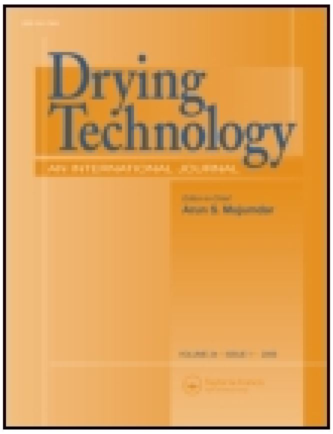

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DRYING WITH SUPERHEATED STEAM

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ABSTRACT

The principle of drying with superheated steam is known for a long time already, and different designs have been worked out and partly realised. The principle of the steam drying described in this paper starts with superheated steam that is blown on to the products to be dried. The superheated steam transfers its sensible heat to the product and the water to be evaporated. The superheated steam acts both as heat source and as drying medium to take away the evaporated water. The majority of the superheated steam has to be recirculated and reheated. The excess steam from this process, corresponding to the evaporated water, can be used elsewhere in the process or plant, thus making an efficient energy recovery possible. Possible emissions from the drying process can be effectively removed by condensation. Drying by means of superheated steam impingement is one of the possible designs that are in progress now for the paper industry. Work is going on with respect to this type of drying for other materials, especially foodstuffs. At present experimental research at the laboratory steam dryer of TNO-MEP is carried out for vegetables, fries,

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herbs, cacao nuts, wheat, flour, etc. Besides the energy savings and environmental benefits, the oxygen free steam atmosphere and the higher product temperatures in the dryer appear to have positive effects on the product qualities. For foodstuffs combinations of steam drying with blanching, pasteurisation, sterilisation, etc. are possible and make the steam drying very attractive for food producers. Modelling of the processes in foodstuffs during steam drying is established, both on macro and micro scale. In this paper examples and results of research on steam drying for specific products will be presented.

Key Words: Additional processing; Drying; Energy; Foodstuff; Superheated steam

The principle of superheated steam drying is known for a long time already, and different designs, such as paper drying (1), Airless drying (2), the Stork exergy dryer, etc., have been worked out and partly realised in praxis. An extensive overview is given by Mujumdar and Devahastin (3). The steam drying principle described in this paper starts with superheated steam that is blown on to the products to be dried. The superheated steam transfers its sensible heat to the product to be dried and the water to be evaporated. During the whole process the steam stays above its condensation temperature. By balancing the amount of superheated steam with respect to the drying rates, it is possible to keep the steam superheated after contact with the product. Thus condensation on the product is prevented, except during the first phase of the drying process when the product comes in cold. The superheated steam thus acts both as heat source and as drying medium to take away the evaporated water. With steam drying the majority of the superheated steam has to be recirculated and reheated. The excess steam from this process, corresponding to the amount of evaporated water, can be used as heat source elsewhere in the process or plant, thus making an efficient energy recovery at a relatively high temperature feasible (see the principle scheme in Figure 1).

Possible emissions from the drying process, present in the drying medium, can be effectively removed by condensation. The polluting substances are sometimes found in the condensate in liquid form, and than have to be separated or drained. Non-condensable pollutants will escape from the condensate in a concentrated gas stream, that can cleaned, for example by after burning.

The possibilities for impingement steam drying of paper and textile have been worked out in an EC sponsored project (1). A proof of principle

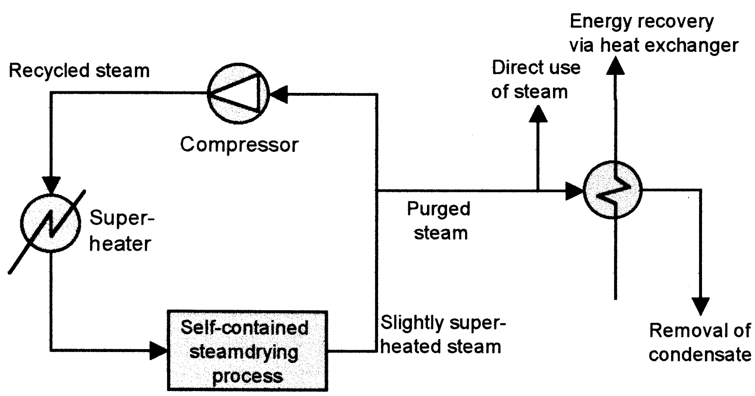

Figure 1. Principal scheme of the steam drying process.

has been demonstrated on a laboratory scale, where high evaporation rates, over 100 kg/m^2.h, have been realised. Excess steam was produced and the possibilities to reuse the excess steam have been elaborated and appeared to be present. The excess heat can be used in the paper industry at the de-inking of recycled paper, the first low pressure drying cylinders of the paper machine, for heating of process water or at the steam boxes (4). In the textile industry reuse possibilities are wash water heating and for fixation in steamers.

Working solutions for the sealing of the paper or textile web entering and leaving the steam dryer have been developed. Drying with superheated steam impingement is one of the possible future designs for the paper industry. This development is in progress now and advantages are expected with respect to energy savings, reduction in equipment size and product qualities.

This paper describes the work going on with respect to superheated steam impingement drying for other materials, especially foodstuffs. At present experimental research at the laboratory steam dryer of TNO-MEP is carried out for vegetables, fries, herbs, cacao nuts, wheat, flour, etc.

Besides the energy savings and environmental benefits, the oxygen free steam atmosphere and the higher product temperatures in the dryer appear to have effects on the product qualities. This sometimes leads to products with better qualities, possibly fit for new markets. The combination of drying with other processes more often occurs during steam drying. For foodstuffs combinations of drying with blanching, pasteurisation and sterilisation, are possible and make the steam drying very attractive for food producers.

Micro-scale modelling of the processes in foodstuffs during steam drying has been established. Validation of the model has been based on lab scale experiments.

In this paper examples and results of research on steam drying for specific products will be presented with respect to quality and process aspects, model predictions, energy savings and environmental benefits.

With superheated steam drying the steam is in direct contact with the product to be dried and the product temperature quickly rises to 100 °C at atmospheric pressure. At 100 °C the constant rate drying period proceeds. When the product starts to be dry at the surface, what happens later than with conventional hot air drying, the falling rate drying period starts, and the product temperature will finally rise to the superheated steam temperature. By applying different steam pressures levels, other drying temperatures will result. This imposes requirements on the equipment with respect to pressure resistance and leakage free input and output constructions. Higher pressures may be attractive when there is need for pressurised steam to reuse, and when the products can benefit from the resulting higher temperatures. Under atmospheric pressures are often required with for example foodstuffs, which are sensitive to higher temperatures due to denaturation reactions.

Products can be solid particles of different shapes, but also liquids can be dried in superheated steam, possibly by spray drying them.

Potential benefits of superheated steam drying are:

- The latent heat of evaporation comes available as slightly superheated steam, and can be recovered on a relatively high temperature level;
- No heat is lost with the big stream of, partly wetted, drying air;
- Studies for paper and textile drying showed possibilities to reuse the excess steam, leading to energy saving potentials from 50 to 75 %, (1);
- From the closed steam drying process emission of odours, dust or other hazardous components is avoided. Possible pollutants are concentrated in the condensate of the effluent steam;
- Product temperatures quickly rise to the condensation/boiling temperature, 100 °C at atmospheric pressure;
- Evaporation rates can be higher compared to hot air drying;
- Increase of the drying speed or reduction of the dryer size is possible;
- The pure steam atmosphere, the absence of air or oxygen, can have qualitative benefits for the product; no oxidation
- Explosion and fire protection are inherent advantages of steam drying
- Combinations of drying with other product treatments like blanching, pasteurisation or sterilising of foodstuffs, or fixation of coated textiles;

- The steam drying process can be operated under pressure, if pressurised steam if needed elsewhere in the process or when higher product temperatures are asked for;
- Pressures under 1 bar(a) can be necessary if product temperatures should be below 100 °C;
- The steam drying principle can be operated with other solvents by using the superheated solvent as the drying medium.

Possible restrictions of superheated steam drying are:

- The sealing of the steam drying process, especially at continuous operation at the entry and exit of the product, needs extra attention because escaping of steam is undesirable;
- Sealings of a steam drying process operated with under- of overpressure are extra critical in this respect;
- (Superheated) steam will condense on any surface having a temperature at or below the condensation temperature, 100 °C at atmospheric pressure. This may cause droplet formation;
- As a consequence the whole inside construction of the dryer has to be above condensation temperature, making appropriate insulation necessary;
- Initially some condensation will always occur on the cold product entering the dryer, before the actual drying starts;
- In order to maximise energetic advantages, it is essential that reuse possibilities for the excess steam exist at the right temperature/pressure level;
- The drying process will be harder accessible because of higher temperatures, condensation of steam and airtight constructions.

MODELLING OF THE STEAM DRYING PROCESS

Macro Scale Model of Steam Drying Process

The macro scale model is used to calculate the energy consumption of the steam drying process. The resulting steam flow rate through the dryer is used to estimate the size of the basic equipment, i.e. the drying chamber, the super heater, the recirculation fan, the ductwork, etc. The macro scale model can also be used to minimise the energy consumption by changing the process conditions (T, p, flow) of the steam drying process, in relation to the possibilities to integrate the excess steam. Furthermore, the model can be used to calculate the energy consumption of a conventional hot air drying process and compare it with the energy consumption of the steam drying process.

The macro scale model is based on the mass and energy balance of the steam drying process. Mathcad 8 Professional is used to calculate the balance equations.

Results of Macro Scale Model: Case of Steam Drying of Carrot

The case of steam drying of carrot pieces is used to demonstrate the use of the macro scale model. The values of the input variables are based on test results and an industrial scale application; see Tables 1 and 2. Figure 2 gives a graphical output of the macro scale model calculations.

Micro Scale Model of Steam Drying Process

The micro scale model is used to analyse and predict the drying behaviour of the product at different process conditions. The model calculates the

Table 1. Input Parameters for the Macro Scale Model

Input	Unit	Value
Product inlet flow rate	kg/h	3600
Product inlet temperature	°C	25
Product inlet moisture content	kg H_2O/kg d.b.	7.0
Product outlet moisture content	kg H_2O/kg d.b.	1.0
Pressure in drying chamber	bar	1.2
Steam temperature drying chamber inlet	°C	200
Steam temperature drying chamber outlet	°C	120

Table 2. Output of the Macro Scale Model

Output	Unit	Value
Steam flow rate	kg/h	44861
Purged steam flow rate	kg/h	2700
Energy consumption superheater	kW_{th}	2212
Energy consumption recirculating fan	kW_{el}	226
Heat recovery purged steam	kW_{th}	1681
Net energy consumption	kW_{th}	1198
	kJ_{th}/kg H_2O	1586

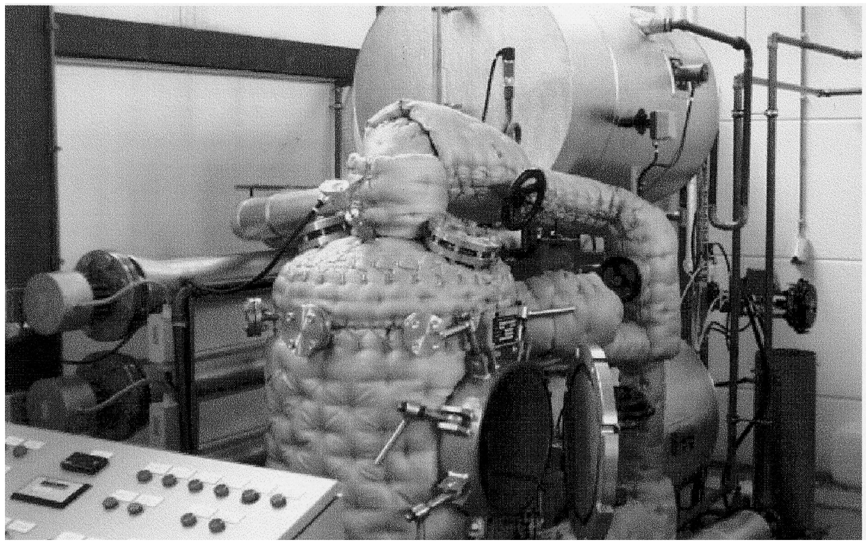

Figure 2. Laboratory steam dryer.

temperature and moisture profiles inside the product during the drying process. The model is based on the Finite Element Method (FEM).

Model Assumptions

- Condensation of steam on the product surface during the heat-up period;
- No mass transport resistance in the vapour phase;
- Internal heat and mass transport is described by diffusion only (lumped diffusion coefficient);
- Sorption isotherm/isobar according to Oswins model (4);
- No shrinkage effects (constant product volume).

Results of Micro Scale Model: Steam Drying of Fries (Potato Bar)

Steam drying of a single potato bar was modelled. The bar (10*10*80 mm) was divided into 9*9*9 = 729 elements. The output of a corner element and the centre element is plotted in Figure 4. The increased moisture content in the corner element at the start of the simulation is a

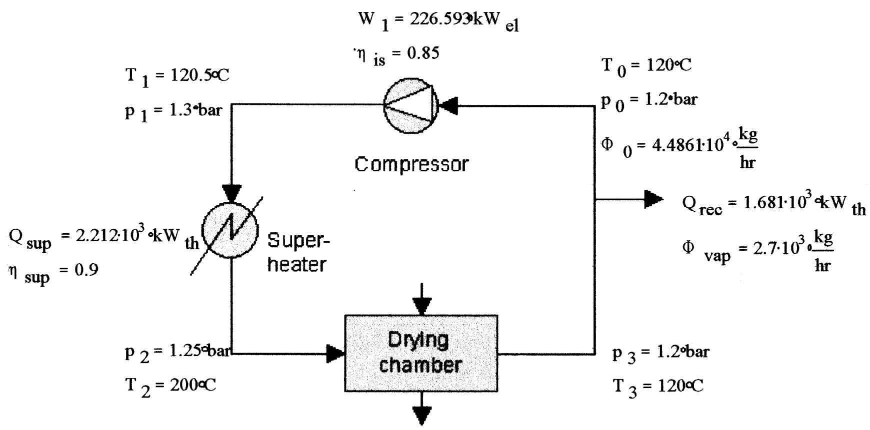

Figure 3. Graphic output of macro scale model.

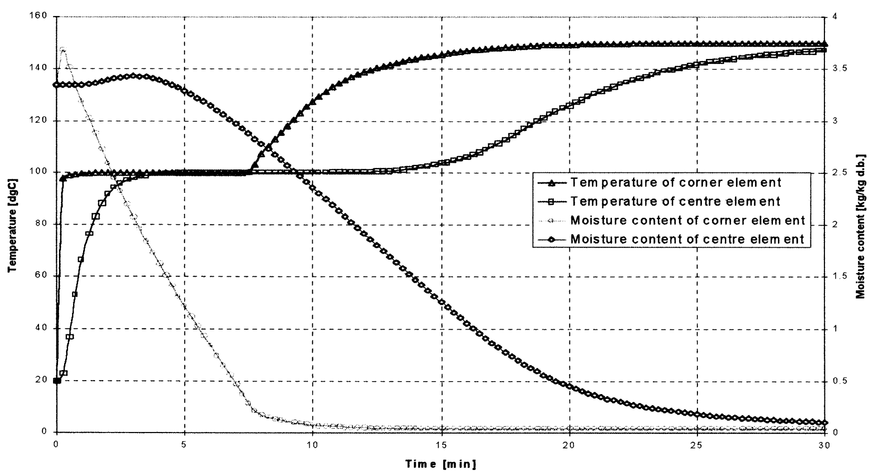

Figure 4. Drying curve of a potato bar.

result of condensation of steam on the cold product. Because of inward mass transport, the moisture content also increases in the centre of the product. The temperature curve corresponds with the theoretic expectations: first a short heat-up period until a temperature of 100 °C is reached, then a period of constant-rate drying at 100 °C, and finally the temperature reaches the steam temperature (150 °C) when the equilibrium moisture content is reached.

STEAM DRYING EXPERIMENTS

Experimental Set-up

Experiments are performed at the steam-drying pilot at TNO Environment, Energy and Process Innovation. The layout of the steam drying pilot is shown in Figure 5 and consists of the following parts:

- Water softener
- Water preheating vessel (degassing, heated by steam)
- Steam generator vessel (tubes with thermal oil inside vessel)
- Electrical super heater
- Drying chamber
- Condenser (water cooled)

Superheated steam enters the drying vessel at the top inlet and passes through or around the product. The slightly superheated steam leaves the vessel at the bottom outlet and is condensed through direct water injection and indirect water-cooling. In contrast with the actual steam drying process, steam is not recycled.

Process conditions that are possible at the current steam-drying pilot are listed in Table 3. Hot air can also be used as a drying medium. Compressed air is then taken from the compressed air system, reduced to the desired pressure and heated in the super heater.

The drying chamber is an insulated stainless steel vessel (diameter 500 mm, height 700 mm). The product to be dried can be held in three different holders (see Figure 6):

A. Perforated plate
B. Porous basket → the basket is held inside a vertical cylinder to ensure a maximum steam flow through the cylinder.

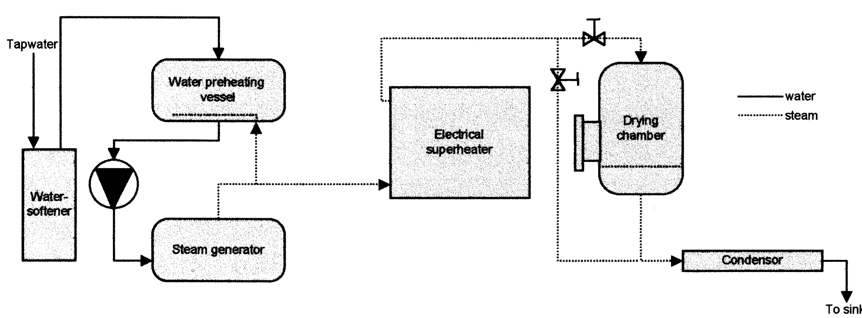

Figure 5. Layout of the steam-drying pilot.

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Table 3. Range of Process Conditions of the Steam-Drying Pilot

Process Variable	Range
Steam temperature	100–400 °C
Steam flow rate	100–400 kg/h
Pressure	1–5 bar(a)
Evaporation capacity	100 kg/h

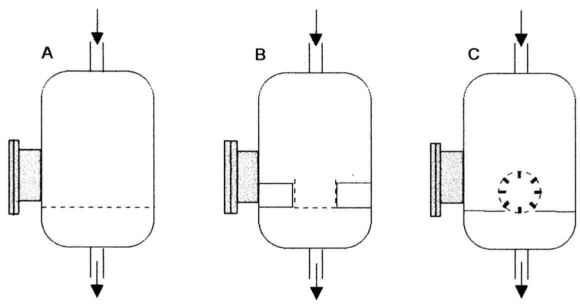

Figure 6. 3 ways to hold the product during drying: A-perforated plate; B-porous basket; C-porous rotating cylinder.

C. Porous rotating cylinder → the inside of the cylinder is coated with Teflon to prevent sticking of the product to the hot cylinder wall. The rotating cylinder is used when a homogenous product quality is desired.

Future Experimental Set-up

With the current layout of the steam pilot pressures below 1 atmosphere are not possible. In the near future, a water ring vacuum pump will be used to create vacuum conditions in the drying chamber. Especially heat sensitive materials will be tested at vacuum conditions, to prevent product quality losses. Pressures as low as 0,2 bar (a) are desirable for heat sensitive products.

Experimental Results: Drying of Printed Textile

Small samples of cotton cloth were printed with various kinds of dye. The samples were pinned on a simple stretcher and were dried for a short time with superheated steam. The tests showed the best results for reactive dyes, which were dried and fixated in one step.

Experimental Results: Drying of Foodstuff

Experiments were performed for different kinds of vegetables (carrot, potato, cauliflower, celeriac, asparagus, leek), cacao nuts, wheat, flour, meat (ham, boiled chicken), herbs (oregano) and spices (paprika powder, onion powder).

Drying and Blanching of Carrot

Pieces of carrot ($10\times10\times2$ mm) are dried in the rotating cylinder. The final moisture content is measured for different pressures, steam temperatures and residence times; see Table 4.

The initial moisture content of cauliflower is approximately 88 wt% on wet basis i.e. 7,3 kg H_2O/kg dry matter. The resulting final moisture content varies between 2 and 5 kg H_2O/kg dry matter.

The final moisture content is mainly determined by the steam temperature and the residence time, and to a lesser degree by pressure. The "readiness" of the cauliflower is mainly determined by the pressure and the residence time, and to a lesser degree by steam temperature.

During drying, the product temperature is equal to the wet bulb temperature, i.e. the boiling temperature of water at the current pressure. At a pressure of 1 bar(a), the boiling temperature is about 100 °C, at 1.5 bar(a) the boiling temperature is about 111 °C.

The product temperature of a small piece (about 1 cm) of cauliflower was measured during a drying run. A thermocouple was put in the centre of a small piece on top of a bed of cauliflower. The steam temperature was measured approximately 10 cm above the bed of cauliflower. From Figure 7

Table 4. Range of Values for Different Process Variable During the Drying of Cauliflower

Process Variable	Range of Values
Pressure	1.1–1.5 bar(a)
Steam temperature	140–220 °C
Residence time	2–10 min.

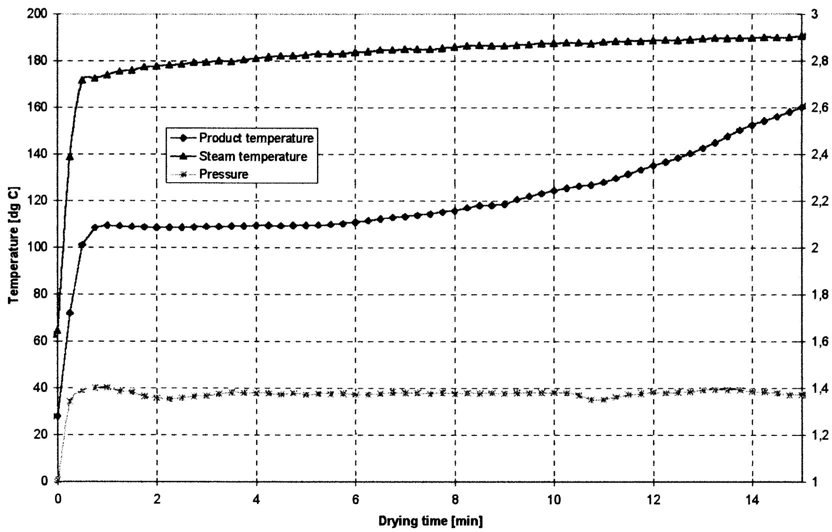

Figure 7. Steam temperature and temperature inside a piece of cauliflower during superheated steam drying.

can be seen that the product reaches the boiling temperature of water within one minute. The next five minutes, the product temperature is fairly constant, indicating the constant-rate period. After 6 minutes, the product temperature starts to rise, indicating the falling-rate period.

Industrial sectors with a high potential for steam drying are the food industry, chemical industry, textile and paper. Especially for paper a long development time may be expected, because of the high production rates and high-speed machines common in this sector.

Other products, likely to be suitable for steam drying are potato products, pasta, herbs, wood, clay forms/bricks, etc.

Foreseen further developments are installation design, demonstration and implementation in industrial applications.

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