should start just after the harvesting from theharvesting temperature to the temperature best suited for the storage.After harvest, the pre-cooling of the agricultural food products is necessary to maintain the product quality and increase the shelf life of product in the market. When food produce were kept at low-temperature, respiration, enzymatic activities and microbial growth decreases. It alsominimizes moisture loss, and reduces ethylene production [1]**.**But due to the uneven distribution of cold air in the room, it becomes quite problematic to obtain homogeneous cooling in large industrial cold rooms. This airflow pattern depends upon various factors like product, cooling fluid, geometry of the product and dimensions of the cold room. Based on mass and momentum conservation equations the airflow velocity distribution can be determined. In simple cases,an analytical solution can be found, but it is very tedious task also time-consuming and costly. Also, it can be done only in the existing storage rooms. So in the case of optimizing the cold room conditions in the early design phase, this approach cannot be used.

Due to the heterogeneity of airflow in the room it is not easy to maintain the uniform rate of heat transfer in the room. **Akdemir et al**. conducted an experiment in the cold room of 19.07 cubic meter volume. Author recorded variation in velocity at different palnes of the room[2]. Velocity ranges from max value at top plane near the evaporater to almost 0 at some points in middle and bottom plane.Temperature readings also shows this type of heterogeneity and a temperature difference of 2.1°C was recorded in the room.**Praeger et al.**also investigated the airflow distribution in an apple storage room. Author observed that velocity inside the bin in upper stack is almost 7 times higher than in lower stacks[3].

Han et al. [4]conducted experiments at low air speed and then by utilizing CFD model for high speed studied the effect of velocity of air on cooling efficiency, cooling rate and energy consumption. Author found that with the increase in air velocity precooling time decreases but energy consumption increases exponentially. Also at higher velocities of air from cooling coil mass transfer coefficient increases results in weight loss of food produce.**Sajadiye et al.** [5]studied different stacking arrangements in the cold storage filled with oranges. Cooling performance parameters were compared for two different stacking arrangements. Staggered array stacking arrangement shows a reduction of 38% in ¾ cooling time when compared with the inline array arrangement.Also in staggered arrangement at boxes walls increased surface heat transfer coefficient was observed.

Chourasia et. al. [6] studied the stack dimensions, arrangement of stacking, horizontal and vertical space between the bins on average product temperature and cool down time of produce.With an increase in aspect ratio(width / height), average temperature of produce and time to cool down both reduced. It is also investigated that, the effect of the gap between the stacks, in the vertical direction or along the height is more effective compare to the horizontal gap between the stacks.**Yongfu et al.** [7]investigated effect of distribution of air on the condensation and sprouting in the potato bulks.The variation in air flow is the primary cause for condensation. Condensation can be restricted by forced ventilation but it ultimately results in the increased moisture loss.

Duret et al. [8]studied the pattern of airflow in the cold room by recording the air velocities at different locations. Author found that due to entrainment effect a secondary flow is generated in the cold room near the evaporator. Due to this secondary flow warm air of the room gets re-circulated in the front pallets resulted in the temperature difference between the pallets. Pallets placed in front side near the wall remains hot when compared with the pallets in the rear side of the room.**Bishnoi et al.**investigated experimentally the air flow field and cooling heterogeneity in the refrigerated room. Temperature heterogeneity with a variation in the range of 0.87°C to 0.97°C at different locations was recorded.Convective heat transfer coefficient at centre of crates varies from 14.6 W/m2/K at rear side to 9.2 W/m2/K at front side[9].

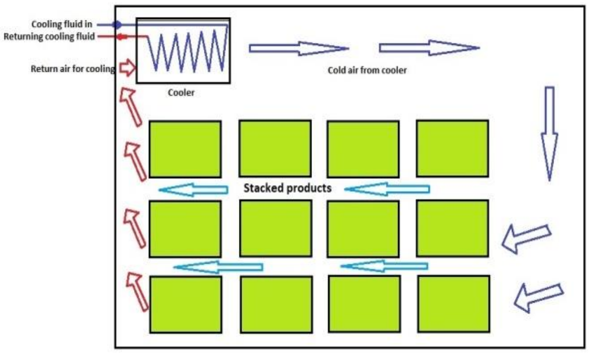

*Figure 1*conventional cold room for storage room of horticultural products.

II. APPLICATIONS OF CFD IN POST-HARVEST STORAGE

Generally in such systems, transport phenomena are complex coupled processes and mathematical models are recommended for understanding and designing refrigerated storage systems [10].With the availability and accuracy of computers along with efficient solution algorithms and processing facilities, this study can be performed. To overcome these limitations of time and physical setup, the governing fluid flow equations can now be solved numerically.The practice of performingComputational Fluid Dynamics (CFD) usingcomputers is highly appreciated and accepted for a wide range of industrial and non-industrial application areas. Several CFD solver software packages such as STAR-CD (CD, London), PHOENICS(Flow solve, London), FLUENT/FIDAP (Lebanon, USA), CFX (AEA, Harwell, UK), etc. are available [1].

CFD provides flexibility and richer details at a much lower cost than an experimental setup. Many researchers performed their studies to develop CFD models for better airflow conditionsinside the cold room. **Hoang et al.**studied the flow pattern of air inside the cold room by modelling a CFD model. Steady state and incompressible flow was considered and Reynolds-Averaged Navier-Stokes equations were solved[1]. **Stamou et al.**verified the results from the CFD model for indoor airflow and heat transfer with obtained experimental results [11]. **Chourasia et al.** done extensive work on potato cold storage experimentally and also applied CFD models to predict the results[12],[13],[14].**Chourasia et al.** investigated moisture loss in potato and heat transfer in storage under steady-state using the CFD technique [13]. They also developed a 3D model on mass transfer, heat transfer and airflow in a partially impermeable enclosure containing agricultural produce during natural convective cooling [14]. **Hong et al.**investigated the airflow and temperature in the cold room by considering 2 different flow restriction approaches [15]. **Nahor et al.** compared his experimental results with the CFD model considering the Ergun equation for airflow restriction [10]. **Deleeet al.** optimized the humidification system of the cold room by designing a 3D CFD model [16],[17].**Zhai et al.** studied and summarised prevalent turbulent models used for airflow predictions in closed rooms [18]. The result from CFD is dependent on various factors such as geometry, meshing type, model selection, etc. The precision and accuracy of the simulation depend on the selection of the turbulencemodel, as it is a crucial matter that affects the simulation.

Chourasia et al. applied a 3D finite volumebased model for airflow, heat and mass transfer to a partiallyimpermeable enclosure containing potato during natural convectivecooling. The model assumed the single bag of potato as a porousmedium and used the Darcy-Forchheimer equation to modelthe pressure drop. The velocity vectors, contours of temperatureand rate of moisture loss were presented for transient cooling aswell as steady-state cooling and compared to experimental profiles [14].**Hoang et al.**compared 2 different CFD modeling approaches for an apple storage unit. In the first approach stacks of apple were assumed as porous medium considering Darcy-Forchheimer equation for airflow restriction, while in the second approach it is considered as a solid block. For the solid block approach space between the locks is considered for airflow. The velocity of air and temperature contours are compared with the experimental results obtained earlier [15]

Han et al.studied the effect of differentflow rates of cold air in an apple cold storage room. By increasing the in-flow rate of cool airupto a certain limit a reasonable increase in cooling rate and uniformity is obtained. Increasing in cooling rate also results in less loss of mass from the fruit as mass loss of fruit is primarily influenced by cooling time rather than air-inflow rate [4].**Delele et al.** developed a combined discrete element (DE)-CFD model. To generate the random stacks of discrete spheres DE method was used and airflow through loaded vented box and bulk was studied. SST k-w turbulence model was used in study. Effect of flow direction, product size, porosity, stacking pattern, confinement ratio, vent hole ratio and randomness of the product filling was studied on the pressure drop coefficient of the stacks[19].**Ayala et al.** performed unsteady state numerical study on a cooling cabinet. Three different approaches are compared for temperature and velocity distribution in the cabinet. The approaches were use of constant properties (CP), approximation of all the properties fitted to temperature polynomials (PFTP) and variation of the density with temperature according to the Boussinesq approximation (BA)[20].**Akdemir et al.** [21] with the help of Management Zone Analysis (MZA) software investigate the temperature, velocity and humidity distribution inside the cold room. Variation in these variables at top, middle and bottom level for full loaded, half loaded and empty cold chamber were recorded and compared with the existing experimental results.

Mishra et al.[22]introduced an induced draught by creating a duct arrangement on one wall of the reduced scale model of cold room. Air is made to flow through the duct with bottom end kept open to deliver the air to the bottom part of the room.Duct arrangement increased the velocity of air in the bottom plane of the room increasing the homogeneity of air velocity in the room. **Hoang et al.** [15]studied the flow field of air and distribution of temperatureinside the cold storage room by comparing two different modelling approaches through CFD. A better product temperature prediction with air flow is obtained by solid block approach as compared to porous medium block approach.Results agrees with some previous research that for cold room simulation SST k-w turbulence model gives the better results with minimum MRE. **Ghiloufi et al.** [23]created a 3D model of a cold room filled with dates and he found that in steady state high temperature zones were formed in the front bins in pallet. To improve temperature homogeneity in the room author suggested three aerodynamically shaped overhead deflectors in the way of cold air from the cooling coil. Deflectors deflect the air in the hot zones and results in better cooling performances. Although the study was only numerical and effect of friction loss heat generation is not taken in the account. **Mustafa et al.** [24]studied the cooling performance of ventilated box during pre-cooling using CFD. Result shows that the air flow rate produces more effect on cooling process for different ventilation sizes in the crates or bins used for the stacking of the products.**Ambaw et al.** [25] analyzed the spatiotemporal temperaturefluctuations inside an apple cool store in response to energy use. Discontinuous use of fan operation was investigated to reduce the heat load of air circulation fan at steady state. Two phase porous medium approach was used to model the apple bins in the cold room.

III. MATERIALS AND METHOD

Computational Domain:

In the present study the domain is considered for preserving 5020 kgs of apple at the temperature of 1.5°C. The dimensions of the room are 5.75m * 3.83m * 3. 75 m and equiped with 252 crates. These dimensions are considered on the basis of existing cold room setup erected in MANIT Bhopal. Wall and the ceiling of the room is constructed by Polyurethane foam (PUF) material due to its very low coefficient of thermal conductivity (k = 0.023 W/m/K).
The physical properties of apples are presented in Table 1[15], [23]

Properties	Apple	Air
Density of material (kg/m^3)	898	1.293
Specific heat of material (J/kg/K)	3829	1004
Coefficient of Thermal Conductivity(W/m/K)	0.463	0.024

Table 1Physical Properties of Apple and Air

Mathematical Model

To determine the temperature and airflow in the room Reynolds Averaged Navier–Stokes (RANS) equations are resolved in three dimensional. SST k-ω turbulence model is used in this study.

RANS-Conservation of mass:

$$\frac{\partial \overline{u_i}}{\partial x_i} = 0 \qquad (1)$$

RANS-Conservation of momentum:

$$\rho_f \frac{\partial \overline{u_i u_j}}{\partial x_j} = -\frac{\partial \overline{p}}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial \overline{u_i}}{\partial x_j} + \frac{\partial \overline{u_j}}{\partial x_i}\right)\right] - \rho_f \frac{\partial \overline{u_i' u_j'}}{\partial x_j} \qquad (2)$$

RANS-Conservation of energy:

$$\frac{\partial \overline{T_f}}{\partial t} + \overline{\mu}_i\left(\frac{\partial \overline{T_f}}{\partial x_i} + \frac{1}{\rho_f C_{p_f}}\frac{\partial \overline{p}}{\partial x_i}\right) = \frac{\partial}{\partial x_i}\left(\frac{\lambda_{eff}}{\rho_f C_{p_f}}\frac{\partial \overline{T_f}}{\partial x_i}\right) \qquad (3)$$

λ_{eff} is the effective thermal conductivity of air and is given by :

$$\lambda_{eff} = \lambda_f + \frac{C_{p_f}\mu_t}{Pr_t} \qquad (4)$$

Where,Pr (Prandtl number) is 0.85.

Heat transfer coefficient of apple:

To consider the heat load inside the cold room, solid block approach is used. The bins in the room is considered to be filled with apples. Each bin is assigned with the physical properties of apple. This is considered to calculate thecoefficient of heat transfer. The transfer of heat between apple and the surrounding air is governed by the coefficient of convective heattransfer (h_{cv}). This coefficient is given by:

$$h_{cv} = \frac{q_{apple-air}}{T_i - T_s}$$

Where ,T_i is the apple initial temperature and T_s is storage temperature.

Numerical Simulation

ANSYS Fluent 2020 R1 is used for the establishment of the CFD. Discretization schemes of second order and for coupling of pressure and velocity SIMPLE algorithm is used. Steady state simulation is performed for the determination of flow field and the coefficient of convective heat transfer at product-air. For the refinement of the simulation results, several convergence criteria are defined.

For the convergence of solution of continuity and momentumequations, the residualsare kept at 10^{-3}. While for the energy equationthe convergence of solution is kept as 10^{-6}.

For better defining the environment of cold room hybrid mesh is created. Volume inside the cold room space is divided in 30,18,672cells with ANSYS Mesher.

Boundary Conditions :

The exit of the evaporator is defined as th inlet for the cold air in the room. Inlet of air is kept at velocity of 4.2 m/s. Temperature of the inlet air is set at 274.5 K. The walls of the room and solid blocks are kept with zero roughness and no-slip condition.For the outlet of air at the evaporator back pressure based outlet condition is defined. As fruits after harvesting release some heat continuously due to the bio chemical changes in it, a energy source of 19.58 W/m^3 is defined at the centre of the solid block which is considered as apple.

IV. DISCUSSION

Case study

To analyze the air flow and temperature distribution inside the cold room, CFD simulations were performed. Dimensions and boundary conditions for the study were discussed earlier. Velocity vector and temperature contour of the blocks were observed.As we discussed earlier due to entrainment effect some amount of the warm air instead of leaving room from the back side of the evaporater gets recirculated in the room which results in a higher temperature of product near the evaporator. The same effect can be seen in the results obtained from the simulation. Fig.2 shows temperature difference of 1.5K in front and rear part of the cold room. This is due to the air flow inside the room as shown in Fig.3. To homogenize the temperature distribution inside the cold room it is required to supress the secondary flow due to the entrainment effect.

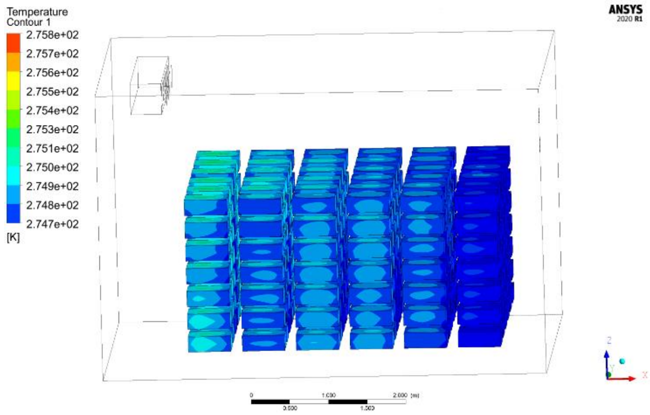

Figure 2 Temperature contour at block surface

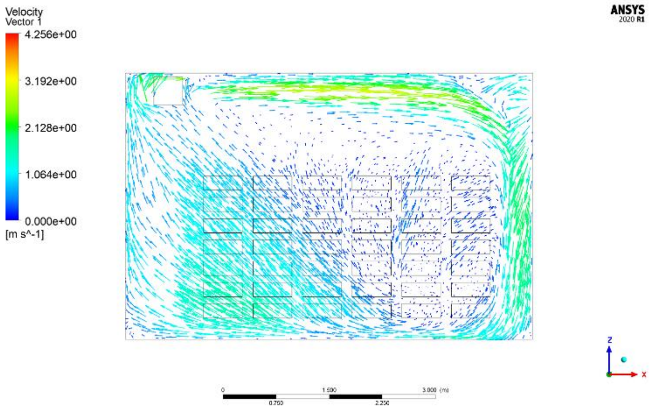

Figure 3 Velocity vector inside the cold room

Proposed arrangement

From the past experiments and current simulation results it is concluded that axial flow cooling coil arrangement alone is not sufficient to produce uniform air circulation system inside the cold room. Along with the conventional cooling coil some forced or induced duct arrangements is required. Duct should be equipped with additional fan and blower arrangement for uniform air distribution inside the room inorder to reduce the temeperature heterogeneity.

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