1. Introduction

Improving food production without proper utilization will not solve the current food security crisis especially in developing country. Injera is a cereal based food and baked after every 3–days interval in every household in Ethiopia. This is primarily related with its higher moisture contents, which results mold spoilage and lose in texture of injera in 3–4 days of ambient storage [1]. Injera is currently distributed in domestic and international market. The exports of injera in year 2015 to North America; Middle East and Europe were 10 million US dollar. Moreover, the future demand for injera is projected to increase exponentially due to its high nutritional values and gluten free diet contributing to the prevention of anemia, obesity, bone disease, and diabetes [1, 2].

In food processing, drying is used to minimize the risk of microbial growth and reaction by reducing the inherent free water from food products [3]. It also reduces the cost associated with the transportation by reducing product size and enables storage under ambient environment compared with fresh food [4]. Traditionally, open sun drying technique is implemented to preserve injera. This technique requires manpower and time. Furthermore, it has an adverse effect on the quality of dried injera (dirkosh) due to contamination risk. Application of solar energy for drying and preservation dates centuries. The use of solar energy as an energy saving measure is rapidly gaining acceptance in various areas to meet thermal energy demand. Since it is pollution free and inexpensive source of energy, the implementation of solar drying could aid the reduction of carbon foot print in food processing [5, 6]. Solar drying of injera helps to minimize the drawbacks of the traditional dirkosh production. Moreover, the solar radiation potential of Ethiopia encourages application of solar dryers [7].

Significant number of research has been done to improve solar dryer design and process. Common classification of solar dryers are based on solar radiation conversion mechanisms (direct, indirect and mixed) and driving forces of airflow (forced and natural) inside the dryer [8]. In mixed mode solar dryers the product temperature is raised by the air coming from solar collector and by direct absorption of solar radiation in the drying chamber [9]. Performance of these types of solar dryer is superior when compared with the indirect solar dryer [10] and simple to manufacture and are economical for small and medium output requirements [11]. However, in conventional multi-tray dryers, final products from different trays contain different moisture content due to saturation of drying air before reaching upper trays. Moisture removal rate inside the drying chamber depends on the distribution of temperature and velocity of drying airflow [12, 13, 14]. This downside of mixed dryers can be eliminated by proper distribution of drying air and by maintaining an optimum flow rate inside the drying chamber [11, 15, 16, 17, 18].

Moisture removal rate inside the drying chamber depends on the distribution of temperature and velocity of drying airflow [12, 13, 14]. The results from air flow simulation within a drying chamber by Mathioulakis et al. [17] and Misha et al. [19] indicated the dependency
of drying rate on drying air velocity distribution. At air velocities lower than 1.2 m/s the effect of air velocity is significant. To study the distribution of air inside solar dryers CFD techniques are widely used [20, 21, 22, 23]. Relying on experimental results of different flow parameters costs huge resource due to the required number of experiments. However, the application of CFD can reduce the cost involved in the experiment [11]. Recently different studies implemented CFD to improve the performance of solar dryers [20, 24, 25, 26, 27, 28, 29, 30, 31]. Demissie et al. [32] employed CFD technique to study an indirect type solar food dryer and predicted the flow field and temperature distribution within the drying chamber. The maximum average temperature difference between the measurement and the simulation was found to be 4.3 °C with a mean flow velocity of 0.14 m/s and 0.12 m/s. Guler et al. [28] used experimental and CFD methods to analyse an indirect type solar dryer. The result of the collector and drying chamber outlet temperature were used for validation showing a maximum deviation of 10%. Amanlou and Zomoridian [33] studied a cabinet dryer using CFD technique. A correlation coefficient above 0.86 was obtained when the experimental results were compared with the CFD results for temperature and air velocity in the drying chamber. Babu et al. [11] designed and evaluated different geometries of a single air pass drying chamber using CFD. The configuration with the drying air flow parallel to the tray was found to be the best configuration based on uniform air flow distribution.

A number of studies in the literatures have been reporting the use of various solar dryers for preserving agricultural products [5, 34]. However, there are few researches that studied mixed mode solar dryers to mitigate non-uniformity of drying air distribution inside mixed mode solar drying unit using CFD technique. In this study, CFD analysis was conducted to test the vertical air distribution channel and simulate transiently the distribution of different drying air parameters through the dryer using SST k-ω model, species transport model and DO radiation model. The study did not take into account the products to be dried. Finally, the CFD result was validated by comparing with the experimental results. The experimental results which were used for validation were extracted from the previous works of Sileshi et al. [7].

2. Materials and methods

2.1. Description of the solar dryer

The solar dryer used for the simulation consists of three parts namely flat plate collector, drying chamber and vertical air distribution channel (Figure 1). The dryer has a capacity of drying 10 kg of injera in a single layer. The collector absorber is black painted in order to heat the incoming air. The drying chamber consists of 4 levels trays with an area of 4.4 m². Transparent materials were used for covering both the collector and drying chamber top. Technical specifications of the mixed mode dryer which is used for this study has been presented in Table 1. All this technical specifications are extracted from previous works of Sileshi et al. [7] which are used as data input for the present work.

![Figure 1. Schematic diagram showing the dryer with air distribution system [7].](image-url)
2.2. Simulation model development

2.2.1. Governing equations

The mixed-mode solar dryer with vertical air distribution channel’s temperature and air flow distribution are examined using computational fluid dynamics. The conservation laws, mass, momentum, and energy equations were used for a fluid moving through a control volume in order to examine the flow characteristics using Eqs. (1), (2), and (3) [31, 35, 36]:

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0 \tag{1}
\]

\[
\frac{\partial (\rho \vec{v})}{\partial t} + \nabla \cdot (\rho \vec{v} \otimes \vec{v}) = -\nabla p + \nabla \cdot (\tau + \rho \vec{g}) + \vec{F} \tag{2}
\]

\[
\frac{\partial (\rho E)}{\partial t} + \nabla \cdot (\rho \vec{v} E) = \nabla \left[ -\vec{q}^i + \sum_j h_j J_i + (\tau_{eff} \cdot \vec{v}) \right] + S_h \tag{3}
\]

2.2.2. Turbulent model

For natural convection flow, the value of Rayleigh number (Ra) determines the nature of the flow (Equation 4). For Ra > 10^9, the flow is identified as a turbulent [37].

\[
Ra = \frac{\rho g (T_h - T_c) L^3}{\mu a} \tag{4}
\]

where \( \beta \) is the coefficient of thermal expansion (K^-1), \( g \) is the gravitational acceleration (9.81 m^2/s^2), \( L \) is the absorber plate length (2 m), \( \Delta T = T_h - T_c \) where \( T_h \) is temperature of absorber surface and \( T_c \) is ambient temperature, \( \rho \) density (1.184 kg/m^3), \( C_s \) specific heat (1003.62 J/kg K), \( \mu \) dynamic viscosity (1.855 \times 10^{-5} \text{Ns/m}^2) and \( k \) represent the thermal conductivity (0.026 W/m K) of the fluid. Property of air is evaluated at mean temperature (\( T_h - T_c \)/2). The values of Rayleigh number of the cases presented in this paper is 1.95 \times 10^{10}.

For turbulent flow in a cavity or through complex geometries, SST k-\( \omega \) model is recommended. The model combines the standard k-\( \omega \) and k-\( \varepsilon \) models for internal boundary layer and for external boundary layer and free stream, respectively [35, 38]. The turbulent scalar quantities (k and \( \omega \)) are calculated using Eqs. (5) and (6), respectively.

\[
\frac{\partial (\rho k)}{\partial t} + \nabla \cdot (\rho k \vec{v}) = \nabla \cdot \left[ \Gamma_k \nabla k \right] + G_k - Y_k + S_k \tag{5}
\]

\[
\frac{\partial (\rho \omega)}{\partial t} + \nabla \cdot (\rho \omega \vec{v}) = \nabla \cdot \left[ \Gamma_\omega \nabla \omega \right] + G_\omega - Y_\omega + D_\omega + S_\omega \tag{6}
\]

The turbulent viscosity (\( \mu_t \)) is calculated using Eq. (7).

\[
\mu_t = \frac{\rho k}{\omega} \max \left\{ \frac{\sqrt{C_{18} \mu}}{\sqrt{k}}, \frac{\sqrt{C_{19} \mu}}{\sqrt{\varepsilon}} \right\} \tag{7}
\]

Where, \( S \) is the strain rate magnitude and \( F_2, a^* \) and \( Re \) are given in Eqs. (8), (9), and (10), respectively.

\[
F_2 = \tanh (\Phi^2) \tag{8}
\]

\[
a^* = \frac{a_a + a_0 \frac{Re}{Re_c}}{1 + \frac{Re}{Re_c}} \tag{9}
\]

\[
Re_c = \frac{\rho k}{\mu \omega} \tag{10}
\]

The model constants for SST k-\( \omega \) turbulence model are given below. The detail explanation and formulation along with value of model constants for SST k-\( \omega \) turbulence model can be found in [35].

\[
s_{k1} = 1.176, s_{\omega1} = 2.0, s_{\omega2} = 1.0, s_{\omega2} = 1.168, a_1 = 0.31, \beta_{11} = 0.075, \beta_{22} = 0.0828, a^* = 1, a_\omega = 0.52, a_0 = 0.5, R_b = 8, R_h = 2, R_{in} = 2.95, \varepsilon^* = 1.5
\]

2.2.3. Species transport model

In modelling the fluid inside the domain, binary mixture is used to represent the air and water vapour mixture. The transport equation for the mixture components is given Eq. (11) [35].

\[
\frac{\partial (\rho Y_i)}{\partial t} + \nabla \cdot \left( \rho \vec{v} Y_i \right) = -\nabla \cdot (\vec{J}_i + \vec{S}_i) \tag{11}
\]

For turbulent flow, the diffusion flux (\( \vec{J}_i \)) of the mixture components (i) due to temperature and concentration gradient is given in Eq. (12).

\[
\vec{J}_i = - \left( \rho D_{mix} + \frac{\mu_t}{Sc_i} \right) \Delta T_i - \Delta T \frac{\Delta T_i}{T} \tag{12}
\]

2.2.4. Radiation model

To model the effect of solar radiation, the heat transfer due to radiation is incorporated using Discrete Ordinates (DO) method. For an absorbing and emitting medium at a position vector \( \vec{r} \) and direction vector \( \vec{s} \), the radiant energy exchange equation was expressed using Eq. (13) [31, 35, 39].

\[
\frac{dI_T}{ds} = \alpha_{s} L_{s} \frac{dI_T}{ds} + \alpha_{s} a_{s} I_{s} \tag{13}
\]

In DO radiation modelling, the angular discretisation and pixilation were set to 4 \times 4 and 2 \times 2, respectively. The non-grey radiation and fair-weather condition is set. The dual band solar spectrum was implemented for band ranging from 0.4 to 2.4 \( \mu \)m and from 2.5 to 180 \( \mu \)m, respectively. Since, moist air can absorb or emit radiative energy due to the presence of water vapour as described in Wong et al. [39], the absorption coefficient of the moist air is set to be equal with the opaque material.
For pressure-velocity coupling the SIMPLE algorithm is used. The residual value for all equations was set to 1e-03, while for DO radiation energy Eqs. 1e-06 is used. The default under-relaxation factor is used in this study. The dryer was simulated with the following assumptions:

a. Transient analysis was done for the problem solution.

b. No air leakages.

c. Constant 2.6 W/m² K convection heat transfer from the glass to environment was considered.

d. The air flow is turbulent since the Rayleigh number (Ra) is greater than 10⁹ for the given conditions and complex geometry involved.

e. The thermophysical properties of solids are considered constant.

f. The resistance to air flow due to the presence of injera was assumed negligible due to the thickness of injera (<4mm) and single layer drying is assumed. So, injera was not modeled as solid objects nor as a porous media and the interaction between injera and air was not considered in this model [44]. Similar approach were followed for the trays.

g. The ambient temperature, velocity and relative humidity were assumed to be 298K, 0.5 m/s and 72%, respectively. All the properties are considered average values for Addis Ababa, Ethiopia.

h. The fluid is viscous and Newtonian.

i. Viscous dissipation was considered insignificant and ignored.

### 2.4. Meshing and mesh independence study

Figures 2 and 3 shows the 3-D geometry and the result of the meshing process, respectively for the solar dryer. The 3-D geometry and the mesh were developed using the design modular and meshing tools in ANSYS Fluent. To represent the actual size of the dryer, the simulation is performed using 3-D model with actual dimensions (1:1 scale). Furthermore unstructured tetrahedral meshing is used as recommended for complex flow domain [47].

The mesh independence study is performed using nine different mesh sizes ranging from 72,000 to 4,100,000 (Figure 4) with acceptable orthogonal quality [48]. From the figure, after 2.4 million mesh elements

### 2.3. Numerical methods

The boundary conditions implemented in this study for different components of the dryer are listed in Table 2. The density of the mixture is defined as incompressible ideal gas and the thermal conductivity and viscosity of the mixture are defined as mass weighted mixing law. However, the thermo-physical properties of components of the mixture are set to its default value. For pressure and convection terms the Standards and second order upwind scheme were used.

![Image](https://via.placeholder.com/150)

**Table 2. Boundary conditions applied for the different components of the solar dryer.**

| Boundary       | Type               | Momentum                                                                 | Thermal Condition                                      | Radiation                           | Species                                      |
|----------------|--------------------|----------------------------------------------------------------------------|--------------------------------------------------------|-------------------------------------|---------------------------------------------|
| Inlet          | Velocity inlet     | 0.5 m/s inlet velocity with turbulent intensity and hydraulic diameter values of 5% & 0.1818 m | Constant convective heat transfer with shell conduction | Boundary temperature                | 0.014 kg of water per kg of dry air          |
| Glass 1        | Wall with refractive index of 1.5 [46] | Stationary wall                                                           | Constant convective heat transfer with shell conduction | Semi-Transparent                    | 0                                           |
| Glass 2        | Wall with Refractive Index of 1.5 [46] | Stationary wall                                                           | Constant convective heat transfer with shell conduction | Semi-Transparent                    | 0                                           |
| Absorber 1     | Wall with Refractive Index of 1 [46] | Stationary wall                                                           | Black painted G.Steel with zero heat flux              | Opaque with IESR and IEIR value of 0.81 & 0.92 | 0                                           |
| Absorber 2     | Wall with Refractive Index of 1 [46] | Stationary wall                                                           | Black painted G.Steel with zero heat flux              | Opaque with IESR and IEIR value of 0.81 & 0.92 | 0                                           |
| Collector side wall | Wall with Refractive Index of 1 [31,46] | Stationary wall                                                           | Black painted plywood with zero heat flux              | Opaque with IESR and IEIR value of 0.81 & 0.92 | 0                                           |
| Drying chamber wall | Wall with Refractive Index of 1 [31,46] | Stationary wall                                                           | Black painted plywood with zero heat flux              | Opaque with IESR and IEIR value of 0.81 & 0.92 | 0                                           |
| Vertical air distributor channel | Wall with Refractive Index of 1 [46] | Stationary wall                                                           | Black painted G.Steel                                 | Opaque with IESR and IEIR value of 0.81 & 0.92 | 0                                           |
| Outlet         | Pressure outlet     | Back flow turbulent intensity and hydraulic diameter values of 5% & 0.1818 m | Atmospheric temperature                                | 298 K                                | Boundary temperature                        |

1. IESR – Internal emissivity for solar radiation.

2. IEIR – Internal emissivity for infrared radiation.
for 3 successive mesh elements the change in total heat transfer rate is found to be less than 0.5%. finally for this study mesh element of 2,474,510 is chosen.

2.5. Statistical validation

To validate the numerical results of temperature distribution with the experiment the following statistical indicators were used (Eqs. (16) and (17)) [35, 49].

\[
R^2 = 1 - \frac{\sum_{i=1}^{N} (X_{\text{pre}} - X_{\text{exp}})^2}{\sum_{i=1}^{N} (X_{\text{exp}})^2}
\]  

(16)

\[
E = \sqrt{\frac{\sum_{i=1}^{N} (e_i)^2}{N}}
\]  

(17)
Where, \( \varepsilon_i = \left( \frac{X_{\text{pre} i} - X_{\text{inj} i}}{X_{\text{inj} i}} \right) \times 100 \)

3. Results and discussions

3.1. Simulation results

Figure 5 shows the transient temperature at collector exit for July month. The figure shows that, the temperature of drying air after a period of heating (20 min) was above 10 K from ambient temperature and maximum temperature of 314 K was observed at solar noon (Figure 5). Based on the collector performance indicator for solar dryer described in Leon et al. [50], the collector design can provide the required drying air temperature elevation for effective drying of injera. Also the drying air temperature elevation above ambient temperature agree very well when compared with the results with temperature elevation in the range of 9 K–13 K reported by Musembi et al. [51], Forson et al. [52] and Madhlopa et al. [53] for natural convection flow solar dryers.

Figure 6 (a) and (b) shows the temperature distribution contour through the modified mixed mode solar dryer at 4 a.m. and 7 p.m., respectively. A uniform temperature distribution of drying air over the drying trays was observed with a maximum temperature at the collector outlet. It was also noticed that after 1 h from the start of the simulation period, the temperature of all trays exceeded the ambient temperature by 5 K.

The average velocity distribution through the drying trays over the drying period is shown in Figure 7. It can be observed that a uniform velocity distribution over the drying tray after the flow domain evolves to steady operating velocity after about 20 min. Thereafter, the average velocity of the drying trays will be uniform with a value of 0.11 m/s. Unlike the temperature distribution, the velocity distribution in the upper tray is smaller than the lower trays. This is due to the air flow resistance on the vertical air distributor walls and kinetic energy drop. The flow velocity deviation from the mean velocity on the upper tray and lower tray is about 0.01 m/s and 0.02 m/s, respectively. This indicates that the distribution of drying air velocity is quite even over the drying trays.
Therefore, using vertical air distributor helps to maintain homogeneous distribution of drying air over the drying tray. The drying rate of products depend on the drying air velocity for velocities less than 1.2 m/s [17, 19, 54, 55]. Therefore, the current result on the drying trays indicates that the drying rate will be homogeneous at different trays. A similar flow velocity within a solar drying chamber was reported by a number of researchers [32, 56] and also with in a range with Babu et al. [11] and Darabi et al. [57].

The result of velocity vector is shown in Figure 8. The result from velocity vector plot indicates higher velocity at the outlet of the drying tray.
chamber due to the reduced flow area. Also, presence of recirculation is observed inside the drying chamber. And these promotes the heat transfer process between the product and drying air [58]. Thus, offers additional thermal energy to the dryer and resulted homogeneous distribution of drying air temperature over drying chamber trays as shown in Figure 6 above [59, 60, 61].

The result in Figure 9 shows the average collector exit velocity and mass flow rate. The flow initially increased and falls but the variation is only 4% from mean value and the flow domain evolves to a steady condition after 20 min. The result indicates an average collector exit velocity and mass flow rate of around 0.48 m/s and 0.0622 kg/s, respectively. Since air flow depends on the temperature gradients in the air, collector exit velocity varies with variation in the air temperature due to solar radiation imposed in the domain through the simulation hours.

The result of mass flow rate in this work is comparable with the reported value of 0.065 kg/s for collector depth of around 0.1 m and it is within the range of collector exit velocity of 0.20–0.40 m/s as reported by Macedo and Altemani [62] for natural convection flat plate solar collectors.

Figure 10 shows the pressure distribution contour through the dryer at 7 p.m. The average pressure through the drying trays shows a slight difference between the bottom and top tray and this pressure difference allows the flow of air through the dryer in vertical direction. The pressure difference between the drying chamber inlet and outlet is comparable with the reported value of 0.21835 Pa by Babu et al. [11].

Figure 11 shows an average relative humidity at the collector outlet and over drying trays. The relative humidity through the drying trays

Figure 8. Velocity vector through the dryer at 6:30 PM.

Figure 9. Average collector outlet velocity and mass flow rate.
reached its minimum value of 56% at 7 p.m. This coincides with the time of maximum temperature and solar radiation. An average relative humidity at collector outlet shows a rapid decrease and reaches below 50% in 1 h. After reaching this point, it shows slight change of 3% until the end of the simulated hour. The relative humidity distribution between the drying trays were almost uniform with 2% variation throughout the simulation period. The result also indicates that the distribution of relative humidity is proportional to the drying air temperature and velocity. This indicates that the drying air flows throughout the drying chamber without stagnation [31].
3.2. Validation of CFD model

Figure 12 shows the ambient temperature, relative humidity and global solar radiation variation when the experiment is performed. The average values of temperature, relative humidity and global solar radiation were 25.31 °C, 75.61% and 447 W/m², respectively.

To validate the reliability of the CFD model for the mixed mode solar dryer analysis, the results of CFD analysis are compared with those obtained experimentally. Figures 13 and 14 present the temperatures at the collector outlet and inside the drying chamber that obtained from experimental versus the corresponding results from the CFD analysis. The average temperature inside the dryer was found to be higher than the ambient temperature. It shows an increase at the start and changes with solar radiation throughout testing period as demonstrates in Figures 13 and 14. The results also shows that a good agreement between the predicted and the experimental values. However, the simulation result for both drying chamber and collector outlet shows slight underestimation of drying air temperature. The reason for such cases of underestimation could be the variability of ambient temperature, air flow and relative humidity in the case of the simulation.

Table 3 shows the validation of CFD results with experimental observations. The result indicates $R^2$ values of around 0.99 and $E$ vary from 3.68% to 3.16% for collector outlet and drying chamber temperature, respectively. This shows a good linear association and closeness of the simulation and experimental data. This finding is in agreement with Sonthikun et al. [36] which obtained $R^2$ value of 0.98–0.99 and $E$ value of 2.3%–5.9%. The coefficient of determination result is consistent with reported value by Villagran et al. [63] between 0.893 and 0.968 and by Jain et al. [30] 0.98. Hence, CFD model for modified dryer presented in this study is in reasonable agreement with the experimental results.
4. Conclusion

In the present work, computational fluid dynamic (CFD) analysis has been carried out to evaluate the performance of air distributors in a mixed mode solar dryer. Uniform distribution of different flow parameters was obtained using the vertical air distribution channel integrated into the mixed type solar dryer. The newly developed and integrated air distribution system will improve the performance and quality of dried products in solar dryers. The modified dryer is a better option to prepare dried injera (dirkosh) for local and international market. The simple design and the construction materials used will promote the commercialization of the dryer. The dryer could be used for new job and income generation for low-income societies.

Declarations

**Author contribution statement**

Kamil Dino Adem: analyzed and interpreted the data; contributed reagents, materials, analysis tools or data; wrote the paper.

Senay Teshome Sileshi: conceived and designed the experiments; performed the experiments; analyzed and interpreted the data; contributed reagents, materials, analysis tools or data; wrote the paper.

Abdulkadir Aman Hassen: conceived and designed the experiments; contributed reagents, materials, analysis tools or data; wrote the paper.

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**Data availability statement**

Data will be made available on request.

**Declaration of interests statement**

The authors declare no conflict of interest.

**Additional information**

No additional information is available for this paper.

**Reference**

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