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A Review on Applications of Computational Fluid Dynamics (CFD) in the Food Industry

Manas Ranjan Padhi

Department of Mechanical Engineering Centurion University of Technology and Management Odisha, India

Email: manas.padhi@cutm.ac.in

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ABSTRACT

Computational Fluid Dynamics (CFD) is a powerful simulation tool to obtain fluid flow and heat transfer simulation with the use of computers along with applied mathematics. It is cost effective method to solve real-life problems in fluid dynamics. Mathematical models in terms of conservation laws represent the flow physics in terms of strongly coupled non-liner partial differential equations. CFD finds wide applications in automobiles, aerospace, manufacturing, process industries, power plant equipment and electronic components as a design and simulation tool. Since most of the processes in food industry involves the application of fluid flow as well as heat and mass transfer, CFD provides a good early-stage simulation for predicting the performance of these processes. It also allows the test engineers to validate the test results obtained from simulation of the food processing equipment with experimental study, thereby help them to improve the design and performance of equipment.

1. Introduction

For several years, CFD has been used extensively in many process industries. However it has recently been used in the food processing industry. Clean room construction, mixing of two fluids, refrigerated transport, static mixers and pipe flow are some of CFD's major applications. An additional benefit in recent years has been the use of CFD to design food processing equipment. Basically, the food processing machines such as dryers, pasteurizers, sterilizers, freezers, mixers and baking ovens are used to design them. The advancement of CFD by means of simulation is very helpful in predicting the air flow movement over the food products within the food processing equipment.

The performance of the baking oven is numerically simulated by predicting the air flow inside it. CFD simulation also calculates the heat and mass transfer and therefore helps to maintain the desired temperature and moisture inside the oven. Therefore, it is apparent that CFD is a decent technique in optimizing the performance of the food processing equipment. The inclusion of mass transfer in CFD model is quite fruitful in controlling the moisture content in bread to improve its quality. CFD has been used by many researchers for numerically predicting the air flow and temperature pattern inside the chillers and freezers. One practical example is air flow distribution prediction in meat chillers, which is supplemented with a two-dimensional CFD model in the design. It is obvious that current CFD technique is useful in determining heat transfer between products and air which takes into account the radiation effect. This will help in proper designing the chiller wall with heat insulating material that will prevent the heat loss and to give exact rate of cooling effect. Since, freezing process involves phase change; it can also be modeled by using CFD particularly the freezers which stores the frozen food for long period of time without deterioration.

CFD has a vital role in impinging food processing equipment like spray freezing and spray freeze drying by determining particle velocity, temperature as well controlling the air velocity. Similarly it can be used for the design and development of impingement jet oven. CFD has been proven to be a good simulation tool to tackle with the problems faced in large scale grain processing industries. One such example is to handle and control the operating conditions of flour mill. Some food items require phase change during their processing. The common example is processing of powdered coffee which requires significant drying. In order to model that drier, the turbulent flow of air inside the drier need to be considered along with heat and mass transfer between air and coffee. The processing of some liquid food products requires the application of pumping and mixing. Since the modeling and analysis of these equipment can be taken proper care of with a simulation tool like CFD. The common purpose of CFD as a numerical simulating tool is to correctly predict the flow pattern and temperature distribution inside the thermal processing of food. Examples of such applications include numerical simulation of velocity and temperature profiles for foods packed in can that are sterilized in a batch retort and during the pasteurization of bottled wine. With the help of such CFD simulations, the temperature distribution pattern inside the containers can be obtained and thereby lowest heating point can be identified. Due to the fast development in the research of fluid dynamics in the last few years, CFD as a tool of numerical analysis can be beneficial to several food processing industries like drying, baking, spraying, sterilizing, mixing and refrigeration.

2. Applications of CFD in various areas of food industry

Computational Fluid Dynamics (CFD) has been used widely in the food processing field to great advantage. Its numerous applications include predicting the gas flow pattern and particle histories such as temperature, velocity, residence time, and impact position during spray drying, modeling of ovens to provide information about temperature and airflow pattern throughout the baking chamber to enhance heat transfer and in turn final product quality, designing of heat exchanger to carryout pasteurization, cleaning of storage tanks, sterilization, crystallization and refrigeration. This paper focuses on various applications and recent developments of CFD modeling in different food processing industries.

A. Improving cleanliness of food processing tank

Food processing tanks are used to store inventories for food items. These inventories include raw materials, finished food items and semi-finished item needs for further processing like mixing, heating, cooling and fermentation. It is necessary to maintain proper cleanliness of these food processing tanks in order to avoid wastage and to improve the efficiency. The improper cooling leads to the formation of biofilm on the equipment surfaces that can results in the formation of corrosion and may cause health hazards. Therefore, it is very essential to keep the tank surface clean and adequate hygiene to be maintained. CFD as simulation tool can be used to analyse fluid flow not only to keep the tank surface clean but also for an improved design with respect to the cleanliness. Along with flow simulations in tanks and pipes, CFD can also be used to deduce the shear stress in the joints of the tank wall and determine the nature of the boundary layer formed, whether laminar or turbulent and accordingly can suggest for a better design. It can be used to compare the results of the preliminary design of the storage tanks with the experimental results obtained so as to assure the design engineers to go for an effective design without much expense. In this way, it will be economical to use it for designing complicated food processing tank structures consisting of many joints and bends. Asteriadou et al. [1] used CFD for the cleaning of food processing equipment with T-joint. They carried out the experiment to clean the salt solution using deionized water. The comparison gave an error which is within acceptable limit for both steady and transient condition.

B. Drying

Drying is an important food manufacturing process. Food products like dry fruits, chips prepared from vegetables and nuts require adequate amount of drying during their processing. We also dry some foods to preserve it for long time. Some organic fruits are properly dehydrated to preserve it. Hence, drying plays a major role in food processing in recent times. Drying not only keeps the moisture away but also inhibits the functions of bacteria and yeast. The velocity, temperature and moisture of air are the main factors in drying food items. Therefore, it is very important to know the velocity and quality of air during its flow inside the drying chamber that leads to give information about the areas of sufficient air velocities for proper drying. The velocity and discharge of air can be measured by means of sensors. But it is a difficult job to place sensors at so many locations and to mount them is not cost effective. Cereals and oilseeds are dried after harvesting to the moisture content that prevent growth of microorganisms. Drying in vegetables not only helps in preventing the microbial growth, but also to avoid the formation of brown colour during storage. CFD as a powerful simulation tool can help in prediction of air flow along with temperature pattern. Determination of pressure and velocity profiles with the aid of CFD can estimate the drying rate and moisture content even in complex physical model of drier. Though prediction of flow pattern and air velocity is not a complicated job using CFD, but to go for accurate measurement of cooling rate and energy consumption, one should go for correct assumptions.

CFD is a powerful tool to aid the prediction of drying process. Mathioulakis et al. [2] applied CFD for the prediction of air flow in an industrial batch type tray drier. They used different fruits for their drying test and concluded from simulation results that the position of fruits inside the drier had considerable impact on extent of dryness. Spray driers are often used in food industry for effective and uniform drying. CFD can be used for evaluating the efficiency and analysing the design and operating conditions of spray driers in food processing industries. Zbicinski [3] carried out the research by developing a numerical model of mass, momentum and energy transfer during spray drying process. He used CFX, a tool of computational fluid dynamics to determine heat and mass transfer of air inside the dryer and to calculate particle trajectories for different phases. The experimental results were validated with numerical results and found to be within acceptable limit. Huang et al. [4] used FLUENT, a commercial software in CFD to analyse the profiles of different parameters such as temperature, velocity and humidity of air at different stages inside a spray dryer. CFD can be a quite convenient tool for forecasting the profiles of gas flow and estimating crucial parameters such as temperature, velocity, and residence time and impact position of gas particles in spray drying. It can also be used as a design tool for chamber designing of spray dryer according to the behaviour of food item along with substantial information on air particle interaction. Many notable researchers like Zbicinski, Zietara, Simon Lo and Huang have used CFD for their analysis in spray dryer. Lo [5] used Euler-Lagrange model in CFD to calculate the motions of the spray droplets and the heat and mass transfers between the droplets and the air stream. Many valuable results were presented in the form of percentage of particle leaving are exit, the operating conditions of the particle like size, temperature and moisture content. Based on the results, the optimum operating conditions can be selected to achieve the desired product quality at minimum cost. During spray drying the adherence of particle to the wall of spray dryer may occur which may affect the product quality. This practical problem can be eliminated by the use of CFD analysis.

C. Pasteurization

Pasteurization is a heating process to keep the food product free from pathogenic bacteria. This process is named after Louis Pasteur. It is generally adopted in the case of liquid food products such as milk, fruit juice and beer. The process involves heating the food products at specific temperature, especially at low temperature for a specific period of time to kill the harmful bacterial that could cause deterioration, disease and undesired fermentation. Both packaged and unpackaged food can be pasteurized. Since it a mild heat treatment process, therefore the control of temperature and duration of heating are very crucial. In less acidic food such as milk and liquid egg, this heat treatment in pasteurization may not be sufficient to remove harmful bacteria. Subsequent refrigeration is also necessary to kill harmful microorganisms. Hence it will be a wise decision to go for simulation software like CFD that can generate temperature file for the effective control of both heating temperature and time. Most liquid foods are subjected to pasteurization in bulk quantities in continuous system consisting of heating zone, holding tube and cooling zone. Therefore, proper designing of this whole system is necessary considering the velocity and temperature of liquid food products. CFD has bigger role to play in this continuous pasteurization system for controlling fluid speed, quantity and temperature. Different types of heat exchangers are used in pasteurization process. Low viscosity food products like different animal milks, nut milks and juices are generally pasteurized by using plate heat exchanger. A plate heat exchanger is a compact heat exchanger which consists of many thin stainless steel plates that separates the liquid from heating or cooling medium. Similarly, scraped surface heat exchanger contains an inner rotating shaft in the tube which can scrap highly viscous material from the tube wall. Common heat exchangers used in pasteurizing plant are shell or tube heat exchanger which are designed for the pasteurization of the Non-Newtonian foods such as dairy products, baby food and tomato sauce. In a concentric tube heat exchanger, food passes through the inner tube and cooling or heating medium is circulated through the outer tube. After the heat exchangers, the products are allowed to flow through a hold tube for a definite period of time to achieve the required treatment. The benefits of heat exchangers are that they provide uniform heating or cooling and simple to analyse because of their construction. Since basic design of all types of heat exchangers are based on the calculation of heat flux, therefore, it is essential to use CFD as a fluid simulation tool to calculate the heat transfer and performance of these heat exchangers. The performance of heat exchanger is expressed in terms effectiveness which is the ratio between actual heat transfer and maximum heat that can be transferred. The effectiveness can be calculated from the temperature results obtained from heat transfer analysis using CFD.

CFD not only useful in designing heat exchanger but also can optimize the important parameters like pressure, velocity and temperature. The leakage inside the pasteurizers can be detected by the effective utilization of CFD by the maintenance engineers. Therefore, both design and maintenance of these foods processing equipment used in the pasteurization process can be taken care of by CFD. There are some investigations using CFD carried out by the researchers. Denys et al. [6] used CFD in their analysis to carry out thermal pasteurization of eggs and validated the experimentally obtained results. Similarly Paul et al. [7] carried out the numerical simulation to determine the temperature distribution inside the canned milk. They took the rotation of can into consideration during their investigation and obtained the effective results. Augusto et al. [8] used packaged pasteurization for beer to increase microbiological stabilization. They carried out their research by changing the orientations of the cans in packaged pasteurization.

D. Sterilization

Sterilization is an important process in food processing industries. It involves applying sufficient heat to a food to minimize the chances of survival of microorganisms or enzymes that is capable of producing enzymatic changes in the food. Sterilization is ideal for packaged foods like sauces, vegetables pickled in oil, jams, creams, candied fruit, canned fruit, soups and juices. The difference between pasteurization and sterilization is that former is applicable to liquid food products while sterilization is used for solid and liquid food products that remove all types of bacterial by supplying sufficient heat. CFD can be used to obtain the flow pattern and temperature distribution in sterilization process to improve the quality of food. Thermal processing deactivates the functions of microorganism but in some cases decreases in quality is observed particularly flavour due to excessive heating. In that context, CFD can be useful for calculation of exact amount of heat transfer without hampering the quality of food products.

Optimization of thermal sterilization of food without compromising with the food quality as well as retaining its nutritional value has been carried out by different researchers from time to time. CFD was used for obtaining transient temperature distribution, generating velocity profile along with the determination of slowest heating zone for carrot soup in pouches. Most of the sterilization of liquid foods is conducted along with packed cans. Some researchers worked to find out the orientation effect of metal can and its shape and size on sterilization. Tattiyakul et al. [9] carried out the research in canned corn by using CFD simulation considering the axial rotation of the can. They observed that the rotation effect prevented the heat transfer in radial direction at higher speed. Kannan and Gourisankar Sandaka [10] carried out numerical analysis of heat transfer on canned food sterilized in a still-retort. Varma and Kannan [11] studied the effect of sterilization by taking different shapes can. They observed that the inclination of can wall as well as its geometry has substantial effect on the sterilization system. The thermal effect on nutritional value during sterilization of packed liquid food was investigated by using CFD by several researchers. Abdul Ghani et al. [12] prevented the destruction of Vitamin C in carrot orange soup packed in pouches. They found that the temperature and concentration profiles of Vitamin C were strongly affected by convection. Shahsavand and Nozari [13] carried out their research on continuous thermal sterilization process for both laminar and turbulent flow. They told that sterility can be enhanced by putting a mixer at the entrance of the holding zone while maintaining quality of food products for laminar condition. They investigated the turbulent flow using CFD and concluded that the thermal resistance of solid particles has considerable effect on performance of continuous thermal sterilization process.

There are many modern techniques which being implemented in food processing in recent time such as ultra-violet, visible and infrared light surface sterilization, plasma sterilization, electrons and X-rays sterlization, pressure sterlization of fresh fruit juices. CFD will be great asset for all these modern techniques in terms of simulation and analysis.

E. Mixing

Mixing is one of the most common operations in food processing industries. Mixing applications involve the substances of gas, liquid and solid. Thought, it appears to be simple but modelling the mixing process and designing the mixing chamber is difficult job without the aid of fluid flow simulation tool. Most of the mixing cases deal with multiphase and turbulent in nature. CFD is a versatile tool not only in modelling such mixing processes but also to give adequate information regarding fluid flow. All types of mixing processes adopt some methods for mixing due to which there is a change in properties like pressure and temperature occurs. It is obvious to control these parameters during mixing process. Since the mixer is basically meant for mixing viscous materials, therefore the proper design of this equipment is essential in order to increase efficiency with a reduction in energy consumption. To make steering effective, a paddle wheel or stirring is often used in mixing. CFD code has been used to enhance the stirrer design with an optimum mixing time that could reduce the energy consumption. Recently, CFD has been employed for study in the modelling of impeller-vessel geometry, energy balance and linkage between the flow fields. The effect of configurations of impeller on hydrodynamics and mixing performance in stirring was numerically optimized by the use of CFD. Aubin and Xuereb [14] carried out their research on multiple impeller stirring tanks by varying the distance and rotation angle between impellers and the system was observed to give better performance when the impellers were rotating at 45^o rather than 90^o.

F. Baking

Baking is a process of preparing food products such as bread, biscuits and cakes that require dry heat inside an oven. During baking, heat is transferred from the surface of the baked item to their center. The baking quality of breads improves as heat travels through it, results a formation of firm dry crust and a softer centre. Baking process involves the simultaneous heat and mass transfer where heat is allowed to transfer into the food from the hot surfaces and both air and moisture gets transferred from the food to air that surrounds it and then removed from the oven. Therefore the role of oven is crucial for retaining the baking quality. With the help of CFD, the temperature and velocity profile of air moving over food inside the oven can be generated with a substantial control of air rate. Since, removal of moisture also determines the baked quality of food, a fluid simulation tool like CFD can be very useful in predicting the mass transfer.

CFD can be used to numerically determine the heat transfer, temperature and velocity profile of air inside the baking oven for laminar flow conditions. For baking industry which employs indirect heating baking process, the heating is carried out four different zones. The temperature profile at each zone is important, on which the final bread quality gets affected. Here the computation fluid dynamics can provide the transient temperature distribution for analysis. Therdthai et al. [15] built a two dimensional mathematical model of continuous baking process which is often used in industry in an oven to study the air flow and temperature distribution pattern inside the baking chamber for different operating conditions. The CFD simulation results helped to modify configuration of oven for better heat distribution. With the help of CFD, the position of the heating source which affects the air circulation can also be optimized. Thus CFD serves as a practical tool for design, optimization and validation of the process control. It can also be used a versatile tool for design, scale up and optimization of baking ovens.

G. Refigeration

The consumption of frozen food has increased its demand in recent years due to good quality and safety aspect. Refrigeration can slow down bacterial growth and preserve food. Hence researchers have used CFD for the modeling of heat and mass transfer in foods during refrigeration (chilling and freezing). Hu and Sun [16] investigated the heat and moisture transfer for determining the cooling rate and weight loss of cooked ham during air blast chilling process by using CFD simulations.

CFD can give correct information regarding design based on temperature modelling with minimum cost before manufacturing the actual refrigeration system. It is very important during refrigeration design that accurate control of temperature is maintained with less cost in short period of time. Taking all these points into consideration, CFD can effectively be used for design optimization of equipment used in refrigeration such as chillier and freezers. With the help of computational fluid dynamics, the simulation of air flow over the food products can be done inside the refrigeration. It can be used as modelling technique for the successful prediction of airflow inside refrigerated space including cold stores, transport equipment and retail display cabinets. Gaspar et al. [17] carried out heat transfer and air flow simulations in an open refrigerated display cabinet to predict air temperature, relative humidity and air velocity.

3. Conclusion

CFD is a possible simulation method for the flow pattern modelling process. It can be used to build performance-enhanced food processing equipment. Storage tank washing, pasteurisation, conventional cyclones, drying, sterilisation, crystallisation, mixing and refrigeration, fermentation, baking, etc. are the key applications. CFD practicability depends on CFD packages, device settings, and the basic knowledge of fluid flow analysis. By performing experiments for validation, it is also important to validate the simulation results since some instances of CFD are based on approximate models with certain assumptions. The versatility and wide range of CFD applications, however is a boon for the food processing industry.

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