WHITE PAPER

The inside story on heat treatment of particulate foods

New findings from Tetra Pak

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Introduction

Who is this booklet for?
This booklet is for anyone who works in the food processing industry, and who is interested in staying abreast of how particles in food affect – and are affected by – heat treatment.

It is especially relevant to those with technical responsibilities in R&D centres, as well as those with operational responsibility for processing lines and plants. It is also relevant to those with responsibility for developing new product and validating recipes involving particles.

The heat transfer challenge
The primary topic we treat here is the issue of heat treatment of foods that contain particles processed in a continuous system. This is complex and makes it difficult to calculate and design the heat treatment system. New research findings from Tetra Pak clearly demonstrate how particles affect different heat transfer processes in a heat treatment system – sometimes going against commonly accepted beliefs.

Findings from extensive experiments run by our expert group have revealed that it is now possible, from a thermal point of view, to calculate an optimal solution: the correct dimension of the heat exchanger and holding tube. This assures a consistent, accurate and predictable heat treatment system.

Heat exchangers are often over-dimensioned when processing foods with particles. The task can be accomplished with downscaled equipment and less energy. This booklet will explain how and why by sharing “the inside story” – what actually happens with the heat transfer when particles are added to the fluid.

The potential benefits to the food processing industry are many:

- Improved food quality with assured food safety
- Reduced operating and maintenance costs
- Reduced product losses
- Reduced environmental footprint
- Reduced installation and commissioning costs and time

Tetra Pak’s expertise
Tetra Pak has made large investments in research and development regarding heat transfer in food production over the past two decades. Our expert group holds expertise within heat transfer, food technology, food safety, microbiology, rheology, modelling, simulation, processing equipment, measurements and calibration.
Now we have studied what happens inside processing equipment when the food contains particles, and we know why it happens. We have cracked the heat transfer code and we have built and validated heat transfer tools that can be used for optimal design for foods with particles.

Our R&D findings are thus built into our competitive product portfolio to meet customer demands for particulate applications. Our specialized knowledge of heat transfer is also available to our customers through Tetra Pak’s Product Development Centres.

Tetra Pak has delivered numerous installations to producers of foods with particles, such as soups, sauces, baby foods, fruit preparations and beverages. See examples 1-3.

Example 1:
Continuous UHT soup lines with inline blending of a 2500 l/h particle stream and a 6000-10,000 l/h liquid stream. The soups contain meat and vegetable particles with a size up to 15 mm in concentrations up to 30%.

![Figure 1: Aseptic dual line with inline dosing](image)

*Figure 1: Aseptic dual line with inline dosing*
Example 2:

Continuous pasteurization lines, 2000-4000 l/h, for fruit preparations with particles such as strawberries, cherries, blueberries and mango pieces with a size up to 15 mm.

![Figure 2: Aseptic single line](image)

Example 3:

Continuous pasteurization beverage lines with particles such as Aloe Vera, Nata de Coco and peach pieces up to 10 mm. The particle stream and liquid stream are blended in a horizontal tank before filling.

![Figure 3: Aseptic dual line with batch blending](image)
Particles and product quality

What are particles and why are they so important?
Solid ingredients in foods are often classified as particles, fibres or pulp. In some cases the term particles or particulates covers all three. In this white paper we refer to particles up to 20 mm in size. The upper limit is restricted by flow equipment, not by the heat transfer process.

The market for particulate foods is increasing. Two major trends are driving this increase: consumer demand for convenience foods with homemade quality, better than what a retort process can give; and beverages giving the consumers new experiences by adding particles. These trends put new demands on processing technology regarding heat treatment and avoidance of product damage during processing.

Interestingly, the traditional borders between beverages and foods are being blurred by the presence of particles. Is it a beverage or a food when one puts walnuts in milk, coconut in juice or Aloe Vera in tea? Where is the border between a beverage and a soup when the particle size or concentration increases?

Particle characteristics
Particles have a wide range of characteristics. They vary in size, shape and composition. The composition such as content of water, carbohydrates, etc., affects the physical properties: density, thermal conductivity and specific heat capacity. Moreover the composition can be affected by how the raw material was produced.

Particle integrity
To achieve good product quality, particle integrity needs to be protected. This can be challenging because particles (as well as fibres and pulp) are sensitive to heating. Optimizing heating in the process design is thus the basis for maintaining product quality, and a key factor is to minimize heating without compromising food safety. This demands knowledge in heat transfer in particulate foods.

To further ensure particle integrity and resistance to mechanical shearing and tearing, particles need to be pumped with minimal mechanical treatment and without rapid pressure changes.

Thus positive pumps of sufficient size with low slippage and limited speed are necessary for retaining product quality.

For more information, please see our whitepaper “Minimizing damage when processing particles, fibres and pulp” published in April 2015.
Particles in motion
What makes particles so special and complex is how they behave inside food processing equipment during continuous processing. Both heat transfer and pressure drop are affected by the presence of particles.

Heat transfer is better with particles present, for several reasons, including:

- The boundary layer at the heat transfer surface is disturbed, improving the heat transfer in the heat exchanger
- Rotation and linear movement of particles increase the agitation in the fluid, which increases the heat convection in the fluid.

In addition, there is a heat transfer process within the particle, as heat is transferred from the surface of the particle to the core. This internal heat transfer must be taken into account, since the core of the particle must reach a minimum temperature in order to destroy microorganisms and maintain food safety. The target temperature might be anywhere from 72 °C to 145 °C, depending on the characteristics of the food and how it will be distributed and stored. Thus results of calculating particle core temperatures are important to secure food safety, as well as economical and environmentally friendly operations.

Moreover, adding particles increases the pressure drop. The pressure drop no longer depends only on the physical properties of the liquid phase in the fluid, but also on particle size, particle shape and the amount of particles.

The heat treatment challenge
We are faced with a complex challenge when adding particles to a recipe: what is the optimal heat treatment to achieve food safety through pasteurization or sterilization, while maintaining the quality of the entire product? How should pumps, valves, heat exchangers, holding tubes, pipes and vessels be dimensioned? How much pumping force should be applied to compensate for increased pressure drops?

There is a clear need for calculation models, in order to enable optimal design. For particle-free products, this has been well-established knowledge for many years. But for foods involving particles, there is a lack of theoretical models for heat transfer and pressure drop. To improve this situation, Tetra Pak has invested in research within this field.

What follows is the inside story on these findings.
Heat transfer

Our starting point is to understand the mechanism behind heat transfer parameters and how those parameters affect particulate food applications. The objectives are to be able to correctly calculate:

- The heat transfer to and from the particulate food in order to correctly dimension the heat transfer area
- The inner temperature of the particles, in order to be able to correctly dimension the length of the holding tube.

Heat transfer area

The required heat transfer area is determined by the overall heat transfer coefficient, which is the combined effect of:

- The local heat transfer coefficient from the heating/cooling medium to the wall surface. This coefficient is a function of the Reynolds number and the Prandtl number. They are determined by the velocity, density, specific heat capacity, heat conductivity, and viscosity of the fluid, plus the geometry of the pipe.
- The thermal conductivity of the heat transfer wall and the thickness of the wall. The thermal conductivity is determined by the choice of material in the wall, with stainless steel being the most common material in the food industry.
- The local heat transfer coefficient from wall surface to the product. This coefficient is a function of the same parameters mentioned in the first bullet above. In addition, the following parameters affect the local heat transfer coefficient.
  - Particle size
  - Particle shape
  - Particle concentration

Particle temperature

It is important that the coldest spot of the particle reaches the specified temperature for pasteurization or sterilization. When measuring the liquid temperature, only the temperature of the carrier phase is determined. The particle temperature is lower than the temperature of the carrier phase when leaving the heating section of a heat exchanger. The reason for this is that it takes time for the heat to penetrate the particle, as the following figure shows.
Figure 4: Heating of the centre of the particle is clearly delayed and the centre does not reach sterilization temperature until it reaches the end of the holding tube.

This means that the holding tube for a fluid including particles cannot be dimensioned in the same way as for a fluid without particles. The time in the holding tube has to be adjusted to take into account the inner temperature of the particle. The temperature of the carrier phase leaving the holding cell is lower than the measured temperature entering the holding cell. However, the core temperature of the particle has increased, as seen in the figure above. In order to obtain a safe product and long shelf life, the holding tube has to be optimally designed.

**Heat transfer models and predictability**

Based on several decades of experience with heat transfer models at Tetra Pak, we have developed well-established calculation tools for dimensioning heat exchangers and predicting the heating and cooling of foods.

In order to improve our calculation tools by accurately including the influence of particles we undertook a series of experiments. The intention of the experiments was to find the mathematical functions of the heat transfer coefficients.
Specifically, we aimed to evaluate the influence of particle concentration, size and shape on:

- The local heat transfer coefficient from wall surface to the fluid
- The local heat transfer coefficient from the carrier liquid phase to the particle.

**Functions of the heat transfer coefficients**

There are not many articles describing the complexity on how much the local heat transfer is increased when adding particles. Through scientific research, Tetra Pak has determined a function for how the heat transfer coefficients are affected by adding particles:

- Coefficient of heat transfer fluid to particle
  \[ \alpha_{fp} = f(\rho, \mu, C_p, \lambda, \varphi_p, D_p, v, D_{pipe}) \]
- Coefficient of heat transfer wall to fluid:
  \[ \alpha_{wf} = g(\rho, \mu, C_p, \lambda, \varphi_p, D_p, v, D_{pipe}) \]

In these formulas, \( f \) and \( g \) represent mathematical functions and the parameters within the parentheses represent what is included in the formulas. The new parameters describing \( \alpha_{wf} \) are \( \varphi_p \) and \( D_p \). These functions have been derived from extensive experiments.

**Formulaic symbols**

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Unit</th>
<th>Explanation</th>
</tr>
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<tbody>
<tr>
<td>( C_p )</td>
<td>J/kgK</td>
<td>Specific heat capacity of fluid</td>
</tr>
<tr>
<td>( D_p )</td>
<td>m</td>
<td>Particle diameter</td>
</tr>
<tr>
<td>( D_{pipe} )</td>
<td>m</td>
<td>Pipe diameter</td>
</tr>
<tr>
<td>( v )</td>
<td>m/s</td>
<td>Mean velocity over the channel cross-sectional area</td>
</tr>
<tr>
<td>( \alpha_{fp} )</td>
<td>W/m²K</td>
<td>Coefficient of heat transfer fluid to particle</td>
</tr>
<tr>
<td>( \alpha_{wf} )</td>
<td>W/m²K</td>
<td>Coefficient of heat transfer wall to fluid</td>
</tr>
<tr>
<td>( \varphi_p )</td>
<td>-</td>
<td>Volume fraction of particles</td>
</tr>
<tr>
<td>( \lambda )</td>
<td>W/mK</td>
<td>Thermal conductivity of fluid</td>
</tr>
<tr>
<td>( \mu )</td>
<td>Pas</td>
<td>Dynamic viscosity of fluid</td>
</tr>
<tr>
<td>( \rho )</td>
<td>kg/m³</td>
<td>Density of fluid</td>
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Particle experiments

Experimental measurements of the heat transfer coefficients for fluids with particles were performed in the Tetra Pak Product Development Centre using a specially designed full scale test rig. Special attention was paid to energy balances and measurement accuracy. Temperatures were measured with three calibrated probes in each position, and calibrated mass flow meters were used to measure product flow rate.

Two versions of this test rig were used. A tubular heat exchanger was used to determine the heat transfer coefficient from the wall to the fluid. A holding tube was used to determine the heat transfer fluid to particle.

**Figure 5: The rig set-up**

**Figure 6: Test rig with well insulated tubular heat exchanger, holding tube and equalizing cell**
In the heat exchanger experiment, two streams of fluids with the same temperatures were prepared and simultaneously pumped to a mixing point:

- A particle slurry
- A continuous liquid

The process parameters (flow rates and physical properties) and particle parameters (concentration, size, shape and physical properties) were calculated or measured. The temperature of the continuous liquid phase was measured at a number of positions along the insulated tube. When the measured values were stable, they were logged during one minute and the average values were used for the evaluation. The data was used to determine the heat transfer coefficient from the wall to the fluid with particles.

![Figure 7: Principle of the flow in the heat exchanger experiments.](image)

As the particulate product propagates through the heat exchanger, the temperature of the fluid changes faster than the temperature of the particles due to the delayed heat flow in the particles. This means that the particles and the carrier fluid have different temperatures at the outlet of the heat exchanger and that the total heat absorbed by the fluid with particles could not be measured and calculated directly based on the measured carrier fluid temperature. Therefore, to verify that the experiments were conducted with negligible heat losses, it was important to know the equalized temperature at the outlet of the heat exchanger, i.e. when the temperature was homogeneous in the particles and equal to the temperature of the continuous liquid phase. The procedure was as follows. At the end of each experiment, the particle mixture at the exit of the heat exchanger was confined in a piece of pipe by means of valves. The temperature in this equalizing cell (EQ cell) was logged until steady state in order to determine the equalized temperature. This temperature together with the incoming temperature of the fluid with particles, plus the incoming and outgoing temperatures on the media side, were used to calculate the heat balance in the heat exchanger.
Many experiments with different parameter settings (detailed in the “Parameter ranges” box below) were used. The results from all experiments were used to create a model for the heat transfer coefficient from the wall to the fluid.

**In the holding tube experiments**, two streams of fluid with different temperatures were prepared and simultaneously pumped to a mixing point:

- A particle slurry
- A continuous liquid

As in the heat exchanger experiments the process and particle parameters were calculated or measured. The temperature of the continuous liquid phase was measured at a number of positions along the insulated holding tube. When the measured values were stable, they were logged during one minute and the average values were used for the evaluation.

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**Parameter ranges:**
- The particles used were carrot cubes in sizes from 4 to 10 mm and peas with a diameter of 9 mm.
- Particle concentrations ranged from 10 to 50%.
- The Reynolds number (the ratio of inertial forces to viscous forces in fluid dynamics; high numbers indicate turbulence) was 200 – 6500.
- Experiments were done in the temperature range of 20 – 70 °C.
- Fluids used were aqueous CMC solutions with flow velocities of 0.5 – 1.5 m/s.
- The inner tube diameter was 18 mm and the ratio of particle size to inner tube diameter varied from 0.2 to 0.6.
As in the case with the heat exchanger, the EQ cell was used to determine the equalized temperature, which was used as a check of the heat balance with the heat flow into the holding cell.

Figure 8: Principle of temperature measurements in the holding tube experiments

The data was used to determine the heat transfer coefficient from the fluid to the particles.

Many experiments with different parameter settings (detailed in the “Parameter ranges” box above) were used. The results from all experiments were used to create a model for the heat transfer coefficient from the fluid to the particles.
Results

The heat transfer model developed from the experimental data was evaluated by comparing measured values with predicted values. In the following graphs (Figure 9-12) the modelled results are plotted against experimental data. The solid lines represent perfect fits.

Figure 9 shows the heat transfer coefficient from wall to fluid. The prediction errors for products with and without particles are in the same range; that is, the plotted points are about the same distance from the line of perfect fit. The data points in the lower range of heat transfer coefficient, within the dotted line, represent experiments for products without particles. These experiments were performed within the same range of flow rate and viscosity as the experiments with particles.

Figure 9: Heat transfer coefficient from wall to fluid, theoretical model vs. experimental data. The solid line represents a perfect fit. The data points within the dotted line represent experiments without particles.
Figure 10 shows the heat transfer coefficient of the fluid to particles using the new model. The figure shows good fit between experiments and model. The fit of both models (Figure 9 and 10) in terms of temperatures is shown in Figure 12.

Using inaccurate heat transfer coefficients leads to incorrectly calculated temperatures for heat exchangers and holding tubes. Figure 11 shows the temperature of the carrier liquid out of the holding tube. The calculated temperatures are based on the traditional theoretical model without particle correlation. The calculated outlet temperature from the holding tube deviates by as much as 12 °C from the measured temperature. When the new model including particle correlation was used, the deviation between calculated and measured values decreased to a maximum of 3 °C, as can be seen in figure 12.
Figure 11: Temperature out of holding tube, traditional theoretical model calculation without particle correlation vs. experimental data. The solid line represents a perfect fit.

Figure 12: Temperature out of holding tube, new theoretical model calculation with particle correlation vs. experimental data. The solid line represents a perfect fit.
Calculation tool updates
In summary, the results of our experiments allowed us to update our calculation tools to enable accurate calculations also for products with particles. The update includes both the heat transfer from wall to fluid and the completely new calculation of the heat transfer from fluid to particles.

In addition to these tools, which are used for dimensioning systems, we have also extended our dynamic simulation tool (Process Simulation), which executes several calculations simultaneously over a given time period: pressures, temperatures, flow rates, compositions, etc. This tool is mainly used to simulate and understand process dynamics. With this extension the tool now also includes the ability to dynamically simulate continuous thermal processes with products containing particles.

Calculation tool validation
To validate the calculation tools with the new particle correlation model included, we compared the calculations with data from experiments using a Tetra Pak coiled tubular heat exchanger system. The experiments were conducted at our Product Development Centre in Lund, Sweden. The Tetra Pak® Coiled Tubular Heat exchanger is designed for heating and cooling of low to high-viscosity and smooth to particulate food products.

Different kind of particulate products were used to validate the calculation tools, such as mango preparations, soup concentrates, chutneys and carrot slurries. The ratio of particle size to the tube inner diameter varied between 0.1 and 0.6.

Figure 13 plots the calculated carrier liquid temperature out of the heat exchanger against experimental data. The average deviation in the graph below is less than 3 °C, which is up to 10 times more accurate than calculations without particle correlation.
Figure 13: Temperature out of holding tube, new theoretical model calculation with particle correlation vs. experimental data. The solid line represents a perfect fit.
Implications for the food processing industry

Given this success in model-building based on empirical data, we have come to a point where we can take the guess-work out of building heat exchangers systems for particulate applications. What does this mean for the food processing industry?

Our findings and new models have the potential to deliver substantial value to our customers’ business in two major areas: cost and product quality. With our new predictive abilities, we are able to deliver optimal heat exchanger designs for particulate applications.

The potential benefits to the food processing industry are many:

- Improved food quality with assured food safety
- Reduced operating and maintenance costs
- Reduced product losses
- Reduced environmental footprint
- Reduced installation and commissioning costs and time

Heating particles takes longer time than heating the carrier fluid in the food. Therefore there is a risk of overheating the liquid, with decreased product quality as a consequence. With these new findings from Tetra Pak, the heating area of the heat exchangers can now be much more accurately calculated, thus minimizing overheating of the liquid while still maintaining the highest level of food safety.

In our practical experience with commercial operations, we have been able to optimize customer installations by decreasing the heat transfer area by up to 45%. A decrease in area also results in a shorter residence time for the same size. The carrier liquid phase experiences a shorter time at elevated temperature and thus maintains its freshness.

When particles are present in a liquid food the heat transfer coefficient is increased, leading to more efficient heating of the liquid. This results in less need of heating area, which can reduce investment costs. Keeping the system volume as small as possible also minimizes product losses. Since the heat exchanger volume is at least one-third that of a sterilizer or pasteurizer, it has a big impact on the system volume if the number of tubes can be reduced.

Smaller system volumes lead not only to smaller product losses but also to reduced consumption of water and cleaning detergents which both have a positive impact on operating costs as well as on the environmental footprint.
Tetra Pak – your processing partner
Together with our network of partners, we stand ready to assist you in many ways with your business and technical questions. Feel free to contact your Tetra Pak representative or connect with us via our website.

www.tetrapak.com

For further details about processing particles in foods:

http://www.tetrapak.com/about/cases-articles/heat-treatment-of-particulate-foods