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Modelling heat transfer and fluid flow inside a pressure cooker

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Abstract

Heat transfer and fluid flow were simulated with a 3-dimensionnal CFD approach inside a pressure cooker in order to predict gas and product temperature evolution and its heterogeneity. Different difficulties appear because of geometric complexity and of many coupled phenomena: evaporation and condensation of vapour in presence of non-condensable gas, natural convection in an unstable configuration, pressure increase with time, density variation with composition, temperature and pressure. The general trends experimentally observed could be reproduced by simulation and some phenomena which are very difficult to characterise experimentally (fluid flow) could be better understood. The further aim of the work is to use numerical simulation for the choice of operating conditions and equipment design.

Keywords : pressure cooker, CFD, heat transfer, fluid flow, condensation

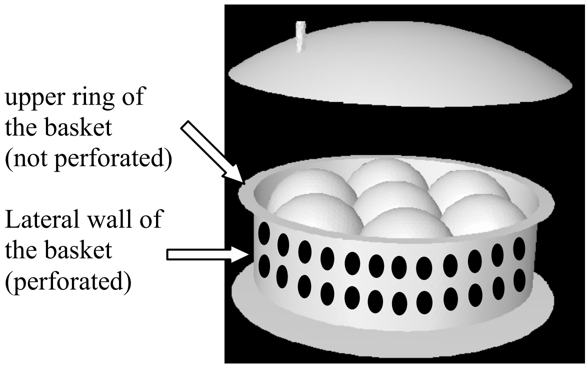
1. Introduction

Pressure cooker allows rapid and energy saving cooking of various food products. Short time - high temperature heat treatment combined with absence of oxygen (excepted at the beginning of treatment) can also lead to a better preservation of some nutriments. But both thermal phenomena and bio-chemical transformation of food during pressure cooking are very poorly understood.

This leads to an empirical choice of operating conditions (required heating power at different stages of cooking, etc) and equipment design (vessel, basket, lid geometry, etc). Indeed, literature which refers to pressure cookers concerns mainly its utilisation to reach temperatures higher than 100°C in presence of water in order to analyse the effect of temperature on various food properties (texture, nutriments, colour, etc) [1]. Some studies are related to energy consumption [2] and a lumped thermal model was proposed for a solar pressure cooker [3]. Some CFD studies were performed on cooking processes [4] including natural convection but few studies deal with evaporation/condensation in presence of non condensable gas in closed cavities [5]. The aim of this study was to simulate with a CFD approach the thermal phenomena inside a pressure cooker in order to predict the temperature evolution in the food product.

2. Modelling approach

Coupled unsteady equations for fluid flow, heat transfer and mass transfer (air and water vapour) were solved using the finite volume method (Fluent software 6.2). The 3-dimensional geometry comprised an almost cylindrical vessel equipped with a pressure valve and a basket containing 7 spherical food products. This geometry was meshed using 736 000 tetrahedral and hexahedral cells (figure 1)



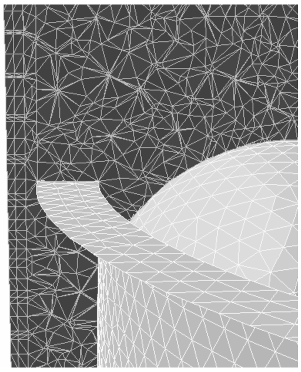


Figure 1 : geometry and mesh

According the Rayleigh number value (based on cooker height and typical temperature difference of 60K) Ra ≈ 3.10^7, gas flow is assumed as laminar in the vessel. The perforated basket is represented by a pressure drop proportional to the squared superficial velocity according to the relation proposed by Van Winkle *et al* [6], the holes area being 50% of the total area. It has to be mentioned that only the bottom and the lateral cylindrical walls of the basket are perforated, the upper ring is a non perforated wall.

Water evaporates from the bottom and condensates on lateral wall, cover and food product surface (liquid water flow is not represented). There is no tool in the software to represent directly condensation or evaporation. But it includes a surface reaction tool which can be used to take into account the coupled mass and energy balances of condensation and evaporation. This approach also takes into account the presence of air which limits condensation. Two ‘reactions’ were defined with specific reaction rates : R_1 and R_2 (mol.m^{-2}.s^{-1})

$$H_20_{vap} \rightarrow H_20_{liq} \quad R_1 = k\, T\, c_{vap} \qquad \text{(eq.1)}$$

where T is the temperature and c_{vap} is the local molar concentration of water vapour (near the condensation surface)

$$H_20_{liq} \rightarrow H_20_{vap} \quad R_2 = k\frac{p_{sat}(T)}{R} \approx k\frac{p_{sat}(T_0)}{R}\exp\left(-\frac{\Delta H}{R}\left(\frac{1}{T}-\frac{1}{T_0}\right)\right) \qquad \text{(eq.2)}$$

where T is the surface temperature, ΔH is the molar latent heat of vaporisation and T_0 is a reference temperature.

Thus, at equilibrium ($R_1 = R_2$), the dew point equation would be satisfied:

$$c_{vap} = \frac{p_{sat}(T_{dew})}{RT} \qquad \text{(eq.3)}$$

The net molar condensation flux can be expressed using the dew point temperature (T_{dew}) and the surface temperature T:

$$kT\left(c_{vap} - \frac{p_{sat}(T)}{RT}\right) = \frac{k}{R}\left(p_{sat}(T_{dew}) - p_{sat}(T)\right) \qquad \text{(eq.4)}$$

This condensation flux corresponds to a heat flux of :

$$\frac{k}{R}\left(p_{sat}(T_{dew}) - p_{sat}(T)\right)\Delta H \approx \frac{k}{R}\left.\frac{dp_{sat}}{dT}\right|_{T_0}\Delta H(T_{dew} - T) = h(T_{dew} - T) \qquad \text{(eq.5)}$$

$$\text{with } h = \frac{k}{R}\left.\frac{dp_{sat}}{dT}\right|_{T_0}\Delta H = \frac{k\,\Delta H^2}{R^2 T_0^2}p_{sat}(T_0)$$

In the present study T_0=373K and h=500 W.m^{-2}.K^{-1}. This corresponds to the thermal resistance of a condensate film of about 1mm. The air and water vapour mixture was considered as a perfect gas, mixing and diffusion was taken into account. Heat transfer included convection and conduction in the gas, conduction inside the food products and latent heat of evaporation or condensation. The thermal properties of potatoes [7] were chosen for the food product. A conducting shell model was used for the cooker walls made in stainless steal. An external heat transfer coefficient of 10 W.m^{-2}.K^{-1} was assumed (value obtained from experimental heat loss estimation). At the beginning of cooking the valve is closed and the pressure increases up to 1.5 bar because of gas temperature rise and imbalance between evaporation and condensation. The Mach number is very low and the Navier-Stokes equations can still be used with a slowly variable and heterogeneous density. At this stage, fluid flow is due to natural convection (density depending on local temperature and composition) and to evaporation/condensation (vapour flowing from or toward the fluid phase boundaries). Further, the pressure is kept constant at 1.5 bar at the valve outlet. At this stage, fluid flow in the vessel is also due to the gas outflow through the valve.

3. Results and discussion

The numerical results were compared with temperature measurements obtained during cooking of almost spherical potatoes. No velocity measurements were performed. The heat flux imposed at the bottom face was 1000 W during all the cooking time. Figure 2 compares experimental and numerical results for the pressure, the gas temperature at the center of the cooker and the core temperature of the central potato. The general trends are similar. But there is a time lag between experimental and numerical results because of the thermal inertia of the hotplate which is not taken into account in the simulation. Other differences appear also which can be due to the approximation of the geometry and of some parameters. For example, the external heat transfer coefficient and the thermal resistance of condensate film should be more precisely estimated and should be different for the cover and the lateral wall. At this stage, the CFD model is not appropriate for quantitative prediction. But it can give qualitative information about fluid flow, air stagnation and heterogeneity of heat transfer.

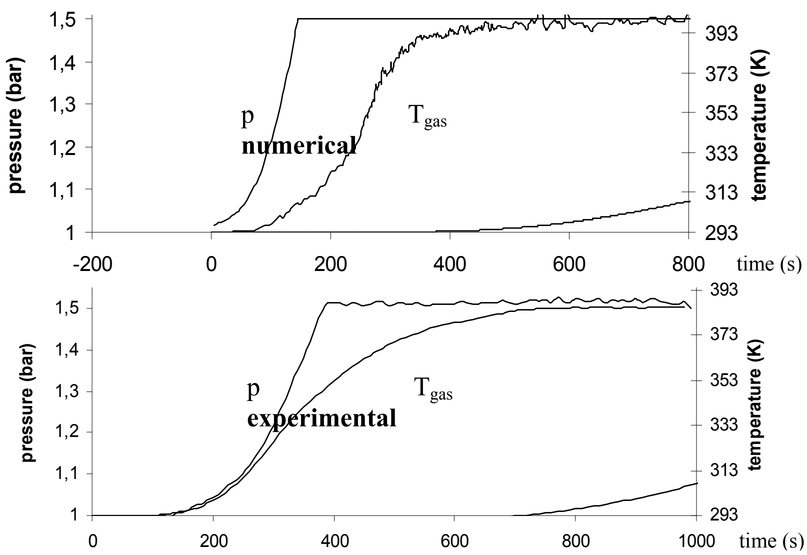


Figure 2 : pressure, gas temperature, core food product temperature

Just before valve opening (t=145s), it can be observed from the simulation (figure 3) that there is a hot and wet zone near the bottom where water is heated up and evaporates. The spherical products and the upper ring of the basket act as a separation between the bottom and top regions. The top zone is quite homogeneous; temperature and humidity remaining close to the initial values at this moment. In the bottom region, convection is due notably to evaporation at the water surface and condensation on the lateral wall (figure 4). In the top region, there is also an intensive gas circulation due to natural convection. But mixing is low between the two regions because of the separation effect of the food products and upper ring of the basket. This type of basket was replaced by some manufactures by totally perforated baskets and the present study confirms the interest of such new types of basket.

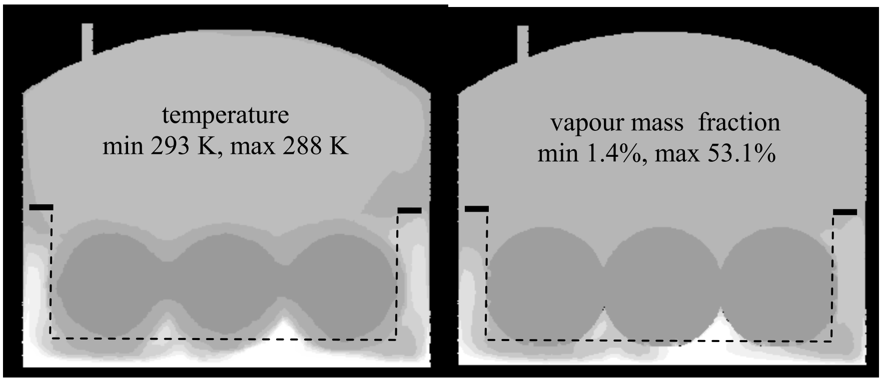


Figure 3 : Temperature and vapour mass fraction in the symmetry plane (vertical plane including the valve) just before valve opening (t=145s).

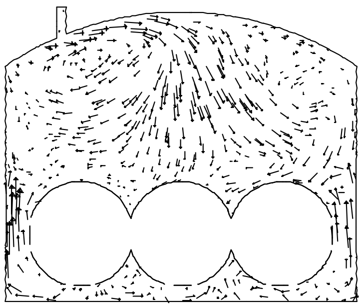


Figure 4 :

Velocity in the symmetry plane (t=145 s) (v_{max} =0.38 m/s)

Condensation is much more important at the bottom face of the food products than at the upper face (figure 5). This can lead to heterogeneity of cooking because starch gelatinization, texture modification, etc are highly thermal dependent.

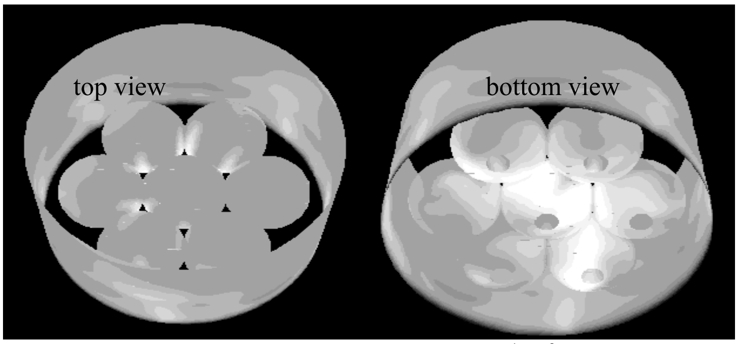


Figure 5 : Condensation mass flow rate (maximal value : 2.5 $g.s^{-1}.m^{-2}$)

4. Conclusions/future work

In spite of the modelling difficulties (condensation of vapour in presence of air, pressure increases, etc) the general trends experimentally observed could be reproduced with 3D CFD. Some phenomena which are difficult to characterise experimentally were observed in the simulation, as for example a separation effect related to an old basket design. The further aim is to use numerical simulation for the choice of operating conditions and equipment design (vessel, basket, lid geometry). The approach used for condensation in presence of non condensable gas could also be applied to analyse spatial heterogeneity for other processes like autoclave sterilisation or industrial cooking in vapour oven.

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