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Review

Recent developments in numerical modelling of heating and cooling processes in the food industry—a review

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Numerical modelling technology offers an efficient and powerful tool for simulating the heating/cooling processes in the food industry. The use of numerical methods such as finite difference, finite element and finite volume analysis to describe the heating/cooling processes in the food industry has produced a large number of models. However, the accuracy of numerical models can further be improved by more information about the surface heat and mass transfer coefficients, food properties, volume change during processes and sensitivity analysis for justifying the acceptability of assumptions in modelling. More research should also be stressed on incorporation of numerical heat and mass transfer models with other models for directly evaluating the safety and quality of a food product during heating/cooling processes. It is expected that more research will be carried out on the heat and mass transfer through porous foods, microwave heating and turbulence flow in heating/cooling processes.

Introduction

Heating (i.e. drying, cooking and sterilisation) and cooling (i.e. chilling and cold storage) are common thermal processes in the food industry. These thermal-processing techniques are widely used to improve quality and safety of food products, and to extend shelf life of the products.

The principles of many thermal processes of solid foods are based on heat and moisture exchanges between a solid food body and medium flow. Heat transfer through solid foods is normally modelled by Fourier's equation of heat conduction and moisture transfer is generally described by Fick's law of diffusion (Cheremisnoff, 1986). For thermal processes of fluid foods, the conservation of mass, momentum and energy in a fluid should be considered together. The continuity equation and Navier–Stockes equations are used to describe fluid flow (Versteeg & Malalaskera, 1995). The actual conditions imposed by the processing equipment are considered as the boundary conditions of the governing equations.

Most heat and mass transfer models can only be solved analytically for simple cases. Numerical methods are useful for estimating the thermal behaviour of foods under complex but realistic conditions such as variation in initial temperature, non-linear and nonisotropic thermal properties, irregular-shaped bodies and time-dependent boundary conditions (Puri & Anantheswaran, 1993). In solving the models, the finite difference and finite element methods are widely used (Ahmad, Morgan, & Okos, 2001; Erdogdu, Balaban, & Chau, 1998a, b, 1999; Jia, Sun, & Cao, 2000a, b, c, d, 2001; Wang & Sun, 2002a, b, c, d, e; Zhang & Fryer, 1995; Zhou, Puri, Anantheswaran, & Yeh, 1995). In recent

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Nomenclature

C_T	intercept for a cooling curve in equations (3) and (4)
D	diffusion coefficient (m^2/s)
D_0	pre-exponential factor in Arrhenius equation (m^2/s)
E	thermal inertia (s)
E_a	activation energy (J/kgmol)
h	heat transfer coefficient (W/m^2 K)
h_{fg}	latent heat of evaporation (kJ/kg)
K_p	surface mass transfer coefficient related to pressure (kg/Pa m^2 s)
P	pressure (Pa)
R	gas constant (8.314 J/molK)
S_1	slope for a cooling curve during first 24 h cooling in Eqn (3)
S_2	slope for a cooling curve after 24 h cooling in Eqn (4)
T	temperature (°C)
t	time (s)
T_K	absolute temperature (K)
X	composition ratio by weight (%)
Greek symbols	
ξ	coefficient in equation (2)
θ	the lowest eigenvalue in equation (2)
Subscripts	
0	initial
K	temperature in Kelvin
lq	liquid
mf	medium fluid
w	water

years, the finite volume method was the main computational scheme used in commercial computational fluid dynamics (CFD) software packages. CFD has been increasingly used to simulate thermal processes of foods for analysing complex flow behaviour (Scott & Richardson, 1997; Sun, 2002).

Numerical modelling technology offers an efficient and powerful tool for simulating the heating/cooling processes in the food industry. Experiments can virtually be carried out on numerical models in an economical and time saving manner. Numerical models can be used to produce much valuable information about the heating/cooling processes of foods under broad experimental conditions within a short time. However, traditional experiments can only be restricted to several special conditions due to experimental cost and time limit. Meanwhile, it should be addressed that the experimental approach is necessary in validating the numerical models. The food industry benefits from numerical modelling in analysing the processes for better understanding of the complex physical mechanisms underlying the processes, evaluating the processes for ensuring the safety and quality of food products, designing and optimising food processes and systems and precisely controlling the processes with an aid of the predictive models.

The objective of this paper was to review the current state of numerical modelling of heating/cooling processes in the food industry. The prospects of further research were examined and various applications of numerical models were discussed.

Overview of numerical methods

Finite difference

Variables such as temperature and moisture used in modelling the thermal processes depend on time and position. The transport equations governing the physical mechanism of heating / cooling processes are thus of a differential type. Finite difference (FD) method is simple to formulate a set of discretised equations from the transport differential equations in a differential manner (Chandra & Singh, 1994). The FD scheme can be easily applied to two or three-dimensional problems. The FD method is normally used for simple geometries such as sphere, slab and cylinder. The FD method has been widely used to solve heat and mass transfer models of many thermal processes such as cooking and frying (Erdogdu *et al*., 1998a, b; Farkas, Singh, & Rumsey, 1996a, b; Pan, Singh, & Rumsey, 2000), drying (Thorvaldsson & Janestad, 1999; Wang & Brennan, 1995; Wang & Chen, 1999), and cooling (Ansari, 1999; Chuntranuluck, Wells, & Cleland, 1998a, b, c; Coulter, Pham, McNeil, & McPhail, 1995; Davey & Pham, 1997; Evans, Russell, & James, 1996). Since the 1970s, there are a number of important publications which have improved the knowledge of the finite difference scheme for predicting the heating/cooling processes in the food industry (i.e., Chau & Gaffney, 1990; Radford, Herbert, & Lovett, 1976). However, for foods with irregular shapes, the surface temperature predictions by the FD method are less satisfactory due to geometric simplification. Table 1 gives a summary of recent development of FD models for simulating the heating/cooling processes of foods.

Finite element scheme

The finite element (FE) method may perform better than the finite difference method for irregular geometries, complex boundary conditions and heterogeneous materials. The FE method involves discretising a large domain into a large number of small elements, developing element equations, assembling the element equations for

Table 1. Summary of finite difference method in heating/cooling processes of foods

Processes	Authors	Affiliation	Heat model	Mass model	Dimension	Temp. dependent properties	Foods
	Rovedo *et al.* (1995)	Ciudad U., Argentina		√	1D	√	Potato
	Simal *et al.* (2000)	U. of Illes Balears, Spain		√	3D	√	Aloe vera
Drying	Ben-Yoseph *et al.* (2000)	U. of Wisconsin-Madison, USA		√	3D	√	Sugar film
	Wang and Brennan (1995)	U. of Reading, UK	√	√	1D	√	Solid foods
	Thorvaldsson and Janestad (1999)	Swedish Inst. for Food and Bio.	√	√	1D	√	Bread
	Wang and Chen (1999)	Hong Kong U. of Sci. and Tech.	√	√	1D	√	Vegetables
	Erdogdu *et al.* (1998a, b, 1999)	U. of Florida, USA	√		2D-axi	√	Shrimp
	Farkas *et al.* (1996a, b)	North Carol. State U. & U. of California, Davis, USA	√	√	1D		Potato
Heating	Pan *et al.* (2000)	Archer Daniels Midland Co., USA & U. of California, Davis, USA	√	√	1D-axi	√	Hamburger patty
	Akterian (1995, 1997)	Higher Inst. of Food & Flavour Industries, Bulgaria	√		1D		Mushroom
	Avila *et al.* (1996)	U. Catolica Portugesa, Portugal	√		3D		Various
	Ghazala *et al.* (1995)	Memorial U. of Newfoundland & McGill U., Canada	√		3D		Various
	Fasina and Fleming (2001)	North Carolina State U., USA	√		2D-axi		Cucumber
	Coulter *et al.* (1995) and Davey and Pham (1997)	U. of New South Wales *et al.*, Australia	√		1D	√	Carcasses
	Evans *et al.* (1996)	U. of Bristol, UK	√		1D		Bolognese sauce
	Chau and Gaffney (1990)	U. of Florida, USA	√		1D		Tomato etc.
	Gowda *et al.* (1997)	Indian Inst. of Sci.	√		2D-axi		Vegetable in bulk
Cooling	De Elvira *et al.* (1996)	Ciudad U., Spain	√		3D	√	Frozen foods
	Bellara *et al.* (2000)	U. of Birmingham, UK	√		2D-axi		Various
	Chuntranuluck *et al.* (1998a, b, c)	Kasetsart U., Thailand, Agr. NZ Ltd & Massey U., NZ	√		1D		Various
	Ansari (1999)	Aligarh Muslin U., India	√		1D		Various
	Chavez *et al.* (1997)	U. Nacional del Litoral & Ciudad U., Argentina	√		1D-axi		Potato
Others	Schmalko *et al.* (1997)	U. Nacional de Misiones, Argentina	√		1D-axi	√	Twigs of yerba mate
	Sahin *et al.* (1999)	Middle East Tech. U., Turkey & Ohio State U., USA	√		1D	√	Potato

the whole domain, and solving the assembled equations. The FE discretisation of the governing differential equations is based on the use of interpolating polynomials to describe the variation of a field variable within an element. Although the spatial discretisation is different for the FE method compared with FD method, it is usual to employ a FD method for the time progression in a transient problem (Rao, 1989; Stasa, 1985). The FE method has been successfully used to solve heat and mass transfer models for cooking (Chen, Marks, & Murphy, 1999; Ikediala, Correia, Fenton, & Abdallah, 1996; Lian, Harris, Evans, & Warboys, 1997; Lin, Anantheswaran, & Puri, 1995; Zhang & Datta, 2000; Zhou *et al.*, 1995), drying (Ahmad *et al.*, 2001; Jia *et al.*, 2000a, b, c, d, 2001) and cooling (Arce, Potluri, Schneider, Sweat, & Dutson, 1983; Carroll, Mohtar, & Segerlind, 1996; Comini, Cortella, & Saro, 1995; Van Der Sluis & Rouwen, 1994; Mallikarjunan & Mittal, 1994, 1995; Wang & Sun, 2002a, b, c, d, e, 2003; Zhao, Kolbe, & Craven, 1998). However, the FE method is complex and computationally expensive than the FD method. An early review indicated that there were a few publications on three-dimensional and/or coupled heat, moisture and stress analysis based on the finite element analysis (Puri & Anantheswaran, 1993). A summary of various finite element models developed recently for analysing heating/cooling processes of foods is listed in Table 2.

Finite volume/computational fluid dynamics

Computational fluid dynamics (CFD) is a simulation tool for the solution of fluid flow and heat transfer problems. In CFD calculation, the continuity equation, momentum conservation equation (also known as the Navier–Stokes transport equations) and energy conservation equation are numerically solved to give predictions of velocity, temperature, shear, pressure profiles, and other parameters in a fluid flow system (Sun, 2002).

Table 2. Summary of finite element method in heating/cooling processes of foods

Processes	Authors	Affiliation	Heat model	Mass model	Dimension	Temp. dependent properties	Foods
	Wu and Irudayaraj (1996)	U. of Saskatchewan, Canada & Utah State U., USA	√	√	2D	√	Starch
Drying	Jia *et al.* (2000a,b,c d, 2001)	U. College Dublin, Ireland & China Agr. U.	√	√	2D-Axi	√	Grain
	Ahmad *et al.* (2001)	Purdue U., USA	√	√	2D-Axi	√	Biscuits
	Chen *et al.* (1999)	U. of Arkansas, USA	√		2D-Axi	√	Chicken
	Ikediala *et al.* (1996)	Technical U. of Nova Scotia, Canada	√		2D-Axi	√	Meat
	Yang and Rao (1998)	Cornell U., USA	√	√	2D-Axi	√	Starch
	Zhang and Datta (2000) Zhang *et al.*, (2001)	Cornell U., USA	√		2D-Axi	√	Various
Heating	Lin *et al.* (1995), Zhou *et al.* (1995) and Vilayannur *et al.* (1998a, b)	Pennsylvania State U., USA	√	√	2D & 3D		Solid foods
	Nicolaï and De Baerdemaeker (1996), Verboven *et al.* (2001), Nicolaï *et al.* (1998, 1999a, b, 2000)	Katholieke U. Leuven, Belgium	√		2D-Axi		Various
	Zhang and Fryer (1995)	U. of Cambridge, UK	√		2D		Various
	Martens *et al.* (1996)	Katholieke U. Leuven, Belgium	√		1D-Axi	√	Broccoli
	Varga *et al.* (2000a, b), Varga and Oliveira (2000)	U. Catolica Portuguesa, Portygal & U. College Cork, Ireland	√		2D-Axi		Various
	Mallikarjunan and Mittal (1994, 1995)	U. of Guelph, Canada	√		2D	√	Carcasses
	Carroll *et al.* (1996)	Purdue U. & Michigan State U., USA	√		1D		Apple & pear
Cooling	Comini *et al.* (1995)	U. degli Studi di Udine, Italy	√		2D		Various
	Wang and Sun (2002a, b, c, d, e)	U. College Dublin, Ireland	√	√	2D-3D	√	Cooked meats
	Zhao *et al.* (1998)	Oregon State U., USA	√		2D	√	Albacore tuna
	Van Der Sluis and Rouwen (1994), Van Der Sluis *et al.* (1999)	TNO-MEP, Netherland	√	√	3D	√	Bakery products & carcasses
	Tewkesbury *et al.* (2000)	U. of Birmingham, UK	√		2D-Axi	√	Chocolate
Others	Hulbert *et al.* (1997)	U. of Tennessee, USA	√		2D		Carrot
	Nahor *et al.* (2001)	Katholieke U. Leuven, Belgium	√		3D	√	Various

Table 3. Summary of CFD in heating/cooling processes of foods

Processes	Authors	Affiliation	Foods
	Straatsma *et al.* (1999)	NIZO Food Research, Netherlands	Particle foods
Drying	Mathioulakis *et al.* (1998)	National Centre for Scientific Research, Greece	Fruits & vegetables
	Mirade and Daudin (2000)	INRA, France	Sausage
	Verboven *et al.* (2000a, b)	Katholieke U. Leuven, Belgium	Various
Heating	Ghani *et al.* (1999a, b, 2001)	U. of Auckland, New Zealand	Canned liquid foods
	Jung and Fryer (1999)	U. of Birmingham, UK	Various
	Tassou and Xiang (1998)	Brunel U., UK	Vegetables
Cooling	Cortella *et al.* (2001) Cortella (2002)	U. degli Studi di Udine, Italy	Various
	Xu and Burfoot (1999a, b)	Silsoe Research Institute, UK	Particulate foodstuffs
	Foster *et al.* (2002)	U. of Bristol	Various
	Mirade and Picgirard (2001); Mirade *et al.* (2002)	INRA, France	Carcasses and meats
	Hu and Sun (2000, 2001a, b, 2002), Sun and Hu (2002, 2003)	U. College Dublin, Ireland	Cooked meats
	Verboven *et al.* (1997)	Katholieke U. Leuven, Belgium	Various
Others	Kondjoyan and Boisson (1997)	Inst. National de la Recherche Agronomique & Inst. de Mecanique des Fluides de Toulouse, France	Various

In the last few years, there has been continuous progress in the development of CFD codes. Some of the common commercial codes include CFX (http://www.software.aeat.com/cfx/), Fluent (http://www.fluent.com/), Phoenics (http://www.cham.co.uk/) and Star-CD (http://www.cd.co.uk). The computational procedure of most of commercial CFD packages is based on finite volume (FV) numerical method. In fact, the FV method was derived from the finite difference method. In the FV method, the domain is divided into discrete control volumes. The key step of the FV scheme is the integration of the transport equations over a control volume to yield a discretised equation at its nodal points (Versteeg & Malalaskera, 1995).

Although CFD has been applied to industries such as aerospace, automotive and nuclear for several decades, it has only recently been applied to the food processing industry due to the rapid development in computer and commercial software packages (Sun, 2002). A review of CFD in the food industry has been given by Scott and Richardson (1997) and Xia and Sun (2002). Langrish and Fletcher (2001) reviewed the applications of CFD in spray drying. Applications of CFD in the food industry include analyses of air flow in ovens and chillers (Cortella, 2002; Cortella, Manzan, & Comini, 2001; Foster, Barrett, James, & Swain, 2002; Mirade, Kondjoyan, & Daudin, 2002; Mirade & Picgirard, 2001), fluid flow of particle foods in processing systems (Mirade & Daudin, 2000), convection flow patterns in containers during thermal processing such as sterilisation (Ghani, Farid, Chen, & Richards, 1999a, b), and modelling of vacuum cooling process (Sun & Hu, 2002, 2003). The transport equations of CFD can be applied to both laminar and turbulent flow conditions. The eddy viscosity models such as κ–ϵ approach, and second-order closure models are used to describe the flow turbulence if the effects of turbulence on the effective viscosity need to be considered. A summary of various CFD models developed recently for analysing the heating/cooling processes of foods is presented in Table 3.

Recent developments of numerical models

Heat transfer without considering mass transfer

Heat transfer through a food body in a liquid system

Heating in a liquid-solid process such as sterilisation, blanching and sous vide processing is widely used in the food industry. For modelling the heating process of a liquid–solid system, the heat transfer through a solid food body is usually described by Fourier's equation of heat conduction. The interaction between the solid and liquid is normally considered in the boundary conditions.

Sterilisation of canned solid particle foods with a brine solution in a container is a typical liquid–solid thermal process. In this system, the low-viscosity brine liquid is heated by convection and the solid particle foods by conduction. Akterian (1995, 1997) used a one-dimensional finite difference heat conduction model to simply determine the temperature distribution in a canned mushroom body. Meanwhile, the temperature of brine liquid in the heated cans, which is variable with the temperature outside of the cans, was described by the regular regime differential equation:

$$\frac{dT_{lq}}{dt} = \frac{T_{mf} - T_{lq}}{E} \tag{1}$$

where the thermal inertia, E, which characterises the temperature lag of the brine liquid from the temperature of outside heating medium, was experimentally determined by monitoring the temperature of the brine with linearly increasing, holding and linearly decreasing the temperature of the medium.

Blanching of fresh vegetables such as cucumbers is another common heating practice in a liquid-solid system, which is used to increase the flaccidity of fresh vegetables to facilitate their packing into jars. Blanching is carried out by placing fresh product into a heating bath of water at temperature of as high as 95°C. As the shape of a cucumber can be assumed to be a cylinder, the heat transfer through the cucumber body during blanching can be described by a two-dimensional axisymmetrical finite difference heat conduction model (Fasina & Fleming, 2001). Their simulations found that variations in heat transfer coefficients of surface convection between 500 and 6000 W/m^{2}K had no significant effect on the surface and centre temperature profiles of cucumbers during the blanching. This means that if the coefficient is big enough, the total heat transfer rate is controlled by conduction through the food body.

Sous vide processing of foods is also implemented in a liquid-solid thermal system. During sous vide processing, raw foods are placed in a pouch, vacuum sealed, cooked slowly under mild heating conditions, chilled and stored at typical 4°C. As heat transfer coefficient of surface convection is normally very large due to good circulation of water in the bath, the effect of the coefficient on the temperature profiles of foods is normally assumed to be negligible. For this reason, the heat transfer coefficient can arbitrarily be set at a very high value in a simulation, and for example, 5000 W/m^{2}K was used in a three-dimensional finite difference heat conduction model for predicting the time-temperature profiles of sous vide processed fish and meat products of a brick shape (Ghazala, Ramaswamy, Smith, & Simpson, 1995).

Heat transfer through a food body with inner heat generation

Respiration normally occurs in vegetables and fruits immediately after harvest. For modelling the pre-cooling process of products, inner heat generation due to respiration is normally included in the equation of heat conduction. The rate of inner heat generation can be correlated to product temperature (Chau & Gaffney, 1990; Gowda, Narasimham, & Murthy, 1997). Simulations carried out by Gowda *et al.* (1997) found that the heat of respiration had no significant effect on processing time during air blast cooling because cooling time is very short as compared to that of cold storage.

Microwave heated foods are becoming increasingly popular in the food market and at home. For modelling microwave heating process, the heat transfer through a solid food body can also be described by Fourier's equation of heat conduction with inner heat generation due to the microwave energy absorbed by the food components. The microwave power density absorbed at any location in foodstuffs can be derived as a function of dielectric properties and geometry of the food. Meanwhile, heat losses on the surface of food body by convention and evaporation can be included in the boundary conditions. For simulating microwave heating of solid food with rectangular and cylindrical shapes, finite element analysis may be a powerful tool to numerically solve the model (Lin *et al.*, 1995).

Heat transfer through a food body with irregular shapes

Many food items such as animal carcasses normally have irregular shapes. An irregular shaped body may be divided into several parts and each small part is then assumed to be a regular shape. For example, a whole shrimp can be divided into several small segments and each segment is then assumed to be cylindrical. The radius of the cylinder can be determined by comparing the measured surface area of the cross-sectional ellipse with that of the fitted circle. In this case, a simple finite difference heat transfer model can still be used to describe the cooking process of shrimp (Erdogdu *et al.*, 1998a, b, 1999).

A whole animal carcass can also be divided into segments such as leg, loin and shoulder. The dimensions of leg (sphere or infinite cylinder), loin (slab) and shoulder (slab) sections can be regressed as functions of carcass weight and fat thickness by using statistical packages since the heat transfer rate of the carcass is primarily influenced by the type of carcass, which is characterised by carcass weight and fatness. For predicting the cooling rate of pig carcasses, the heat transfer through each section can be further described by using a one-dimensional finite difference heat conduction model (Coulter *et al.*, 1995; Davey & Pham, 1997).

However, the finite element method can directly solve equations of heat transfer over an irregular body. For example, a two-dimensional finite element heat transfer model was used to simulate the chilling and freezing processes of albacore tuna, which has a shape of infinite elliptical cylinder (Zhao *et al.*, 1998). A two-dimensional axisymmetrical finite element heat transfer model was also used to investigate the conventional cooling of cooked meats in ellipsoid shape (Wang & Sun, 2002a, b).

Although differential equations of heat transfer through a body of an irregular shape cannot be solved analytically, practically, it is simple to determine the processing time required for the temperature to reach the desired value by an analytical solution as expressed as (Carroll *et al.*, 1996):

$$\frac{T - T_{\mathrm{mf}}}{T_0 - T_{\mathrm{mf}}} = \xi e^{-\theta t} \tag{2}$$

For the governing equation of heat transfer over an irregular body, it is impossible to analytically obtain the lowest eigenvalue, θ, and the coefficient, ξ, in eqn (2). However, the pair of parameters θ and ξ can be evaluated numerically by the finite element method (Carroll *et al.*, 1996).

Alternatively, simple equations for determining cooling or heating time can also be obtained by regressing the temperature calculated by using a numerical method against cooling time. For example, the following equations were given for the cooling process of carcasses (Mallikarjunan & Mittal, 1995):

$$\log\left(\frac{T - T_{\mathrm{mf}}}{T_0 - T_{\mathrm{mf}}}\right) = C_T + S_1 t \ \ (t \leqslant 24 \ \mathrm{h}) \tag{3}$$

$$\log\left(\frac{T - T_{\mathrm{mf}}}{T_0 - T_{\mathrm{mf}}}\right) = C_T + 24 \times (S_1 - S_2) + S_2 t \ \ (t > 24 \ \mathrm{h}) \tag{4}$$

where values for the coefficients C_T, S_1 and S_2 were obtained in terms of carcass and operation parameters.

Heat transfer with evaporation on surface of foods

In some situations, cooling rates of foods in air cooling are accelerated by latent heat of evaporation due to moisture loss from the surface of foods. For reducing the temperature of foods such as vegetable and meats by 30°C, the total energy loss is about 100 kJ/kg. However, if the moisture loss is 1% of the weight before cooling, the energy loss by evaporation is about 25 kJ/kg, which is 25% of the total energy loss.

Therefore, heat transfer by evaporation on the surface of foods should also be taken into account in boundary conditions if evaporative cooling is significant (Chuntranuluck *et al*., 1998a, b, c).

The evaporation causes weight loss of products. Cooling should be carried out under such conditions that minimise microbial activity and weight loss due to evaporation. For predicting both the cooling rate and weight loss during cooling of carcasses, a simple one-dimensional finite difference heat conduction model can be used to describe the heat transfer through each part of the carcass as discussed before. Meanwhile, natural and forced convection, radiation and evaporation heat transfer on the surface of the carcass should be considered in the boundary conditions (Davey & Pham, 1997).

Mass transfer without considering heat transfer

The drying process is mainly characterised by moisture loss of foods. For a drying process with a small Biot number, a uniform temperature profile in foods can be assumed in simulation. This uniform temperature can be determined by a heat balance between the dried food body and drying medium (Ben-Yoseph, Hartel, & Howling, 2000; Rovedo, Suarez, & Viollaz, 1995), or assumed to be the air temperature (Simal, Femenia, Llull, & Rossello, 2000). The moisture transfer through the foods is normally described by the differential equation of Fick's law of diffusion, which is expressed as:

$$\frac{\partial X_w}{\partial t} = \nabla \cdot (D \nabla X_w) \tag{5}$$

The diffusion coefficient is important for the accuracy of model prediction. The diffusion coefficient can be regressed as a function of temperature and concentration by using data in literature (Ben-Yoseph *et al*., 2000). Alternatively, the diffusion coefficient can be determined by Arrhenius law (Rovedo *et al*., 1995; Simal *et al*., 2000; Wang & Brennan, 1995) as:

$$D = D_0 \exp\left(-\frac{E_a}{RT_K}\right) \tag{6}$$

and E_a and D_0 are varied during simulation until a reasonable agreement between predicted and experimental results is obtained.

On the surface of a food body, external mass transfer is normally assumed to be proportional to the vapour pressure difference between the surface and the drying media (Wang & Brennan, 1995).

Conjugated heat and mass transfer through a porous food body

Heat and mass transfer in porous media is a complicated phenomenon. Thermal processes of porous foods include the drying of moisture materials, vacuum cooling of porous and moisure foods, heating and conventional cooling processes with significant moisture loss. The heat and mass transfer was normally described by Fourier's equation of heat conduction and moisture diffusion equation of Fick's law, respectively (Chen *et al*., 1999). The problems of coupled heat transfer and mass transfer through a porous food body can also be modelled by Luikov's coupled system (Luikov, 1975; Wu & Irudayaraj, 1996).

Heating

Air convection-heating oven is popular thermal processing equipment. For predicting transient temperature and moisture distribution in chicken patties of regular shapes in a cooking oven, a two-dimensional axisymmetric finite element coupled heat and mass transfer model was found to give better prediction than that of heat transfer only model (Chen *et al*., 1999). In some cases, if it is difficult to find data for mass diffusivity and mass transfer coefficient, a volumetric moisture loss rate due to evaporation can be experimentally determined and the heat removed due to moisture loss can then be incorporated into Fourier's equation of heat conduction as inner heat generation (Ikediala *et al*., 1996).

During microwave heating, a big moisture loss sometimes occurs. In this case, a coupled heat and mass transfer model should be developed and additional moisture transfer through a solid food body can be modelled by the diffusion equation of Fick's law (Zhou *et al*., 1995). The moisture evaporation rate on surface can be obtained by using drying experiment and regressed as a function of temperature (Vilayannur, Puri, & Anantheswaran, 1998a, b).

As discussed above (Mass transfer without considering heat transfer), for a drying process with a small Biot number, a uniform temperature profile in foods can be assumed in simulation and a single mass transfer model can thus be used to describe the drying process. However, for a drying process with a big Biot number, a coupled mass and heat transfer should be taken into account in the simulation. For the drying process of a composite food system, the simulation found that the predicted temperature, moisture and pressure distributions in the composite food system by the coupled model agreed with experimental data. However, there was a big difference between the predicted values by the uncoupled model and experimental data (Wu & Irudayaraj, 1996).

Drying of food materials is normally a complex process involving simultaneous coupled heat and mass transfer in the materials. In most cases, it is often assumed that moisture diffuses to the outer boundaries in a liquid form and evaporation takes place only on the surface. The diffusion models do not separate liquid water and water vapour diffusion (Wang & Brennan, 1995). However, in some cases, inner water evaporation during drying is significant and therefore simultaneous heat, water and vapour diffusion should be considered for simulating drying processes (Thorvaldsson & Janestad, 1999). For example, for predicting the drying process of breads, simultaneous heat, water and vapour diffusion through breads was described by using a one-dimensional finite difference coupled heat and mass transfer model (Thorvaldsson & Janestad, 1999). The three governing equations of heat, moisture and vapour were connected by the relationship between saturated vapour pressure and local temperature. Calculation of the temperature and water content was divided into the following steps: (1) temperature was calculated from the heat transfer equation; (2) local water vapour content was determined from the pressure–temperature relationship; (3) local water vapour content was also calculated by the diffusion equation of water vapour; (4) after diffusion, the amount of vapour to be condensed or water to be evaporated was determined by comparing two local vapour contents calculated in steps 2 and 3; and finally, (5) moisture content was calculated by the water diffusion. Comparisons between the predicted and experimental water content and temperatures showed that the assumption of evaporation and condensation in the model described the diffusion mechanisms in porous foods well (Thorvaldsson & Janestad, 1999).

Simulations on the drying process of vegetables and fruits using a one-dimensional finite difference coupled heat and mass transfer model confirmed that the assumption of evaporation-condensation front in the drying model was valid for drying of porous moisture materials with big permeability such as banana (Wang & Chen, 1999). However, it was also emphasised by Wang and Chen (1999) that the assumption of evaporation–condensation front was invalid and more comprehensive analysis was necessary if the permeability of dehydrated foods and vegetables was below 10^{-19} m^2.

A microwave is also used in drying of some heat-sensitive foods (Lian *et al*., 1997; Ahmad *et al*., 2001). During microwave drying, the heat and moisture transfer is coupled. In modelling the coupled heat and moisture transfer through biscuits during microwave-assisted drying, the heat and moisture transfer can be described by Fourier's equation of heat conduction with inner heat generation and the differential equation of Fick's law of diffusion, respectively. The model can be solved by a finite element scheme (Ahmad *et al*., 2001). In modelling the coupled heat and moisture transfer through porous materials during microwave-assisted vacuum drying, a combination of liquid water and vapour transfer should be taken into account in the equation of moisture transfer. Meanwhile, heat transfer can be described by Fourier's equation of heat conduction with an inner heat generation term covering latent heat of water evaporation and source heat of microwave power. However, as moisture transfer is caused by the temperature gradient in foods, the equation of moisture transfer can even be simplified into an isothermal equation if the temperature gradient is too small (Lian *et al*., 1997).

Cooling

Normally, for predicting conventional cooling process of an animal carcass, a single heat transfer model is used to describe heat conduction through a carcass body with consideration of convention, radiation and evaporation heat transfer on surface of the carcasses. Surface moisture loss due to evaporation is assumed to be proportional to the vapour pressure difference between on the surface and in cooling medium. The vapour pressure on the surface is determined by saturation pressure of water at surface temperature and water activity. However, a coupled heat and mass transfer model can also be used for predicting cooling processes of carcasses. The carcass can be divided into five zones of round, sirloin, loin, rib and chuck, heat and mass transfer in vertical direction of each zone can be neglected. Therefore, a two dimensional finite element coupled heat and mass model can be used to predict the temperature and moisture profiles in each zone. The mass and heat transfer in each zone is normally described by using the diffusion equation of Fick's law and Fourier's equation of heat conduction, respectively (Mallikarjunan & Mittal, 1994).

Vacuum cooling is used to rapidly chill some leafy vegetables and cooked foods such as large cooked meat joints (Wang & Sun, 2002d, e, 2003). Vacuum cooling is different from conventional slow air, air blast and water immersion cooling methods in the internal generation of cooling source due to water evaporation under vacuum pressure. Mathematical modelling of vacuum cooling of cooked meat joints involves coupled heat transfer with inner heat generation and mass transfer with inner vapour generation in inner pores of cooked meats. The finite element method can be used to solve the coupled heat and mass transfer model for cooked meat joints in commercial ellipsoid or brick shape during vacuum cooling (Wang & Sun, 2002d, e, 2003).

Coupled heat transfer and fluid flow

As discussed above, in modelling the heating/cooling processes of solid foods, Fourier's equation of heat conduction and/or the diffusion equation of Fick's law are widely used to describe the heat and mass transfer through the solid foods. The fluid flow of the heating/

cooling medium through the surface of the solid foods are normally considered in the surface heat and mass transfer coefficients, which determined by experiments or empirical correlation equations. With the advance in computer power, the coupled heat and mass transfer through the solid foods and the fluid flow of the heating/cooling medium can be modelled together and the models can be solved in the modern computers. The heating/cooling processes of liquid (or powder) foods such as sterilisation and spray drying are also typical coupled heat transfer and fluid flow problems. Recent development of coupled heat transfer and fluid flow models can be found in modelling the starch dispersion (Yang & Rao, 1998), food cooking in a convection oven (Verboven, Scheerlinck, De Baerdemaeker, & Nicolaï, 2000a, b), sterilisation of canned liquid foods (Ghani *et al*., 1999a, 2001), spray and convection drying of foods (Straatsma, Houwelingen, Steenbergen, & De Jong, 1999), and convection cooling and storage of foods (Xu & Burfoot, 1999a, b; Foster *et al*., 2002; Hu & Sun, 2000, 2001a, b, 2002).

Heating

With powerful computers available, heating of solid foods in an industrial convection-type oven can be modelled as a fluid flow and heat transfer problem. CFD offers an efficient and effective tool to analyse the performance of industrial convection-type oven such as hot-air electrical forced convection ovens. In the CFD models, the electrical heating coils and the fan can be modelled in the momentum equation (the Navier-Stokes equations) as a distributed resistance and a distributed body force in the region of the flow domain where the coils and fan are positioned. The value of turbulent viscosity in the momentum equation can be obtained by using the standard and renormalisation group version of the κ–ϵ turbulence model (Verboven *et al*., 2000a, b).

Starch dispersion process before initial gelatinisation temperature is a typical fluid flow and heat transfer problem. For predicting transient core temperature profile of 3.5% corn starch dispersion in a vertical cylindrical-shaped can during heating at 121°C, a two-dimensional axisymmetrical finite element coupled heat, mass and momentum model was developed by Yang and Rao (1998). The complex viscosity was obtained by using a thermo-rheological model based on experimental rheological data during starch gelatinisation at 65–95°C in combination with an assumed model for decreasing viscosity at 95–121°C (Yang & Rao, 1998).

Sterilising process of canned liquid foods is another typical example of fluid flow with heat transfer. CFD model can thus be used to predict transient flow patterns and temperature profiles in a can filled with liquid foods (Ghani *et al*., 1999a). For simulating the sterilising process of canned liquid foods, the energy equation needs to be solved simultaneously with the continuity and momentum equations. For predicting the transient temperature, velocity profiles and the shape of the slowest heating zone in a pouch containing carrot-orange soup during heating sterilisation, a three-dimensional CFD model should be developed (Ghani *et al*., 2001).

Continuous sterilisation processes of single-phase mixtures such as milks and fruit juices have become more and more common. The continuous process is called the HTST (high-temperature-short-time) sterilisation process, which gives the same level of sterility but a reduced quality loss as compared to batch sterilisation process. For optimising the quality of foods during continuous sterilisation, the laminar flow of liquid foods in circular pipes with uniform wall temperature can be described by a CFD model (Jung & Fryer, 1999).

During spray drying processes, coupled heat, mass and pressure transfer phenomenon occurs. The drying of droplets is influenced by external and internal transport phenomena alike. For simulating gas flow in a spray dryer and calculating the trajectories and the course of the atomised particles, CFD is widely used (Straatsma *et al*., 1999). The κ–ϵ turbulence model is used to calculate the gas flow field. The differential equation that describes the diffusion process in spherical particles is then solved simultaneously with equations for external heat and mass transfer.

For drying fruits and vegetables in an industrial batch-type tray air dryer, pressure profiles and velocity of heated air above products can be determined by a CFD model (Mathioulakis, Karathanos, & Belessiotis, 1998). In this case, the turbulent flow, which is characterised by relatively high velocity and the presence of many obstacles in the air dryer, can be described by the Chen–Kim κ–ϵ model (Chen & Kim, 1987).

Cooling

Cold room and air blast chilling are widely used for cooling of vegetables and fruits in bulk. Food products are normally arranged in layers stacked one above the other and with a gap between the product layers to provide evenly distributed air channels in the package. Chilled air is then used to blow through the package to reduce the temperatures. In this case, heat transfer through the solid food and the fluid in the channels can be modelled, respectively, and a finite difference or finite element model can be developed to analyse the heat conduction through the solid body of products (Comini *et al*., 1995; Gowda *et al*., 1997). Meanwhile, modelling the variations in air temperature and humidity along the height of the package can be achieved by using energy conservation equation in the air stream (Gowda *et al*., 1997). As an alternative to the continuous analysis of coupled velocity and temperatures of fluid in the channels, the average fluid velocities and convective heat transfer coefficients can be estimated first by standard engineering procedures with a given fluid temperature. The values can then be used to calculate the detailed temperature distribution in the solid and the bulk temperature variation in the fluid (Comini *et al*., 1995).

In a cold store, if air velocity is too small, heat transfer by natural convection becomes much more significant than that by forced convection. In this case, natural convection due to buoyancy effects should be considered. During simulation, cold stores filled with foods in air-penetrable boxes or bins can be assumed to be a porous media, and the void fraction and average diameter of products are experimentally measured. For simplicity, if the size of individual food items is very small, the temperature within the individual items is normally assumed to be uniform. Simulations show that the porous media model could be used to describe fluid flow and heat transfer through stored commodity in penetrable bins or boxes (Tassou & Xiang, 1998).

Most foodstuffs, such as grain, potatoes and onions, are normally stored in piles, silos or boxes. The bulk of stored particulate foodstuffs is also a typical porous media. Air flows, temperature and moisture changes of air and solids in porous bulk storage of particulate foodstuffs can thus be predicted by using a CFD model. Meanwhile, moisture diffusion and heat conduction within the solids are modelled to predict the temperature and moisture profiles in solid foods, and the heat of respiration, which can be expressed as an empirical function of temperature, is considered to be the inner heat generation term in the energy conservation equation. The CFD model can be used to predict conditions in the bulk under which the food damage due to condensation is likely to occur (Xu & Burfoot, 1999a, b).

During air blast cooling of cooked meats, heat conduction occurs through the meat body, while forced convection, radiation heat transfer and moisture evaporation take place on the interface between the cold airflow and the meat. In order to investigate the effects of variable operating conditions such as local surface heat transfer coefficient and the fluctuation of inlet temperature on the prediction accuracy, Hu & Sun (2000, 2001a, b, 2002) developed a CFD model to simulate the airflow condition in the air blast chiller with two fans for cooked meat joints and to further predict chilling rate and weight loss of the meats.

Future research topics

Improvements in accuracy of modelling

Although continuous progress has been made in recent years in improving the accuracy of the modelling, much research work still need to be carried out. The following discusses the possible areas where further research could be performed in order to further improve the accuracy of model prediction.

Surface heat and mass transfer coefficients

Heat and mass transfer coefficients are important parameters in modelling heating and cooling processes. The heat transfer coefficients of surface convection are mostly calculated using a correlation between a set of dimensionless numbers: Nusselt number ($\mathrm{Nu} = h_c L/\lambda$), Prandtl number ($\mathrm{Pr} = c\mu/\lambda$), Reynolds number ($\mathrm{Re} = \rho L u/\mu$) and Grashof number $\left(\mathrm{Gr} = L^3\rho^2 g\beta\Delta T/\mu^2\right)$ for flow across a body (Mallikarjunan & Mittal, 1994; Davey & Pham, 1997; Wang & Sun, 2002a, b, c). The surface mass transfer coefficient can be determined by using the Lewis relationship of heat and mass transfer coefficients, which is expressed as (Lewis, 1987):

$$\frac{h}{K_p h_{\mathrm{fg}}} = 64.7\ Pa/K \tag{7}$$

It should be noted that those correlations are normally restricted to a given range of operating conditions and reasonable accuracy can only be ensured under the given range of operating conditions. More attention should be paid to select a suitable correlation for a given case.

The heat transfer coefficients of surface convection can also be determined by fitting predicted temperatures to experimental data. The coefficient is determined by a trial and error method until the predicted model gives a good fit with experimental data (Sahin, Sastry, & Bayindirli, 1999; Varga & Oliveira, 2000). For an aseptic system of fluid-particle foods, the coefficient of each particle can be determined by a trial and error matching of predicted temperature contours from a numerical heat transfer model and magnetic resonance imaging (MRI) images (Hulbert, Litchfield, & Schmidt, 1997).

For simplicity, an average heat transfer coefficient of surface convection is used in most of simulations. However, with the advance of CFD technology, a CFD model can offer an effective and efficient tool to calculate the average and local heat transfer coefficients of surface convection with an acceptable cost (Kondjoyan & Boisson, 1997). Verboven, Nicolaï, Scheerlinck, and De Baerdemaeker (1997) used a two-dimensional CFD model (CFX package) to investigate the variation in heat transfer coefficient around the surface of foods. Their simulations found that around the rectangular shaped foods, there was a large variation in the local surface heat transfer coefficients. Using the local coefficients instead of the average surface coefficient caused changes in temperature in the foods to be considerably slower especially for slab-shaped foods and the coldest point was also no longer at the geometric centre.

Food properties

Thermal properties are another one of the most important factors determining the accuracy of model predictions. Part of thermal properties of food products can be found in publications available (i.e., Lewis, 1987; Mellor, 1983; Mellor & Seppings, 1976; Miles, van Beek, & Veerkamp, 1983; Rahman, 1995; Sweat, 1985).

The thermal properties of foods can be directly measured by experiments (Fasina & Flemin, 2001; Ghazala *et al*., 1995). For measuring physical properties, heat transfer models can be used to optimise the experimental design (Nahor, Scheerlinck, Verniest, De Baerdemaeker, & Nicolaï, 2001). The prediction accuracy of a model can be significantly improved by including temperature and composition-dependent thermal properties (Chen *et al*., 1999; Tewkesbury, Stapley, & Fryer, 2000). However, it is difficult for experimental measurement to obtain a detailed description of the relationship between thermal properties and temperature and compositions of foods. Alternatively, thermal properties of foods can be calculated from the compositions of foods and the thermal properties of each composition (Davey & Pham, 1997; Evans *et al*., 1996; Wang & Sun, 2002a, b, c, d, e). The compositions of foods can be measured before and/or after processing and the variation in the compositions during processing can be determined by mass transfer models. The main compositions of foods usually are water, protein, and fat and other compositions such as salt and ash are very small. The temperature-dependent thermal properties of those compositions can be measured or found in literatures (i.e., Lewis, 1987). It should be noted that the calculations for thermal properties from food compositions are based on empirical or semi-empirical relationship. More attention should be paid to select suitable correlation equations for a given case.

Thermal properties of foods can also be inversely found by using analytical or numerical heat transfer models and experimental temperature history. For determining a thermal property, an assumed value of the thermal property is first used to solve the numerical model. The predicted temperatures for given locations are compared with their corresponding measured values. The value of the thermal property is acceptable if the minimum difference between the predicted and measured temperatures is achieved (Schmalko, Morawicki, & Ramallo, 1997).

Shrinkage during thermal processes

Shrinkage in foods occurs due to moisture loss during thermal processes. Effects of shrinkage on the accuracy of models are sometimes significant (Balaban, 1989). Shrinkage is normally taken into account in models of drying processes (Rovedo *et al*., 1995; Simal *et al*., 2000; Wang & Brennan, 1995) and vacuum cooling (Wang & Sun, 2002d, e). Shrinkage can be expressed as functions of moisture and the functions are determined by experiments (Balaban, 1989; Wang & Brennan, 1995; Wang & Sun, 2002d, e).

Sensitivity analysis for judging assumptions in models

Accurate modelling of a thermal process of foods is complex. For simplification and saving of computational time, some assumptions made in the modelling are necessary. Furthermore, although cheap and high speed computers have become widely available, the computational speed is always very important for a processing control scheme with a numerical model. Most of assumptions come from the geometrical dimension and shape, surface heat and mass transfer coefficients, food materials properties and volume change during thermal processes. Before simulation, whether or not to use a model of coupled heat and mass transfer or coupled heat transfer and fluid flow should also be determined.

Sensitivity analysis can make judgement for the acceptability of an assumption in the modelling. Some research has been carried out to investigate the sensitivity of variables in interest such as temperature on operating conditions of a thermal system and thermal properties of foods (De Elvira, Sanz, & Carrasco, 1996; Nicolaï & De Baerdemaeker, 1996, 1999; Nicolaï, Verboven, Scheerlinck, & De Baerdemaeker, 1998; Nicolaï et al., 1999; Nicolaï, Scheerlinck, Verboven, & De Baerdemaeker, 2000; Varga, Oliveira, & Oliveira, 2000; Varga, Oliveira, Smout, & Hendrickx, 2000; Verboven, Scheerlinck, De Baerdemaeker, & Nicholaï, 2001). Findings from the research include that the time and location-dependent variations in operating conditions such as variable temperature and surface heat transfer coefficient cause the detachment of the thermal and geometric centres during processing of foods (De Elvira *et al*., 1996). For simulating a thermal process with low heat transfer coefficient, small deviations in the coefficient may result in large deviations in the core temperature of foods (Nicolaï & De Baerdemaeker, 1996; Verboven *et al*., 2001). The disturbances of different means but with the same scale of fluctuation in heating/cooling medium temperature resulted in comparable centre temperature variation (Nicolaï *et al*., 1999). For a typical sterilisation process, it found that thermal-physical properties were the most important sources of variability (Nicolaï *et al*., 1998; Nicolaï & De Baerdemaeker, 1999; Nicolaï *et al*., 2000).

It is stressed from the findings of sensitivity analyses in the publications that more efforts should be made to judge the acceptability of an assumption in the modelling.

Coupled heat and mass transfer with other models for analysing food safety and quality

One of the critical roles of modelling technology in the food industry is to analyse a thermal process for producing a food product with high safety and quality. During heating/cooling processes, biochemical reaction such as enzyme inactivation, microbial deactivation such as bacterial growth, and mechanical characteristics such as thermal and hydro stress are temperature and moisture-dependent. More attempts can be made to associate other models such as biochemical reaction (Chavez, Luna, & Garrote, 1997;Martens, Scheerlinck, De Belie, & De Baerdemaeker, 2001), microbial deactivation (Avila, Manso, & Silva, 1996; Bellara, McFarlane, Thomas, & Fryer, 2000; Ghani *et al*., 1999b) and mechanics models (Jia *et al*., 2000b) with the current heat and mass transfer models for further evaluating the safety and quality of foods during heating/cooling processes.

Computer-assisted design and model predictive control

The application of numerical modelling of heating/cooling processes will benefit the understanding of the physics of a food processing operation and thus aid in design, optimisation and control of a processing system. With a large volume of models available in the food industry, more research should be stressed to practically use those models in design and control of a thermal processing system. For designing a heating/cooling system, a numerical model is a powerful engineering tool. With advances in computer power, the accuracy of numerical models can be improved by including less assumption. However, for a control scheme with a numerical model, computational speed is always very important to make a model operative.

A heating/cooling system cannot be manually controlled with the precision required to realise its advantages. Therefore, it is necessary to develop an advanced control system integrated with process optimisation for a thermal process. Most of advanced control strategies use a predictive model to improve the performance of the controlled system. Model predictive controls (MPC) are especially well suited for food processes because of their ability to deal with delays (Haley & Mulvaney, 1995). Van Der Sluis, Vijge, and Wouters (1999) has recently reported a successful application of a finite element on-line predictive simulation scheme in the control system of a refrigeration plant.

Challenges in the mechanisms underlying in the mathematical models

Heat and mass transfer through porous foods

Drying and vacuum cooling of moisture and porous foods are widely used in the food industry. Those thermal processes involve coupled heat and mass transfer through a porous media. It is still difficult to predict the moisture transfer rate through a porous media because the mechanisms involved are complex and not completely understood. As a result, the design of drying process and vacuum cooling process remains largely an art based on experience gained from trial and error testing. Often, the controlling resistance is internal mass transfer and the internal mass transfer may occur through the solid phase or within the void spaces. Several mechanisms of internal mass transfer including vapour diffusion, moisture diffusion and surface evaporation, hydrodynamic flow and capillary flow have been proposed. However, Bruin and Luyben (1980) point out that modelling is complicated because there is nearly always more than one mechanism to the total flow.

Microwave heating process

During microwave heating, the heating patterns can be uneven. Food factors such as dielectric properties, size and shape play a more important role as compared to conventional heating because they affect not only the magnitude of heat generation but also its spatial distribution (Zhang, Datta, Taub, & Doona, 2001). Modelling of microwave heating process involves solutions of electromagnetic equation and the energy equation. Lambert's law is a simple and commonly used power formulation, according to which the microwave power is attenuated exponentially as a function of distance of penetration into the sample. Although Lambert's law is valid for samples thick enough to be treated as infinitely thick, it is a poor approximation in many practical situations. In such cases, a rigorous formulation of the heating problem requires solving Maxwell's Equations, which govern the propagation of electromagnetic radiation in a dielectric medium (Ayappa, Davis, Crapiste, & Gordon, 1991, Burfoot, Raitton, Foster, & Reavell, 1996). During microwave heating, a large temperature change may cause significant variations in dielectric properties, resulting in big change in the heating pattern. Therefore, a coupled Maxwell's equation with the heat transfer model is necessary to describe the microwave heating process. Besides, the potential for nonuniformity in the microwave heating process should be comprehensively described. Also, there occurs moisture accumulation at the food surface during microwave heating (Datta & Ni, 2002). Therefore, challenging is to understand the mechanism of microwave heating, gain insight into the changes in heating patterns and verify the temperature distribution during microwave heating, and develop a coupled heat, moisture and electromagnetic transfer model.

Turbulence flow during heating and cooling processes

Turbulence is a phenomenon of great complexity and has puzzled theoreticians for over a hundred years. What makes turbulence so difficult to tackle mathematically is the wide range of length and time scales of motion even in flows with very simple boundary conditions. No single turbulence model is universally accepted as being superior for all classes of problems. The standard k–ϵ model is still highly recommended for general purpose CFD computation. The mechanism of k–ϵ models is derived for equilibrium flows in which the rates of production and destruction of turbulence are nearly balanced (Versteeg and Malalasekera, 1995). This assumption has been proven to be valid only in high Reynolds number flows and relatively far from the wall in the boundary layer. At low Reynolds numbers (smaller than 30,000), it was known that simplified turbulence models, such as k–ϵ models or even the modified k–ϵ models by the near-wall treatment based either on a wall function or on Wolfshtein's low-Reynolds number are rough approximations of reality. In many cases these semi-empirical models will fail to predict the correct near-wall limiting behaviour near the product surface. However, k–ϵ models remain popular because of their availability in user-friendly codes, which allows a straightforward implementation of the models, and because they are cheap in terms of computation time. Predictions by general codes based k–ϵ model are often very different from experimental data. As the shape of many food products is very complex, the experimental determination of heat transfer coefficients remains at the time quicker and much more reliable than predictions. The calculation based on the current CFD codes has to be used with caution and more research is needed to improve near-wall modelling particularly around blunt bodies placed in a turbulent flow. A full treatment of turbulence would require more complex models such as large eddy simulations (LES) and Reynolds stress models (RSM). However, LES models require large computing resources and not of use as general-purpose tools. As the RSM accounts for the effects of streamline curvature, swirl, rotation, and rapid changes in strain rate in a more rigorous manner compared to the k–ϵ models, it has greater potential to give accurate predictions for complex flows. However, the fidelity of RSM predictions is still limited by the closure assumptions used to model various terms in the exact transport equations for the Reynolds stresses. The modelling of the pressure-strain and dissipation-rate terms is particularly challenging. Therefore, the RSM with additional computational expense might not always yield results that are clearly superior to simpler models in all cases of flows. The mathematical expressions of turbulence models may be quite complicated and they contain adjustable constants that need to be determined as best-fit values from experimental data. Therefore, any application of a turbulence model should not beyond the data range. Besides, the current turbulence models can be used to guide the development of other models through comparative studies.

Conclusions

The finite difference scheme, which is a simple numerical method in its implementation, is widely used to model heating/cooling processes of simple geometric foods in the food industry. However, the finite element method may perform better than the finite difference method for irregular geometries and heterogeneous materials. The finite volume method is widely used in the CFD scheme, and computationally expensive CFD scheme can be used to deal with complex boundary conditions and coupled fluid flow and heat transfer problems.

The use of numerical methods to describe the heating/cooling processes in the food industry has produced a large number of models. Some assumptions such as simplified geometrical shape, constant thermal physical properties, constant surface heat and mass transfer coefficients and no volume change during processing were widely used in modelling. However, more research should be conducted to justify the acceptability of those assumptions by sensitivity analysis and to improve the accuracy of models by finding more information on surface heat and mass transfer coefficients, food properties and shrinkage during processing. Before numerical methods can become a quantitative tool for correctly analysing thermal processes, determination of thermal physical propensities and surface mass and heat transfer coefficients remains an important area to be studied.

The numerical heat and mass models have the potential to incorporate with other models such as biochemical reaction, microbial reaction and mechanical stress for further evaluating the safety and quality of food products during heating/cooling treatments. It is expected that more research will be carried out on the heat and mass transfer through porous foods, microwave heating and turbulence flow in heating/cooling processes. More research on the applications of numerical models for practically designing and controlling food heating/cooling processes is significant.

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