RESULTS

Numerical Simulations and Experiments with

BACON PREPARATION IN A MICROWAVE

EiT - Matematikk Innen Anvendelser

gruppe 5 - FUÞARK - ᚠᚢᛏᚼᚾᚱᚴ -

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2011

Abstract

Text in abstract

Preface

Text in foreword

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April 6, 2011

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Chapter 1

Introduction

1.1 Problem formulation

The problem considered in this project is the preparation of bacon in a microwave oven. Bacon is defined as cured meat from side and back cuts of a pig. A microwave oven in this context is a household appliance typically delivering 750 W of microwave effect at a frequency of 2.1 GHz to a Faraday cage of volume 40 liters.

The motivation for the problem formulation was clear. As soon as modeling of food preparation was brought on the table, bacon seemed a prime choice. A microwave oven may seem an odd choice for bacon, but previous experiments have shown that optimal bacon can consistently be attained with this preparation method. Obvious advantages over traditional bacon preparation include less cleaning up to do afterwards and a shorter time-to-plate. The caveat is that microwave preparation is less suitable for feedback during the cooking process, as the bacon is obscured from view. To the traditional bacon chef, used to a touch-and-go approach, this is an obstacle to implementation, as overcooking bacon in a microwave oven yields inedible results. The purpose of this work, then, is to establish reliable numerical simulations that can serve as a basis for estimating cooking time for an arbitrary slice of bacon.

As the project considers the optimal preparation of bacon in a microwave oven, two natural questions were formulated:

- How is preparation of bacon in a microwave oven modelled numerically?
- How does water and fat content affect the preparation, and what preparation time is optimal?

1.2 Reasoning behind the problem formulation

The first question is obvious, as any attempt at predicting the preparation time necessitates a numerical model of bacon in a microwave oven; a simple glance at the relevant equations tells the experienced numerics person that no analytical solution exists. With a numerical solution of the heat and mass transport equations, the optimal preparation time can be predicted. But this presumes an understanding of what makes good bacon. So what does?

Work done by [1] and [3] suggest that two factors are important in determining good bacon. The first is a high enough temperature that the Maillard reaction can take place, which happens around 140^{circ}C. The second is that a significant proportion of the fat has melted and has been transported out of the bacon. Both of these factors are naturally affected by the composition of the bacon; especially water and fat content will play a major role.

Having identified these two factors as the important criteria for an optimal solution, experimental work is needed to determine the correlation between temperature and fat loss, and how finished bacon is. This is, of course, also a subjective question - different people prefer different grades of crispness.

Another experimental question is how much of the microwave effect that is absorbed by the bacon. The second law of thermodynamics dictates that some of the effect is lost in the microwave magnetron, the question is how much effect is dissipated in the bacon. This may include losses besides that of the magnetron, which has a typical efficiency of 65% [4]. It turns out that common household microwave ovens are rated to include this loss, with standardized calibration procedures published by the IEC's SC 59K, so a 750 W microwave oven will typically draw 1.1 kW of electrical power from the mains socket. This means using the rated power will be good enough for our purposes.

Finally, experiments are needed to verify the accuracy of the numerical results. As heat and mass transport is a Complicated Problem, this is not guaranteed a priori.

Chapter 2

Theory

2.1 The physical system

The physical system to be modeled is a thin, rectangular strip of bacon which is subjected to approx. 750 watts of microwave radiation at the frequency of 2.4 GHz. To be modeled is the heat in the strip, phase transitions and transport.

2.2 Our approach

Figure 2.1: Our initial approach to the problem. xkcd.com/793

Initially, our approach to modelling was to use a staggered approach: first solve the heat equation for the three media meat, solid fat, and liquid fat, thus giving the temperature at step n. Then at step $n+1$, the temperature is regarded as known, and we solve the transport equation for liquid fat out of the bacon. Then we know the distribution of liquid fat at step $n+2$, where we solve the heat equations again, and we repeat ad nauseam.

2.3 The heat equations

The differential equations governing the heat transport are all variations of the heat equation, with various source terms, eq. (2.1):

$$(\rho c_p)_m \frac{\partial T}{\partial t} - \alpha_m \nabla^2 T = J^{MW} \quad \text{m}, \tag{2.1}$$

$$\eta_s (\rho c_p)_s \frac{\partial T}{\partial t} - \eta_s \alpha_s \nabla^2 T = J^{MW} - J^{Melt} \quad \text{s}, \tag{2.2}$$

$$\eta_l (\rho c_p)_l \frac{\partial T}{\partial t} - \eta_s \alpha_l \nabla^2 T - \eta_l (\rho c_p)_l (\mathbf{v} \cdot \nabla) T = J^{MW} \quad \text{l}. \tag{2.3}$$

Here the subscript m denotes meat, s denotes solid fat, and l denotes liquid fat. J^{MW} is the source term representing the microwave oven. In the initial approach, this is modelled as a cylindrically symmetric term, with the radial power distribution on the form eq. (2.4),

$$J^{MW}(r) = 0.5 + 2.55008x - 0.588013x^2 + 0.032445x^3 + 0.00124411x^4 - 0.0000973516x^5, \tag{2.4}$$

i.e. a fifth degree polynomial, interpolated from the results in [2].

Furthermore, there is the term J^{Melt} which represents heat loss due to latent heat absorbed in the solid-liquid phase transition. This can be written as

$$\frac{L\rho}{T_2 - T_1} \frac{\partial T}{\partial t}, \quad \mathrm{T} \in (\mathrm{T}_1, \mathrm{T}_2),$$

where the fat is melting between the temperatures T_1 and T_2. For fat these are typically around 30-50°C. For $T \notin (T1, T2)$ this term is zero, and it is readily seen that this is equivalent to a modification of the constant $c_{p,l}$ in eq. (2.1) when $T \in (T1, T2)$, thus it is not a serious complication.

In the last of the heat equations, there also appears what is called a convective derivative, on the form $(\mathbf{v} \cdot \nabla)T$. This is a somewhat more complicated term, and is essentially a modification due to transport of liquid fat implying an implicit transport of heat. But, we're in luck, boys!

As the bacon strip is essentially two-dimensional, transport will almost exclusively happen in the vertical (small) direction. In our approach, the source terms don't vary in the vertical direction, so this term will be a transport of heat in the vertical direction. This will not affect the heat transport in the horisontal directions. As we're not really interested in the vertical temperature distribution, this means that we can happily neglect this term, in the spirit of Richard Feynmann: “it doesn’t give any new physics”.

2.4 The transport equations

The transport equation used in our approach is the one-dimensional Navier Stokes equation, with the additional assumptions of an incompressible, Newtonian flow. This is the same as ignoring phenomena where sound waves or shock waves are important, which makes sense here. This leads to the equation eq. (2.5)

$$\rho\left(\frac{\partial\vec{v}}{\partial t}+\vec{v}\cdot\frac{\partial\vec{v}}{\partial x}\right)=-\frac{\partial p}{\partial x}+\mu\nabla^2\vec{v}+\vec{f} \tag{2.5}$$

where $\vec{f}$ includes any additional forces, such as gravity. This term is discussed in further detail below. An interesting term here is $\frac{\partial p}{\partial x}$, where p is the pressure in the fluid. Following the work by [**?**], we replace this with a term inspired by eq. (2.6)

$$\frac{\partial p}{\partial x}=-C\frac{1-\eta^2}{\eta^3}\vec{v_a} \tag{2.6}$$

where η is the melted fraction in the current volume element, and $\vec{v_a}$ is an apparent velocity. This is known as the Carman-Kozeny equation for flow in a pouros medium, and is applicable to materials where melting does not happen at one specific temperature, but instead over a range of temperatures. This is typical for a material with a combination of slightly different fats, e.g. chocolate or in this case bacon. When a volume element is partially melted, it is assumed to have a dendritic structure, and it is said to be in a “mushy” phase. The dendritic structure itself, and whether the flow is parallell or orthogonal to the dendritic structure, will influence the constant C.

Chapter 3

Numerics

3.1 Numerical schemes

In this project we have use the Cranch-Nicholson method to discretize the heat equation eq. (2.1) in 3D over a finite grid. The Crank-Nicholson method is based on the equation eq. (3.2), where the trapezoidal rule eq. (3.3) is used to approximate the integral on the right hand side. We insert the right hand side of the heat equation in the resulting expression eq. (3.3), and use Taylor-expansion to obtain the discretizaion. We use the notation eq. (3.1) in the rest of the document.

$$\partial_x^k u = \frac{\partial^k u}{\partial x^k}, \qquad \partial_t^k u = \frac{\partial^k u}{\partial t^k} \qquad u_m^{n+\alpha k} = u(x_m, t_n + \alpha k) \tag{3.1}$$

$$u(x_m, t_{n+1}) - u(x_m, t_n) = \int_{t_n}^{t_{n+1}} u_t(x_m, t)dt \tag{3.2}$$

$$\int_0^k f(t)dt = \frac{1}{2}k(f(0) - f(k)) - \frac{1}{12}k^3 f''(\frac{k}{2}) + ... \tag{3.3}$$

We thus obtain

$$\begin{aligned} u_m^{n+1} &= u_m^n + \frac{1}{2}k(\partial_t u_m^n + \partial_t u_m^{n+1}) - \frac{1}{12}k^3\partial_t^3 u_m^{n+\frac{1}{2}} \qquad (3.4) \\ &\overset{\text{heat eq.}}{=} u_m^n + \frac{1}{2}k(\partial_x^2 u_m^n + \partial_y^2 u_m^n + \partial_z^2 u_m^n + \partial_x^2 u_m^{n+1} + \partial_y^2 u_m^{n+1} + \partial_z^2 u_m^{n+1}) - \frac{1}{12}k^3\partial_t^3 u_m^{n+\frac{1}{2}} \end{aligned}$$

Using central differences eq. (3.5), and denoting the step sizes in x, y, z direction by h, f, g respectively, gives

$$\begin{aligned} u_m^{n+1} &= u_m^n + \frac{1}{2}k(\frac{1}{h^2}\delta_x^2 u_m^n + \frac{1}{f^2}\delta_y^2 u_m^n + \frac{1}{g^2}\delta_z^2 u_m^n + \frac{1}{h^2}\delta_x^2 u_m^{n+1} + \frac{1}{f^2}\delta_y^2 u_m^{n+1} + \frac{1}{g^2}\delta_z^2 u_m^{n+1}) \\ & -\frac{1}{2}k(\frac{1}{12}h^2\partial_x^4 u_m^n + \frac{1}{12}g^2\partial_y^4 u_m^n + \frac{1}{12}f^2\partial_z^4 u_m^n + \frac{1}{12}h^2\partial_x^4 u_m^{n+1} + \frac{1}{12}g^2\partial_y^4 u_m^{n+1} + \frac{1}{12}f^2\partial_z^4 u \\ & -\frac{1}{12}k^3\partial_t^3 u_m^{n+\frac{1}{2}} \end{aligned}$$

where

$$\delta_r^2 U_m^n = \frac{U_{m+1}^n - 2U_m^n + U_{m-1}^n}{\Delta r^2} \tag{3.5}$$

We thus obtain the implicit method for the heat equation

$$u_m^{n+1} - k(\frac{1}{h^2}\delta_x^2 u_m^{n+1} - \frac{1}{f^2}\delta_y^2 u_m^{n+1} - \frac{1}{g^2}\delta_z^2 u_m^{n+1}) = u_m^n + k(\frac{1}{h^2}\delta_x^2 u_m^n + \frac{1}{f^2}\delta_y^2 u_m^n + \frac{1}{g^2}\delta_z^2 u_m^n) \tag{3.6}$$

with truncation error error

$$\frac{\tau_m^n}{k} = -\frac{1}{12}k^2\partial_t^2 u_m^{n+\frac{1}{2}} - \frac{1}{12}h^2\partial_x^4 u_m^{n+\frac{1}{2}} - \frac{1}{12}g^2\partial_y^4 u_m^{n+\frac{1}{2}} - \frac{1}{12}f^2\partial_z^4 u_m^{n+\frac{1}{2}} \tag{3.7}$$

$$= O(k^2 + h^2 + g^2 + f^2) \tag{3.8}$$

Here we have used that $\frac{1}{2}(\partial_x^4 u_m^n + \partial_x^4 u_m^{n+1}) = \partial_x^4 u_m^{n+\frac{1}{2}} + O(k^2)$. The truncation error $\tau_m^n \Rightarrow 0$ as $h, f, g, k \Rightarrow 0$, and the Crank-Nicholson method is consistent for the heat equation. To see if the method converges we perform a von Neumann analysis of the numerical scheme.

3.2 Von Neumann analysis of the Crank-Nicholson-scheme

The von Neumann analysis is based on Fourier analysis. The method consist of substituting

$$U_m^n = \xi^n e^{i\beta x_m} \qquad i = \sqrt{-1}$$

in the difference equation and solve for ξ. For the method to be stable it has to meet the condition

$$\mid \xi \mid \leq 1 \tag{3.9}$$

Here we only perform the Neumann analysis for the one-dimensional heat equation problem. We thus obtain the expression

$$\xi^{n+1}e^{i\beta x_j} = \xi^n e^{i\beta x_j}(1-2D) + \xi^{n+1}D\left(e^{i\beta x_{j+1}} - 2e^{i\beta x} + e^{i\beta x_{j-1}}\right) + \xi^{nD}\left(e^{i\beta x_{j+1}} + e^{i\beta x_{j-1}}\right)$$

where

$$D = \frac{1}{2}\frac{\alpha \Delta t}{(\Delta x)^2}$$

A typical **C**ourant-**F**riedrichs-**L**ewy condition is an inequality of the form $\frac{\Delta t}{\Delta x} < C$, with C a constant.

Dividing by $\xi^n e^{i\beta x_j}$, and using $x_{j+1} = x_j + h$ one obtains

$$\begin{aligned}
\xi\left[1 - D\left(2\cos\beta h - 2\right)\right] &= 1 - 2D\left(1 - \cos\beta h\right) \\
\cos\beta h &= \frac{1}{2}\left(1 - \sin^2\frac{\beta h}{2}\right) \\
\xi\left(1 + 4D\sin^2\frac{\beta h}{2}\right) &= 1 - 4D\sin^2\frac{\beta h}{2} \\
\xi &= \frac{1 - 4D\sin^2\frac{\beta h}{2}}{1 + 4D\sin^2\frac{\beta h}{2}}
\end{aligned}$$

As the maximum value of $\sin^2 x$ is 1, the methods meets the stability condition 3.9.

$$|\xi| = \left|\frac{1-4D}{1+4D}\right| \tag{3.10}$$

Since D always are positiv, we get that the Crank-Nicolson scheme for the heat equation is *unconditionally stable*. In practice it may happen that the method oscillates if the time steps and space steps do not fulfill a CFL-condition.

From Lax' equivalent theorem, which state that a consistent difference scheme will converges if and only if it is stable, the Crank-Nicholson scheme will converge.

3.3 Truncation error in the Crank-Nicolson scheme

The Crank-Nicholson method is based on the trapezoidal rule. From the trapezoidal rule the truncation error is represented by

$$\int_0^k f(t)dt = \frac{1}{2}k(f(0) - f(k)) - \frac{1}{12}k^3 f''(\frac{k}{2}) + ...$$

Using the formula

$$u(x_m, t_{n+1}) - u(x_m, t_n) = \int_{t_n}^{t_{n+1}} u_t(x_m, t)dt$$

and approximating the integral by the trapezoidal rule, and abbreviate the notation $u_m^{n+1/2} = u(x_m, t_n + \frac{1}{2}k)$, one obtain

$$\begin{aligned}
u_m^{n+1} &= u_m^n + \frac{1}{2}k(\partial_t u_m^n + \partial_t u_m^{n+1}) - \frac{1}{2}k^3\partial_t^3 u_m^{n+\frac{1}{2}} \\
&\overset{\text{heat eq.}}{=} u_m^n + \frac{1}{2}k(\partial_x^2 u_m^n + \partial_y^2 u_m^n + \partial_z^2 u_m^n + \partial_x^2 u_m^{n+1} + \partial_y^2 u_m^{n+1} + \partial_z^2 u_m^{n+1}) - \frac{1}{2}k^3\partial_t^3 u_m^{n+\frac{1}{2}}
\end{aligned}$$

Discretizing the double derivative with central differences, and denoting the step sizes in x, y, z direction by h, f, g respectively, gives

$$\begin{aligned}
u_m^{n+1} &= u_m^n + \frac{1}{2}k(\frac{1}{h^2}\delta_x^2 u_m^n + \frac{1}{f^2}\delta_y^2 u_m^n + \frac{1}{g^2}\delta_z^2 u_m^n + \frac{1}{h^2}\delta_x^2 u_m^{n+1} + \frac{1}{f^2}\delta_y^2 u_m^{n+1} + \frac{1}{g^2}\delta_z^2 u_m^{n+1}) \\
&\quad -\frac{1}{2}k(\frac{1}{12}h^2\partial_x^4 u_m^n + \frac{1}{12}g^2\partial_y^4 u_m^n \frac{1}{12}f^2\partial_z^4 u_m^n + \frac{1}{12}h^2\partial_x^4 u_m^{n+1} + \frac{1}{12}g^2\partial_y^4 u_m^{n+1} \frac{1}{12}f^2\partial_z^4 u_m^{n+1}) \\
&\quad -\frac{1}{2}k^3\partial_t^3 u_m^{n+\frac{1}{2}} \\
&= u_m^n + \frac{r}{2}(\delta_x^2 u_m^n + \delta_x^2 u_m^{n+1}) + \frac{p}{2}(\delta_y^2 u_m^n + \delta_y^2 u_m^{n+1}) + \frac{q}{2}(\delta_z^2 u_m^n + \delta_z^2 u_m^{n+1}) + \tau_m^n
\end{aligned}$$

where $r = k/h^2$, $p = k/f^2$, $q = k/g^2$, and τ_m^n is the truncation error times k. The expression for τ_m^n is

$$\tau_m^n = -\frac{1}{12}k^3\partial_t^2 u_m^{n+\frac{1}{2}} - \frac{1}{12}kh^2\partial_x^4 u_m^{n+\frac{1}{2}} - \frac{1}{12}kg^2\partial_y^4 u_m^{n+\frac{1}{2}} - \frac{1}{12}kf^2\partial_z^4 u_m^{n+\frac{1}{2}}$$

where we have used $\frac{1}{2}(\partial_x^4 u_m^n + \partial_x^4 u_m^{n+}) = \partial_x^4 u_m^{n+\frac{1}{2}} + O(k^2)$. Hence, the truncation error is

$$\begin{aligned}
\frac{\tau_m^n}{k} &= -\frac{1}{12}k^2\partial_t^2 u_m^{n+\frac{1}{2}} - \frac{1}{12}h^2\partial_x^4 u_m^{n+\frac{1}{2}} - \frac{1}{12}g^2\partial_y^4 u_m^{n+\frac{1}{2}} - \frac{1}{12}f^2\partial_z^4 u_m^{n+\frac{1}{2}} \\
&= O(k^2 + h^2 + g^2 + f^2)
\end{aligned}$$

Chapter 4

Implementation

4.1 Tools

The programming language chosen to implemented the system was c++. The arguments leading to this choice was:

- Most of the group members had some earlier experience with the language.
- It allows for a high level of abstraction without loosing control of the underlying hardware.
- The code can be easily parallelized for shared memory machines using OpenMP.
- Many libraries exist for c++ that implements highly optimized linear algebra functionality.

Other languages cosidered where Matlab and c.

The tool chosen to visualize the resulting data was gnuplot and ffmpeg. Writing a program using OpenGL was considered, but dismissed on the grounds of beeing too time consuming.

4.2 Program design

The program mainly consist of three parts:

- C++ implementation of Linear algebra functionality of the discrete equations.
- C++ implementation of the conjugate gradient method for solving the equations described.

- Bash script for generating plots and and movie of the generated data.

The Bash script is not discussed in further detail as it can be considered simple.

4.3 The physical system

The main task of the physical system is to implement a matrix-vector multiplication procedure for the heat equation and a method of calculating the heating properties of a microwave.

4.3.1 Partitioning of the problem

4.3.2 Updating alpha and beta values

4.3.3 Calculating the distribution of the microwave effect

4.3.4 The matrix-vector multiplication procedure

4.4 The conjugate gradient method as an iterative algorithm

Chapter 5

Experiments

5.1 Equipment

- 750W Microwave oven
- Bacon: two types, thick bacon ("skogsbacon") and regular bacon.
- Ruler
- Slide caliper
- Mettler AE50 (weight)
- Paper
- Grease-proof paper
- Scissors

5.2 Execution

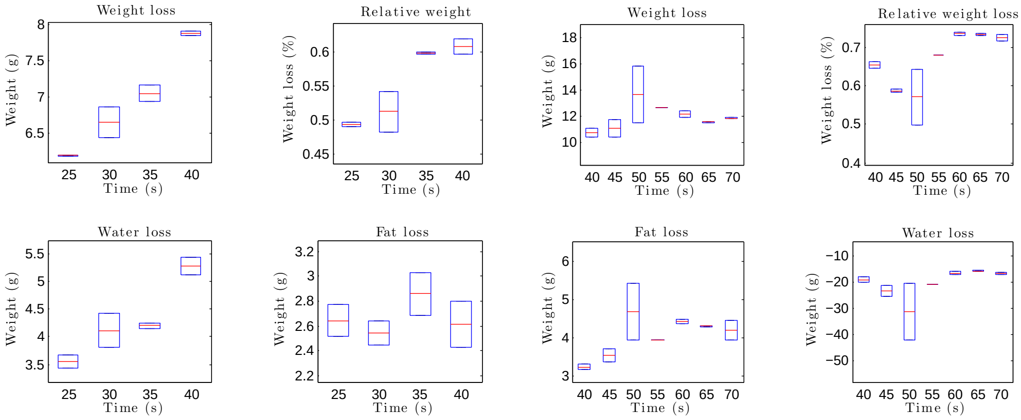
The baocn slice was laid between one sheet of paper on top, and one sheet of grease-proof paper beneath. Earlier experiments with dual layer paper had resulted in fusing of the bacon and paper. Still we needed to absorb the fat output, so a compromise was to combine paper (for fat absorption) and grease-proof paper (preventing fat spillage).

First we measured the weight of the wrapping (paper and grease-proof paper), and then we measured the dimensions of the bacon; weight, length, thickness and width. The bacon slice was wrapped and baked in the microwave oven for the desired amount of time. After completion we measured new dimensions, both of bacon and wrapping and assigned a number between 0.0-1.0 describing how crisp the bacon had gotten.

5.3 Measurements

First we measured weight gain in the wrapping, then weight loss in the bacon. We assumed that all gain in the wrapping came from fat absorption, and that the weight loss in the bacon consisted of fat melting and water evaporation. The new dimensions of the bacon were also documented.

The assumptions combined with our measurements made it possible to quantify fat loss, water loss and shrinkage of the bacon. This gave us the plots in fig. 5.1a and fig. 5.1b.



(a) Thick bacon (b) Regular bacon

Figure 5.1: Schematic representation of measured data

5.4 Results and discussion

As we can see in fig. 5.1a the water loss from 30-35 seconds is approximately constant, the fat loss on the other hand is increasing on the same time interval. This shows that around 30-35 seconds fat starts to melt, “stealing” heat from the water, this is in correspondence with weight loss as a function of time. The fat loss continues to be linearly increasing up to about 50 seconds, see fig. 5.1b. After 50 seconds the fat loss stabilizes, indicating that no more fat can be lost, and that further baking time results in burnt bacon.

These results coincides with our anticipations, that the weight loss would stabilize after a critical time. Something that is clearly demonstrated in fig. 5.1. It is worth commenting that the big variation in fig. 5.1b for $t = 50$s is due to one enormous (relative to the others) bacon slice.

Chapter 6

Conclusion

6.1 Conclusion

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