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Review article

Applications of computational fluid dynamics (CFD) in the food industry: a review

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Abstract

Computational fluid dynamics (CFD) is a simulation tool, which uses powerful computer and applied mathematics to model fluid flow situations for the prediction of heat, mass and momentum transfer and optimal design in industrial processes. It is only in recent years that CFD has been applied in the food processing industry. This paper reviews the application of CFD in food processing industries including drying, sterilisation, refrigeration and mixing. The advantages of using CFD are discussed and the future of CFD applications is also outlined. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Computational fluid dynamics; CFD; Food; Refrigeration; Cooling; Drying; Sterilisation; Mixing; Chilling; Modelling; Simulation

1. Introduction

Computational fluid dynamics (CFD) uses powerful computers and applied mathematics to model fluid flow situations. The yardstick of success is how well the results of numerical simulation agree with experiment in cases where careful laboratory experiments can be established, and how well the simulations can predict highly complex phenomena that can not be isolated in the laboratory (Sethian, 1993). As a developing science, CFD has received extensive attention throughout the international community since the advent of the digital computer. Since the late 1960s, there has been considerable growth in the development and application of

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CFD to all aspects of fluid dynamics (Parviz and John, 1997). As a result, CFD has become an integral part of the engineering design and analysis environment of many companies because of its ability to predict the performance of new designs or processes before they are ever manufactured or implemented (Schaldach et al., 2000). Researchers, equipment designers and process engineers are increasingly using CFD to analyse the flow and performance of process equipment, such as baking ovens (Mills, 1998–1999), refrigerated display cabinets (Cortella et al., 1998), stirred tanks (Sahu et al., 1999), spray dryers (Kieviet et al., 1997), heat exchangers (Kumar, 1995) and some other equipment. In design and development, CFD programs are now considered to be standard numerical tools which predict not only fluid flow behaviour, but also the transfer of heat, mass (such as in perspiration or dissolution), phase change (such as in freezing, melting or boiling), chemical reaction (such as combustion or rusting), mechanical movement (such as an impeller turning, pistons, fans or rudders) and stress or deformation of related solid structures (such as a mast bending in the wind). Furthermore, CFD has been applied to deal with problems in environment and architecture. Table 1 summarises the application area of CFD besides food processing.

However, it is only in recent years that CFD has been applied in the food processing area (Scott, 1994). Since the consumer demand for convenient and high

Table 1
CFD application in various areas

Industrial applications	Aerospace
	Architecture
	Automotive
	Biomedical
	Chemical and Process
	Combustion
	Electronics and computers
	Glass manufacturing
	HVAC (heat, ventilation and cooling)
	Petroleum
	Power
	Marine
	Mechanical
	Metallurgical
	Nuclear
	Train design
	Turbo machinery
	Water
Environmental applications	Atmospheric pollution
	Climate calculations
	Fire in buildings
	Oceanic flows
	Pollution of natural waters
	Safety
Physiological applications	Cadiovascular flows (heart, major vessels)
	Flow in lungs and breathing passages

quality meals has been growing over the last several years, the development of new food processing practices and technologies has been stimulated. CFD application in the food industry would assist in a better understanding of the complex physical mechanisms that govern the thermal, physical and rheological properties of food materials. Scott and Richardson (1997) and Quarini (1995) have reviewed the general application of CFD to the food processing industry. Moreover, other literatures are also available on specific CFD application areas such as clean-room design, refrigerated transport (Janes and Dalgly, 1996), static mixers (Scott, 1977) and pipe flow (Scott, 1996). Since CFD technique can be of great benefit to the food processing industry, fast development has taken place in the past few years. Therefore, in this paper an overview is given of the recent advances in CFD application in the food processing industry.

2. Advantages of using CFD

CFD has grown from a mathematical curiosity to become an essential tool in almost every branch of fluid dynamics. It allows for a deep analysis of the fluid mechanics and local effects in a lot of equipment. Most of the CFD results will give an improved performance, better reliability, more confident scale-up, improved product consistency, and higher plant productivity (Bakker et al., 2001). Some design engineers actually use CFD to analyse new systems before deciding which and how many validation tests need to be performed. The advantages of CFD can be categorised as (Wanot, 1996):

- It provides a detailed understanding of flow distribution, weight losses, mass and heat transfer, particulate separation, etc. Consequently, all these will give plant managers a much better and deeper understanding of what is happening in a particular process or system.
- It makes it possible to evaluate geometric changes with much less time and cost than would be involved in laboratory testing.
- It can answer many 'what if' questions in a short time.
- It is able to reduce scale-up problems because the models are based on fundamental physics and are scale independent.
- It is particularly useful in simulating conditions where it is not possible to take detailed measurements such as high temperature or dangerous environment in an oven.
- Since it is a pro-active analysis and design tool, it can highlight the root cause not just the effect when evaluating plant problems.

Many food processing operations such as chilling, drying, baking, mixing, freezing, cooking, pasteurisation and sterilisation rely on fluid flow. The transfer of CFD approaches to the food industry has provided food engineers new insight and understanding to the likely performance of food equipment at the design stage and confidence in the quality or safety of food products (FRPERC, 1995). Equipment such as ovens, heat exchangers, refrigerated display cabinets and spray dryers has been improved through the application of CFD techniques in aiding the understanding of their operation and design process. CFD has become a powerful tool in the development, trouble shooting and optimisation of food processes.

3. Performing a CFD analysis

To perform a CFD analysis, the analyst will state the problem and use scientific knowledge to express it mathematically. Then the CFD software package will embody this knowledge and expresses the stated problem in scientific terms. Finally, the computer will perform the calculations dictated by CFD software and the analyst will inspect and interpret their results. In principle, three different major tasks should be done to perform a CFD simulation (Shaw, 1992).

3.1. Pre-processing

All the tasks that take place before the numerical solution process are called pre-processing. This includes problem thinking, meshing and generation of a computational model.

Problem thinking is the first stage in using CFD. Before committing to practice, it is worth thinking about the physics of the problem that is faced. In this stage the analyst should consider the flow problem and try to understand as much as possible about it. The second stage is meshing. In this stage the analyst should create the shape of the problem domain that needs to be analysed. This can usually be done with the help of a standard CAD program. It is possible to import data generated by such program into a CFD package. Then the problem domain is sub-divided into numerous cells, also known as volumes and elements. Most CFD packages have the program to do meshing and define the shape simultaneously. Fig. 1 shows an example which is the meshing structure of a commercial air blast chiller with a ham inside (Hu and Sun, 2001b). Once meshing has been completed, the boundaries of the problem domain can be found and the necessary boundary conditions, determined in the initial stage, should be applied. These conditions together with some fluid parameters and physical properties specify the actual flow problem to be solved. Advanced CFD software packages have the program to carry out the following operations: defining a grid of points, also volumes or elements, defining the boundaries of the geometry, applying the boundary conditions, specifying the initial conditions, setting the fluid properties and setting the numerical control parameters. However, it is not easy to generate a complicated mesh. For example, despite the steadily increasing power of computers, it is still difficult to discretise the solution domain in the case of 3-D turbulent problems with a grid fine enough for the solution to be truly independent (Mirade, 2001).

3.2. Processing

Processing involves using a computer to solve mathematical equations of fluid flow. Once the meshing is completed, the model input values should be specified

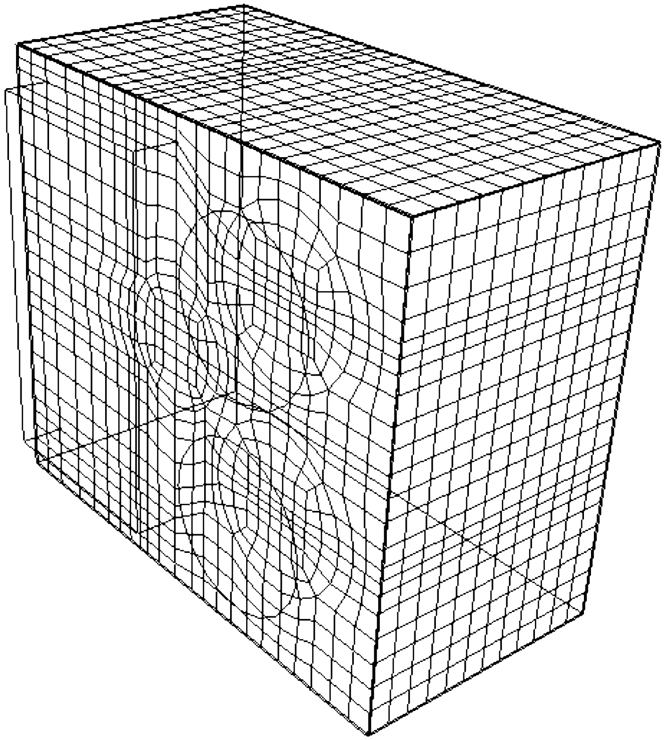

Fig. 1. Meshing structure of a commercial air blast chiller with a ham inside (Hu and Sun, 2001b).

and then the software can solve the equations of state for each cell until an acceptable convergence is achieved. This is a very intensive process and usually it requires the computer to solve many thousands of equations. In each case, the equations are integrated and the boundary conditions are applied to it. This is known as equation discretisation and is applied to each individual cell of the mesh. The process is repeated in an iterative manner until a required accuracy is achieved. This step can be a time-consuming process and although it is the core of any CFD software package, little of its operation can be seen.

3.3. Post-processing

The post-processing program is used to make evaluation of the data generated by the CFD analysis. When the model has been solved, the results can be analysed both numerically and graphically. Post-processing tools of the powerful CFD software can create visualisation ranging from simple 2-D graphs to 3-D representations. Typical graphs obtained with the post-processor might contain a section of the mesh together with vector plots of the velocity field or contour plots of scalar variables such as pressure. In such graphs, colours are used to differentiate between the different size of the values. Fig. 2 gives an example of velocity vectors in the

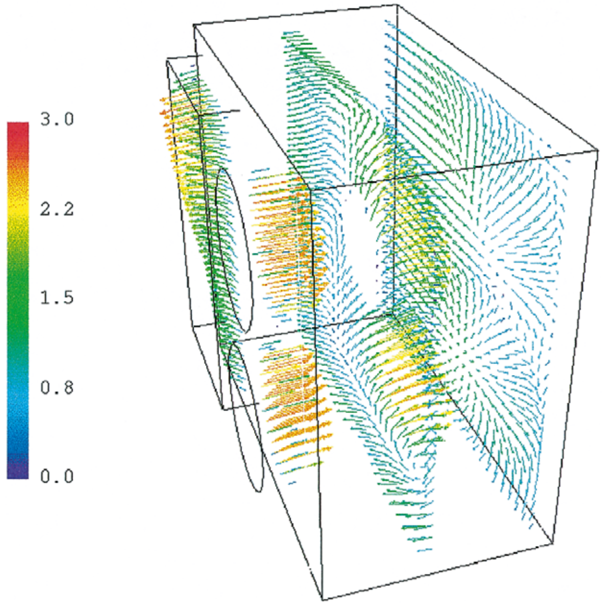

Fig. 2. An example of the flow field in the chiller shown in Fig. 1 predicted by CFD code (Hu and Sun, 2000b).

chiller shown in Fig. 1 and Fig. 3 is the corresponding temperature distribution of the ham during chilling (Hu and Sun, 2001b). When some results have been obtained, they must be analysed, first to check that the solution is satisfactory and then to determine the actual flow data that is required from the simulation.

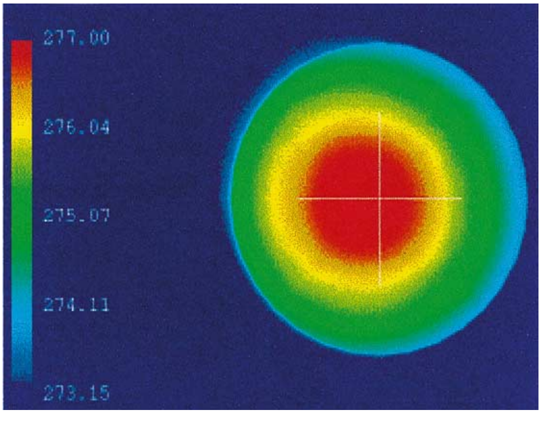

Fig. 3. An example of temperature distribution of the ham during chilling in the air blast chiller shown in Fig. 1 (Hu and Sun, 2001b).

Table 2
Commercial CFD code list

CFD code	Company	Web site
CFX	AEA Technology	http://www.software.aeat.com/cfx/
FLUENT	Fluent Inc	http://www.fluent.com/
PHOENICS	Concentration Heat & Momentum Ltd (CHAM)	http://www.cham.co.uk/
STAR-CD	Computational Dynamics Ltd	http://www.cd.co.uk
FLOW3D	Flow Science, Inc	http://www.flow3d.com
CFD-ACE	CFD Research Corporation	http://www.cfdrc.com
ICEM CFD	ICEM Technologies	http://icemcfd.com/icepak.html
AMI-VSAERO	Analytical Methods, Inc (AMI)	http://www.am-inc.com
STORESIM/TETMESH	Computational Mechanics Company, Inc	http://www.comco.com/
IGG™	NUMECA International SA	http://www.numeca.com/
TECPLOT	Amtec Engineering, Inc	http://www.amtec.com/
PAM-FLOW	Engineering Systems International SA	http://www.esi.com.au/
FLOVENT	Flomerics Inc (FLOVENT)	http://www.flomerics.com/
AVS/EXPRESS	Advanced Visual Systems, Inc	http://www.avs.com/
FLO++	Softflo	http://www.softflo.com/
CFD++	Metacomp Technologies, Inc	http://www.metacomptech.com/

4. Commercial CFD codes

In the last few years there has been continuous progress in the development of CFD codes. These codes can now cope with a high level of complexity in many research fields, which makes them attractive to use. However, CFD codes that are used in the food processing industry have not reached a relatively mature state, they still require to be improved in accuracy, ease of use, robustness and computational efficiency (Spalding, 1999a,b). Of all the commercial CFD codes there are some codes for general purpose as well as for specific applications (e.g. non-Newtonian flow). Most of these commercial CFD codes can be supported on the platforms of UNIX on workstations and WINDOWS or LINUX on high-end Intel Pentium PCs. Table 2 summarises the main commercial CFD codes. Some of the common commercial codes are described as follows.

4.1. CFX (http://www.software.aeat.com/cfx/)

CFX Engineering Software is part of the AEA Technology. There are several kinds of CFX software, from CFX-4, CFX-5 (general purpose) to CFX-TASCFLOW (for mechanical engineering design and analysis) and CFX-PROMIXUS (for mixer design). CFX software package has been widely used in the food processing area. For example, Verboven et al. (1997) studied the local surface heat transfer coefficient in thermal food process with CFX. Moreover, Hu and Sun (2001a,b, 2002) investigated the air-blast chilling process using different k–ε models by applying the CFX software.

CFX-4 software offers powerful tools such as direct CAD access, automatic geometry creation tools, advanced models for turbulence, radiation and multiphase flows to predict the complex flows encountered in the process and chemical industries. CFX-5 combines CAD input, automatic meshing and a fast solution algorithm, with two-phase modelling capabilities and coupled-multigrid implementation. Pressure and momentum conservation equations are solved simultaneously in CFX-5, thus reducing the usual iterative process and CPU time. Geometries can be created directly within CFX-5's pre-processor, or import them from CAD packages in native format. CFX-5 then builds a complete mesh automatically, using menu-defined modelling options, boundary conditions and fluid properties.

4.2. FLUENT (http://www.fluent.com/)

Fluent is one of the world's largest providers of commercial CFD software. It offers FLUENT, FIDAP and POLYFLOW (for polymer process) codes for a wide range of industrial applications. There are many researcher using FLUENT software, for example, Rousseaux et al. (2001) applied it in the simulation of precipitation in the sliding–surface mixing device. Also FLUENT is used in the optimisation of air-flow conditions during the chilling and storage of carcasses and meat products (Kondjoyan and Daudin, 1997b).

FLUENT 5 is the fully unstructured, mesh-based technology with parallel computing capabilities, common-sense interface and user-defined functions capability. As the first step in building and analysing a flow model, pre-processing is performed in two tools of FLUENT, GAMBIT and TGRID. FLUENT provides a wide array of advanced physical models for turbulence, combustion, and multiphase applications. FIDAP is a flow modelling tool with lots of physical models and efficient solution methods. Based on the finite element method, FIDAP offers complete mesh flexibility and robust and efficient calculations.

4.3. PHOENICS (http://www.cham.co.uk/)

PHOENICS is a general-purpose CFD software package. PHOENICS can run on all hardware platforms, from PCs, through UNIX, to single- or multi-processor supercomputers. On PCs, the operating systems may be DOS, WINDOWS or LINUX. Some research institutes and companies have applied PHOENICS in their research development. For instance, Mathioulakis et al. (1998) simulated the air movement in a dryer with the application of PHOENICS software package. The temperature increase in frozen food packaged in pallets was also studied with the aid of PHOENICS by Moureh and Derens (2000).

PHOENICS solves finite-domain equations of mass, momentum, energy conservation, etc., for steady or unsteady flow and 1, 2 or 3-D geometries. There are some specialised tools of PHOENICS, such as HOTBOX for electronic cooling, FLAIR for heating and ventilation and PHOENICS-CVD for chemical vapour deposition. PHOENICS code possesses many unique or especially strong features, for example, the parabolic option, simultaneous solid-stress analysis, the multi-fluid turbulence model, the LVEL model of turbulence, use of domain-decomposition for CFD parallel processing and remote computing via the internet.

4.4. STAR-CD (http://www.cd.co.uk/)

STAR-CD is a commercial CFD code which addresses the full complexities of industrial geometries using fully-unstructured hybrid meshes in conjunction with efficient finite-volume solution methodology. Like CFX, FLUENT and PHOENICS, STAR-CD is also widely used in the food industries. Sorensen et al. (2001) investigated the local heat transfer and flow distribution in a three-pass industrial heat exchanger with the application of STAR-CD. Another example is that Zhang et al. (2000) applied STAR-CD to model the influence of process parameters on the heating and acceleration of particles during plasma spraying.

STAR-CD can handle complex geometries, through state-of-the-art meshing flexibility and solver technology that achieves accurate solutions on a wide range of mesh types. STAR-HPC is a special tool for parallel computing which employs scalable message-passing technology with fully automated domain decomposition.

5. Application

CFD, as a tool of research for enhancing the design process and understanding of the basic physical nature of fluid dynamics (Anderson, 1995), can provide benefits to the food processing industry in many areas, such as drying, sterilisation, mixing, refrigeration and other application areas. In the past few years' great development has taken place in these areas.

5.1. Drying

Drying is a common food manufacturing process. The drying rate is a strong function of air flow or air velocity. Therefore, it is of great importance to know the air flow and velocity in the drying chamber, thus leading to know the areas of adequate air velocities for proper drying. However, air flow and air velocity are difficult to measure during operation because several sensors are needed to be placed at various directions of air flow and locations. Since there are some difficulties in modelling the complex phenomena, especially the gas turbulence (Oakley, 1994), CFD is a powerful tool to aid the prediction of drying process.

CFD has been used to predict the air flow and velocity during drying. Mathioulakis et al. (1998) used CFD to simulate the air movement inside an industrial batch-type, tray air drier. Drying tests of several fruits were performed and the result showed that the degree of fruit dryness depended on its position within the drier. Determination of pressure profiles and air velocities by CFD showed that the main cause of the variations in drying rates and moisture contents was the lack of spatial homogeneity of air velocities within the drier. With the aid of CFD, Mirade and Daudin (2000) studied velocity fields in a modern sausage drier in order to provide information on air circulation inside the drier, which showed that CFD was able to predict the effects of filling level on air-flow patterns and also to identify measurement errors in areas where the main air flow direction was horizontal. However, the quantitative comparison between the simulated and measured air velocities showed wide discrepancy with means of absolute differences of about 0.6 m s^{-1}. Although, the flow pattern and air velocity in the drier can be predicted using CFD modelling, further study on how to control the drying process and to reduce the energy cost is still a research topic for CFD modelling. Meanwhile, more attention should be paid on the assumptions such as spatial homogeneity (Mathioulakis et al., 1998) because of such assumptions could lead to inaccuracy in prediction.

CFD has also been used to investigate the performance and the design of spray dryers in the food industry. Spray dryers are used to produce products such as milk and coffee powder, as well as detergents. However, the design of spray dryers for the food industry is difficult because the performance of spray dryers is heavily influenced by the complexity of air and spray flow patterns inside the dryers. Therefore, there is considerable scope for the application of CFD simulation including optimum design of spray dryers and solutions for operational problems, such as wall deposition (Langrish and Fletcher, 2001). In the past several years, researches, such as modelling and measuring the air flow pattern in a co-current pilot plant spray dryer (Kieviet et al., 1997) and analysing the effects of air inlet geometry and spray cone angle on the wall deposition rate in spray dryers (Langrish and Zbicinski, 1994) have been performed. All these studies show that there appears to be a large scope for using CFD for other purposes. For example, CFD can be used to simulate the air flow in a spray dryer in two dimensions and calculate the trajectories and the course of the drying process of the atomised particles. Straatsma et al. (1999a,b) developed a drying model utilising turbulence model to calculate the gas flow field and showed that the drying model was an effective tool in giving indications of how to adapt the modelling in industrial dryers to obtain a better product quality or to optimise the drying performance of the unit. However, as the applications and specifications of dryers become more and more complex, so does the need for improved test work in pilot plants, and CFD simulations become more important in providing quick and valuable information (Masters, 1994).

5.2. Sterilisation

It is known that consumer demands for food products focus on safety, product quality and cost. Therefore, it is of great necessity to enhance quality and assure safety of the food supply. Sterilisation is an important technique for food storage and preservation. CFD can be used to study both temperature distribution and flow pattern of food in the process of sterilisation so as to optimise the quality of food products.

Thermal processing remains the most significant technique of sterilisation which results in microbial inactivation, but in the mean time, quality loss and flavour development. Excessive heating will affect food quality and its nutritive properties. With the application of CFD, there has been a number of studies to optimise the thermal sterilisation of foods (Datta and Teixeira, 1987; Akterian and Fikiin, 1994; Abdul Ghania et al., 1999a,b, 2001). These studies had led to substantial improvement on the optimal control of the process and the retention of the nutritional and sensory quality of the food. Abdul Ghania et al. (1999a,b) carried out a series of research work in canned food sterilisation with CFD simulation. The work varied from those simulating the changes of bacteria diffusion and their transient spatial distribution during sterilisation process to those simulating natural convection heating within a can of liquid food during sterilisation. It is only in recent years that the food pouches have been introduced to the market and, therefore, little or no study has been executed on sterilisation of food in pouches. CFD code was used for the purpose to simulate the transient temperature, velocity profiles and the shape of the slowest heating zone in sterilisation of carrot soup in pouches (Abdul Ghania et al., 2001). The modelling of a continuous sterilisation process to optimise the quality of safe food has also been developed (Jung and Fryer, 1999) and the results showed that CFD modelling could be of significant help to the liquid food sterilisation.

However, all of these investigations about CFD application in sterilisation are on the thermal sterilisation in the limited area of liquid foods. There are still many challenges in the area of sterilisation with the application of CFD. For instance, Ultra-violet, visible and infra-red light surface sterilisation, plasma/corona sterilisation, electrons and X rays sterilisation, nascent oxygen/ozone sterilisation of fruits and vegetables, pressure sterilisation of fresh fruit juices and cooked ham. The application of CFD in these sterilisation fields of food is still to be developed in the future. Moreover, assumptions are normally made to simplify CFD modelling. For example, specific heat, thermal conductivity and volume expansion coefficient were assumed to be constants in the study by Abdul Ghania et al. (1999a) although, all the parameters are temperature dependent. More studies should be carried out to minimise these assumptions and thus to improve the accuracy of CFD prediction. Another area for the application of CFD is the real time control of the sterilisation. Effective real-time monitoring of sterilisation will improve the quality and safety of foods. Above all, the ultimate objective is to optimise the sterilisation process of the food and to obtain food with excellent quality and safety. With the aid of CFD application, the sterilisation process can be improved.

5.3. Mixing

In the food processing industry, mixing is one of the most common operations. Mixing applications involve the substances of gas, liquid and solid. And the mixing of fluids is one of the most important unit operations for the food processing industry. However, mixing is a complicated process as regards to the multiphase turbulence during mixing and the design of a mixer.

CFD is a powerful tool for the modelling of mixing processes. It provides a natural method to link food process and fluid flow information. With the help of

CFD, the phenomena in an agitated vessel can be predicted (Delaplace et al., 2000). During mixing, a common method of enhancing the process is to use some kind of stirrer or paddle. CFD codes have been applied in optimising the mixing process to minimise energy input and to shorten the processing time. Therefore, research has been carried out on the distribution of energy in mixing vessel and on the effects of mixing quality when the stirrer is in different position. Such prediction of the mixing process within these units was impossible in the past (Quarini, 1995). Recently, CFD modelling of mixing in stirred tanks has been carried out by Sahu et al. (1999), with several important points about impeller-vessel geometry, energy balance and the linkage between the flow field and the design objective being addressed. Although no experiments were carried out in the study, the predicted values of mixing time were compared with published experimental data and the agreement was within 5–10%. This study will benefit the design of the stirred tanks, and some technical problems about the impeller types, mixing time and equipment size can be avoided (Sahu et al., 1999).

The design of mixing devices is an important topic in analysing the mixing process. Therefore, some research work focusing on the application of CFD on the design of mixing devices, for instance, shallow bubble columns, has been investigated (Rousseaux et al., 2001; Ranade and Tayalia, 2001). The results of these studies will provide benefits including easy measurement of the drop size distribution, the velocities of the phases and the degree of mixing, and accurate description of the turbulence, swirling and vortices generated in the mixer. Thus, all the development of CFD application on the mixing in the food processing industry will lead to more accurate monitoring, control and optimising of mixing process. In the mean time, it will form a good basis for mixing process improvement.

5.4. Refrigeration

The consumption of frozen foods has increased continually in the past years because frozen foods have demonstrated good food quality and safety record. Refrigeration can slow down bacterial growth and preserve food. Therefore, researchers have recently applied CFD in the modelling of heat and mass transfer in foods during refrigeration (chilling and freezing). They have developed the modelling of air blast and vacuum cooling (Hu et al., 1998; Hu and Sun, 1999, 2000a), chilling (Davey and Pham, 1997, 2000), cold chain (Moureh and Derens, 2000), cold store (Van Gerwen and Van Oort, 1989a,b; Pala and Devres, 1988), refrigerated room (Mariotti et al., 1995) and refrigerated display cabinets (Foster, 1996).

CFD simulation of heat and moisture transfer for predicting cooling rate and weight loss of cooked ham during air blast chilling process has been investigated (Hu and Sun, 2000b). Both experimental and predicted results showed that the core temperature of the cooked ham was cooled down from 74.4 to 4 °C within approximate 530 min. The experimental accumulative weight loss was 4.25%, while the simulated results were 4.07 and 4.22%, respectively, obtained from standard k–ε model and LRN k–ε model. At the same time the effect of fluctuation in inlet airflow temperature was studied (Hu and Sun, 2001a), indicating that setting the boundary condition of airflow temperature is an important factor affecting the predicting accuracy. If a constant temperature was assumed for the inlet air, the weight loss (4.37%) was over predicted. Furthermore, the effects of different $k-\varepsilon$ models and thermocouple positions on the prediction accuracy of CFD modelling of air-blast chilling process were also analysed (Hu and Sun, 2001b, 2002). Mirade and Daudin (1995) developed a two-dimensional simulation model for the airflow in two industrial meat chillers. Recently, Moureh and Derens (2000) investigated the temperature increase in frozen food packaged in pallets in the distribution chain by means of CFD modelling. Good agreement was found between the experimental and modelling results with the differences normally within 10%. The study showed that the controlled temperature throughout the cold chain was necessary to ensure a high food quality with long storage duration (Moureh and Derens, 2000). Although the modelling of air flow and temperature distribution has been well developed, models for phase transition, such as condensation and evaporation are not yet available.

Since refrigerated foods require strict temperature control, the design of equipment or stores for refrigerated foods is very important. With the utilisation of CFD, designers can examine the whole range of modifications before manufacturing and designing at a minimal cost and in a short time (Foster and James, 1996). A large amount of research work has been accomplished about the simulation and optimisation of the design of refrigerated cases or stores using CFD (Stribling et al., 1996; Xiang and Tassou, 1998; Wang and Touger, 1990; Cortella et al., 1998). Cortella et al., (2001) analysed the velocity and temperature distributions in refrigerated open cabinets based on CFD simulation. The average value of the predicted temperature (6.54 °C) did not differ much from the average measured value (6.3 °C) showing good agreement (Cortella et al., 2001). A model about the environment in a wet air-cooled vegetable store has been developed by Tassou and Xiang (1998). Although the accuracy of the results can be improved further, the modelling results are in agreement with experimental data. For cooling beetroot in the store, the maximum difference between the measured and predicted temperature after 15 h of cooling was 0.5 °C (Tassou and Xiang, 1998). However, since the commercial CFD software packages lack several features that are important for the design of cool store, such as turbulence modelling for mixed convection problems with heat and mass transfer, more efforts on the modelling should be made (Nicolai et al., 2001). Nevertheless, these researches will lead to the optimising of the design of equipment or store for refrigerated foods and the increase of the confidence of food safety and quality. Some of the CFD applications in refrigeration are summarised in Table 3.

5.5. Other applications

Applications of CFD have been found in other areas of food processing industry, including heat exchanger, clean room condition, forced convection ovens (Verboven et al., 2000a,b), baking process (Vries et al., 1994), vegetable storage and condensation (Xu and Burfoot, 1999a,b).

5.5.1. Heat exchanger

Heat exchangers are used throughout the food processing industry. There are mainly three kinds of heat exchangers such as shell, tube and plate exchangers. However, in the food processing industry plate exchangers tend to be preferred. In order to predict and control food quality during heating process, CFD has been used to simulate and study the flow distribution and temperature distribution of the fluid. Kumar (1995) numerically analysed secondary flows in helical heat exchanger using CFD codes. The trend towards aseptic processing, combined with the aim of minimising cooked flavours in heat processed products is leading heat exchangers to be constantly redesigned and improved. In this case CFD can be used to optimise such redesign of heat exchanger.

5.5.2. Clean room condition

In the food processing industry, it is necessary to maintain the cleanliness and ventilation. CFD has been used by designers to simulate the airflow within a clean room. With the particle tracking techniques, the movement of air and other particulate matter in the clean room can be predicted (Quarini, 1995). The airflow in a food-processing clean room has been investigated by using CFD (Havet and Rouaud, 2000). The design of suitable ventilation equipment, the position of air supply and extraction ducts and the optimal location of working areas and

Table 3
CFD application in refrigeration

References	Codes	k–ε model	Object	Conditions
Hu et al., 1998; Hu and Sun, 2001a,b, 2002	CFX	LRN k–ε model; Standard k–ε model; RNG k–ε model	Ham	Chiller conditions: air flow, 0 °C; inlet velocity, 2.53 ms^{-1}
Moureh and Derens, 2000	PHOENICS		Frozen food packaged	Temperature and humidity: +4 °C/80% and 22 °C/50%
Stribling et al., 1996, 1997	FLUENT		Display cabinets	Store side boundary: 1 atm, 20 °C
Xiang and Tassou, 1998	FLUENT	RNG k–ε model	Display cabinets	Ambient conditions: 22 °C, 60% RH
Wang and Touger, 1990	PHOENICS		Refrigerated room	
Cortella et al., 1998, 2001	CFX	LES (Large eddy simulation procedure)	Display cabinets	Ambient conditions: 25 °C, 60% RH
Hoang et al., 2000	CFX	Standard k–ε and RNG k–ε model	Cold store	
Kondjoyan and Daudin, 1997a,b	FLUENT		Carcasses and meat	Chilling conditions: 40 °C, 80% RH
Davey and Pham, 1997	PHOENICS	RNG k–ε model	Beef	Chiller conditions: Air temperature: −1 to 10 °C; air velocities: 0.4–1.3 m s^{-1}

machines can benefit from the use of the CFD (Scott, 1994). The application of CFD in the control of clean room condition will provide good working environment and enhance sanitary in the food processing industry.

5.5.3. Other equipment design

CFD can be used for early conceptual studies of new designs, for detailed product development and for scale-up. In the past few years new developments have been made on the design of food equipment. For example, using CFD as a method of modelling fluid flow and heat transfer in food processing equipment design was investigated (Geiss, 1997). Janes (1996) reviewed the art of bakery equipment manufacture and the use of CFD in the design as well as set up of baking ovens. Baerdemaeker (1993) discussed the equipment considerations for sous vide cooking. It is shown that CFD provides a powerful means to investigate the effect of modifications in the process conditions and equipment characteristics on the internal temperature of the food. Consequently, CFD plays a crucial role in the food equipment design, which will eventually lead to better design in terms of safety, reliability and uniformity of food product quality (Baerdemaeker, 1993).

6. Application problems

CFD has already proven to be a valuable tool to the food processing industry in many areas. The effectiveness and practicability of a CFD simulation in the food processing industry rely on several factors (Spalding, 1999a):

- specific food materials properties and food process;
- accurate algorithm for the equations of motion;
- powerful CFD packages; and
- high speed and large computers.

There are still some problems that hinder the widespread use of CFD. First, the materials in food processing (milk, vegetables, fruit juice, meat, etc) differ in many ways from (rheological flow properties, thermodynamic properties, physical properties, etc) those to which CFD is conventionally applied (air, water, etc). Conventional CFD has been able to predict only those 'mixture-average' properties, however, the quality of food material is closely associated with its size, texture and composition. The processing of food can be understood and controlled efficiently only if physical-chemical, organic-chemical and micro-biological models are available, however, conventional CFD packages do not feature in such processing.

Secondly, the food industry must employ well-versed CFD experts. Although vendors of commercial CFD software often claim that their codes do not require specialised knowledge of CFD, some knowledge is principally indispensable. It is necessary to be familiar with physical flow modelling and numerical techniques in order to set-up a proper simulation and to judge the value of its results, while taking into account the capabilities and limitations of CFD. Therefore, the biggest problem in CFD is probably not the mesh generation, nor the necessary computer power or the CFD solvers, but to find the people who really can do the full job.

There will be a considerable demand for specialists to apply and develop CFD methods throughout the food industry (Eisenga, 1998).

7. Future of CFD in food industry

Although the application of CFD in the food industry will benefit the understanding of the dynamics and physics of a food processing operation and thus aid in the optimisation and design of existing and new processing equipment, constraints are the requirement for faster, easier and less expensive CFD techniques. In the new millennium, the application of CFD in the food industry has reached a critical juncture, since it is becoming more and more apparent that the future growth in CFD will be qualitative, quantitative and effective in work (FLUENT, 2000).

In the coming years, food engineers may not need to worry about non-engineering issues such as mesh structure and cell shapes because of the development of fully automated mesh generation for CFD (Aftosmis et al., 1997). The continued high rate of advancement in computer power and in CFD software development will turn automatic design and optimisation in realities and the development of web-based CFD will allow more people to access the technology. All these developments will contribute CFD to becoming a mature discipline and a powerful engineering tool. As a result, more widespread and rapid adoption of the use of CFD in the food processing industry will take place in future.

8. Conclusions

This paper reviews the application of CFD in the food processing industry. CFD can be used as a tool to predict food processes as well as to design food processing equipment. There has been considerable growth in the development and application of CFD recently in the area of drying, sterilisation, mixing and refrigeration. However, the simulation results should be validated by experiments because CFD use many approximate models as well as a few assumptions. Although there are still some obstacles such as inability in accurate simulation of large 3-D problems on an affordable computer, in particular, in large-scale sophisticated plants, the trend of widespread application of CFD in the food processing industry will continue in the 21st century.

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