A REVIEW ON COMPUTATIONAL FLUID DYNAMICS SIMULATION METHODS FOR DIFFERENT CONVECTIVE DRYING APPLICATIONS

by

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This paper focuses on the CFD studies on one of the commonly used drying processes for different applications. First, a brief information about drying is given with determining important properties that effect drying characteristics. Next, basic principles of CFD modelling are explained while capabilities of computational processing are presented. A detailed literature survey about CFD studies in convective drying process is then conducted. Finally, some sound concluding remarks are listed. It may be concluded that the CFD is a powerful and flexible tool that can be adopted to many different physical situations including complex scenarios, results of CFD simulations represent good predictions for fluid-flow, heat and mass transfer of various drying methods and those numerical studies can be used for validation and controlling of applicability of new drying systems.

Introduction

Industrial or domestic drying applications of moist products is a dehydration/dehumidification process for several purposes, which depend on type and utilization of the products with ensuring end product quality [1]. An energy (heat) transport from ambient area to humid solid and moisture transfer from humid solid to surrounding area take place during drying process. Thus, enclosing air gets humidified while the humid object loses moisture. In the drying process, water is the liquid being removed in most of the cases. For this reason, infrequently evaporation of solvents is experienced. The drying process is a fundamental process in various industries such as agricultural, chemical, food, biotechnological, pharmaceutical, wood processing, mineral processing, pulp and paper [2]. Requested moisture content of the end product varies according to quality and sort of the products that are dried and also due to demand of consumers. In this regard, different methods for drying have been used in relevant industries. Removing moisture from high moisture nourishment like fruits and vegetables is a conventional method to increase shelf and storage life of them while preserving the product quality. Some types of food are dried for ease of use and handling such as milk, eggs and spices. On the other hand, products like ceramics or bricks are dried for durability and strength. In order to achieve

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desired quality or minimize quality losses, reduction in cost of transportation, preventing from chemical or microbial deteriorations are some of the reasons to apply drying processes to feed stocks. Drying is utilized generally for convenience of transportation, storage, packaging and dosage for some materials and to attain moisture content within a certain range for desired quality purposes [3]. To comply with contractual or legal limits for many products (*e.g.*, salt, yarn, sand; *e.g.*, tobacco, flour) is an important reason for drying. During some production steps, it can be necessary to decrease moisture content to make the process easier. For instance, dried rubber chemicals are used in the vulcanization process of tires because high moisture causes swollen forms. High moisture in some kind of textile products causes mildew and bacterial growth so drying to a specific value prevents product from that deleterious situation.

Basic features of drying effect drying kinematics and it is a challenging area that needs comprehensive R&D studies. For instance, product thicknesses change in range from microns to tens of centimeters, porosity varies from 0-99.9%, so parameters like those effect drying times or type of drying. In this process, the products may be stationary (no movement) or dynamic (moving). The drying air temperature may range from under triple point to above critical point of product. Operating pressure also ranges due to varying parameters and heat transfer may happen by convection, conduction, radiation, electromagnetic field or combinations of them.

The drying duration is an important parameter effects energy and operating costs with the quality of dried product. For example, drying of a tissue paper takes 0.25 seconds to dry while it takes five months to dry certain hardwood species. As drying is an intensive process including diversity of products from different industries, determining the optimal combination of various parameters is a necessity for drying process. To choose the best fit for efficiently reducing or removing moisture from any product, the parameters be considered mainly as: initial moisture content of the feedstock, desired moisture content of the end product, shape and size of the product, thermal, physical and chemical constraints and limitations not to reduce product quality, storage, preservation and transportation terms and conditions of product and conjunctive applications of drying and other processes (baking, heating, sanitizing, rinsing, *e.g.*) through products.

Various types of dryers are commercially in use while R&D studies for novel dryer systems are also being performed. The main reason of this diversity is connected to the variety of products being dried. Some drying systems are constituted for only a unique product because of critical parameters of the process (expected drying time, physical and chemical deterioration, quality entailments... *e.g.*) are matchless in their class. In many types of dryers, the drying process is carried out by hot air-flow (convection). With the effect of hot air, the water in the humid object evaporates and is transferred to the ambient air, and while the humidity of the object decreases, the ambient air also gains moisture. Many numerical studies have been carried out, which deals with this physical state as the main process or together with other methods.

Factors affecting the drying rate

The moisture in a solid can be bound or unbound. Evaporation and vaporization are the two phenomena of removing unbound moisture from a solid [4]. Evaporation can be made by two methods, one is increasing the temperature to the boiling point of moisture as in roller dryers, the other is, for heat-sensitive materials, decreasing the pressure (vacuum operation) below triple point and then add heat for sublimation as in freeze dryers. Removing moisture by convection of warm air through solid product is the vaporization method of drying as seen in convective dryer types. Atmospheric pressure is above the saturated vapor pressure of moisture in this state.

Due to different methods of drying, drying rate is affected by many factors. Drying rate can be defined as two ways, one is the mass of moisture removed from unit mass of dry content per unit time, Φ, the other is, called water flux, N, the mass of moisture removed from unit area per unit time.

Drying rate is basically represented in the form of drying curves. A drying curve plots drying rate (Φ or N) *vs.* drying time or moisture content in the solid during drying. Drying rate is basically represented in the form of drying curves. Converting the generally form of drying rate equation, with different boundary conditions for range of drying techniques, varying models were developed in the referenced literature for different types of drying curves [5-10]. There are alsa several thin-layer drying curve models [11] for using generally in numerical studies.

Factors that affect drying rate can be sorted as two groups: internal conditions and external conditions. External conditions include properties of drying environment such as temperature, humidity, and velocity of drying air, and those conditions are important at the early periods of drying process where there is unbound free water on the surface of product. Internal conditions affect the movement of bound moisture inside the material, and generally about the physical properties of the material like moisture content, diffusivity, temperature.

The moisture is the volatile part of a solid product. In porous moist solid, water is bonded to the pores inside the product. The amount of water in the product is called as moisture content. Moisture content is defined by two ways, MC on wet basis and MC on dry basis. Moisture content on a wet basis and on dry basis are defined, respectively [12]:

$$MC_{\text{wb}} = \frac{\text{mass of water}}{\text{total mass of material}} \times 100\% = \frac{\text{mass of water}}{\text{mass of dry solids} + \text{mass of water}} \times 100\% \tag{1}$$

$$MC_{\text{db}} = \frac{\text{mass of water}}{\text{mass of dry solids}} \times 100\% \tag{2}$$

In high moisture products such as fresh fruits and vegetables, MC_{db} can be at the range of 300-500%. This means that there is so much unbound free water inside the pores and spaces. At constant rate period of a drying curve, due to existence of free water film on evaporating surface, external rates conduct heat and mass transport. Evaporation is independent from material in this stage and at a critical point where the supply of water from internal sides of material to the surface drops below rate of evaporation, drying rate starts to decrease sharply to the point of equilibrium moisture content where evaporation stops. Temperature of the product increases above the wet bulb temperature to reach the dry-bulb temperature of air. Moisture content at the point where drying rate starts to drop is called as critical moisture content, X_{c}. If the vapor pressure is in equilibrium with surrounding environment vapor pressure, moisture content at this condition is called as equilibrium moisture content, X_{eq}. In other words, throughout drying process, if moisture content of a hygroscopic material reaches the value that is in equilibrium with the surrounding atmosphere, that means the material has equilibrium moisture content [13]. At this moisture content, the material neither gains nor loses moisture, and the material is a dry product. This factor is an important property that has influence on drying rate. A plot of equilibrium moisture content vs. relative humidity of surrounding air is defined as sorption isotherm or moisture isotherm. These graphics are used to describe hygroscopic properties of a material. Sorption isotherms are also dependent on temperature of the product.

Another way to define drying kinetics is characteristic drying curves. It is a simplified approach first mentioned by van Meel [14] with a plot of normalized moisture content *vs.* time. Normalized moisture content can be defined as moisture ratio:

$$MR = \frac{X - X_{\text{eq}}}{X_0 - X_{\text{eq}}} \tag{3}$$

where X_0 initial moisture content and X_{eq} is equilibrium moisture content. If equilibrium moisture content has a very small value compared with initial moisture content, it can be neglected.

Heat is transferred from hot air to the solid material in thermal drying process, and absorption of heat causes moisture diffusion from solid. Movement of moisture from material surface to air called as external diffusion, and diffusion the surface from the interior of the body is called internal diffusion. These two types of diffusion also depend on different physical phenomena like capillary flow, molecular diffusion, Knudsen diffusion or hydrodynamic flow [15]. Fick's second law defines the generally combination for all diffusion models:

$$\frac{\partial X}{\partial t} = D_{\text{eff}} \nabla^2 X \tag{4}$$

where D_{eff} is the effective diffusivity for all kind of products, including heterogeneous materials. Equation (3) shows the change in the amount of moisture within the solid over time. If the controlling mechanism is moisture diffusion, drying rate can be calculated using this equation [16], or the equation is a suitable model for calculating drying time [17]. Several models are developed by Fickian equation for varying initial and boundary conditions [18]. Diffusivity of a product depends strongly on temperature and moisture content of the product [19-27]

An important feature for drying is, thermal conductivity, is a measure of materials for conducting heat. This property basically depends on chemical composition and also physical structure, state of the substance and temperature [28]. It is expressed using varying experimental methods and it is a moisture content and temperature dependent property as seen in the models in referenced literature [29-34].

Chemical composition of the product is one of the properties that effect drying rate. Minor changes on composition of a material can affect its drying characteristics such as diffusivity, thermal conductivity or porosity. Besides, equilibrium moisture content which is an important parameter which influences drying rate, also depends upon chemical composition of the material [15]. Experimental studies gave the result that, composition of raw material effects the moisture binding energy which implies the amount of free water to be evaporated [23]. Composition of the product is also essential for determining optimal parameters of drying. One of the reasons for choosing a drying method is to preserve the composition of the solid to be dried and drying rate can be changed due to the method of drying. Chemical deterioration of the material is undesirable in the drying process in order to protect the quality of the product. Experimental and numerical studies indicated that chemical composition of materials effects binding energy of materials which has an influence on prevailing factors of moisture transport like porosity, moisture content and effective diffusivity [35-39].

External conditions are effective on initial stages of drying where unbound free water exists on the vicinity of material surface. Temperature of drying air has an essential impact on drying rate in all kinds of thermal drying methods. Besides, it is one of the main parameters especially in direct drying applications. Thermal properties of drying air influence heat and mass transfer coefficients which have considerable effect on drying rate. Many studies were performed to investigate effects of temperature on drying rate [40-45], in some studies increasing temperature to admissible values for drying has a favorable effect on drying kinetics, while drying at high temperatures revealed negative results on drying rate in others. Drying air temperature varied in a range of acceptable minimum and maximum values in most of studies and they combined with other varying parameters such as relative humidity, pressure and diffusivity. Due to physical structure and composition of dried material or other parameters that effect drying, most suitable value of air temperature for efficient drying can be high or low. Although high air temperatures accelerate the drying process, it can cause structural deterioration in heat sensitive materials. Drying at high temperatures can cause undesired changes on morphology of materials, especially foods. Ziegler *et al.* [46] investigated the effect of drying air temperature of red corn grains on morphology, digestibility and technological properties of starch. Experiments gave the result that, drying at high temperatures (100 °C) changed internal structure and native morphology of corn starch and reduced digestibility compared with lower temperatures (40 °C) which promoted fewer changes on structural and technological properties. On the other side, higher drying temperatures have obtained different results for tomato and sweet pepper in the experimental study of Kaur *et al.*, at 60 °C color retention was better for tomato while it was better at 40 °C for pepper [46]. Lang *et al.* [47] investigated drying temperature factor on composition of black rice phenolics under varying storage conditions in their experimental study. They observed that changing temperature effected binding energy of phenolics and at higher temperatures, reduction in free phenolics is seen. There are variety of experimental and numerical studies in literature investigating influence of dry air temperature on drying kinetics and physical properties like shrinkage, color and shape, chemical composition and quality of dried materials. Those studies are made for presenting a contribution specify optimal drying parameters with high energy efficiency and low operating costs.

Relative humidity has an important effect on drying as an external feature, describes the percentage of to the actual vapor density to the saturated vapor density in the air. It is a temperature dependent property in general, in addition, relative humidity close to the surface of the material depends on the material moisture content [48].

Relative humidity is essential especially when shrinkage occurs in the product with drying process. After the removal of initial free moisture, high moisture gradients occur between internal parts of the product and the surface. That causes too much tension within the product due to excessive shrinkage, and consequently it gets the result of cracking and warping. In order to prevent this situation, conserving high relative humidity with controlled safe movement of moisture from interior to surface inhibit unreasonable evaporation. On the other hand, if shrinkage is not a considerable factor, most of experimental researches gave the result that decreasing relative humidity in the air causes drying rates to increase [49-53].

Computational fluid dynamics solution methods used in drying applications

Mathematical models for drying processes

In the presence of various drying methods and due to the complexity of drying applications, mathematical modelling has become necessary for projection, operation, optimization and control of those systems [33]. The models vary according to content of the physical problem Mathematical modelling of a physical problem can be developed by three methods which are theoretical models that use mathematical description of physics laws, empirical models that use empirical correlations of related previous studies and models that use both physical and empirical approaches.

In theoretical models, the classifications are done to derive the fractional moisture ratio (MR) from two physical laws: Newton's law of cooling and Fick's law of diffusion. Effective diffusivity, D_{eff}, represents the transport of moisture from the body due to molecular diffusion, capillary flow or Knudsen flow. Models used under these two classifications can be found in the study of Erbay and Icier [54]. Mathematical modelling with empirical data is easier and computable compared with physics-based models, in drying processes of porous humid materials, most of the parameters such as thermophysical properties, porosity and permeability are calculated with empirical equations. Those empirical formulations usually give good predictions in solutions and they are easy to compute. On the other hand, basis equations describing heat and mass transport (HMT) cannot be defined by empirical models for drying processes. Those governing equations must be solved by using physic-based approach. There are also empirical models that express MR related to time of drying according to experiment of drying particular foods [55-57]. In most of numerical drying studies, researchers use physic-based models for solving governing equations, and they use empirical or semi-empirical models for defining specific parameters that effect drying characteristics.

The scale of the drying problem is one of the features of classification. In the macro-scale approach, every part of the object to be dried is considered homogeneous, and the physical properties are uniform and instant, no matter what part of the object. Lumped parameter models can be used in this approach and moisture transport generally happens only in one phase by diffusion at the interfacial area between the solid part and air [11, 28, 58-61]. Micro-scale approach considers the object as a heterogeneous body with solid part, pores with liquid and pores with gas. A heterogeneous structure is valid for the geometrical model where the properties change spatially along the body [62]. Thermal and concentration equilibrium are assumed for this approach, so the local changes on temperature and moisture are not taken into account [63-65].

Another classification for numerical investigation of convective drying is coupled (conjugated) and segregated (non-conjugated) models. In most of the numerical studies, simultaneous heat transfer is computed for only solid product and convetive transfer coefficients (CTC) are assumed to be constant or calculated along the surfaces of the product. These studies are called as non-conjugated problems. In conjugated problems, transport phenomenon is calculated for both the solid domain and the air domain. The CTC changes by time and space during the problem in these models.

Shrinkage and deformation are important especially for drying fresh fruits and vegetables; and taken into account in many studies for convective drying. The removement of moisture and the effect of hot air cause changes in shape and deformation, so this phenomenon needs to be investigated. There are empirical and semi-empirical models to express shrinkage [61, 66-69], mechanistic models that considers the moisture loss is equal to the change in dimension for the product [70-74]. The deformed geometry (DG) and arbitrary-Lagrangian-Eulerian (ALE) methods are used frequently by CFD codes for describing shrinkage and deformation in recent years [7, 75-79] natural convection mixed-mode solar drying experiments were carried out with potato cylinders of varying diameters (8 mm, 10 mm, and 13 mm). Table 1 shows summary of numerical convective drying studies as they are classified according to the features explained previously. Classification of numerical studies in general is done according to the solution method, previous dependent experimental studies, the properties of the solid and the drying parameters.

The CFD is a capable and powerful tool to predict the behavior of physical problems about fluid-flow by means of mathematical modelling with the help of digital computers. Generally, fluid-flow is a complex phenomenon that problems about this physics cannot be solved analytically, in this situation, PDE are used to solve these physical problems. The CFD obtains a flexible approximation by using a discretization method that approximates the PDE by a system of algebraic equations, and solve them mostly by using digital computers. Discretization is performed by applying of the equations to small domains. These domains can be in space or

Table 1. Summary of numerical CD studies classified as given parameters

<table>
<tr><th>Scale</th><th>Segregated/ coupled</th><th>Phase of MT</th><th>CTC</th><th>Thermophysical prop.</th><th>Deformation</th><th>References</th></tr>
<tr><td rowspan="2">Multi</td><td rowspan="9">Segregated</td><td rowspan="12">Liquid phase</td><td rowspan="5">Constant</td><td rowspan="6">Constant</td><td rowspan="2">Shrinkage</td><td>[83]</td></tr>
<tr><td>[84, 85]</td></tr>
<tr><td rowspan="11">Macro</td><td rowspan="5">Neglected</td><td>[86]</td></tr>
<tr><td>[87]</td></tr>
<tr><td>[88]</td></tr>
<tr><td rowspan="6">Variable</td><td>[89]</td></tr>
<tr><td rowspan="4">Variable</td><td>[90-92]</td></tr>
<tr><td>Shrinkage</td><td>[93]</td></tr>
<tr><td rowspan="4">Neglected</td><td>[94]</td></tr>
<tr><td rowspan="5">Coupled</td><td>[95]</td></tr>
<tr><td>Constant</td><td>[96]</td></tr>
<tr><td rowspan="2">Constant</td><td rowspan="8">Variable</td><td>[97]</td></tr>
<tr><td rowspan="4">Multi phase</td><td rowspan="2">Shrinkage</td><td>[28, 98]</td></tr>
<tr><td rowspan="3">Multi</td><td rowspan="4">Variable</td><td>[99]</td></tr>
<tr><td>Segregated</td><td rowspan="7">Neglected</td><td>[100]</td></tr>
<tr><td rowspan="4">Coupled</td><td>[101]</td></tr>
<tr><td rowspan="5">Macro</td><td rowspan="3">Liquid phase</td><td>[102]</td></tr>
<tr><td>Constant</td><td>[103, 104]</td></tr>
<tr><td rowspan="3">Variable</td><td>[105]</td></tr>
<tr><td rowspan="2">Segregated</td><td rowspan="2">Multi phase</td><td rowspan="2">Constant</td><td>[106]</td></tr>
<tr><td>[107]</td></tr>
</table>

time or both, so the solution obtains the results at discrete locations in space or time. Such as the accuracy of an experimental data is dependent on the quality of the tools used, the precision of a numerical solution depends on the quality of discretization modeled [80].

The PDE governing fluid-flow, heat, mass transfer and related phenomena are solved by numerical algorithms and those generate the CFD codes [81]. Conservation of mass, momentum and energy equations govern fluid-flow and associated physics described as follows.

Conservation of mass (continuity): The equation describes the balance of the mass-flows entering a fluid domain between the mass-flows leaving the domain. It is called as mass balance equation also and described:

$$\frac{\partial \rho_a}{\partial t} + \nabla\left(\rho_a \vec{u}\right) = 0 \tag{5}$$

Conservation of momentum: This equation describes Newton's second law of motion and it describes that the total external forces acting on a fluid are equal to the momentum change in that fluid:

$$\rho_a \frac{\partial u}{\partial t} + \rho_a \vec{u}\nabla\vec{u} = -\nabla p\vec{I} + \nabla\left\{\left(\mu_a\right)\left[\left(\nabla\vec{u}\right)+\left(\nabla\vec{u}\right)^T\right] - \frac{2}{3}\left(\nabla\vec{u}\right)\vec{I}\right\} \tag{6}$$

Conservation of energy: The equation defines the First law of thermodynamics which states that energy cannot be created or destroyed, this means the change of internal energy of a fluid is equal to the heat added to the liquid and the work done on the system described:

$$\rho_{\mathrm{a}} c_{p,\mathrm{a}} \frac{\partial T}{\partial t} - \nabla\left(k_{\mathrm{a}} \nabla T\right) + \rho_{\mathrm{a}} c_{p,\mathrm{a}} \vec{\mathrm{u}} \nabla T = 0 \tag{7}$$

The CFD codes are convenient tools that propose the following benefits [82]:
- They help to understand physics like fluid-flow, heat and mass transfer, weight losses..., *etc*. in detail.
- They're useful for simulating exhaustive measurement conditions that are not possible to be performed.
- They reveal not only the effects of the problems, but also the origins of them.
- They can be described as numerical experiments and give information about behavior of many physical phenomena with high complexity.

The CFD code contains three basic elements pre-processor, solver and post processor. All phases briefly explained in fig. 1 (Versteeg, 1995).

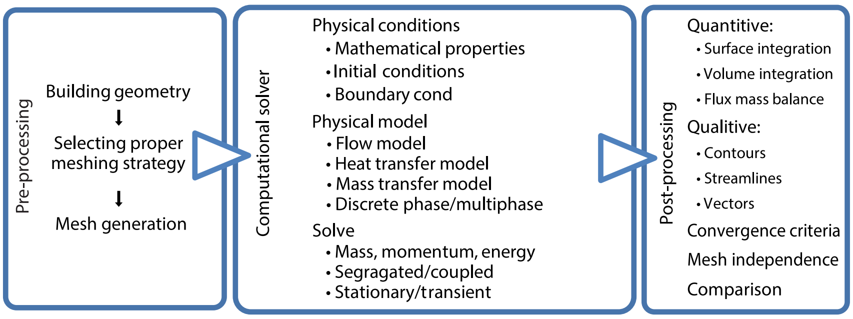

Figure 1. Elements of a CFD code

With the strengthening of computers in recent years, many complex physical problems can be solved by using CFD software including combination of more than one physics.

The numerical problem is a convective drying of a wood piece in an industrial kiln [108]. First the problem is needed to be analyzed and then computational domain is developed. Because of the symmetrical geometry of wood, solving for a quarter part of the wood can be satisfying. After constructing the geometry, boundary conditions for given data is determined. Assuming computational model as a continuum model, problem is solved for an averaging volume of the geometry, and it is applied on every element of the mesh.

Over the years, with the advancement of technology, the robustness and accuracy of CFD software also increase with easier steps for solving problems. Commercial CFD codes are generally supported by the platforms of operating systems on high end computers and workstations [109].

Review of computational fluid dynamics studies in drying processes

Convective drying applications are also called as direct drying systems that the stream of hot air passes through the humid product and causes the moisture evaporation of water from it. The simultaneous heat, mass and momentum transfer leads the water remove from the moist object. Considering the system as a physical problem including air-flow, convective heat transfer and moisture transport, those physics can be defined by a suitable CFD code comprising various values of the parameters. The complexity of a hot air-drying system is valid when the air-flow is turbulent, and this condition converts the physical problem to a challenging issue. The geometry of the drying object is standardized for simplicity like rectangular, sphere, and cylindrical geometries. A rectangular shape is commonly used in CFD models because of the ease of meshing and convergence of transport equations [110]. Even though analytical models are capable for solving simple linear problems, the approximations of the PDE can be done by various numerical methods for the complex problems including fluid-flow, convection and conduction heat transfer and molecular diffusion. The main three methods can be used for solving drying problems numerically according to mathematical model and initial/boundary conditions which are fine differences, finite volume and finite elements [62]. In finite difference approach, the domain is discretized by describing the unknown variables of the problem by means of node points of a grid of a co-ordinate-line. Approximation of the derivatives is done by replacing each derivative of a node with the nearest formula. Taylor-series expansions are used to define an unknown variable at a node by using the information of neighboring grid points. If the geometry of the problem is simple enough to generate a uniform grid, FD discretization method is useful. Finite volume method was developed as a special finite difference formulation. In this method, the domain is divided into small volumes or cells. Differential form of the governing equations is solved for each small volume. The accuracy of the solution is dependent on the shape, size and position of the control volumes and definition of the boundary conditions. Finite element methods use simple piecewise functions to describe the local variations of unknown field variables. The computational domain is divided to smaller parts (finite elements) and solution of each small domain is done from the linear basis functions of each node. Choosing the proper method for discretization depends on the geometrical model (computational domain), the complexity and type of the physical problem and the power of the computer that is used for solving.

An explicit finite volume method was used for 2-D heat and moisture transfer analysis by Hussain and Dincer [111]. An axisymmetric cylindrical geometry was simulated and the thermophysical properties of porous medium were taken from experimental data set of cylindrically shaped broccoli. A macroscopic non-conjugated approach was adopted considering diffusive mass transfer (MT) from the surfaces. According to the results, temperature raised rapidly at the early stages of drying, and the rise was nearly constant during the latter periods. The same effect was seen for moisture gradients, higher gradients were seen on the early stages when the moisture gradient was nearly constant as drying progressed. Mohan and Talukdar [112] performed a coupled 3-D convective drying problem of a rectangular porous object. A finite volume discretization was done with a fully implicit scheme for solving the problem and effects of varying external parameters such as drying velocity and temperature were evaluated. Results indicated that with the increase of both air velocity and temperature, the heat transfer coefficient (HTC) was increased, and solutions with constant HTC did not give good predictions for drying mechanism. The geometrical description, velocity and temperature profiles are shown in fig. 2. Mass transfer mechanism is generally described by diffusion of the liquid phase at the interfacial area of the solid surface. For this reason, choosing a proper diffusion is important to predict drying mechanism in a correct way. A theoretical moisture and temperature evolution of carrot slab drying was performed by Ruiz-Lopez *et al.* [83] and results were validated with the experimental convective carrot drying. The diffusion models for mass transfer in cylindrically shaped foods was performed by using FVM by da Silva *et al*. [113, 114] in their consecutive studies In the first study, drying of thin-layer peeled bananas were studied numerically. Three models were used with the variations of volume, V, and diffusivity, D, as they are constant or variable, and for all models mass transfer coefficient is constant. The model that both V and D were as-

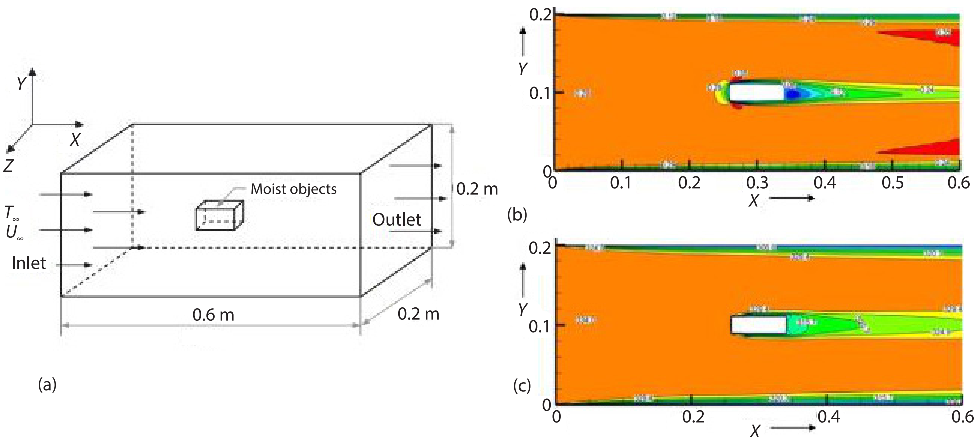

Figure 2. Schematic description (a) velocity (b), and temperature (c) profilers of [112]

sumed to be variable were chosen to be the best to describe drying process. In the latter study of researchers, a numerical solution for diffusion equation was applied to solids obtained through the revolution of arbitrary bi-dimensional geometries. The FVM was used for discretization of the model with symmetrical geometries. A good agreement with the related analytical solutions was achieved from the proposed solutions that described diffusion processes. The multi-phase models consider both diffusion from the surface area and convection from the interior parts of the moist object. Yiotis *et al.* [115] studied coupled convective-diffusive mass transfer of a porous medium in drying process. A microscale approach was used for porous medium including a dry region, film region and liquid region with coupling the air-flow domain. The results showed that when mass transfer is happened externally dominantly from the surfaces rather than diffusion of moisture from the internal pores of the medium, drying rate remained practically constant. A 2-D coupled transport mechanism for drying of prunes was made by Sabarez [116]. A microscale model was developed by representing a composite body including a flesh body and a stone body. Figure 3 shows the mesh discretization of the geometry. An experimental set-up of a computer-controlled laboratory-scale tray dryer was built to validate the results. The numerical solution was performed by using FEM method coupled with arbitrary Lagrangian-Eulerian procedure (ALE) to account shrinkage phenomena. Numerical results showed that drying air velocity, initial MC and the size of prunes had important effect on drying kinetics and comparison of the predicted and experimental temperature profiles and drying curves were in good agreement according to the results. There are several studies that Dehydration of grapes are investigated numerically by Gavrilla *et al.* [117] for an unsteady convective drying process in a static bed. In the study, local material averaged drying rate and heat flux in dependent on temperature and relative humidity of drying air were evaluated, and a predicted drying time was calculated as 38 hours 21 minutes from the simulations with a reduce from 75-15% in moisture content. The results were also in good agreement with the experimental data. Heydari *et al.* [118] studied heat transfer induced stresses in convective drying and validated the results with dried Kaolin samples. In the numerical study, heat transfer induced stresses were

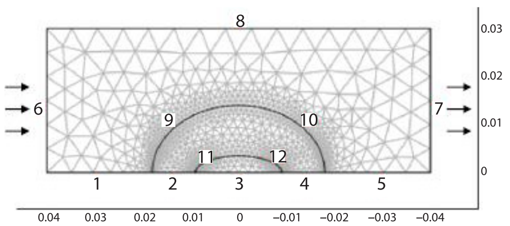

Figure 3. Mesh generation with boundaries for the [116]

less important than mass transfer induced stresses according to the results. Kumar *et al.* [119] performed a comprehensive study of convective drying of apple slices. A non-conjugated approach was simulated as an axisymmetric cylindrical geometry was constructed and the CTC were assumed to be constant. Most evaporation was seen on and near the surface of the sample with highest temperature profile on the surfaces and results were in good agreement with experimental data. A 3-D conjugated multi-phase approach was constructed for drying rectangular shaped porous objects by Selimefendigil *et al.* [120]. Effects of varying air temperatures and velocities on MC evolution were calculated and results showed that increasing both parameters had a positive effect on reducing of MC. A similar study of the same researchers was developed for optimization of the convective drying process by changing the configuration of the objects in the channel. The optimized distance between three rectangular objects in a 3-D channel that resulted the best drying rate was found by using COBYLA algorithm by using the steady-state heat transfer values from the CFD solver and then used the parametric data to get optimum mass transfer configuration [107]. A schematic description of the problem is shown in fig. 4. Table 2 summarizes CFD studies about convective drying in literature.

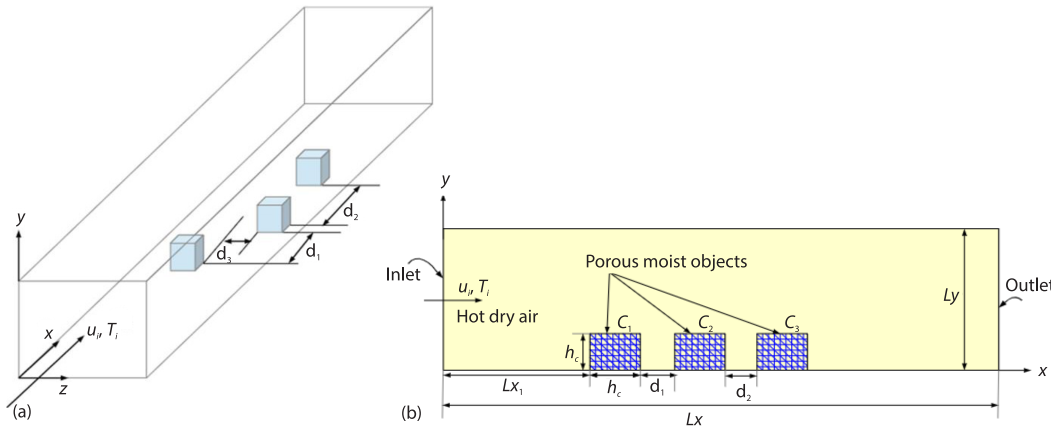

Figure 4. The 3-D (a) and 2-D (b) schematic view of the computational model of [107]

Conclusion

In this study, a review work is presented for the CFD studies in convective drying applications. One can understand that essential points and solving steps of CFD modelling of a convective dryer after reading this article. The CFD simulations allow studying a wide range of drying processes, every stage of drying can be investigated in detail for different conditions. Combination of different drying techniques that have different physical disciplines can be coupled and solved with CFD modelling. Some concluding remarks can be listed are as follows.

Numerical simulations give good predictions for optimization and reformation of drying processes.

- The external flow conditions can be simulated with CFD and obtained heat and mass transfer coefficients can be used as boundary conditions for the mass transport in moist object. It is also possible to use a direct coupling of the external flow and porous moist object with the computational fluid dynamics simulationols.

Table 2. The CFD studies including convective drying in literature

Material/ Shape	Scope of the study	Method/ Dimension	Results	Ref.
Grapes Cylindrical	*Unsteady convective drying in a static bed *Shrinkage due to change in solid density *Constant thermal properties	*FEM *3-D	* Drying rate increased at initial stages *A sharp decrease on drying rate at the end of drying * MC wb decreased from 75% to 15%	[117]
Material not reported Rectangular	*Forced convection drying of rectangular objects with different aspect ratios *An analogy between HTC and MTC is done	*FVM *2-D	* Temperature increases and moisture content decreases rapidly by time at low aspect ratios * Shorter AR provide lower drying times.	[90]
Porous Ceramic shell Thin layer	* Convective drying of a single-layer non-hygroscopic porous body. * Transportation due to capillarity, diffusive and convective fluxes.	*FEM *1-D, 2-D, and 3-D	* Liquid saturation and temperature profile during drying were in good agreement with previous studies	[121]
Potato, Carrot Cylindrical	Convective drying of hygroscopic non-porous objects * Simultaneous HMT * Deff were obtained from true isothermal conditions	*FEM *3-D	* Moisture profiles were uniform at initial stages of drying * Temperature distribution had the most significant effect on diffusivity	[122][a]
Material not reported Rectangular	* Simultaneous HMT * CHTCs at the surfaces were computed by a CFD code. *An analogy was done for CMTCs	*FVM *3-D	* HMT increased with increasing air velocity * Drying rate increased with increment of air temperature	[112]
Apple Rectangular plates	* Conjugate and non-conj. pair of blunt plates drying * Different configurations are made for the plates	*FVM *2-D	* Side-by-side case has better drying	[123]
Potato Rectangular	* Transport mechanism and shrinkage * Coupling of food domain and air domain	*FEM *ALE *3-D	* The measured and simulated dimensions of the potato sample are agreed.	[124]
Gypsum board Rectangular	* Influence of air speed, turbulence intensity and air temp. were investigated	* FEM *1-D, 2-D	* The paper liner on gypsum layer has preventing effect on reduce in MC * A limited effect of varying parameters is seen when there is a paper liner	[125]
Apple Disc-shaped	* Mechanistic shrinkage model * Moisture and temp. dependent diff. coefficient	*FDM *1-D	* Air temperature is an effective external property. * Shrinkage effect moist. diff. significantly	[126]
Quince slices Cylindrical	* Coupled HMT * Semi-empirical diffusion coef. * Turbulent air-flow	*FVM *1-D, 2-D	* A diffusion model with a correction factor was proposed * Good agreement with exp. data	[93]

→

Table 2. Continuation

Material/ Shape	Scope of the study	Method/ Dimension	Results	Ref.
Material not reported Rectangular	*Coupled, steady HMT *Moving solid in a rect. channel *Turbulent flow	*FVM *2-D	*Analytical and numerical results fitted well for drying rates *Drying rate is higher at lower object speed	[127]
Porous asphalt Rectangular	* Convective scalar transport of macroporous material for drying	*FVM *2-D/3-D	*Wind speed had an important effect on scalar transport *Diffussive flux is higher than conv. flux at 1.5 m/s wind speed	[128, 129]
Apple Circular	*Transport mechanism happens by capillary and binary diffusion, and convection * Constant CTC' s	*FEM *3-D axisym	*Both convective and diffusive fluxes are higher near the surface of sample *Higher evaporation rate near surface *Good agreement with experimental data	[119]
Clay-like Rectangular	* Convective drying of a saturated and shrinking media *Transient conditions	*FEM *ALE *2-D	*External radius reduction was 16.41 mm *Volumetric shrinkage was 30.16% *Good agreement with experimental data	[118]
Potato Rectangular	*Coupled multi-phase transport mech. *A rotating cylinder mounted over the solid domain	*FEM *2-D	* Average HT increases with increasing air velocity * MC is lower at the surface and evaporation is higher at high air velocities	[130]

- Molecular diffusion is an important feature that express mass transfer in most studies so range of studies has been done with using different diffusion models form physics laws and empirical studies.
- With the development of digital computers and diversity of physical phenomena that have been subject in numerical studies, mass transfer of multi-phase structures has been taken into account regarding pressure driven convection and capillary flow additionally. Those multi-phase numerical studies has been performed in recent years especially coupling the flow domain and the porous domain.
- The computational cost can be drastically reduced by using 2-D simplified models or axis-symmetric models as compared to a full 3-D simulation model.
- Regarding most of the literature survey, if a physical problem is well-developed with defining the operating parameters clearly, results of the CFD studies are fitted with the experimental studies well.
- Reduced order modelling approaches can be utilized to derive ordinary differential equation form of governing equations in parametric form by using the results from computational fluid dynamics simulations in drying applications.

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Nomenculature

c_p – specific isobaric heat capacity, [Jkg^{-1}K^{-1}]
D – diffusivity, [m^{2}s^{-1}]
$\vec{\mathrm{I}}$ – identity vector
k – thermal conductivity, [Wm^{-1}K^{-1}]
p – pressure, [Pa]
T – temperature, [K]
t – time, [s]
$\vec{\mathrm{u}}$ – velocity components, [ms^{-1}]

Greek letters

μ – dynamic viscosity, [Nm^{-2} s^{-1}]
ρ – density, [kgm^{-3}]

Subscripts

a – air
eff – effective

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