Commission of the European Communities

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DEVELOPMENT OF ENERGY EFFICIENT ELECTRICAL HOUSEHOLD APPLIANCES

Part Two: COOKING

Report

EUR 10449 EN

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Part Two: COOKING

J. HOLCK, L.B. GOLDSCHMIDT, J. HEEBØLL,
N.H. PEDERSEN
Technical University of Denmark
DK-2800 Lyngby, Denmark

Contracts Nos EE-A-3-025-DK (G) and EE-A-3-068-DK (SD)

FINAL REPORT

Research financed by the Commission of the European Communities
within the frame of the energy R & D Programme
- ENERGY CONSERVATION -

Directorate-General Science, Research and Development

1986 EUR 10449 EN

Published by the
COMMISSION OF THE EUROPEAN COMMUNITIES

Directorate-General
Telecommunications, Information Industries and Innovation

Bâtiment Jean Monnet
LUXEMBOURG

Objective

This report describes the second out of three parts of the work designing more energy efficient appliances. The objective of this part was to develop a technology to lower the electricity consumption associated with electric cooking, both on hot plates and in ovens. Compared to the annual electricity consumption for cooking per household in 1975, we have aimed at a 50 % reduction.

1. Summary

The work has been focussed on the development of a small, highly insulated electric oven, low heat-capacity hot plates and an accurate electronic thermostat for electric hot plates.

Two versions of a prototype oven have been built, LEO1 and LEO2 (Low Energy Oven 1 and 2). During tests, LEO2 has shown an energy consumption around 1/5 to 1/3 of ordinary sized ovens. The consumption relative to the volume (a concept only meaningful if you fill up the oven) is 1/3 to 1/2 of other ovens.

The work with energy saving ovens can not be said to be finished, even though the prototypes save more than our objective. However, it has proved, that energy saving ovens can be built with good energy economy and at a reasonable price, so it has been estimated that there is a market for these ovens. What now is needed, is, in cooperation with a manufacturer of electric ovens, to develop an oven, ready for production.

Experiments with low heat-capacity hot plates made of aluminum have been carried out. Theoretical calculations have indicated possible energy savings around 20 %, but the difficulties in producing such hot plates have proved to be considerable and requiring know-how and experience outside that of the laboratory.

During the project, it has been illustrated that a significant electricity saving, namely 20 %, may be obtained by supplying electric cookers with an accurate thermostat. This corresponds to an electricity saving of 1 % on a national basis. The thermostat is shown to give rise to significant improvements of comfort, and it is estimated that this will justify the somewhat higher price for the cooker. If one takes into consideration the novelty value and the improvements of comfort, the estimated extra retail price of 750 Danish Kroner does not seem unreasonable.

An experimental microprocessor based setup has been built for the investigation of different principles of control. Two principles have been examined: direct substitution in the model equations and prediction of the pan bottom temperature. The first principle has been tested experimentally, but the results have shown that the model, on which the control has been based, does not give an adequate description of the system. The second principle has appeared promising in computer simulations, but these results have not been verified experimentally.

We finally conducted a small study of the efficiency af boiling water in different ways. If we in the future assume the use of electric kettles in stead of normal hot plates for boiling water, combined with the use of the controller and the oven described in this report for the rest, we can achieve a saving in electricity for cooking of more than the 50 % we aimed at. However, as mentioned, some problems remain on the controller, and the use of radian rings and efficient pans might achieve similar savings.

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2. Introduction

At Physics Laboratory III, The Technical University of Denmark, there has for a long time been carried out research in energy savings, and especially the energy consumption of the domestic sector has been investigated. In earlier it has reports been estimated that significant energy savings can be obtained in this sector, and it has been shown that these savings also will be important on a national basis. Denmark has only a few heavy industries and thus a relatively large portion of the energy is consumed in the domestic sector. Apart from electrical space heating, a subject not dealt with in this work, no single appliance can be said to be the main energy consumer in the households, and domestic energy (electricity) saving is thus a result of savings for each of the appliances used in an ordinary household.

Although the electricity consumption in Denmark on a national basis is very well worth reducing, regarding pollution, trade balance and saving of resources, it does not always seem this way to the domestic consumer. The electricity bill is for many people too small to be worth considering, and this means, that electricity saving can not be the sole advantage of electricity saving domestic appliances. If they are to be sold and used, they must be at least as attractive as the ordinary appliances regarding comfort, ease of use, look etc. It has therfore been a main effort in this project to make appliances, that will work, look and cost almost like ordinary appliances.

Two major problems must be overcome if these new appliances shall be bought and used by ordinary consumers. First, as the usual appliances are produced in large quantities they are cheap due to the advantages of mass-production. New energy saving appliances must not be much more expensive, and this has prevented a development of new technologies as is known from other fields. The new development in microelectronics has, however, made electronics cheap and reliable, and it is currently being introduced in many domestic appliances. It is not unusual to see washing machines, cookers and even food mixers equipped with microprocessors to-day. The price of a microprocessor is in 1984 approx. 2 $ if bought in large quantities.

Further, domestic cooking is a conservative sphere. Once a person has learned to cook in a specific way, he or she is likely to be unwilling to change these habits. This means, that when designing energy saving household appliances, one should take great notice in making them operate almost like the usual appliances.

The research in cooking has been a part of a project funded by the Commission of the European Communities under contracts no. EE-A-3-025-DK (G) and EE-A-3-068-DK (SD). The other parts of the project has been devoted to washing machines and refrigerators, and are documented as parts 1 and 3 of the present report.

The work has been carried through at first with M.Sc. Jørgen Nørgård and M.Sc. John Heebøll as project managers, and later (since summer 1983) with M.Sc. Jesper Holck as project manager. M.Sc. Lars B. Goldschmidt from the Department of Chemical Engineering has developed the algorithm for the electronic thermostat, M.Sc. Niels Hald Pedersen has been working with the electronics and the microcomputer software and Jens Wåle from the La-

boratory of Engineering Design has made a prototype of the highly insulated oven as his masters thesis.

Also the Danish manufacturer of household appliances, A/S Ernst Voss Fabrik, the Danish Government Home Economics Council ("Statens Husholdningsråd") and the Department of Domestic Science within the electricity distribution company NESA have been involved. The final report has been reviewed and commented on by Jørgen Nørgaard, Tom Guldbrandsen and Niels I. Meyer, and I would here like to thank everybody who has been engaged in the project.

The work has tried to make a connection between the quite cautious attitudes of Voss, and the more adventuruos ideas from the Technical University. The major differences have been in opinions concerning how "new" the developed appliances should be. Voss, the manufacturer, has been of the opinion that only small changes in the appliances should be introduced if they were to be produced and sold. Physics Laboratory III has on the contrary been of the opinion, that only new appliances and altered habits can result in significant energy savings. The result of the work is a compromise between these opinions.

As mentioned above, this report is the formal conclusion of the EEC-sponsored research project. Since it is the only documentation of the 3 years of work, and since the results of the project may be interesting to persons outside the Commission, the report is also written for readers interested more generally in energy savings or adaptive control strategies.

During a research project like this, a lot of time and effort is spent on subjects, which later prove to be blind alleys or too complicated to be dealt with in the limited time set aside for the project. These subjects will only be dealt with briefly in the report, the greatest importance being attached to the final design of the thermostat and the oven.

3. Energy saving cookers

The cooker is one of the main electricity consumers in the Danish households. It is used to heat food or water to a given temperature and maintain this temperature for some time. The most frequent use is probably to heat water (with or without food) to the boiling point, and keep it boiling for some time. Some of the consumed energy is thus transferred to the water or food, and the rest will be considered lost. The "lost" energy will of course heat up the kitchen, but much of this heat will be delivered during the summer time and will be of no use, and even in the winter time, the kitchen will often get too warm when cooking. It is estimated that only 1/4 of this energy will actually result in savings on the heating budget.

The efficiency of a cooker, or rather a combination of cooker, pan and contents, may thus be defined as the ratio between the energy transferred to the food and the consumed energy. This ratio will of course be dependent on the kind of food being prepared and the operation of the cooker. Throughout the project we have chosen a simple standard test-procedure: bringing a certain amount of water to the boil.

We have assumed, that the normal way of operating the cooker to boil water, is to apply full power to the hot plate until boil, and then to switch off power and remove the kettle. Some people will switch off power before boil to save energy. On the other hand, many people will not detect at once that the water is boiling, and so leave it boiling for some time. Improvements in efficiency has therefore been defined as the energy saved by using the electronic thermostat in stead of switching off power when the desired temperature is reached. If one uses an ordinary cooker and kettle with 1 litre of water, and do not switch off the cooker before the water is boiling, the efficiency is around 50 %. There is thus room for considerable improvements.

4. Preliminary research in potential savings on hot plates

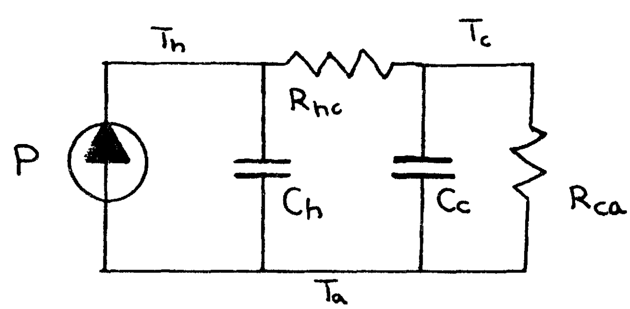
The energy consumption during cooking is determined by the equipment used, the food, the recipe and the cooking habits of the person operating the cooker. In Denmark it has for a long time been attempted to teach the population energy saving cooking habits and recipes, as these are probably the most significant means for reducing energy consumption. Examples are: reduced use of water when boiling potatoes, eggs etc., always keep the lid on the pot, use of "hay box" etc. Typically these prescriptions require some more work and supervising. This is probably the main reason for the limited impact of these new habits. In this project, emphasis has therefore been given to the development of new cooking equipment, that will **both** reduce energy consumption if used like ordinary equipment **and** will make the use of energy saving recipes and habits easier.

To get a measure for the energy consumption related to different equipment, it is necessary to define a few standard experiments, carry these through with the various equipment and compare the results.

The experiments chosen have been to place a kettle or pan with some cold water on a cold hot plate, switch on power to the plate and bring the water to the boil. To get a preliminary impression of the significance of various parameters in the hot plate / pan system a lot of experiments should be carried out using all kinds of plates, pans and contents. As this would require a lot of equipment and a lot of time, it was chosen to make a mathematical model of the system and simulate it on a computer. Some of the results from these runs should then be compared with experimental results.

A simple model with only two heat capacities and two coefficients of heat transfer was chosen, as it proved satisfactory when compared to experimental results.

The model may be described, using electric equivalents, as:



Notation:

P: Power applied to the hot plate.
Th: Temperature of the hot plate.
Tc: Temperature of pan and contents.
Ta: Temperature of the ambient.
Ch: Heat capacity of the hot plate.
Cc: Heat capacity of pan and contents.
Rhc: Heat resistance from plate to pan and contents.
Rca: Heat resistance from pan and contents to the ambient.

Figure 4.1

The differential equations are:

1) dTh/dt = (P - (Th-Tc)/Rhc)/Ch
2) dTc/dt = ((Th-Tc)/Rhc - (Tc-Ta)/Rca)/Cc

Model no. 1

Typical values of these parameters were found to be:

P: 0 - 2000 W
Th: 20 - 400 °C
Tc: 15 - 100 °C
Ta: ~20 °C
Ch: 400 - 800 J/K
Cc: 400 - 8000 J/K
Rhc: 0.1 - 0.2 K/W
Rca: 1 - 1.5 K/W

(Note that in this paper the term "heat resistance" is used, which is the reciprocal of the "coefficient of heat conductance" used in e.g. chemical litterature).

The various parameters of the model was found experimentally, and a computer program was written to simulate the system. The advantage of the computer model was that it was easy to alter given parameters and then compute the new energy consumption (given the model was good enough). The model proved in fact to be satisfactory for these simple simulations, and with a large number of runs it was concluded that:

- The heat resistance between a good pan and a good hot plate is so small, that only minor energy savings can be achieved by reducing it further. The analysis showed, however, that if the heat resistance is greater than that obtained with good equipment, the energy consumption will show a marked increase. If the heat resistance is tripled, the energy consumption will typically rise 25 %.

- The heat capacity of the hot plate has a significant influence on the energy consumption. If it is halved, the energy consumption will drop some 15 - 20 % for typical use.

- The power of the hot plate has only got a small influence on the energy consumption. If one reduces the power of the hot plate, the energy consumption will be somewhat smaller, but the time spent in heating the pan will increase correspondingly, thus causing a significant decrease of comfort.

- The heat resistance between the pan and the ambient air is so large that it only has an influence if the cooking time is long (1 hour or more). Increasing the resistance 40 % (e.g. by insulating the pan), will typically reduce energy consumption with less than 10 %.

- If power is not switched off before the desired temperature is reached in the pan, a considerable amount of energy is lost as waste heat in the hot plate. This energy can be reduced by making hot plates with a smaller heat capacity (e.g. aluminum plates or radiant rings) or by switching off power to the hot plate in due time before the desired temperature is reached, thus utilizing the heat stored in the hot plate.

- Only minor energy savings can be obtained using pressure cookers. The amount of energy required to obtain the higher temperatures is almost as large as the energy saved because of the reduced cooking time.

On basis of this investigation it was concluded that the main effort should be directed towards:

1) Developing a thermostat capable of switching off the power to the hot plate at the moment that will make the heat accumulated in the hot plate be just sufficient to make the contents of the pan reach the desired temperature.

2) Developing a hot plate with reduced heat capacity.

The former has been the main purpose of the following work, as the latter had to be given up (see chapter 5).

5. Work with low heat capacity hot plates

As mentioned in chapter 4, the energy consumption of a cooker can be significantly reduced, if the hot plate can be made with a low heat capacity. Further, this will have a positive influence on the comfort of operation, since a smaller heat capacity of the hot plate will mean a faster response to changes in the power applied to the hot plate.

In fact, the heat capacity of hot plates has been lowered during the last decades, and thin, low heat capacity hot plates (radiant rings) have been introduced. They have not had much success in Denmark however, probably because they are more difficult to clean than ordinary hot plates.

A hot plate made of aluminum would mean both a low heat capacity and easy cleaning, and we have attempted to make such a plate. Unfortunately we have not been able to produce the ceramics in which the hot wire is imbedded. It has proved difficult to make the ceramics in a way that would ensure no air bubbles and no water of chrystallization.

As will be seen later, the problem of making an accurate electronic thermostat is not an easy one. One of the main complications is the heat capacity of the hot plate. Thus, the problems of controlling the temperature of the contents would be much diminished if a low heat capacity hot plate could be produced.

6. Prospects of the electronic thermostat

The basic quality of an accurate thermostat must be the ability to reach and maintain any given temperature (within certain limits) of the contents of a pan placed on the hot plate. This quality is not obtained with the well-known capillary tube type thermostats found in many cookers. As they only measure the temperature of the pan bottom, they do not have a one to one correspondence between the setting of the adjustment knob and the temperature obtained inside the pan. This means, that to make the thermostat work properly, the user must learn and remember which setting to use for each combination of pan, contents and set-point temperature. Naturally, the consequence is that these thermostats seldomly are used correctly, most often the only setting used is maximum. These problems should be overcome with the electronic thermostat, as it can be made more intelligent, and as it can have several temperature measurements and thus will receive more information about the system.

If we presume that an electronic thermostat can be made, which will be able to control the temperature of the contents, it will have the following advantages:

1) An optimum utilization of the heat in the hot plate, thus reducing energy consumption, as illustrated in figure 6.1.

2) A minimization of the heat loss caused by evaporation. This is due to the facts, that only a minimum of energy will be delivered to the hot plate to maintain a given temperature, and that for many cooking purposes (e.g. cooking rice) the temperature of the food may be kept just below the boiling point, thus reducing this heat loss to close to zero.

3) On an ordinary cooker, energy may be saved by cooking potatoes and the like by steam, using a pan with a lid and only a small quantity of water. A minimum quantity of water is needed to ensure that the pan does not boil dry, and this minimum quantity can be reduced using the thermostat, causing a further saving of electricity.

4) For many cooking purposes, the thermostat will increase user convenience, as the risk of the food catching, boiling dry or boiling over is reduced. In many cases the need for supervising and for manual adjustments will be reduced. As an example may be mentioned that, when boiling water, once the kettle has been placed on the hot plate and the thermostat adjusted to 100 °C, no further actions will be necessary. The water will be heated to the boil and kept at the boilingpoint for a virtually unlimited time.

5) The introduction of other energy saving propositions will be eased. Insulated pans have such a small heat loss, that they will boil furiously, even when the hot plate is set to minimum power. This will not be a problem with this thermostat. Hot plates made of light-alloy metal will need some sort of protection against too high temperatures, and this protection may easily be installed in an electronic thermostat.

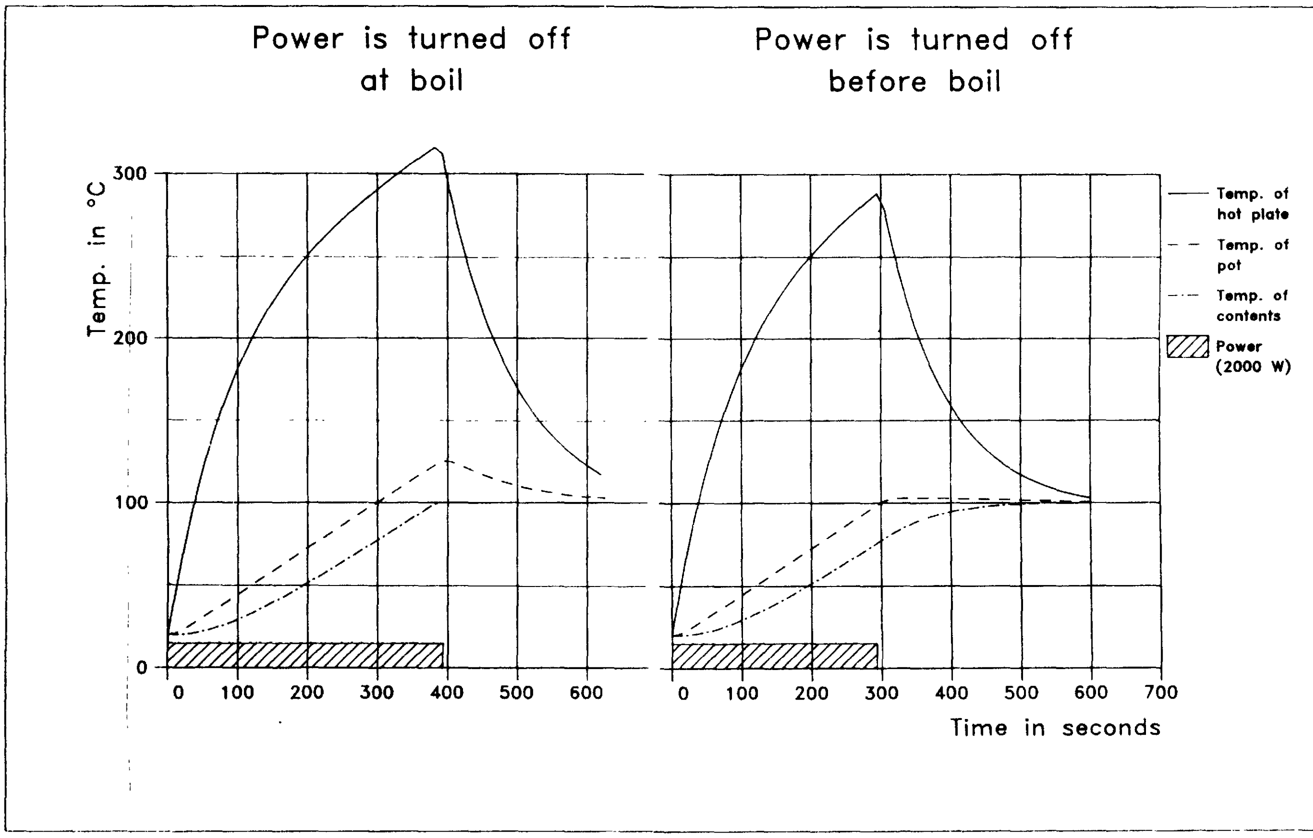


Figure 6.1

When compared to an ordinary hot plate controller, an electronic thermostat must overcome the following problems:

1) The price for the energy saving is a prolongation of the cooking time. The fastest way to heat water is of course to apply full power to the hot plate all the time until boil. As the thermostat will switch off power earlier, some prolongation will occur. If the thermostat works properly, the prolongation will typically be 1 to 1.5 minutes which should cause no trouble. It should not be more than 2 to 3 minutes.

2) A cooker equipped with this thermostat will be more expensive than ordinary cookers. A normal use of an electric cooker gives an electricity consumption around 600 kWh/year. If the thermostat can save 20 % of this, it will be an economic saving of approx. 120 Danish Kroner (12 $) per year. Given a pay back time of 10 years, this will allow maximum extra price for the thermostat of 1200 D.Kr. (120 $). The price of an ordinary controller for one hot plate is approx. 50 D.Kr., giving a saving of 100 D.kr. (10 $). Thus, the price of an electronic thermostat for 2 hot plates should not be greater than 1100 D.Kr. (110 $). In the introductory phase the price can be somewhat higher, as the thermostat will primarily be sold to motivated customers.

3) The electronic thermostat will require a change in the consumers attendance of their cookers. The majority of the consumers can not be expected to change their habits very

much, so the thermostat must be easy to operate. The thermostat described here will have an adjustment knob with a graduation in °C for each hot plate, and will work almost like the thermostat used for electric ovens.

4) The ordinary controllers for electric hot plates are reliable and easy to repair. The same must also be true of the electronic thermostat. As an electrician can not be expected to service the controller, it should be easy to remove it from the cooker for service. The electronic thermostat should also be reliable, even when ill-treated, for instance by spilling water on the plate, leaving the plate switched on with no pan etc.

If a reliable and accurate thermostat can be produced for a reasonable price, the advantages will greatly outweigh the disadvantages, and the market for the thermostat should be quite big.

7. Requirement specification for the thermostat

We will now draw up the requirements the electronic thermostat must meet:

1) The production price of the thermostat, including sensors, knobs and housing must not be greater than 1000 D.Kr, if produced in quantities of 10,000 per year.

2) The thermostat must be able to handle 2 ordinary hot plates.

3) Operation of the thermostat must be by ordinary, graduated knobs, calibrated in °C.

4) The thermostat should not damage itself, hot plates or pans, even though it may be operated erroneously.

5) It must be able to work for at least 2 years without service.

6) For most common use, the thermostat must be able to control the temperature of the contents in the range from 40 to 250 °C with an accuracy of 2 °C around 100 °C, and with an accuracy of 10 °C around 250 °C. For more unusual use, greater inaccuracies may be tolerated.

7) It shall be possible, independently of the actual temperatures, to ensure that the hot plate is switched on or off. This requirement shall, however, be restricted by no. 4.

8) For ordinary use, the thermostat must not prolong the time for heating more than 2 minutes. For more unusual use, greater prolongations may be tolerated.

9) There must be an indication of the actual state of the thermostat, e.g. a lamp telling for each hot plate whether it is switched on or off.

10) The time between an adjustment of a knob and a change in the indication of the state of the thermostat shall not be more than 2 seconds.

11) Only a minimal adjustment shall be necessary at the factory or at installation.

12) The design of the housing shall be in accordance with Voss (the Danish manufacturer) standard.

13) The assembly of a cooker with an electronic thermostat shall be almost like an ordinary cooker.

14) Service of cooker and thermostat shall be easy, e.g. with the possibility of automatic diagnostics.

15) The reliability of the thermostat should be good, as it will be very sensitive to bad publicity in the introductory phase.

16) The cooker must fulfil the requirements of DEMKO, the Danish authority for approving electric appliances.

17) In the design of the cooker it must be considered, that it will often be treated roughly, mechanically as well as thermally and chemically.

18) The electronics shall be prepared for a later extension with a clock and an oven-control.

We have made the following proposal for a test-procedure for the thermostat.

Pans shall be chosen to fit the hot plate and must be provided with tight fitting lids.

1) A sauce pan containing 1/2 kg potatoes and 0.1 litre of water is placed on a cold 15 cm ø hot plate. The thermostat is adjusted to 100 °C. The water shall be brought to the boil within 5 minutes and shall be kept boiling.

2) A sauce pan containing 2 litres of milk and 200 g rice for porridge is placed on a cold 18 cm ø hot plate. The thermostat is adjusted to 95 °C. The porridge shall be done within 1 hour without significant catch or burn.

3) A sauce pan with 100 g chocolate is placed on a cold 15 cm ø hot plate. The thermostat is adjusted to 50 °C. The chocolate shall melt without problems.

4) A sauce pan containing 1 litre of deep fry oil is placed on a cold 18 cm ø hot plate. The thermostat is adjusted to 200 °C, and the oil shall reach this temperature within 10 °C.

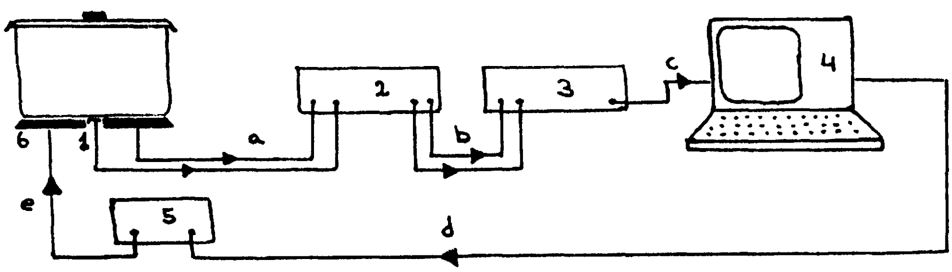
5) A kettle with 1 litre of water is placed on a cold 18 cm ø hot plate. The thermostat is adjusted to 100 °C, and it is checked that the water is boiling within 6 minutes and is kept boiling.

6) A frying pan is placed on a cold 18 cm ø hot plate. The thermostat is adjusted to 180 °C, and a bit of fat is placed on the pan. It is checked, that the pan surface reaches this temperature within 15 °C.

8. Overall system description

We will in this chapter give a description of the thermostat - pan - hot plate setup, including the experimental setup and the planned setup for the produced thermostat.

Experimental setup



1. Thermocouples (TC).
2. Thermocouple amplifiers and cold junction compensation (TCA and CJC).
3. Multiplexer and analog/digital converter (ADC).
4. Osborne Executive personal computer with extended input/output facilities.
5. Solid state relays (SSR).
6. Hot plate.

a. Thermocouple voltages.
b. Thermocouple voltages, amplified and cold junction compensated.
c. 12 bit digitized thermocouple voltages and control signals to and from the analog/digital converter and multiplexer.
d. Pulse width modulated control signals.
e. Pulse width modulated power.

Figure 8.1

The temperatures are mesured with chromel-alumel thermocouples. These have been chosen, as they are more accurate and stable than the usual type J thermocouple (iron-constantan) and they are cheaper than type S, Platinum thermocouples. Each thermocouple is connected to a "thermocouple amplifier", an electronic circuit, which amplifies the low voltages of the thermocouples to a 0-10 V level. The amplifier is connected to a Cold Junction Compensation, a circuit that produces the voltage needed to compensate for the voltage of the thermocouple cold junction.

The output voltages from the thermocouple amplifiers are measured with an 8 channel, 12 bit analog/digital converter (ADC). The ADC is in turn connected to a conventional 8-bit personal computer, the Osborne Executive, through a Parallel Input/Output Circuit (Z80 PIO).

The computer is connected to a programmable counter/timer chip (8253), that controls the Solid State Relays which switch on and off the power to the hot plate(s). The relays are driven by pulse width modulation, which means that they are set on for a given number of power cycles and then off in another number of cycles.

Thus, in the setup one can measure the temperatures of pan and hot plate. These temperatures are used as input to the control algorithm in the computer, and this algorithm calculates the power to be delivered to the hot plates.

The circuits mentioned here will be described in more detail in chapter 16.

Final setup

For the final production-ready thermostat, all the electronic circuits will be put on one circuit board. The board will only contain a few components, a microprocessor and a custom designed integrated circuit. The latter will contain nearly all the above mentioned electronic functions, the only one not included will be the power control for the hot plates, which will be handled by triacs.

In between the experimental and the final setup, it is planned to make a setup with all the electronic circuits assembled on one board. This board will make the cooker transportable, and will be used for testing the thermostat "in the field", that is in ordinary kitchens and with external test facilities.

9. Developing a mathematical model for the pan - hot plate system

In order to develop a computer based thermostat, it is first necessary to obtain a satisfactory model for the system to be controlled. For one thing, it is decisive to have a good description of the system in order to choose between different control strategies. And secondly, a good model is needed to run a large number of computer simulations for the thermostat - if all these tests should be run experimentally, they would require much too much time.

As for all real world systems, the pan / hot plate system is very complex, and if it should be completely described, it would require a very complicated mathematical model. The system contains, as indicated by the sectional drawing below, many distributed parameters. This means, that e.g. the hot plate can not be said to have **one** temperature - the temperature is different for different parts of the hot plate. The same holds, even more, for pan and contents, especially if the contents is very viscous or inhomogeneous.

The model must be made to meet certain requirements:

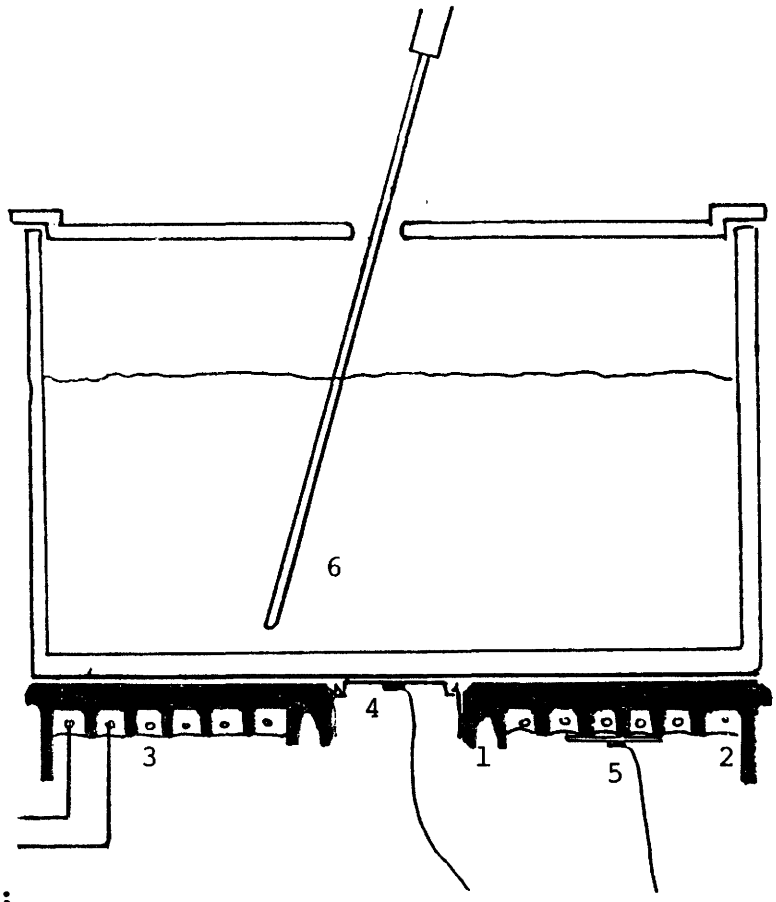
1) It should be as simple as possible.

2) It should describe the experimental results well, even though it is only necessary for the model to be valid within the limits set by common use of pans and hot plates. This also means, that the model should contain the physical obtainable measurements.

3) It should contain "physically understandable" parameters, that is, the parameters of the model should have as close a relation to physically measurable quantities as possible. This requirement is not imperative, but may be used to choose between alternative models.

Once installed in the cooker, the thermostat will only yield two measurements: the temperature of the bottom of the pan (or rather, the temperature of the little metal disk shown on the sectional drawing), and the temperature of the hot plate (or rather, the temperature of a specific point of the hot plate). During the experiments in the laboratory, we are also capable of measuring the temperature of the contents while heating, and we can measure the heat capacities of plate, pan and contents. The model should, if possible, contain these measurements as parameters or variables.

In the previously described model, the temperature of pan and contents were assumed to be identical. As we are able to measure both of them, and as they certainly are not identical, this model can not be used here.



Notation:

1. Hot plate cast iron.
2. Hot plate ceramics.
3. Hot plate resistance wire.
4. Thermocouple pan bottom temperature sensor.
5. Thermocouple hot plate temperature sensor.
6. Thermocouple pan contents temperature sensor.

Figure 9.1

Instead we have chosen another simple model, containing only 3 heat capacities and 3 coefficients of heat transmission:

1) $dTh/dt = (P - (Th-Tp)/Rhp) / Ch$
2) $dTp/dt = ((Th-Tp)/Rhp - (Tp-Tc)/Rpc)) / Cp$
3) $dTc/dt = ((Tp-Tc)/Rpc - (Tc-Ta)/Rca)) / Cc$

Notation:

Th: Temperature of hot plate
Tp: Temperature of pan(-bottom)
Tc: Temperature of contents
Ta: Ambient temperature
P: Power applied to the hot plate
Ch: Heat capacity of hot plate
Cp: Heat capacity of pan(-bottom)
Cc: Heat capacity of contents (and the sides of the pan)
Rhp: Heat resistance from hot plate to pan
Rpc: Heat resistance from pan to contents
Rca: Heat resistance from contents to the ambient

Model number 2

As mentioned earlier, the temperatures measured cannot be said to be **the** temperatures, neither for plate nor pan nor contents, and therefore the model can only be evaluated for a specific set of temperature detectors. The detectors used will be described thoroughly in the next chapter, but in short they are:

- For the measurement of Tc, an ordinary thermometer or a thermocouple has been placed on the bottom of the pan through a hole in the lid.

- For the measurement of Tp, a thermocouple or an NTC-resistor has been placed in the centre of a stainless steel disk placed in the centre of the hot plate. The disk is pressed against the bottom of the pan by means of a spring.

- The temperature of the hot plate, Th, has been measured by means of a thermocouple or nickel wire, attached to the under side of the plate.

- The ambient temperature has been measured using an ordinary thermometer placed in the room.

The model should be able to describe the time response of these temperatures. To examine the model, one can use various approaches, depending on how much the parameters of the model shall resemble the real world physical quantities. One approach is just to measure the 3 (4) temperatures and the power applied to the hot plate and then run an identification algorithm to determine the parameters of the model. Another approach is to make physical measurements of the three heat capacities and the three coefficients of heat transmission. When the parameters have been estimated, a number of experiments should be carried out, and the simulated and the measured results compared.

An example of experimental results in comparison with the computer model is depicted below. It is seen, that the model gives (under these circumstances) a good description of the real world.

Typical values for the parameters have been:

Ch: 400-800 J/K
Cp: 100-400 J/K
Cc: 500-10000 J/K
Rhp: 0.2 K/W
Rpc: 0.02 K/W
Rca: 1 K/W

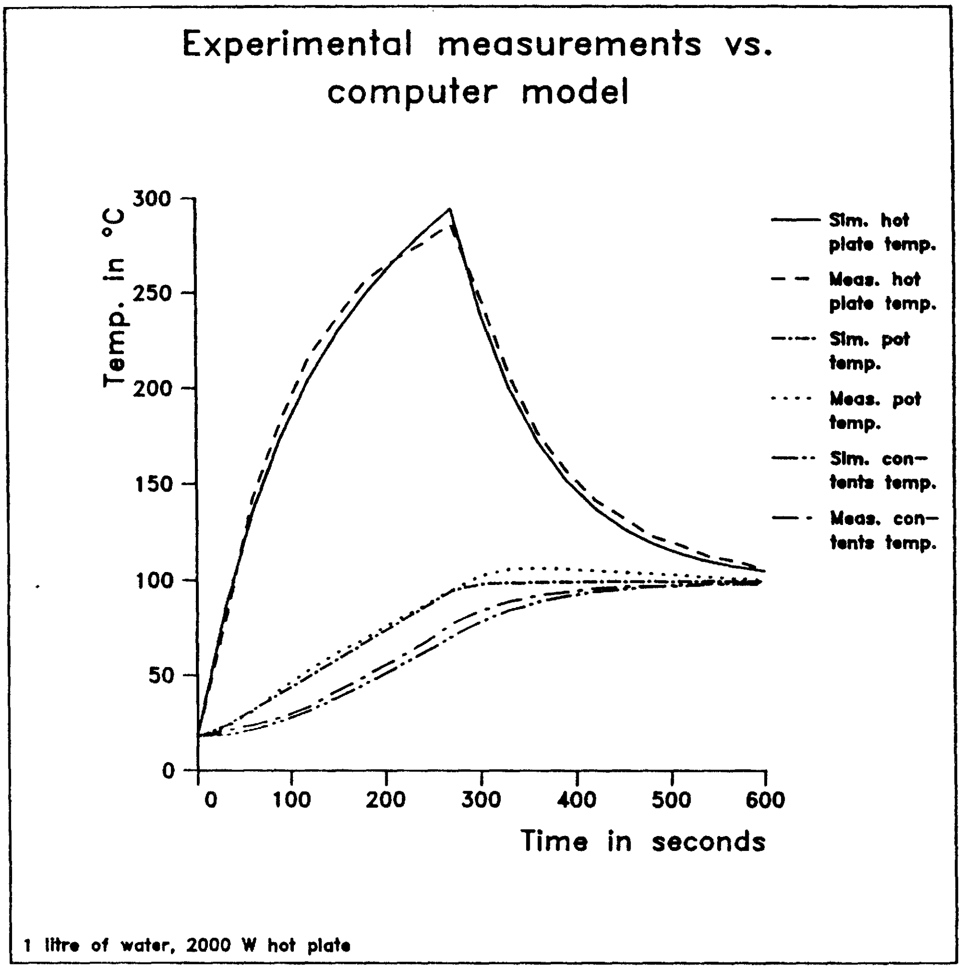

Experimental measurements vs. computer model
Temp. in °C
300
250
200
150
100
50
0
0
100
200
300
400
500
600
Time in seconds
Sim. hot plate temp.
Meas. hot plate temp.
Sim. pot temp.
Meas. pot temp.
Sim. contents temp.
Meas. contents temp.
1 litre of water, 2000 W hot plate

Figure 9.2

10. An analogue controller

The first attempt in the design of the thermostat was to develop a controller, based on conventional, analogue electronics.

Ideally, the equations based on the system model should be solved to determine the exact moment to switch off power to the hot plate. These equations are, however, difficult to solve, and to get the exact solutions one should know all parameters of the system. These parameter values will change from one experiment to another, so this path has been considered impassable.

Instead, a heuristic path has been chosen. For several combinations of pan and contents used on a specific hot plate, the contents were heated and the optimum switch-off time found experimentally. For each experiment, the temperatures of pan bottom and hot plate were measured.

It was then assumed, that the correct switch off time could be expressed as the moment $t = t_0$ when:

$$a*Th(t_0) + b*\frac{dTh}{dt}(t_0) + c*Tp(t_0) + d*\frac{dTp}{dt}(t_0) = Tset$$

Several experiments were carried out, giving an overdetermined set of equations in four unknowns. These equations were solved using least squares optimization, and the result gave the equation:

1) $$33\ \text{sec} * \frac{dTh}{dt} + 0.8*Tp(t_0) = Tset.$$

A verbal reasoning for this equation may be, that a large value of dTh/dt will imply little water in the pan or bad contact between pan and plate, and for both these cases the surplus heat in the hot plate is relatively large giving a relatively early switch off time. Tp is the closest approximation obtainable to the temperature of the contents.

This principle is only useful during heating, and should be substituted by an ordinary thermostat function, when power has been switched off.

2) $$Tp(t_0) = Tset$$

The electronics to realize this principle has been designed, built and tested. A diagram is shown in figure 10.1 and some of the experimental results are summarized in figure 10.2.

The experiments showed, that energy savings can be obtained, and that the controller did in fact facilitate the cooking. The thermostat was used for the preparation of the Danish dish "Risengrød", a porridge made of rice boiled in milk. This is a dish very likely to catch and requiring almost constant stirring. The thermostat was set to 90 °C and a pan with milk placed on the plate. When the controller switched off power for the first time, the rice was added and the whole thing left alone for 1 hour. This worked fine, the porridge did neither catch nor boil over.

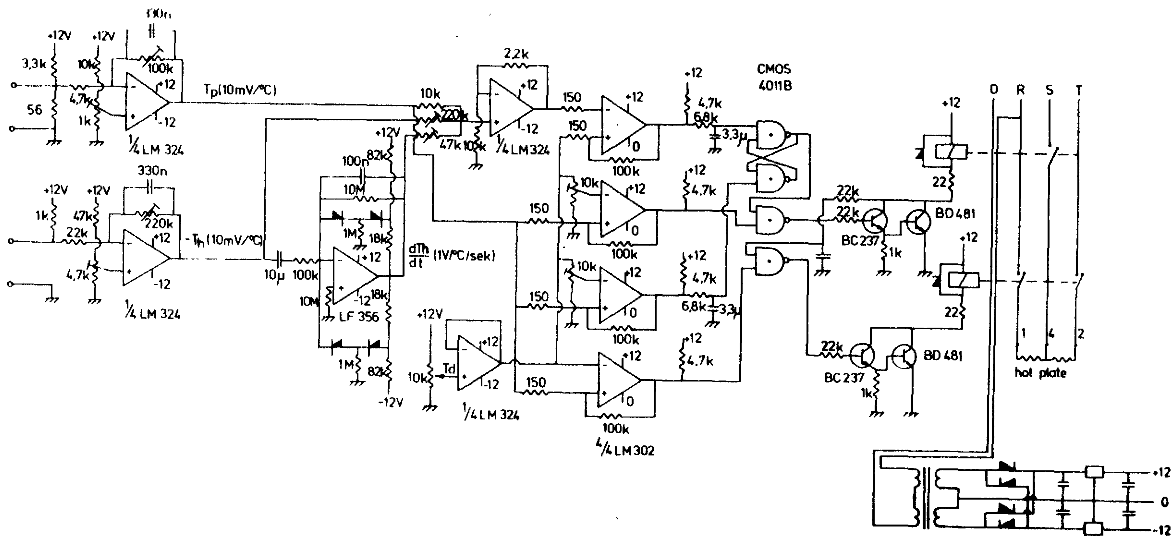


Figure 10.1

	EXPERIMENT	CONTROLLER/ ORDINARY COOKER	ENERGY CONSUMPTION DURING HEATING	ENERGY CONSUMPTION DURING KEEPING AT BOIL	TOTAL	REDUCTION %
1	½ kg potatoes, 0.82 ℓ water (potatoes just covered) heat and boil for 20 min.	ORDINARY	173 Wh	50 Wh	223 Wh	0
2	½ kg potatoes, 0.1 ℓ water, heat and boil for 20 min.	ORDINARY	78 Wh	50 Wh	128 Wh	43
3	½ kg potatoes, 0.1 ℓ water, heat and boil for 20 min.	CONTROLLER	67 Wh	53 Wh	120 Wh	46
4	1 ℓ water, heat and boil for 10 min.	ORDINARY	167 Wh	24 Wh	191 Wh	0
5	1 ℓ water, heat and boil for 10 min.	CONTROLLER	133 Wh	8 Wh	141 Wh	26
6	½ kg rice, 1 ℓ water, heat and boil for 20 min.	ORDINARY	175 Wh	50 Wh	225 Wh	0
7	½ kg rice, 1 ℓ water, heat to 90°C and keep for 20 min.	CONTROLLER	153 Wh	8 Wh	161 Wh	28
8	120 g rice, 1 ℓ milk, heat and boil for 1 hour	ORDINARY	170 Wh	150 Wh	320 Wh	0
9	120 g rice, 1 ℓ milk, heat to 90°C and keep for 1 hour	CONTROLLER	167 Wh	89 Wh	256 Wh	20

Figure 10.2

The analogue controller had unfortunately serious drawbacks, the main one being unreliability. In some experiments power was not switched off at all, and in other experiments power was turned down much too soon, giving a very long heating time. The latter was caused by the fact that once power had been switched off, it took a very long time for the pan bottom temperature to fall below Tset. The simple thermostatic principle (2) was therefore very slow in reapplying power.

The principle should therefore be enveloped by other principles assuring a reasonable behaviour of the controller. With analogue electronics, it is however very laborious to introduce new principles and adjust their parameters. Further, the price of microprocessor based electronics slumped, and in this light it was decided to develop a microprocessor based digital algoritm.

11. Mathematical formulation of the control problem

In a digital controller, an algoritm will be running on a computer used for controlling the system or process. The computer will sample the necessary data (here the temperatures), make a calculation on basis of these and earlier data and decide which output to give to the process (here, what power should be induced to the hot plate). As can be seen from the system model described in chapter 9, the computer will need a lot of data (heat capacities, heat resistances and temperatures) to be able to calculate the optimum moment to switch off power. Not all of these data are available to the computer, however, so some will have to be estimated. The main problem to be solved by the computer is to give reasonable estimates to these parameters and temperatures.

Before we deal with this problem, we have to make a definition of what is meant by "the optimum moment to switch off power".

As a first approximation we will reformulate the purpose of the control to be: To bring the contents of the pan to a given temperature in a limited time span with a minimum of energy.

If the power to the hot plate is switched off, the system will settle in a stable state, all parts having the same temperature, neglecting the heat conduction to the surroundings. The stable state in which the contents have the set point temperature is thus the state in which all parts of the system have this temperature. Therefore, the minimum required energy consumption is the difference between the present thermal energy of the system, and the thermal energy of the system with all parts having the set point temperature.

This leads to a formulation of two control objects, derived from the above mentioned control task:

Control criterion 1:

Tset - Taverage = 0
Taverage ≡ (Th*Ch + Tp*Cp + Tc*Cc) / (Ch + Cp + Cc)

Control criterion 2:

Th - Tset > 0 and, for every positive i:
0 < Tp(t+smplt*i) - Tset < a + b/i

The first criterion implies that if the present average temperature is equal to the set point temperature, the system will settle at this temperature if power is switched off. If the temperature must be reached in a limited time, a margin for the overshoot must be defined.

The second criterion implies, that at any time "t", power should only be switched off if the predicted hot plate temperature Tp(t+smplt*i) ("smplt" is the time between two samples) for every positive "i" is greater than the set point temperature, Tset, and less than the expression Tset + a + b/i, "a" and "b" being positive constants.

Both criteria are valid during the heating as well as close to the set point. The time limit in criterion 1 and the overshoot in criterion 2 should however be diminished close to the set point.

The problem of estimation

On-line modelling and estimation are used to obtain knowledge concerning states and parameters, that are part of the control object and the control algorithm. The choice of models and principles of estimation will therefore depend upon the chosen control strategy. In the following, we will discuss first the discretization of the model, principles of estimation and problems of observability concerning criterion 1, and then concerning criterion 2.

12. Control criterion 1

This criterion implies known values of Cc, Cp, Ch and Tc and a time limit for the system. Ch must be expected to be a constant for the given hot plate, but the other parameters and Tc are specific for the task and can be expected to change in time. The problem of estimation is therfore an off-line estimation of Ch and an on-line estimation of states and parameters including Cc, Cp and Tc. Two methods of solving this problem will be investigated:

1. Extended Kalman-filtering. This method demands much computing, but constitutes the limit for todays possibilities of combined state and parameter estimation. This method may thus be used as a kind of reference for short-cuts during the implementation of the control algorithm.

2. Direct substitution in the system equations. This method is chosen because of the simple implementation.

Both of the above mentioned methods presume the system and the parameters to be observable.

Extended Kalman-filtering

Extended Kalman state and parameter estimation, as the name indicates, is an extension of the traditional Kalman state estimation. Given a linear system model:

$$\frac{d}{dt}\mathbf{X}(t) = \mathbf{AX}(t) + \mathbf{Bu}(t)$$

$$\mathbf{Y}(t) = \mathbf{CX}(t) + \mathbf{Dv}(t)$$

Here $\mathbf{X}(t)$ is the system state and $\mathbf{Y}(t)$ the system output, $\mathbf{Bu}(t)$ is system noise and $\mathbf{Dv}(t)$ is measurement noise. Traditional Kalman estimation will determine a filter matrix, $\mathbf{K}$, to minimize the square of the error in the estimate of $\mathbf{X}(t)$, $\varepsilon\mathbf{X}(t)$, given by the equation:

$$\frac{d}{dt}\varepsilon\mathbf{X}(t)/dt = \mathbf{A}\varepsilon\mathbf{X}(t) + \mathbf{K}(t) * (\mathbf{Y}(t) - \mathbf{C}\varepsilon\mathbf{X}(t))$$

$\mathbf{K}(t)$ is determined by solving a dynamic Ricatti-equation.

In extended Kalman filtering the same path is followed, but the system model is extended with the unknown parameters. This will often result in a non-linear model, which in this case is linearized around the point of operation.

The description of the model will be given in continuous time, as the parameters are most easily described in this way. The results concerning observability can be applied in discrete time as the best obtainable, but discretization of the extended system model must be dealt with separately.

Extension of the system model

From chapter 9 it is seen, that the system model is linear in the temperatures and, if we neglect the heat loss to the surroundings, may be written as:

$$\frac{d\mathbf{X}}{dt}(t) = \begin{Bmatrix} \frac{-1}{Rhp*Cp} & \frac{1}{Rhp*Ch} & 0 \\ \frac{1}{Rhp*Cp} & \frac{-1}{Rhp*Cp} - \frac{1}{Rpc*Cp} & \frac{1}{Rpc*Cp} \\ 0 & \frac{1}{Rpc*Cc} & \frac{-1}{Rpc*Cc} \end{Bmatrix} \mathbf{X}(t) + \begin{Bmatrix} \frac{1}{Ch} \\ 0 \\ 0 \end{Bmatrix} P(t)$$

$$\mathbf{Y}(t) = \begin{Bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \end{Bmatrix} \mathbf{X}(t)$$

The vector **X** contains the three temperatures, Th(otplate), Tp(ot) and Tc(ontents), and the vector **Y** the two measurable temperatures, Th and Tp.

With extended Kalman filtering, all parameters in the extended matrix **A** must be known, and use of this method will therfore also require an estimation of Rpc and Rhp, in excess of what is needed for criterion 1.

After extension of the state vector and linearization around Xo the state vector **X**(t) and the system matrix **A** will be:

$$\underbrace{\begin{Bmatrix} Th \\ Tp \\ Tc \\ Cp \\ Cc \\ Rhp \\ Rpc \end{Bmatrix}}_{\mathbf{X}} \quad \underbrace{\begin{Bmatrix} \frac{-1}{Rhpo*Ch} & \frac{-1}{Rhpo*Ch} & 0 & 0 & 0 & \frac{-Tho+Tpo}{Ch} & 0 \\ \frac{1}{Rhpo*Cpo} & \frac{\frac{-1}{Rhpo} - \frac{1}{Rpco}}{Cpo} & \frac{1}{Rpco*Cpo} & \frac{\frac{-X1+X2}{Rhpo} - \frac{X2-X3}{Rpco}}{Cpo2} & 0 & \frac{-X1+X2}{Cpo*Rhpo2} & \frac{X2-X3}{Rpco2*Cpo} \\ 0 & \frac{1}{Rpco*Cpo} & \frac{-1}{Rpco*Cco} & 0 & \frac{X2-X3}{Rpco*Cco2} & 0 & \frac{X2-X3}{Rpco2*Cco} \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{Bmatrix}}_{\mathbf{A}}$$

The matrix **C**:

$$\begin{Bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 \end{Bmatrix}$$

Observability

For use in the analysis of observability, following Evans (ref. 5), the binary form of the matrices **A** and **C** will be written down.

The binary matrices are:

$$\mathbf{A}: \begin{Bmatrix} 1 & 1 & 0 & 0 & 0 & \underline{1} & 0 \\ 1 & 1 & 1 & 1 & 0 & 1 & \underline{1} \\ 0 & 1 & 1 & 0 & \underline{1} & 0 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{Bmatrix}$$

$$\mathbf{C}: \begin{Bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 \end{Bmatrix}$$

The term rank is calculated from the matrix **C-A** (the underscored interactions) to be 5. Hence, the maximum number of observable states is 5. The 5 states may be chosen as a number of different combinations, but never more than 5. Whether all 5 are observable is seen from the reachability matrix **R**:

$$\mathbf{R}: \begin{Bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{Bmatrix}$$

It is seen that all states may be reached by observing either of X1 (Th), X2 (Tp) and X3 (Tc), but not by observation of the parameters. Here, the parameter observed can of course be reached. That the term rank is less than 7 implies, that all states may be seen, but they may not be seen separately.

Conclusion concerning the use of extended Kalman filtering

As not all the parameters depending on the experiment are observable on-line, it will be necessary to assign some of these parameters fixed values before an extended Kalman filtering. Presently, we cannot expect these values to be reasonably accurate. Therefore it does not seem adequate to use such an effective method as the Kalman filtering for the accurate determination of the rest of the parameters, as the determination of these will depend on the error in the choice of the fixed parameters. We have therefore chosen to look at what may be done by direct substitution in the system equations.

Direct substitution in the system equations

By direct substitution is meant, that the discrete model equations together with the measurements in the last sample point(s) are considered to be a set of simulataneous equations, determining some of the unknown parameters. These parameters may then be filtered adequately, regarding the expected time-dependency of the parameters. The method may be expected to work only if the measurements are very little influenced by noise.

The substitution must be done in a discrete system model, as we have measurements in discrete moments only. The discretization of the model must be done in a way that will make it possible to isolate the parameters we are looking for. The discrete model has the form:

X(t+smplt) = exp(**A***smplt)**X**(t) +
(exp(**A***smplt) - **I**)**AinvBU**(t)

If the exponential function is approximated with a Taylor series, truncated after the second term, the model will be:

(1) X1(t+smplt) = X1(t) + smplt*(P - (X1(t) - X2(t))/Rhp)/Ch

(2) X2(t+smplt) = X2(t) + smplt*((X1(t) - X2(t))/Rhp +
(X3(t) - X2(t))/Rpc)/Cp

(3) X3(t+smplt) = X3(t) + smplt*(X2(t) - X3(t))/(Rpc*Cc)

This approximation may be improved in different ways, which will be dealt with later. Here we will discuss what in principle may be observed with this model.

From equation 1, one can determine Rhp if Ch is known. As Rhp must be expected to be constant during the experiment, this determination may be extended with filtering with diminishing importance attached to new informations.

From equation 2, one can determine Rpc and Cp if X3(t) is known, as one can draw up two equations with two unknowns from two moments of measurement. Another possibility is to determine X3(t), given Cp and Rpc.

From equation 3, one can determine Cc, given X3(t), X3(t+smplt) and Rpc, or vice versa.

Cc and Rhp will most likely with this model be changing during the experiment. Even though their physical values may be constant, the estimated values of these parameters will be changing to compensate for model inadequacies. The estimated value of Cc will, e.g., be influenced by the heat transmission to the surroundings. Thus they should be filtered, but with most importance attached to new informations.

It may be seen from the above, that with this method we may form a rough identification of the maximum number of observable parameters and states of the system. The implemented version will be described in chapter 14.

13. Control criterion 2

For the application of this criterion we need a good predictive model for Th and Tp. For obtaining such a model we follow the method of Jørgensen et al. (ref. 2) for constructing structured time series models for selftuning control.

In discrete time the third order system model from chapter 9 has the following structure if we neglect heat loss to the surroundings:

$$\begin{Bmatrix} Th(t+1) \\ Tp(t+1) \\ Tc(t+1) \end{Bmatrix} = \begin{Bmatrix} a11 & a12 & a13 \\ a21 & a22 & a23 \\ a31 & a32 & a33 \end{Bmatrix} \begin{Bmatrix} Th(t) \\ Tp(t) \\ Tc(t) \end{Bmatrix} + \begin{Bmatrix} b1 \\ b2 \\ b3 \end{Bmatrix} P(t)$$

a13, a33, b2 and b3 will be second order interactions proportional to the sample time. Using the q-transformation and eliminating Tc, we get a model with the structure:

$$\begin{Bmatrix} Th(t+1) \\ Tp(t+1) \end{Bmatrix} = \begin{Bmatrix} a11 & a12 \\ a21 & a22 \end{Bmatrix} \begin{Bmatrix} Th(t) \\ Tp(t) \end{Bmatrix} + \begin{Bmatrix} a13 & a14 \\ a23 & a24 \end{Bmatrix} \begin{Bmatrix} Th(t-1) \\ Tp(t-1) \end{Bmatrix} + \begin{Bmatrix} b11 \\ b21 \end{Bmatrix} P(t) + \begin{Bmatrix} b12 \\ b22 \end{Bmatrix} P(t-1)$$

In an attempt to increase the convergence rate we have reduced this model by neglecting the second and higher order interactions and obtained the model used in the following simulations:

$$\begin{Bmatrix} Th(t+1) \\ Tp(t+2) \end{Bmatrix} = \begin{Bmatrix} a11 & a12 \\ a21 & a22 \end{Bmatrix} \begin{Bmatrix} Th(t) \\ Tp(t) \end{Bmatrix} + \begin{Bmatrix} 0 & 0 \\ 0 & a23 \end{Bmatrix} \begin{Bmatrix} Th(t-1) \\ Tp(t-1) \end{Bmatrix} + \begin{Bmatrix} b1 \\ b2 \end{Bmatrix} P(t) + \begin{Bmatrix} c11 & 0 \\ 0 & c22 \end{Bmatrix} \begin{Bmatrix} e1(t) \\ e2(t) \end{Bmatrix}$$

As in the original system model from chapter 9, the parameters in this model are expected to be constant or slowly varying and therefore suited for the chosen RELS method. The Recursive Extended Least Squares implementation with variable forgetting used in the simulations are described in Jørgensen et al. (ref. 2).

Having obtained a model, the predictions are computed recursively using this model. The control inputs are computed according to criterion 2 with four different expressions for the Tp-overshoot decay ratio.

a) $Tp-Tset < 10/i$
b) $Tp-Tset < 8/i$
c) $Tp-Tset < 10 * 0.95^i$
d) $Tp-Tset < 30/i$

Simulation, using the model as the system, and using the parameters:

Ch:	477	J/K
Cp:	243	J/K
Cc:	8192	J/K
Rhp:	0.181	K/W
Rpc:	0.023	K/W
Rca:	1.2	K/W
P:	1500	W
Sampletime:	5	sec.

gave essentially constant estimated parameters after 20 samples. At t = 465 seconds, just before power switch off, the estimated parameters were:

a11: 0.944, a12: 0.054, b1: 0.0102, c11: 0.000
a21: -0.0023, a22: 1.660, a24: -0.657, b2: 0.0000, c22: 0.157

The ratios between the variances of the residuals and of the measurements were:

var(res1)/var(Th) = 0.0003
var(res2)/var(Tp) = 0.001

Including boiling in the system model gave rise to rapid adaption of a21, a22 and a24 at the boiling point to the new values:

a21: -0.0016, a22: 1.620, a24: -0.621

The energy consumption and heating periods for three kinds of cooking simulations can be seen in table 13.1.

The simulations are:

a) the one mentioned above.
b) as a), but with Cc = 4192 J/K.
c) as a), but the initial temperature of the contents was 40 °C above the ambient temperature, Ta.

The simulations are made with the above mentioned 4 expressions for the Tp overshoot decay, and the results are compared to a strategy ("a ref") with full power until the water reaches the setpoint.

Experiment	Overshoot decay expression	Elapsed time in seconds	Energy used in kJ	Overshoot or boil
a 1	a	760	743	1 °C
a 2	b	830	733	boil
a 3	c	760	743	boil
a 4	d	740	768	4 °C
a ref		570	855	
b 1	a	430	424	6 °C
b 2	b	430	424	6 °C
b ref		355	533	
c 1	a	515	416	1 °C
c ref		350	525	

Table 13.1

Conclusion on control criterion 2

The simulation results indicate that it will be possible to develop and implement a regulator based on control criterion 2. The modelling method from Jørgensen et al. (ref. 2) makes it possible to modify the prediction model struture if necessary due to differences between the model and the actual system.

The procedure is attractive because it does not need any off-line determined parameters, but it is demanding in both programming and computing power.

14. Suggestion for a suboptimum control algorithm

Parameter estimation for the use of control criterion 1 using direct substitution in a first order Taylor approximation to the discrete model equations has been implemented on an Osborne Executive for control of the experimental setup.

The algorithm is implemented in the following form.

Ch, Cp and Rpc are presumed known, heat losses to the surroundings are neglected.

First, compute the change in Th and Tp:

```
dTh  := Th(t+1) - Th(t)
dTp  := Tp(t+1) - Tp(t)
```

Compute the mean value during the sample interval of the temperature difference Th - Tp:

```
dThTp := (Th(t) - Tp(t) + Th(t+1) - Tp(t+1)) / 2
```

The value of Rhp during this sample interval is calculated:

```
Rhp,new := dThTp / (P - Ch*dTh/smplt)
```

This value is used together with the old value of Rhp to estimate a new value of Rhp. If the elapsed time, t, is large, little importance will be attached to new measurements of Rhp.

```
Rhp := Rhp + (Rhp,new - Rhp) / (a*t + b)
```

Now, Tc may be calculated as:

```
Tc(t) := Tp(t) - Rpc * (dThTp/Rhp - Cp*dTp/smplt)
dTc := Tc(t) - Tc(t-1)
```

A new value for Cc may now be computed from the old value of the variable dTcCc (the change in the heat energy of the contents):

```
Cc(t) := dTcCc(t-1) / dTc
```

And a new value of dTcCc:

```
dTcCc(t) := dThTp*smplt/Rhp - dTp*Cp
```

Now, we have:

```
Taverage(t+1) := (Th(t)*Ch + Tp(t)*Cp + Tc(t)*Cc + P(t)*smplt)
                                                   / (Ch+Cp+Cc)

Terror(t+1) := (Tset - Taverage(t+1))*c + d
```

The error function shall ensure some overshoot, meaning that the setpoint is reached in a limited time. The factors "a" through "d" must be tuned experimentally.

Tuning parameters used:

```
a = 0.2, b = 2.0, c = 1.1, d = 3.0
```

Robustness

From the physical knowledge about the system, a number of conditions concerning updates of parameters and states may be laid down. All parameters are, e.g., positive by definition. The conditions used, are:

Parameters:

(1) 0.1 K/W < Rhp < 0.5 K/W

(2) 200 J/K < Cc < 50000 J/K

States:

(3) If dTcCc > 0, then Tc(t) >= Tc(t1)

If power is induced into the pan, the temperature of the pan will not go down. This will not be true if frozen food is added to the pan, but the condition will merely assign dTc the value 0, and the power induction will be continued.

(4) If P(t) = max, then Taverage(t+1) >= Taverage(t)

If full power is induced to the system, the average temperature will not go down. The same remark as above will be valid here.

15. Temperature sensors

In the project, much time and effort has been put into the design of the two temperature sensors, the sensor for the hot plate temperature and the sensor for the temperature of the pan bottom. The choice of sensors for these measurements will now be expounded.

3 possibilities

For the conversion of a temperature to an electric signal, three possibilities are to be considered.

1) NTC-resistors are resistors with a large Negative Temperature Coefficient, in fact their resistance will go down several decades if the temperature goes up a 100 °C. Their advantages are that they can be made very small, that they can give a large electric signal, and that they are relatively cheap. Drawbacks are that they are not stable when exposed to elevated temperatures or physical stress, and that their large temperature coefficient may be a problem, as the electronics must be able to handle signals varying 3 to 4 decades.

2) Resistance thermometers (RTDs). For many pure metals, the specific resistance is temperature dependent. A measurement of the resistance of a long, thin wire (to give a measurable resistance) will therefore be a way of measuring the temperature of the wire. The metal chosen must be chemically inactive, as even small oxidations will cause a change in the resistance. The two metals most often used are nickel and platinum, and of these platinum is too expensive to be used for this thermostat, and nickel, unfortunately, is not considered stable enough in the long run to be useful. Thus the use of resitance wire thermometers has been refused.

3) Thermocouples can be made very small, they are mechanically reliable and cheap. Their drawbacks are that they do not measure an absolute temperature, but only a temperature difference and that they produce relatively small voltages (around 35 µV/°C). The former makes it necessary to make a so called cold junction compensation (see chapter 16), and the latter places heavy demands on the electronics.

Experiments have been carried out with all three kinds of sensors. A fourth principle has been considered, but rejected. It was infrared radiation measurements, which can measure the temperature from a distance, but it is fragile and expensive.

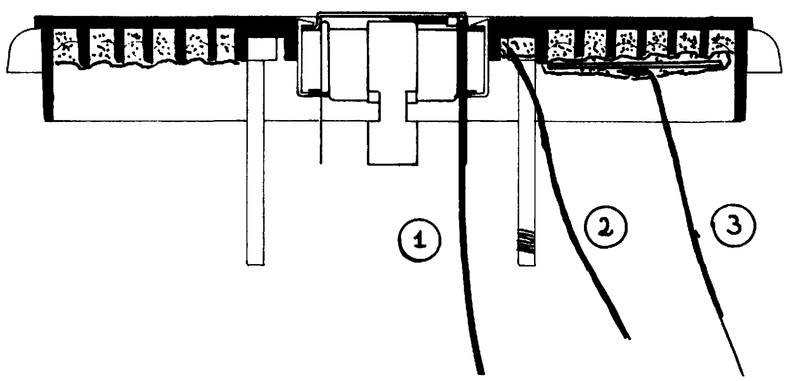
We have therefore chosen to use thermocouples, both for the measurement of the hot plate temperature and the temperature of the pan bottom.

Choice of thermocouple

The most widely used thermocouple for industrial purposes is the so called type J, which is made of iron and constantan. It does for our purpose not have a time stability sufficiently long, especially if exposed to temperatures around 500 °C. We have instead chosen to use thermocouples of type K, with a nickel-aluminum alloy and a nickel-chromium alloy (hence the name chromel-alumel). They are not as expensive as the very stable thermocouples made of platinum, tungsten and rhenium, and according to Kørtvelyessy (ref. 4) they have got good long time stability and reliability.

The output of a type K thermocouple is relatively small (around 40 µV/°C) and it can not be considered linear, if we want to measure with 1 °C accuracy. The electric ouput must therefore be converted to a temperature in the microprocessor, using a polynomial obtained from Kørtvelyessy.

Sensor for the hot plate temperature



Notation:

1: Pan bottom temperature sensor
2: Hot plate cast iron temperature sensor
3: Hot plate ceramics temperature sensor

Figure 15.1

The hot plate must be expected to have a non-uniform temperature distribution, and therefore the placing of the sensor should be considered. As mentioned earlier, the chosen mathematical model does not include any delay in time between the applied power and its influence on the temperature of the hot plate, and if this model shall give a good description of the system, the temperature must therefore be measured close to the resistance wires. In order to measure an average hot plate under side temperature, a strip of aluminum has been placed between the thermocouple and the hot plate, covering all the resistance wires, and the whole thing has been placed in a layer of ceramics. The placing of the sensor is shown as number 3 in figure 15.1.

For a thermostat ready for production, it should be possible in cooperation with the hot plate manufactorer, to cast the thermocouple and the resistance wires onto the plate simultaneously.

For experimental purposes another sensor has been placed in the indentation close to the centre, as shown on figure 15.1, number 2. This sensor will measure a temperature close to the temperature of the cast iron part of the hot plate, thus providing additional information about the system. The sensor may even be used in the final thermostat if it proves difficult to control the hot plate by only measuring the temperatures of the back side of the hot plate and the pan botom.

Sensor for the temperature of the pan bottom

Several requirements must be met for this sensor:

1) It must keep a good contact with the pan bottom.
2) The heat resistance towards the hot plate must be large.
3) The heat capacity of the sensor must be small.
4) The sensor must be robust, as it may be exposed to strong chemical and mechanical load.
5) The sensor shall fit in the same hole in the hot plate as do the ordinary capillary tube sensors.
6) It must be easy and cheap to produce and mount.
7) It must look good and be easily cleaned.

Several versions of this sensor has been produced. They have all been compared with what has been considered an "ideal" sensor, namely an NTC-resistor attached directly to the pan bottom. As the sensor shall provide the most important input to the control algoritm, it is very important that the time constant introduced is as small as possible. Thus, the fastest sensor has been chosen, as it also appeared to meet the above mentioned requirements.

The time lag introduced by the sensor in the measurement of the pan bottom temperature can be derived from figure 15.2.

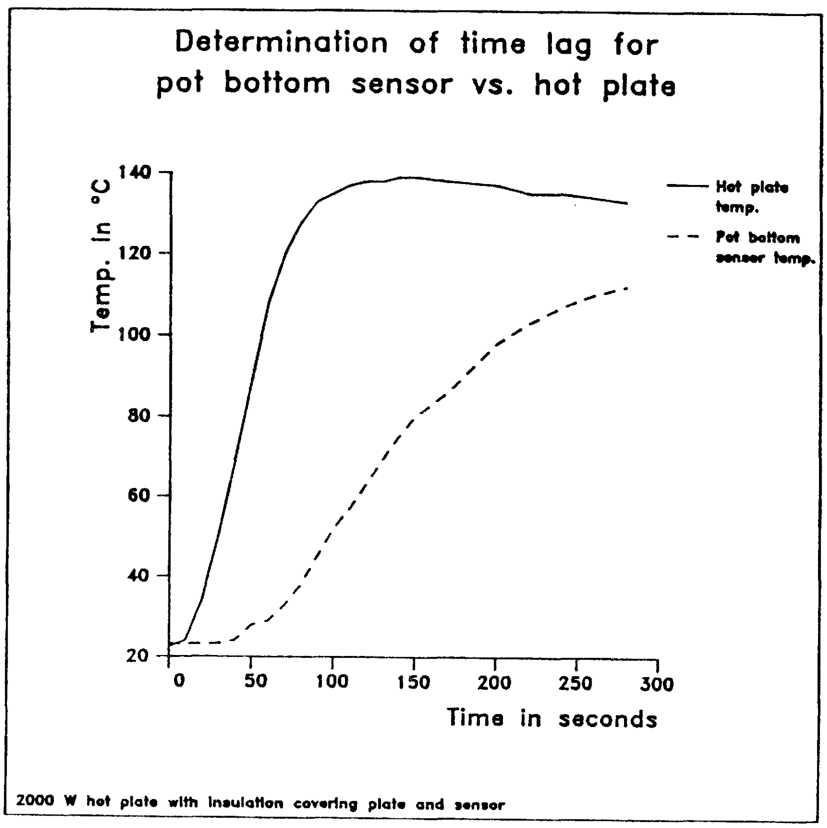


Figure 15.2

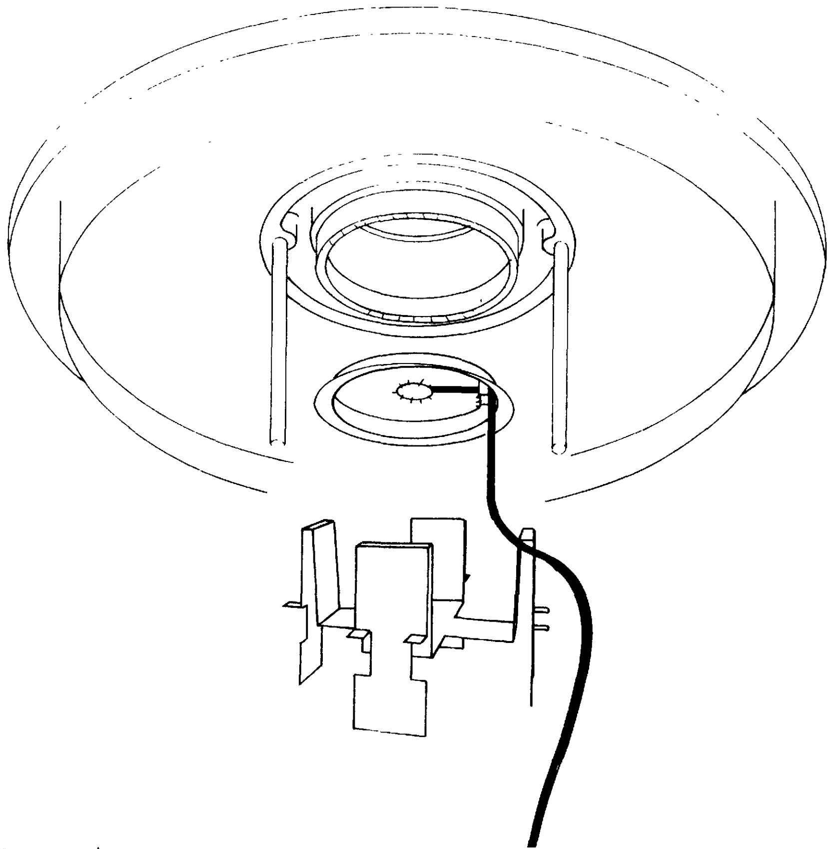
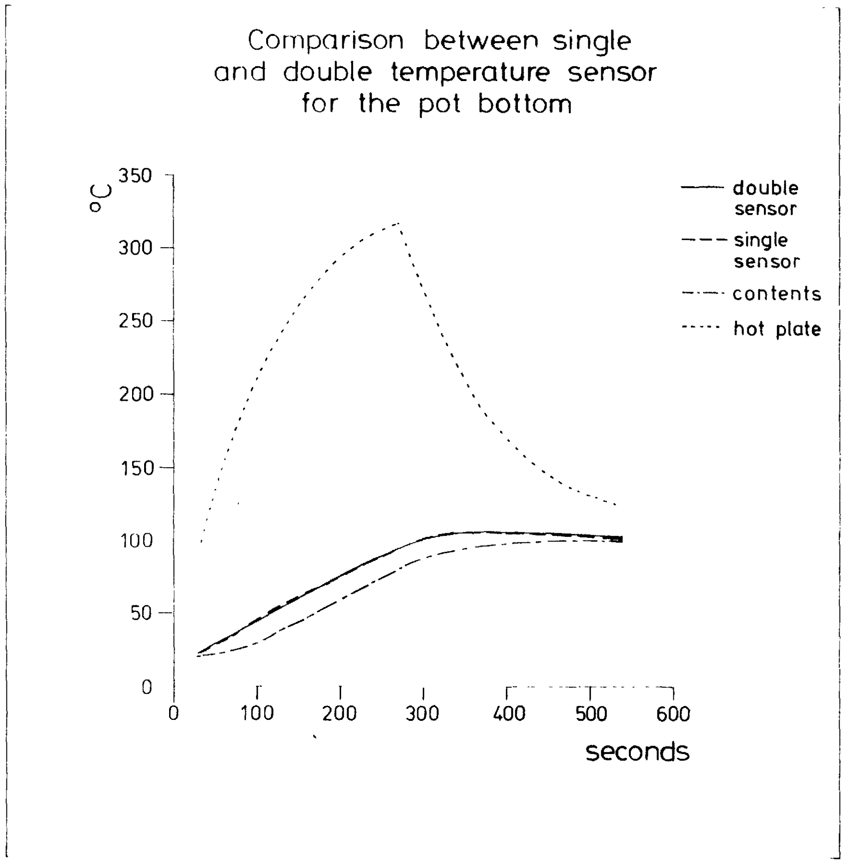


Figure 15.3

The sensor is made up of a 0.5 mm stainless steel disc with an insulated thermocouple attached to the back side. The disc is pressed against the pan bottom with a spring, the spring being held in position with a stainless steel clip. The clip is also preventing the disc from slipping through the hole in the hot plate.

A second version of this sensor has also been tested. To obtain a better temperature insulation from the hot plate, it had, through a hole in the centre of the steel disc, a smaller steel disc, attached to the thermocouple. The small disc was pressed against the pan bottom by means of a spring. This spring was held in position by means of a gadget, mounted on the large steel disk.

This sensor has a slightly better heat resistance towards the hot plate, but was refused because of the more complicated construction. An experimental comparison between the two sensors is shown in figure 15.4, and it is seen not to justify a preferation of the double disc sensor.



Comparison between single
and double temperature sensor
for the pot bottom
°C
350
300
250
200
150
100
50
0
0
100
200
300
400
500
600
seconds
double sensor
single sensor
contents
hot plate

Figure 15.4

16. Electronics

As mentioned in chapter 8, the electronics used for the experimental setup has been designed around an ordinary 8-bit personal computer, the Osborne Executive. The computer controls the temperature measurements, reads the setting of the control knobs and directs the power applied to each hot plate. The electronics used for the conversion of the temperatures to digital quantities, and for the conversion of digital quantities to electrical power will be described in this chapter. The design of the thermocouple amplifiers and the cold junction compensation is thoroughly described by Niels Hald Pedersen (ref. 7).

Thermocouple Amplifiers

The thermocouple amplifiers have the task of amplifying the small voltages delivered by the thermocouples (approx. 50 µV/°C) to voltages utilizing the accuracy of the analog/digital converter as well as possible. The full scale input range of the analogue/ digital converter used is approx. 10 V (10.23 V), so the maximum temperature to be measured should be converted to a voltage close to 90 % of 10 V (not 100 %, as this would hinder a distinction between overflow and maximum temperature). Further, it will often be adequate to choose a "nice" amplification. This may be an amplification making 1 °C correspond to an integer number of mV, or it may be a round number.

The thermocouple used, chromel-alumel, has a nonlinear characteristic, so it has been chosen to use a "round" amplification.

	Pot bottom	Hot plate
Max. temperature	230 °C	450 °C
Thermocouple voltage at max. temp.	10.2 mV	20.6 mV
Full scale input range of ADC	10.23 V	10.23 V
Amplification	1000	500

The small voltages delivered by the thermocouples put stringent demands on the off-set voltages and bias currents of the amplifier. We have therefore used a special ultra-low off-set voltage operational amplifier, namely the OP-07 from Precision Monolithics (PMI).

It is hoped, that in the final electronics it will be possible to use a less expensive amplifier, but it has been an aim in the development of the thermostat to use electronics, that certainly will be accurate and stable enough. When the final version of the control algorithm has been chosen, the required accuracy will also be given, and hopefully this will be lower than the accuracy used in the experimental setup.

As the thermocouples only measure a temperature **difference**, some compensation must be made for the temperature of the so-called cold junction. This is done with a special cold junction compensation voltage amplifier described below. This circuit delivers a voltage that is subtracted from the amplified thermocouple voltage in the thermocouple amplifiers.

Besides the amplifiers, the circuit contains two low pass filters for each amplifier. The first filter is meant to cut off high frequencies, and has a cut off frequency of 5 kHz. The second filter is a second order filter, which is primarily used to filter off the mains frequency, and has a 10 Hz cut off frequency.

Cold junction compensation

This circuit measures the temperature of the cold junctions of the thermocouples. This temperature is then converted to a voltage, corresponding to the voltage delivered by the cold junction thermocouple, and this voltage is subtracted from the thermocouple voltage in the thermocouple amplifiers. The cold junction temperature is measured by means of a transistor, as they can be made with linear characteristic and calibrated from the factory. A constant current is lead through the transistor, giving a voltage proportional to the temperature. This voltage is amplified to a level usable in the thermocouple amplifiers.

Analogue/digital converter and multiplexer

The converter used is a 12-bit analogue/digital converter (ADC) module with 8 analogue inputs from 0 to 10.2375 V and a cycle time less than 100 µs. The module is interfacing with the computer via a standard 16-bit parallel port.

The elements of the module are: a solid-state MOS multiplexer (AD 7501), a sample/track-hold circuit (AD 582), an integrated analog/digital converter (AD 574A), all from Analog Devices, a quad D 4-bit latch (4042B) and a few discrete components. The converter is of type SAR (succesive approximation register) and is converting 12 bit in less than 35 µs, giving a cycle time for the module of around 100 µs.

In short, a measuring sequence will be:

1) Load the multiplexer with the number of the channel to be measured. This will give rise to the start of a "dummy"-conversion, which is then waited upon to finish.

2) Set the sample/hold circuit to "hold" the input.

3) Start the conversion.

4) Wait for the conversion to finish, approx. 35 µs.

5) Set the sample/hold circuit to "sample".

6) Read the digital output from the ADC-circuit.

Interface to the computer

The computer used in the experimental setup is a standard portable 8-bit personal computer, the Osborne Executive. It is equipped with a Z80 processor and one parallel and two serial input/output ports. These ports were not found adequate for the purpose, so two Z80-PIO (Parallel Input Output) integrated circuits were connected to the Z80 bus. One of these was then used for the interface to the ADC module. As seen from the computer, a PIO circuit is 4 input/output ports called: port A, port B, control port A and control port B. Each of port A and B may be used for the actual input or output, and the control ports are used for programming the ports respectively.

To control the power induced to each hot plate, a 8253 integrated programmable interval timer was also added to the Z80 bus. Pulse width modulation is used for varying the power. This means, that a fixed time interval is chosen; during this, the power will be switched on and held on for a given time period, and then swithed off and held off for the rest of the interval - then the cycle will be repeated. The power may in this way be given values between 0 and 100 %, the number of different values being limited by the number of clock-cycles to the 8253 during the fixed time interval (60 for the chosen setup). The actual value of the power is also determined by the zero-crossings of the mains voltage, as described under the heading of Solid State Relays.

The 8253 circuit contains 3 programmable timers, each of them are supplied with a 60 Hz clock frequency from the Osborne computer. One timer is running with the fixed interval, and the other two are giving the power-on period for each of two hot plates.

Solid state relays

The control signals delivered by the 8253 timer circuit are converted to electrical power by means of two solid state relays. The relays function like ordinary relays, except that they do not get worn in the same way and that they ensure "zero voltage turn-on". This means, that they always turn power on (and off) in the zero crossing of the mains voltage (to be exact, the moment is detemined by the zero crossing of the current, but with a pure resistive load they are identical), almost preventing electrical noise and high inrush currents. The relays used have been of the type Crydom D4808 from International Rectifier.

Test of hardware

The hardware described has been thoroughly tested, and it has proved to be satisfactory. There has been no problems due to hum, noise, drift etc. The circuits described have been constructed and adjusted without significant problems, but as expected, some time has been spent in this. The equipment used is both quite expensive and quite demanding in adjustment etc.; much more expensive and demanding than acceptable for the production-ready thermostat. This has been chosen to assure that the accuracy of the hardware does not constitute a limitation in the development of the control algorithm. It is to be hoped that when a control algorithm has finally been chosen, it will tolerate greater inaccuracies in the temperature measurements, thus implying cheaper and simpler hardware.

The temperature sensors have been installed as described in chapter 15, and have been working fine. Especially the pan bottom temperature sensor seems mechanically and electrically very reliable.

17. Software environment

Microcomputer software

A suboptimum control algorithm based on the principle from chapter 14 has been written in Pascal and tested on an Osborne Executive personal computer. The program consists of several modules, that can be compiled and tested independently.

```
                      +--------------------+
                      |                    |
                      |        KOGE        |
                      |                    |
                      +--------------------+
                                |
                                |
             +-----------------+-----------------+
             |                 |                 |
      +-------------+   +-------------+   +-------------+
      |             |   |             |   |             |
      |   ADAPTIV   |   | THERMOSTAT  |   |    PSRBS    |
      |             |   |             |   |             |
      +-------------+   +-------------+   +-------------+
             |                 |                 |
      +-------------+          |                 |
      |             |          |                 |
      |    DCON     |          |                 |
      |             |          |                 |
      +-------------+          |                 |
             |                 |                 |
             +-----------------+-----------------+
                               |
                               |
             +-----------------+-----------------+
             |                 |                 |
      +-------------+   +-------------+   +-------------+
      |             |   |             |   |             |
      |     SYS     |   |    HARD     |   |   LOGGING   |
      |             |   |             |   |             |
      +-------------+   +-------------+   +-------------+
```

Figure 17.1

The hierarchical composition of the program is shown in fig. 17.1. It is composed of 5 modules:

KOGE

The main program KOGE (Danish for boil or cook) is a framework administering the execution of the appropriate subprograms according to the experimenters choice at run time. A menu is provided, giving 4 choices:

1) Run an experiment using the adaptive control algorithm while logging data.

2) Run an experiment using a thermostat algorithm, controlling the temperature of any of the sensors.

3) Run an experiment with a pseudo-random-binary-sequence controlled power input and data-logging.

4) Initialize the power electronics (in order to prevent an initial turn-on of power to the hot plate during start-up of the system).

Choices 1, 2 and 3 will call separate program modules, ADAPTIV, THERMOSTAT and PSRBS respectively. These modules shall be described in some detail in the following paragraphs.

THERMOSTAT

This module features a thermostat. The operator is prompted for the choice of one of the 4 sensors to be used in the thermostatting process. After choice of sensor, the operator is prompted for a set-point temperature and the power to be used when the thermostat is "on" and when it is "off".

While the program is running, the screen will display the current power, the elapsed time, the total energy-consumption and the temperatures measured. The program will run until a key is pressed on the computer keyboard.

ADAPTIV and DCON

These modules implement the adaptive control algorithm described in chapter 14. The general administration of the experiment is carried out by ADAPTIV, which after each sampling will call DCON (Discrete CONtrol), containing the discrete regulator algorithm. Relevant parameters for system and regulator will be logged by ADAPTIV by calling routines in the module LOGGING.

At start-up, the operator is prompted for an optional change in any of the default parameters. If this is required, a special menu for this purpose, along with the actual parameters, will be displayed.

Then a set-point is prompted for, the regulator will start and will continue running. When a key is pressed, the regulator will stop, and the operator will be asked whether he wants processing of the logged data. If so, control will be transferred to a routine in the module LOGGING, which will prepare a disc file or a printout containing selected values.

PSRBS

This module provides control of the power input with a pseudo random binary sequence while logging the system parameters. Thus, it is not a regulator, but rather a perturbator, and the primary use is generation and collection of data intended for later transmission to the mainframe system and subsequent analysis with a parameter estimation program. The pseudo random binary sequence is used to assure a broad frequency spectrum in the perturbation.

The perturbations will persist until a key is pressed, and appropriate routines in module LOGGING will be called for the creation of a disk file containing selected parameters.

LOGGING, SYS and HARD

These modules contain utility and hardware service routines, and serve as a foundation for the formerly described programs.

The routines of module LOGGING facilitates the logging of measurements and parameters; the values being stored as appropriately scaled two-byte integers in a large, fixed-format array. Further, the module contains a routine for preparing a printout or a text-file from the logged data.

The module SYS contains routines for the administration of the real-time clock, cursor positioning etc.

The routines of module HARD service the hardware peripherals, which are described in chapter 16. The module also contains routines for converting the thermocouple voltages to °C along with calibration constants etc.

File transmission

Further, programs for communication with the local computing center, NEUCC, have been implemented. They have mainly been used for transmitting measured data from the Osborne-microcomputer to NEUCC, for further analysis and/or plotting.

Mainframe software

At the computing centre NEUCC (Northern European University Computing Centre) various utility programs have been installed on the IBM 3081 computer, running MVS/TSO:

1) PAREST. A parameter estimation routine capable of estimating a maximum of 5 parameters in a given model with given measurements of the variables (ref. 8). PAREST has been used for off-line estimations of heat capacities and -conductances. The results have been used to supply DCON with initial estimates of the parameters and to compare with DCON's results.

2) DCON. Almost the same as the Osborne/Pascal routine of the same name. This program has been supplied with temperature measurements from experiments, and it has thus been possible, in a fast and simple way, to examine the routine with various constants and estimation principles. It is, e.g., very fast to decide what the initial estimate of Cc should be for a given experiment, to assure the fastest convergence of the estimates. A potential risk involved in this procedure is to overinterpret the response of the routine to a single set of measurements, without considering the variance from one experiment ot the other.

3) SIMSYS/SIL. Two simulation programs used for comparing the system-models with the real system (ref. 9 and 10).

4) EASYPLOT. A simple, yet effective plotting program (ref. 11).

18. Experimental results for hot plates

Scope

Following the test-procedure from chapter 7, DCON should be lead through a number of different experiments. We have, however, started with experiments with water only, on the assumption that the ability to boil water is a necessary condition to pass the complete test.

Most of the experiments have been with a 3 litres pan with a lid and an 18 cm 2000 W hot plate, with approx. 1 litre of water in the pan. The choice of almost constant parameters in the experiments should imply an easier task for DCON, that assumes constant and known values of Ch, Cp and Rpc.

A possible drawback to this approach, is the risk of wasting time making DCON able to boil water, if the control-principle cannot be used for other cooking.

Procedure

1) Ch, Cp and Rpc are by DCON presumed known, and must thus be determined off-line, e.g. by the program PAREST, described in ref. 8. PAREST is given measurements of Th, Tp, Tc and P, and will estimate Ch, Cp, Cc, Rhp and Rpc (Rhp and Cc will also be estimated by DCON).

2) DCON is run as a part of the ADAPTIV program on the Osborne Executive. The various runs have been different with respect to:

   - Actual values of Ch, Cp, Cc, Rhp and Rpc (due to the use of different pans and contents)
   - Initial estimates of Rhp and Cc
   - Filtering of the parameter estimates
   - Filtering of the power-variable to compensate for a possible time-delay from a change in the applied power to a measurable influence on Th
   - Extension of the model by including heat loss from the hot plate and from the contents to the surroundings, Rha and Rca, respectively
   - Sampling time

   The measured and estimated data are logged on a disk file.

3) Optionally, the NEUCC version of DCON may be run with the same experimental data. It will then be possible to vary these runs in the same way as for the Osborne version of DCON - except of course the actual parameters of the system. The NEUCC version of DCON will calculate the power to be applied in each moment, but the value of the power variable will be the power determined (and logged) by the Osborne version.

Tuning of DCON

Off-line determined constants

Ch, Cp and Rpc are by DCON presumed known and constant. It is thus a task in tuning DCON to choose "proper" values for Ch, Cp and Rpc. These values may be found in 3 ways:

1) By physical measurements.
2) By mathematical analysis based on the model structure and experimental measurements.
3) By choosing values that will make DCON work "nice".

Ideally, if the model gave a good description of the real world, these 3 methods should give identical results. This is, unfortunately, not so. Of the 3 ways, the direct physical measurements presupposes a good connexion between the model and the physical reality, whereas the last way is independent of the connexion between model and reality.

As an example may be taken the determination of Ch. If the model is correct, the heat capacity of the hot plate may be determined by removing the plate from the cooker and measuring the heat capacity in a calorimeter.

The mathematical determination of Ch (e.g. PAREST may be used) will not necessarily determine the heat capacity of the hot plate, but the heat capacity of that part of the hot plate/pan system, that will cause the closest resemblance between the model and the experimental results. This heat capacity may be smaller than the "physical" heat capacity, if a part of the hot plate actually acts more as a part of the pan than as a part of the hot plate.

The value chosen for Ch by method 3 may very well be different from the value chosen by method 2. For instance, choosing a value for Ch, known to be smaller than the values obtained with method 1 and 2, could cause a more cautious and stable operation of DCON.

We have mostly used method 2 with the program PAREST to choose values for these constants. It has been possible to obtain reasonable values for Ch and Cp, but Rpc seems to be too dependent on the actual experiment and the actual temperatures to make it possible to choose a single, reasonably good value.

On-line determined constants

Rhp and Cc are determined on-line by DCON. For both, and for each sample-time, an instantaneous value is found from the system equations. If this value is within a certain "credibility-interval", the old value will be updated. This updating has the form

New_value := Old_value + (Instantaneous_value - Old_value) / f.

"f" may be chosen as a constant or a time-dependent function, all dependent on whether the old or the new values are expected to be most trustworthy. New values may be better than old if the constants are expected to drift, and the old values may be better if the system is heavily influenced by noise.

Experience has showed, that due to the model shortcomings it is most advantageous to attach the greatest importance to the latest values. The "credibility-interval" has been chosen much wider than would seem reasonable from physical reflections, as this also seems to some degree to compensate for the model shortcomings. It is possible, that even negative values should be considered within the "credibility-interval", but this has not been thoroughly tested.

Influence of the parameters of DCON

To illustrate the influence of the various parameters to the DCON-procedure, a number of experiments have been made. The DCON-procedure has been run a number of times on NEUCC, each time with the same set of experimental data, but with different values of the parameters. For each run, the estimates of Tc have been compared with the measured values.

The "reference" experiment has been with the following parameters:

Ch	: 660	J/K
Cp	: 850	J/K
Rhp-init	: 0.12	K/W
Rpc	: 0.019	K/W
Rhp-min	: 0.005	K/W
Rhp-max	: 0.5	K/W
Cc-min	: 200	J/K
Cc-max	: 20000	J/K
a	: 2	
b	: 0.1	
c	: 10	

These values have also been used in the other experiments, except the ones noted:

Experiment no.	Parameters changed
0	none
1 2	Ch = 300 J/K Ch = 1000 J/K
3 4	Cp = 400 J/K Cp = 1200 J/K
5 6	Rhp = 0.05 K/W Rhp = 0.2 K/W
7 8	Rpc = 0.01 K/W Rpc = 0.03 K/W
9 10	a = 1, b = 0 a = 10, b = 0
11 12	c = 1 c = 50
13 14	Rhp-max = 10 K/W, Rhp-min = 0 K/W Rhp-max = 0.2 K/W, Rhp-min = 0.05 K/W
15 16	Cc-max = 100000 J/K, Cc-min = 0 J/K Cc-max = 10000 J/K, Cc-min = 1000 J/K
17	Alternative calculation of Tc
18	dTc/dt and Cc * dTc/dT identical signs
19	sampletime = 5 seconds

Table 18.1

The results of these experiments are shown below.

Reference experiment

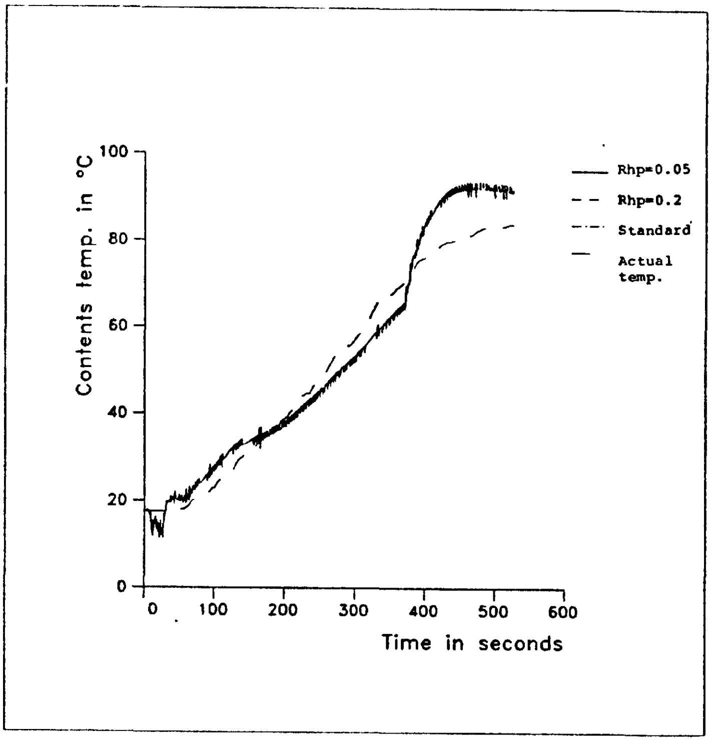


Figure 18.1

The graph shows the temperature measured inside the pan, Tc, and the temperature estimated by DCON, X3. The greatest divergences between the two are at the very start of the heating and after power has been turned off. The first divergence, where DCON estimates the temperature of the contents far below the real value, is probably due to the fact that the temperature of the hot plate is not rising as fast as would be expected from the model. DCON will try to "explain" this by assigning the contents a low temperature, but a more likely explanation is a time delay in the heat transport from the resistance wire to the hot plate temperature sensor.

The other divergence, which will be dealt with in more detail below, is the significant rise in the estimates of the contents temperature when power is turned off.

Influence of the estimate of Ch

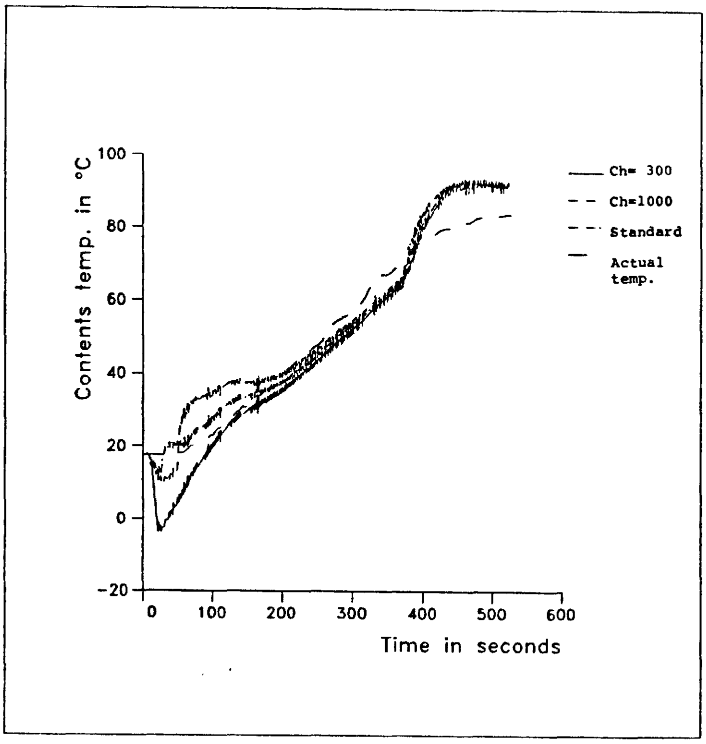


Figure 18.2

This graph shows the influence of the off-line estimated value of Ch, the heat capacity of the hot plate. The influence is most in evidence in the beginning of the heating period, as this is the time where the temperature of the hot plate is most rapidly changing. When power is turned off, the heat capacity of the hot plate seems to become unimportant for the estimates of the temperature of the contents.

Influence of the estimate of Cp

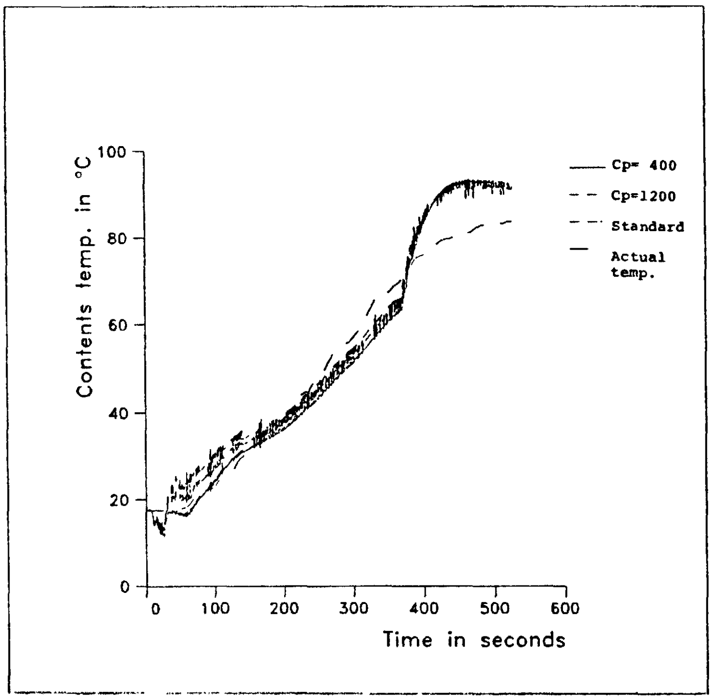


Figure 18.3

The heat capacity of the pan is also estimated off-line, and these curves show the influence of this estimate. The influence does not seem to be critical, so it seems reasonable to assume that this value may be regarded as a constant.

Influence of the estimate of Rhp

Rhp is estimated on-line, and the experiment showed no significant influence of the initial estimate of Rhp. The result will, however, look differentially if exponential filtering of the estimates of Rhp (i.e. new estimates become less and less important) is used.

Influence of the estimate of Rpc

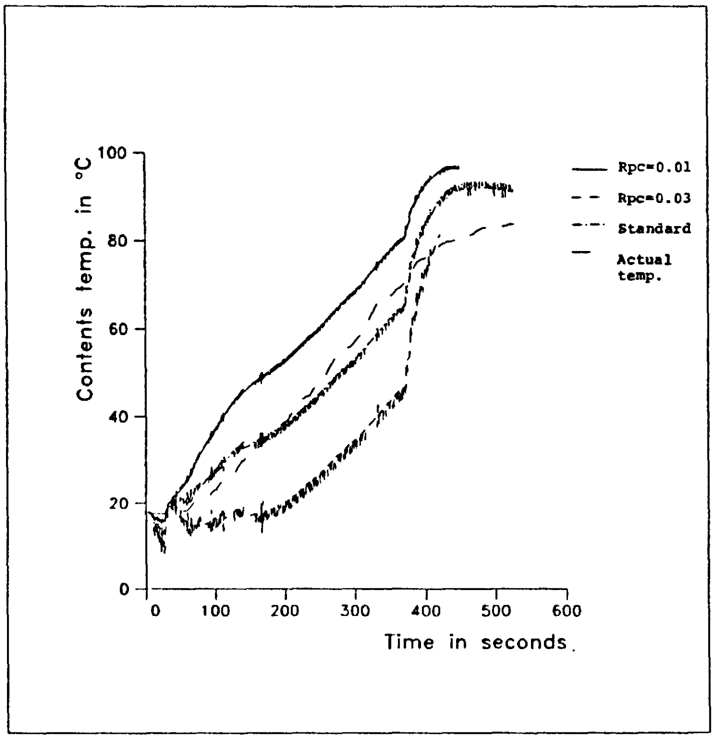


Figure 18.4

This shows the influence of the off-line estimated value of Rpc. This parameter has a great importance during the heating period, and it is thus very decisive for a good control with DCON to have a good estimate of Rpc. Unfortunately the parameter can hardly be regarded as a constant, as will be demonstrated later. It seems to be very dependent on the temperature close to the pan bottom and on the nature of the contents.

Influence of filtering of Rhp-estimates

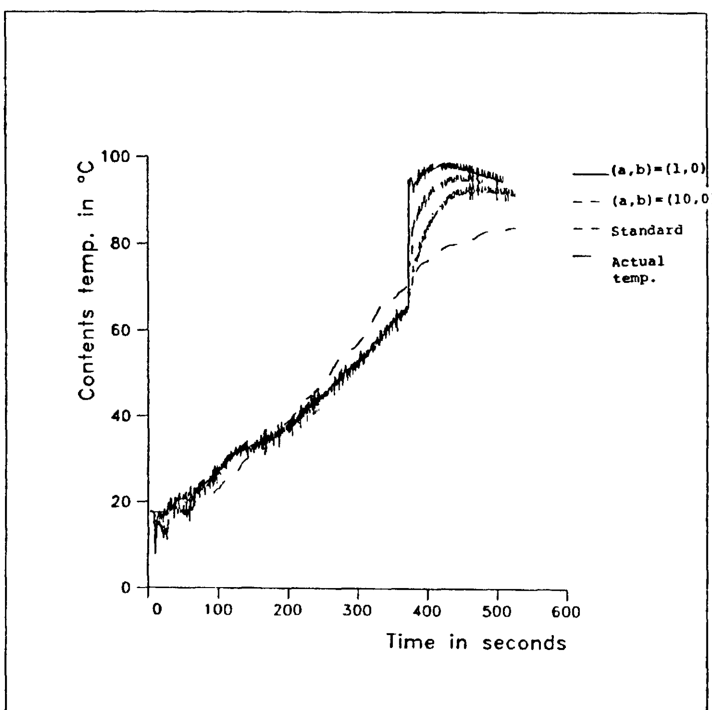


Figure 18.5

As mentioned above, the estimate of Rhp is being updated as: New_value := Old_value + (Instantaneous_value - Old_value) / f, where f = a + b*nc, "nc" being the number of samples so far. The curves show the consequence of assigning "b" the value 0, i.e. the filtering is time independent, and "a" the values 1 (which means New_value = Instantaneous_value), and 10 (New_value = 0.9 * Old_value + 0.1 * Instantaneous_value). The influence is most important when power is turned off, as this causes a large change in the estimates of Rhp.

Influence of filtering of Cc-estimates

Changing the filtering constant "c", used in the updating of the estimates of Cc, did not seem to have any influence on the estimates of Tc for this experiment.

Influence of limitation of Rhp-estimates

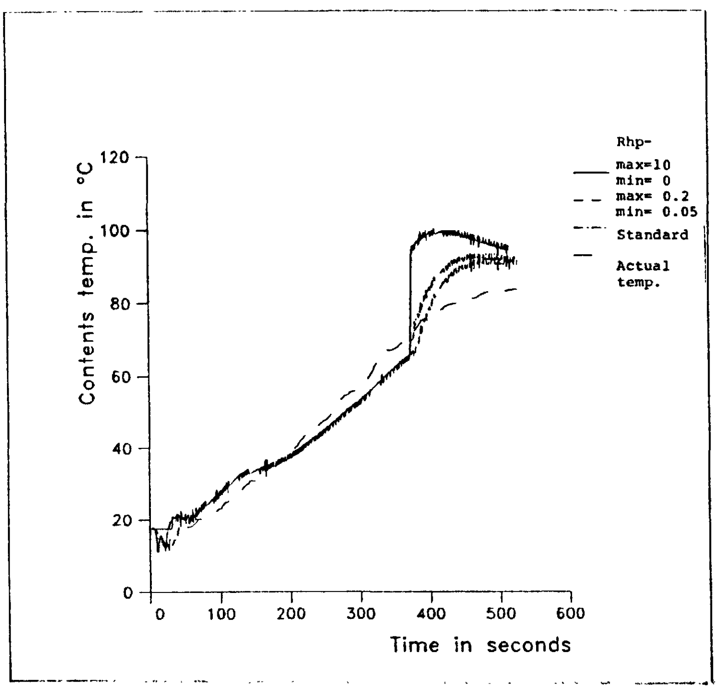


Figure 18.6

The new estimates of Rhp are being compared with a maximum and a minimum value before they are used in the updating of the old estimate of Rhp. If they are outside this interval, the old estimate of Rhp is not updated. The drastic change in the system when power is turned off, is seen to cause a large fluctuation in the estimates of Rhp, which may be diminished if the "credibility-interval" is kept small.

Influence of limitation of Cc-estimates

The "credibility-interval" for the estimates of Cc did not seem to have any influence on the estimates of Tc.

Alternative Tc-calculation

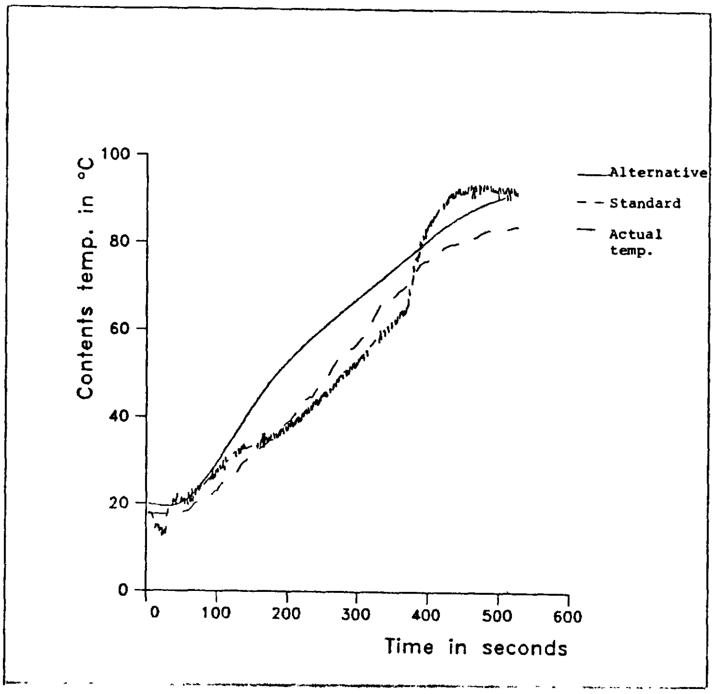


Figure 18.7

As described in chapter 14, Tc is usually found from the equation:

Tc = Tp - Rpc ((Th - Tp)/Rhp - Cp*dTp/smplt).

Another way to estimate Tc is the equation:

dTc = smplt * (Tp - Tc) / (Rpc * Cc).

As this equation is dealing with changes in Tc only, the estimates of Tc may be expected to drift, but they are not much influenced by noise.

Influence of dTc-restriction

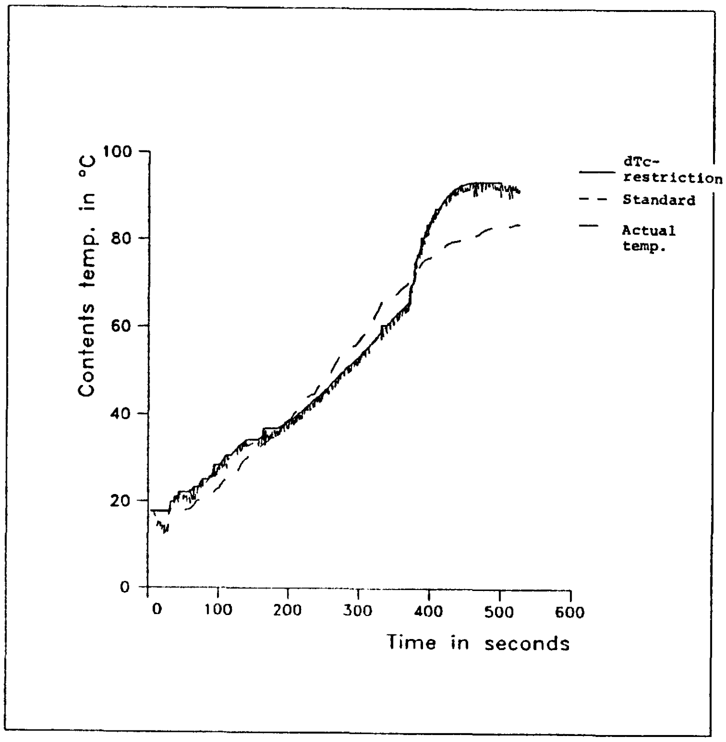


Figure 18.8

In the program, a value is found for Cc * dTc/dt. A reasonable assumption could be that as long as Cc * dTc/dt > 0, Tc(t) >= Tc(t-1). This assumption has been tested in this figure, and it can be seen to work fine as long as power is induced to the system, but when power is turned off, the estimates of Tc become much too high, and with this restriction, DCON will not allow Tc to fall towards the measured Tc.

Influence of sample interval

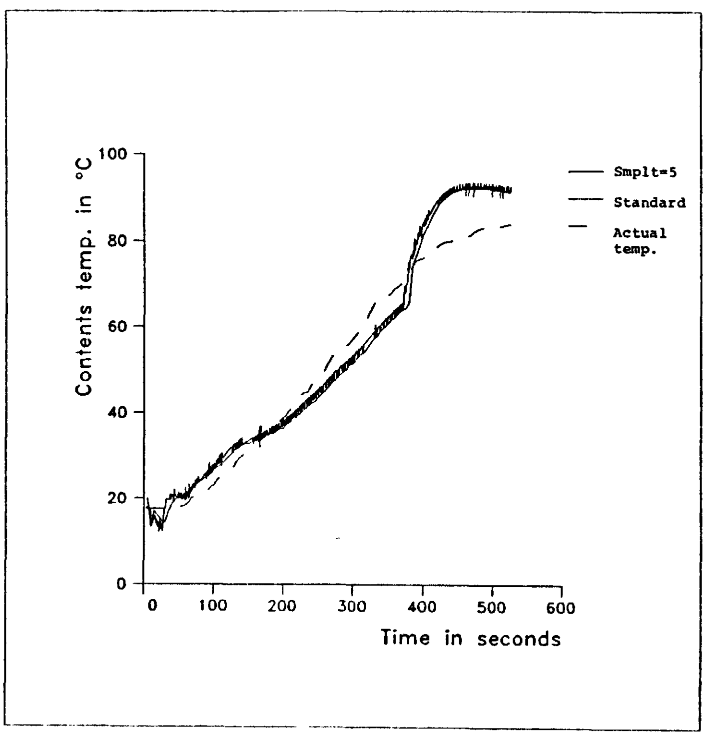


Figure 18.9

Here the sampletime has been set to 5 seconds instead of 1. This causes a reduced noise on the estimates of Tc, and does not seem to have any drawbacks for this experiment.

Estimation troubles when power is turned off

It has been characteristic for all the experiments with DCON, that even if the procedure has had a very good estimate of Tc before power is turned off, the estimate becomes poor for a long time after turn-off. To examine this behaviour in more detail, the heat flows of the system have been examined for a random chosen experiment. Ideally the heat-flows should satisfy Kirchoffs laws - the net heat flow to each node of the model should always be 0.

In the following calculations, we have used the parameter values estimated by DCON just before turn-off:

```
Cc  = 6762  J/K
Rhp = 0.071 K/W
```

and the parameter values estimated off-line:

```
Ch  = 500   J/K
Cp  = 400   J/K
Rpc = 0.017 K/W
```

When these parameters are known as well as the temperatures and their derivatives, the heat flows can be found as

```
Php (flow from hot plate to pan)         = (Th - Tp)/Rhp
Ppc (flow from pan to contents)          = (Tp - Tc)/Rpc
Ph  (heat accumulated in the hot plate)  = dTh/dt * Ch
Pp  (heat accumulated in the pan)        = dTp/dt * Cp
Pc  (heat accumulated in the contents)   = dTc/dt * Cc
```

Just before power was turned off, the heat flows could be calculated as (t = 200 sec.):

```
    P                   Php                Ppc

+- 2000 W ->---+-- 1866 W ->---+-- 1578 W ->---+
|              |               |               |
|         125 W            90 W            1352 W
|       Ph     |        Pp     |        Pc     |
|              V               V               V
|              |               |               |
+--------------+---------------+---------------+
```

Just after power was turned off (t = 220 sec.), the flows were:

```
+-    0 W ->---+-- 1651 W ->---+-- 1659 W ->---+
|              |               |               |
|        1000 W            80 W            1578 W
|              |               |               |
|              Δ               V               V
|              |               |               |
+--------------+---------------+---------------+
```

After 250 seconds:

```
+-     0 W ->---+--  850 W ->---+-- 1447 W ->---+
|               |               |               |
|          1200 W              0 W          1352 W
|               |               |               |
|               Δ               V               V
|               |               |               |
+---------------+---------------+---------------+
```

After 300 seconds:

```
+-     0 W ->---+--  375 W ->---+-- 1012 W ->---+
|               |               |               |
|            217 W            33 W            451 W
|               |               |               |
|               Δ               Δ               V
|               |               |               |
+---------------+---------------+---------------+
```

And after 400 seconds:

```
+-     0 W ->---+--  104 W ->---+--  465 W ->---+
|               |               |               |
|             50 W            16 W             68 W
|               |               |               |
|               Δ               Δ               V
|               |               |               |
+---------------+---------------+---------------+
```

It is seen, that even though the net heat flow to each node of the system is not exactly 0 before turn-off, the deviation is within 10-20 %. After 400 seconds, however, the deviation is much more than 100 %, and it is thus obvious that DCON is not able to estimate reasonable parameters based on this model.

The reason for the failure of the model after power turn-off is not known, but an explanation could be, that during the heating of the system, the main heat flow has been vertical, from the plate through the pan bottom to the contents. When power is turned off, it is possible that the heat flow becomes more radial, i.e. from the centre of the hot plate and the centre of the contents to the periphery. In this connexion it might be a problem, that the pan bottom temperature sensor is not placed vertically above the hot plate temperature sensor.

Heat loss to the ambient will also become more significant, but it can be seen from the figures above, that extending the model with heat losses from plate and contents to the ambient, will not cause a satisfactory improvement. (The total heat loss from the system to the ambient is around 100 W).

Conclusion

The experiments have shown, that even a well-tuned version of DCON is not able to give an adequate control of the system. DCON will often work fine, but there is a considerable risk of estimating the temperature of the contents 20 °C wrong, and there are severe problems in estimating the temperature when power has been turned off.

Some of these problems may be overcome by choosing a better fitted model for the system. This model should contain

- the temperature of the cast iron part of the hot plate as a variable
- a distinction between the pan bottom sensor temperature measurement and the pan bottom temperature
- some description of the time delays in the system
- a better description of the relation between the pan bottom temperature and the contents temperature.

19. Economical estimates

Expenses

The hardware cost of the thermostat when produced in 10,000s will be (the thermostat replaces two ordinary hot plate controllers):

A one-chip microprocessor	15.00 D.kr.
Electronics	120.00 D.kr.
A custom-designed chip	80.00 D.kr.
Power supply	70.00 D.kr.
Triacs	40.00 D.kr.
Box, knobs etc.	80.00 D.kr.
Sensor	100.00 D.kr.
Total	505.00 D.kr.
Cost of two ordinary controllers	- 100.00 D.kr.
Extra cost	405.00 D.kr.

The extra cost for the consumer must be expected to be somewhat higher, due to profits, wages etc. It is here estimated to be 750 D.kr.

Savings

In 1975 the consumption of an electric hot plate cooker was estimated by Jørgen Nørgård (ref. 12) to be approx. 750 kWh per year. It is expected that the thermostat will be able to reduce this consumption by 20 % or 150 kWh per year. This will give rise to an economic saving of approx. 115 D.kr. per year.

The thermostat will thus have a simple economic pay-back time of around 6.5 years.

It will, however, be unfair not to look at the improvements of comfort caused by the electronic thermostat, so the long pay-back time will probably not be prohibitive for a large group of consumers.

20. Conclusion and further work regarding the electronic thermostat

During the project, it has been illustrated that a significant electricity saving (20 %) may be obtained by supplying electric cookers with an accurate thermostat, corresponding to an electricity saving of 1 % on a national basis. The thermostat will also make the operation of the cooker more comfortable, and it is estimated that this will justify the somewhat higher price for the cooker.

An experimental microprocessor based setup has been built for the investigation of different principles of control.

Two principles have been examined:

1) Direct substitution in the model equations. This principle has been investigated experimentally with the procedure DCON. The results show that the model, on which DCON is based, does not give an adequate description of the system.

2) Prediction of the pan bottom temperature. This principle has appeared promising in computer simulated experiments, but the results have not been verified experimentally.

The work will be continued at Physics Laboratory 3, funded by the Danish Department of Energy. The continuation is based on the following programme:

1) Testing of the prediction principle with real, experimental data.

2) Extension and improvement of the system model in order to give a more complete description of the system.

3) Rewriting the procedure DCON, based on the new system model.

4) Test of the improved version of DCON.

5) Final choice of control principle.

After these steps, a second phase of the research project will follow, intended to make the thermostat ready for industrial production:

6) Requirement specification for electronics and sensors, based on the given control algorithm.

7) Optimization of the control algoritm with respect to storage and time demands.

8) Development and construction of a one-board microprocessor with all the required electronics. This board will be built into an electric cooker, and will be tested both at Physics Laboratory 3 and at other institutions and companies.

9) Final evaluation of electronics, sensors and computer programme before the construction of a production-ready thermostat. This last phase will be in cooperation with a manufacturer of electronics and the Electronics Institute at the Technical University of Denmark. The latter will develop a

custom designed integrated circuit containing most of the required electronics.

21. An energy efficient oven

A part of the project has been devoted to another piece of the equipment frequently used, namely the electric oven.

The electric oven is, as the cooker, one of the major electricity consumers in the Danish households. During the last decades, new ovens have become bigger and easier to clean, but there has been very little attention to the energy consumption.

The electric energy consumed in an oven is (nearly) all converted to thermal energy. This thermal energy heats up the food, the oven itself and the ambient air. Only the heating of the food is desired, and therefore the efficiency of an oven may be defined as the heat transferred to the food divided by the total electrical energy consumed.

The best way to save electricity with an electric oven is to fill it up whenever one uses it, as the effiency of an oven is smaller if it is not filled. In many Danish kitchens, however, the oven is relatively large (60 - 80 litres) and it is often used for roasting a chicken or baking a single loaf. Hence the average efficiency of the electric ovens is poor. One way of bringing down the energy consumption is to make a smaller oven. Then one can use the old, big oven the few times in a year it is needed, while the small, efficient oven is used for the daily cooking.

A small energy efficient oven will probably also cause electricity savings in the households as it can be used in stead of the cooker for many purposes. The energy efficiency when roasting a chicken in a pan will be poorer than the one obtained when roasting chicken in the oven, and this has previously been the other way around.

It must be expected, that the economic saving alone cannot justify an investment in an energy efficient oven, so the oven must have other advantages to have a reasonable market. These advantages are, for the prototype oven, a good design and an accurate temperature control, that will work even down to room temperature.

Two versions of a prototype oven have been built, LEO1 (figure 21.1) and LEO2 (figure 21.2) (Low Energy Oven 1 and 2). LEO1 was a preliminary experiment of constructing a small, well insulated oven. As it gave satisfactory results, work was carried on, and LEO2 was developed. The development of LEO2 was part of a Masters Thesis of M. Sc. Jens Waale at the Laboratory of Engineering Design, also at the Technical University of Denmark. The design was carefully studied with respect to technical construction, optimum thickness of insulation, choice of material etc. Part of the study was based on a computer model, which proved to give satisfactory results.

From the work with LEO2, as described in Jens Waale's Master Thesis (ref. 3), a few results will be mentioned. It has been found, that with respect to energy consumption there is an energy optimum thickness of insulation. The reason is, that the energy saved in the steady state by increasing the thickness of insulation is outweighed by the extra energy required to heat up the thicker insulation. The thickness naturally depends on the duration of use, a short time giving a small thickness of insulation and vice versa. If the average period of use is 1 hour, the optimum thickness for the oven described is 7 cm.

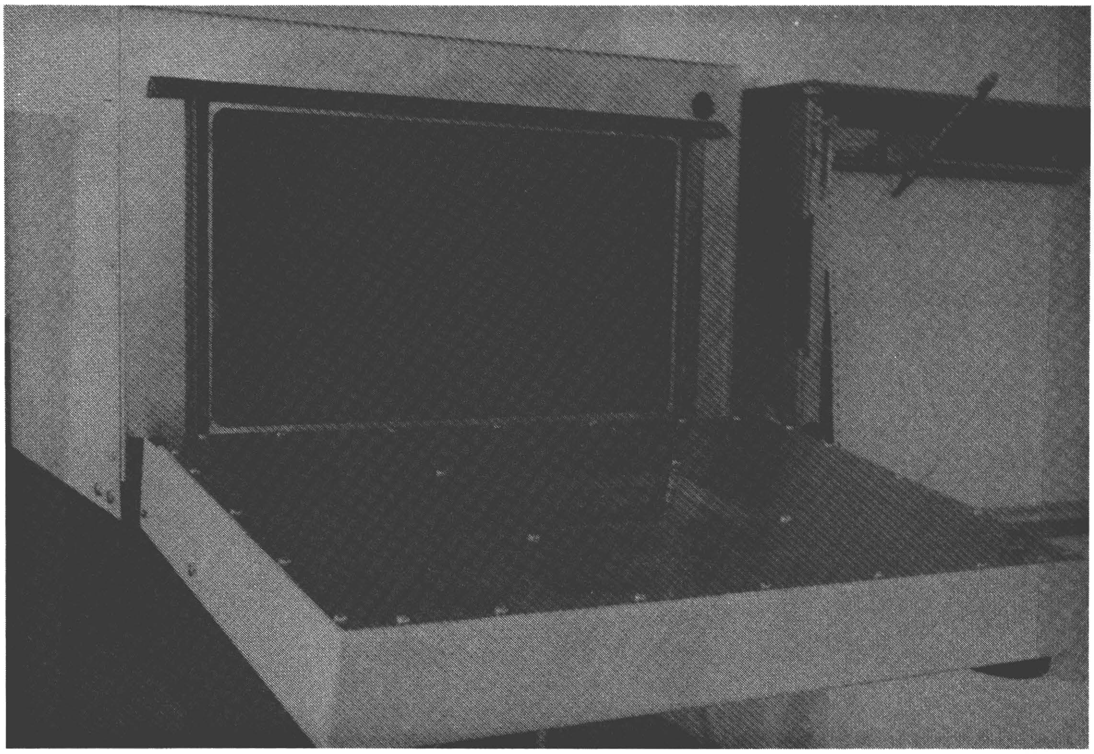


Figure 21.1   LEO1

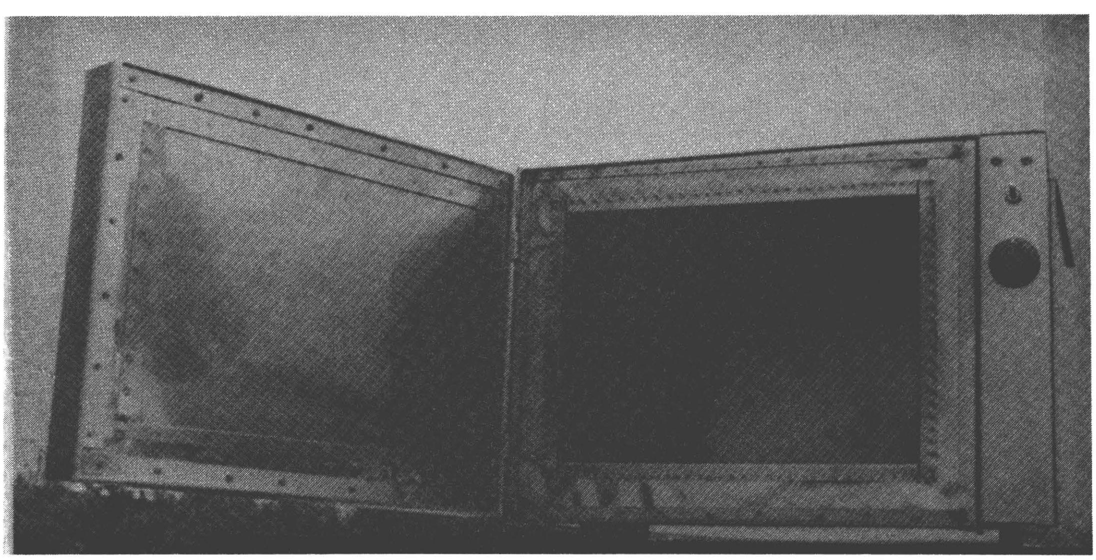


Figure 21.2   LEO2

For ordinary ovens, the energy required to heat up the oven itself has been small, compared to the energy transferred to the surroundings, but this is not true for small, highly insulated ovens. If the prototype is used for 1 hour, half the energy is used for heating up the oven.

With a highly insulated oven, the importance of thermal bridges rises. Much effort has therefore been put into a design with only few and low conductance thermal bridges. Especially around the oven door, where much energy normally is wasted, it has been attempted to reduce heat flow.

During tests, LEO2 has shown an energy consumption around 1/5 to 1/3 of ordinary sized ovens. The consumption relative to the volume, a concept only meaningful if you fill up the oven, is 1/3 to 1/2 of other ovens.

Oven		LEO2	Husqvarna Regina	Gorenje E64K
Volume		23 l	38 l	69 l
Energy-consumption	Heating to 200 °C	153 Wh	260 Wh	477 Wh
	1 hour at 200 °C	144 Wh	353 Wh	1000 Wh
	Total	297 Wh 12.0 Wh/l	613 Wh 16.1 Wh/l	1477 Wh 21.4 Wh/l

The work with energy saving ovens can not be said to be finished. It has proved so far, that energy saving ovens can be built with good energy economy and to a reasonable price. It has been estimated that there is a market for these ovens. What is now needed, is, in cooperation with a manufacturer of electric ovens, to develop an oven, ready for production.

22. Comparative analysis of the energy efficiency of cooking

As a part of the investigations of the energy (electricity) consumption related to different cooking habits and equipment, the energy consumed when boiling water, using different kinds of equipment, has been measured. The investigation has been carried by Peter Lund-Sørensen, Lisa Tobiesen, Thomas Bjerre, Jørgen Kirchoff, Lars Thougård Kristensen, Pernille Kaltoft, Hans Poulsen and Carsten Pedersen, all students at the Technical University.

The equipment under test has been:

- Cast iron hot plates
  (manufactured by EGO, placed in a Voss-stove type 63 410)
- Radiant rings
  (manufactured by Satchwell Sunvic)
- an electric kettle
  (manufactured by Swan)
- a coffee-brewer
  (manufactured by EVA, type 261600)
- an immersion heater

The hot plates and the radiant rings have been tested with 3 different pans.

The test-procedure chosen (which is close to the test-procedure suggested by the Danish Council for Declaration of Goods, "Dansk Varefaktanævn"), has been to heat water from 20 °C. When 95 °C is reached, power is turned off and the electricity consumption read from a kWh-meter. The efficiency is then calculated as

$$\text{Efficiency} = \frac{(\text{heat capacity of the water}) * (95°C - 20°C)}{\text{electricity consumption}}$$

For hot plates this procedure may seem a little unfair, as energy may be saved by turning down power before 95 °C is reached. For the coffee-brewer the procedure cannot be used, and the efficiency must be defined in another way. In a coffee-brewer the water is boiled and steam pumps the water through the system to the pot. The final temperature of the water, and with this the calculated heat energy transferred to the water, can thus be defined in two ways. Either as 100 °C (boil) or as the temperature of the water in the pot after brewing. Both efficiencies have been calculated.

The results of the investigation is summarized in table 22.1.

Heating equipment	Pot	Litres of water	Time min.sec	Efficiency in %
Immersion heater (1280 W)	1	1.0	5.35	74
	1	1.6	8.18	79
	1	2.1	9.50	84
	1 lid	2.1	9.20	87
	5	2.1	11.06	73
	2	1.0	4.55	85
	2 lid	1.0	4.50	84
	2	1.4	6.37	88
Electric kettle (2000 W)		0.5	1.42	77
		1.0	3.04	89
		1.6	4.45	88
		1.7	5.00	90
Coffee brewer (720 W)		0.25	2.52	49 67
		0.5	5.05	62 84
		1.0	9.00	66 86
18 cm hot plate (2000 W)	2	1.0	5.40	44
	2 lid	1.0	5.10	46
	2	1.6	7.35	54
	2	2.1	9.10	59
15 cm hot plate (1500 W)	1	0.5	5.00	35
	1	1.0	7.40	45
	1 lid	1.0	7.20	46
	1	1.6	11.00	57
	3	1.0	7.35	46
	4	1.0	6.40	52
16 cm radiant ring (1680 W)	1	0.5	4.15	40
	1	1.0	6.20	52
	1	1.6	9.10	59
	3	1.0	5.50	57
	4	1.0	5.35	58
13 cm radiant ring (920 W)	1	1.0	9.40	61

Table 22.1

Pots:

1: Al-pan, 2 litres
2: Al-pan, 4.5 litres
3: Cu-pan, 3 litres
4: Steel/Al-pan, 2 litres
5: Coffeepot made of glass

("lid" indicates that a lid was used on the pan).

The table shows that

- The efficiency of radiant rings is better than that of ordinary cast iron hot plates.

- The efficiency of a small hot plate is greater than that of a large hot plate.
- The efficiency increases if the volume of water increases.
- Some pans give rise to notably greater efficiencies than other.
- Use of lid causes only a slightly better efficiency (as long as only short heating periods are considered).
- The efficiency of the equipment with immersed heating elements are far better than the efficiency of ordinary plate/pan combinations. Especially the electric kettle showed a very good efficiency.

The results for 1 litre of water are also shown in figure 22.1.

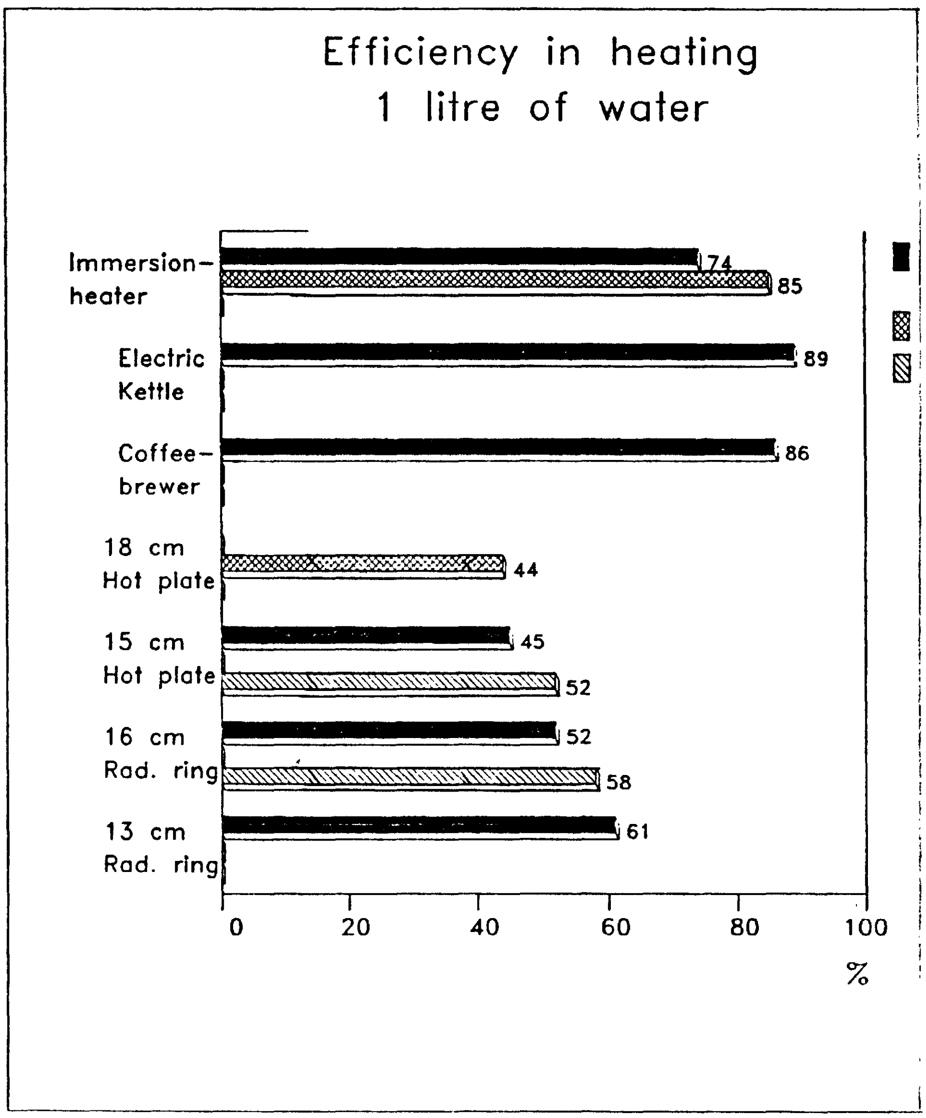


Figure 22.1

23. Environmental consequences of energy efficient cooking

The environmental costs and benefits of replacing typical cooking with low energy cooking as described in the previous chapters are evaluated below. Basic principles for doing that are similar to what was done for refrigerators in part one.

Embodied energy in equipment.

Cooking pattern and equipment are so complicated that we refrain from making a quantified assessment of the energy used in producing the efficient equipment compared to making the usual models. One basic principle, however, in making low energy cooking equipment is to avoid large masses of metal to be heated together the food etc. An electric kettle for electric cooking is **lighter** than a traditional kettle, since the latter has got a heavy, stable bottom. Furthermore a hot plate, possibly of the heavy type, is saved. Also for the oven, one of the measures consists in making the inner cabinet lighter. Altogether, it is likely that low energy equipment will require less metal and hence less energy to produce than the traditional equipment. Considering the uncertainty about energy embodied in the extra electronic equipment in low energy cooking, we shall assume no net change in energy input in manufacturing the efficient equipment

This implies that the electricity savings obtained by running the efficient cooking equipment are net savings.

National electricity savings.

In this paragraph we shall estimate the savings on a national basis, obtainable with the equipment described in this report. There is unfortunately no reliable data concerning the energy consumption for cooking in Denmark, or for the composition of this consumption. In reference 12, it is assumed that an electric cooker has an average consumption of approx. 2.6 kWh per day. The total stock of electric cookers in Denmark is expected to be 1.5 million, giving a total electricity consumption of cookers in Denmark of 1.42 TWh per year. This consumption is assumed to be composed as

680 GWh for boiling water
450 GWh for other cooking on hot plates
300 GWh for the ovens.

If an electric kettle was always used for boiling water, replacing the usual hot plates, approx. 50 % of the 680 GWh could be saved, according to chapter 22.

Considering the cooking on hot plates, a saving of 20 % may be obtained by using radiant rings, efficient pots and eventually an improved version of the adaptive controller.

Use of the energy saving oven LEO2 described in chapter 21 may be expected to save 2/3 of the electricity consumed for ovens in Denmark.

This adds up to the following totals:

	Present Consumption	Possible Saving	Future Consumption
Boiling water	680 GWh	340 GWh	340 GWh
Cooking	450 GWh	90 GWh	360 GWh
Oven	300 GWh	200 GWh	100 GWh
Total	1430 GWh	630 GWh	800 GWh

Table 23.1

The result is depicted in table 23.1. The 630 GWh electricity saved each year corresponds to 2.5 % of Denmarks total electricity consumption.

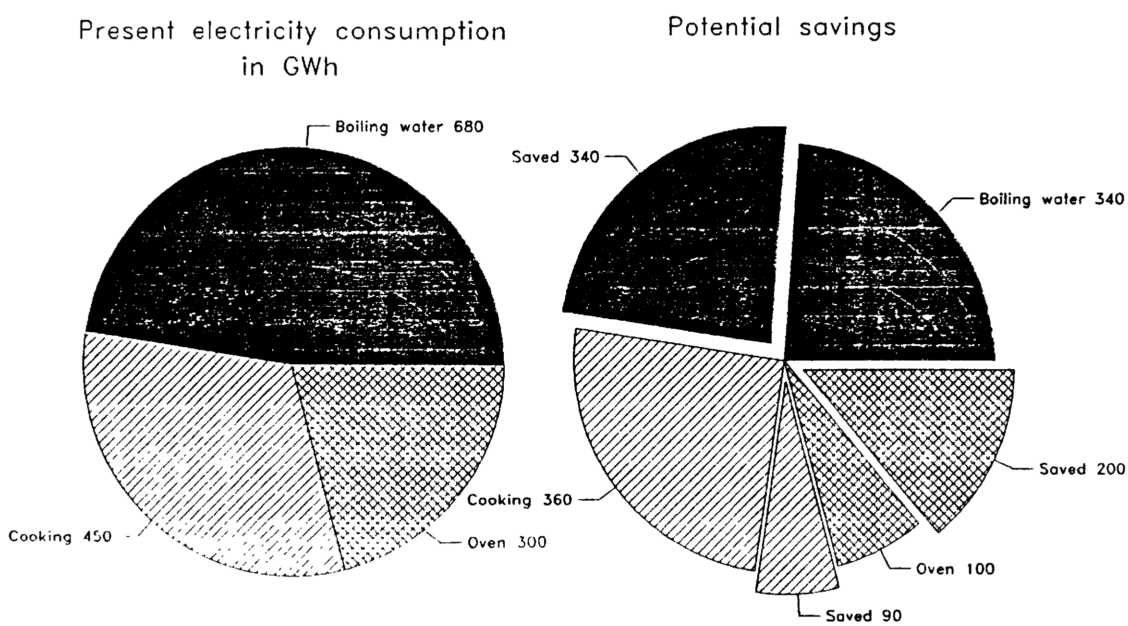


Figure 23.1

Evironmental benefits of efficient cooking.

On the basis of the method used in part one for refrigeraters, annual reduction in pollution achieved through efficient electric cooking is found as shown in table 23.2.

Pollutant and waste	Specific emissions and waste (g/kWh)	Annual reduction of emision	
		per cooker (kg/year)	Denmark (ton/year)
SO_2	9	3.8	5500
NO_x	5	2.0	3000
CO	0.3	0.1	200
Particles	1.4	0.6	900
Fly ashes	40	17	25,000

Table 23.2

We have not made calculations of the environmental benefits for the EEC as a whole, due to lack of information on the distribution of electric cookers as compared to gas cookers and other cooking equipments, and due to unknown variations in cooking habits. Compared to achieving the reduced pollution through technical cleaning measures at power plants, however, the reduced electricity consumption has two obvious advantages over stack cleaning as an enviromental improvement measure. First, it is free of cost, since the saved energy pays for the investment. Second, it does not leave us with the concentrated pollutant materials such as piles of dust etc.

24. Conclusions on cooking

After the EEC-sponsored work described in this report terminated by August 1984, the work has been extended, financed by the Danish Ministry of Energy (ref. 13).

The conclusion on our experiments with electromic controllers for hot plate cooking is that for general purpose cooking it seems difficult to develop a satisfactorily working system. Only for specific tasks like boiling water and perhaps cooking some vegetables like potatoes, an electronic controller might be made to work.

On the other hand, the potentials for saving electricity in electric cooking through other technical changes look promising. We developed a small oven which uses only around one third of what a normal oven uses. This oven, however, is not developed into a real prototype, ready for production. Outside our projects, various progress has occurred towards efficient cookers, primarily through the use of special electric cooking devices with built-in heating elements, like the electric kettle mentioned in chapter 22.

Further work should be directed towards developing more precise thermostats for controlling the pan bottom temperature, useful for frying and for cooking porridge for instance. Electronic thermostats could be a significant improvement here, compared to the traditional capillary types.

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