DEVELOPMENT OF FOULING MITIGATION METHODOLOGY
AT THE HEAT EXCHANGER DESIGN STAGE

P. Tochon
GRETh

A.J. Karabelas, N. Andritsos, S. Yiantsios and V. Hatziapostolou
Chemical Process Engineering Research Institute

H.U. Zettler¹, H. Müller-Steinhagen²
¹Department of Chemical & Process Engineering, University of Surrey
²Department of Thermodynamics and Thermal Engineering, University of Stuttgart

M. Förster, W. Augustin, M. Bohnet
Technical University of Braunschweig TU BS.

B. Rumpf
BASF AG, Ludwigshafen

B. Wilhelmson
Alfa Laval Thermal

C. Roussel
Alfa Laval Vicarb

Gilles GHNASSIA, Xavier SOUARD
CIRDC/Groupe DANONE

J.C. Leuliet, L. Filliaudeau, J. Jacquemont, G. Ronse, T. Six
INRA / LGPTA

F. Quenard
ACTINI

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1. **Summary**

The project concerns the development of:

- a methodology for optimising the configuration and the design of compact heat exchangers with respect to fouling and for obtaining criteria helpful in selecting heat exchanger type,
- predictive tools for two major classes of applications (cooling water, food products) to assist in taking appropriate measures,
- a novel multifunctional computer-aided method for fouling assessment and mitigation

For that, several major directions have been investigated and lead to the following information:

- Experimental studies on some key aspects of fouling mitigation practices have been performed by UniS, TU-BS, CPERI and GRETh. The effect of use of ion implantation to generate plate heat exchanger surfaces with reduced stickability, evaluation of the adhesive forces between deposit and heat transfer surface, colloidal particle agglomeration and influence of particles on precipitation rate, effect of flow arrangement of the plate heat exchangers have been investigated.
- Fouling measurements have been carried out in industrial installations at GRETh and BASF, under carefully controlled conditions, in order to enrich the database on which the proposed new methods have been founded.
- For the two systems of major practical significance: cooling water and protein dispersions, the new and available data have been assessed in order to allow improvement of models or development of correlations.
- Geometrical configurations of compact heat exchangers (CHE's) less prone to fouling have been identified by numerical simulation of the flow field inside CHE channels by UniS, GRETh, ALT and AlfaLaval Vicarb.
- A model fluid, able to describe both rheological and fouling behaviour of an industrial milky dessert have been developed by INRA and DANONE.
- A new device, less prone to fouling for dairy products, has been developed, tested and patented by ACTINI. Tests at INRA, based on eggs treatment furnished by DEGUT, have shown a significant improvement in the field of fouling mitigation.
- The novel predictive method has been developed by CPERI on the basis of software modules devoted individually to a ‘fouling data bank, ‘models/correlations’ and ‘chemistry’ calculations.
2. Partnership

<table>
<thead>
<tr>
<th>Partner</th>
<th>ADDRESS</th>
<th>Project leader</th>
</tr>
</thead>
<tbody>
<tr>
<td>TU BS</td>
<td>Technical University of Braunschweig</td>
<td>Prof. M. Bohnet</td>
</tr>
<tr>
<td></td>
<td>Pockelsstrasse 14</td>
<td>Phone : +49-531-3912780</td>
</tr>
<tr>
<td></td>
<td>D-38106 Braunschweig</td>
<td>Fax : +49-531-3912792</td>
</tr>
<tr>
<td></td>
<td>Germany</td>
<td><a href="mailto:m.bohnet@tu-bs.de">m.bohnet@tu-bs.de</a></td>
</tr>
<tr>
<td>GRETh</td>
<td>GRETh – CEA Grenoble</td>
<td>Dr P. Tochon</td>
</tr>
<tr>
<td></td>
<td>17, rue des Martyrs</td>
<td>Phone : +33-4-38783199</td>
</tr>
<tr>
<td></td>
<td>38054 Grenoble cedex 9</td>
<td>Fax : +33-4-38785435</td>
</tr>
<tr>
<td></td>
<td>France</td>
<td><a href="mailto:patrice.tochon@cea.fr">patrice.tochon@cea.fr</a></td>
</tr>
<tr>
<td>CPERI</td>
<td>Chemical Process Engineering Research Institute</td>
<td>Prof. A.J. Karabelas</td>
</tr>
<tr>
<td></td>
<td>P.O. Box 1517</td>
<td>Phone: +30 31 996201</td>
</tr>
<tr>
<td></td>
<td>54006 University City Thessaloniki</td>
<td>Fax: +30 31 996209</td>
</tr>
<tr>
<td></td>
<td>Greece</td>
<td><a href="mailto:karabai@alexandros.cperi.forth.gr">karabai@alexandros.cperi.forth.gr</a></td>
</tr>
<tr>
<td>UniS</td>
<td>University of Surrey</td>
<td>Prof. H.M. Steinhagen (Institute of Thermodynamics and Thermal Engineering - University of Stuttgart - Pfaffenwaldring 6 - D-70550 Stuttgart)</td>
</tr>
<tr>
<td></td>
<td>Department of Chemical &amp; Process Engineering Guildford - Surrey GU2 5XH</td>
<td>Phone: +49-711-685-3536</td>
</tr>
<tr>
<td></td>
<td>U K</td>
<td>Fax: +49-711-685-3503</td>
</tr>
<tr>
<td></td>
<td></td>
<td><a href="mailto:hms@itw.uni-stuttgart.de">hms@itw.uni-stuttgart.de</a></td>
</tr>
<tr>
<td>Alfa Laval</td>
<td>ALFA LAVAL Thermal AB</td>
<td>Dr Bjorn Wilhelmsson</td>
</tr>
<tr>
<td>Thermal (ALT)</td>
<td>Box 74, S-221 00 Lund</td>
<td>Phone : +46 46 36 69 12</td>
</tr>
<tr>
<td></td>
<td>Sweden</td>
<td>Fax: +46 46 30 75 77</td>
</tr>
<tr>
<td></td>
<td></td>
<td><a href="mailto:Bjorn.Wilhelmsson@alfalaval.com">Bjorn.Wilhelmsson@alfalaval.com</a></td>
</tr>
<tr>
<td>Alfa Laval</td>
<td>ALFA LAVAL VICARB</td>
<td>M. Claude Roussel</td>
</tr>
<tr>
<td>VICARB (ALV)</td>
<td>1-9 rue du Rif Tronchard</td>
<td>Phone: +33 4 76 56 50 38</td>
</tr>
<tr>
<td></td>
<td>38522 Le Fontanil Cornillon</td>
<td>Fax: +33 4 76 75 79 09</td>
</tr>
<tr>
<td></td>
<td>France</td>
<td><a href="mailto:Claude.Roussel@alfalaval.com">Claude.Roussel@alfalaval.com</a></td>
</tr>
<tr>
<td>INRA</td>
<td>INRA/LGPTA</td>
<td>Dr Jean-Claude Leuliet</td>
</tr>
<tr>
<td></td>
<td>369 rue Jules Guesde</td>
<td>Phone: +33 20 43 54 93</td>
</tr>
<tr>
<td></td>
<td>BP 39 Villeneuve d’Asc cedex</td>
<td>Fax: +33 20 43 54 26</td>
</tr>
<tr>
<td></td>
<td>France</td>
<td><a href="mailto:leuliet@lille.inra.fr">leuliet@lille.inra.fr</a></td>
</tr>
<tr>
<td>DANONE</td>
<td>DANONE VITAPOLE</td>
<td>M. Xavier Souard</td>
</tr>
<tr>
<td></td>
<td>Techno-valeur – 15 rue Gallilée</td>
<td>Phone: +33 1 41 07 84 07</td>
</tr>
<tr>
<td></td>
<td>92350 Le Plessis-Robinson</td>
<td>Fax: +33 1 41 07 47 88</td>
</tr>
<tr>
<td></td>
<td>France</td>
<td><a href="mailto:xsouard@danone.com">xsouard@danone.com</a></td>
</tr>
<tr>
<td>ACTINI</td>
<td>ACTINI SA</td>
<td>M. François Quenard</td>
</tr>
<tr>
<td></td>
<td>Parc de Montigny</td>
<td>Phone: +33 4 50 50 74 74</td>
</tr>
<tr>
<td></td>
<td>Maxilly – 74500 Evian Cedex</td>
<td>Fax: +33 4 50 74 98 07</td>
</tr>
<tr>
<td></td>
<td>France</td>
<td><a href="mailto:actini@compuserve.com">actini@compuserve.com</a></td>
</tr>
<tr>
<td>BASF</td>
<td>BASF AG Ludwigshafen,</td>
<td>M. Bernd Rumpf</td>
</tr>
<tr>
<td></td>
<td>Zentralbereich Ammoniaklaboratorium</td>
<td>Phone: +49 621 60 55446</td>
</tr>
<tr>
<td></td>
<td>ZAT/C-L540</td>
<td>Fax: +49 621 60 74789</td>
</tr>
<tr>
<td></td>
<td>D-67056 Ludwigshafen</td>
<td><a href="mailto:bernd.rumpf@basf-ag.de">bernd.rumpf@basf-ag.de</a></td>
</tr>
</tbody>
</table>

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3. **Objectives and strategic aspects.**

This project is a step forward on the way to the effective mitigation of the fouling problem. Based on the study of cooling water and dairy product treatment, this project has been divided in the following parts.

**TASK 1** Determination of “Optimum” configuration of CHE’s

**Subtask 1.1 Flow distribution and particulate fouling in PHE’s**
The objective of the subtask 1.1 is to investigate the effect of particulate fouling on the flow maldistribution in PHE. The ultimate goal of the work is a better understanding of the link between PHE configuration, flow maldistribution and particulate fouling propensity.

**Subtask 1.2 Flow distribution and precipitation fouling in corrugated HE plates**
The objective of this subtask is to carry out experiments under precipitation fouling conditions, in an existing test CHE rig and numerical flow simulations with available software to identify nearly optimum gross flow patterns.

**Subtask 1.3 PHE design for dairy product**
The objective of the subtask 1.3 is to study numerically the flow and heat transfer of dairy products inside PHE. The specific objective is to understand clearly the flow behaviour inside complex geometry, especially for non-Newtonian fluid and to propose some recommendations to reduce the risk of cooking.

**TASK 2** Improvement of H.E. surfaces

**Subtask 2.1 Improvement of heat exchanger surfaces**
The objective of the subtask 2.1 is to improve numerically surfaces for electric heated tube. The ultimate goal is to design new concepts of enhanced tubes less prone to fouling.

**Subtask 2.2 Development of low fouling surfaces**
The objective of subtask 2.2 is to test various novel surface modification techniques for low fouling CHE plates.

**TASK 3** Investigation of key factors in plate H.E. fouling

**Subtask 3.1 Deposition and removal in precipitation fouling**
The objective of the subtask 3.1 is to investigate the behaviour of crystallisation fouling in a CHE in the presence of particulates. The ultimate scope of the work is a better understanding of the complex fouling phenomena, which may lead to measures towards minimising scale formation.

**Subtask 3.2 Deposition and removal in particulate fouling**
The specific objective of the subtask is to obtain experimental data (in a model system) and theoretical results helpful in the development of rational predictive models.

**Subtask 3.3 Effect of operating parameters on fouling in industrial heat exchangers**
The aim of subtask 3.3 was to measure cooling water fouling in a typical industrial environment. For that purpose, a test rig had to be constructed comprising two plate heat exchangers run in parallel. Measurements using different plate treatments like amorphous carbon, nano-crystalline graphite and silicon ion implantation should be performed. Moreover, the influence of operating parameters like flow velocity, temperature etc. on the fouling caused by cooling water should be studied.
TASK 4  Data assessment - Modelling

Subtask 4.1  Cooling water systems
The aim of subtask 4.1 (Cooling water systems) was to develop a predictive tool to describe
and predict fouling processes caused by cooling water.

Subtask 4.2  Food products
The aim of subtask 4.2 (Food product) was to develop a predictive tool to describe and predict
fouling processes caused by dairy products.

TASK 5  Development of a Novel Computer-Aided Method for fouling
Assessment/Mitigation

Subtask 5.1  Preparation of Data Base
The objective of the subtask 5.1 are to retrieve, organise and screen experimental data sets
and to develop a database mainly comprised of measurements of thermal fouling resistance
and/or deposition rate with time, fouling deposit properties, fluid composition, process
parameters (flow velocity, temperatures, heat flux, other), heat exchanger geometry.

Subtask 5.2  Method and general applications software development
The objective of the subtask is the development of a computer program (relating to fouling) as
a multipurpose tool.
4. Technical Description

TASK 1 Determination of “Optimum” configuration of CHE’s

Subtask 1.1 Flow distribution and particulate fouling in PHE’s

Plate heat exchangers are commonly used in industrial processes, as they are more efficient and more compact than classical heat exchangers. It is generally assumed that they are less prone to fouling than classical shell and tubes heat exchangers. However, if fouling occurs, their thermal performances can be rapidly altered. Moreover, in the industry, a large number of plates are generally used. In that case flow maldistribution can occur. The main parameters are the number and geometry of the plates, the operating conditions (temperatures and flow rates), the flow arrangements (U and Z), the position of the inlet ports and the number of passes. In clean conditions, an optimum has to be found which can be altered if fouling occurs. Some configuration result in less uniform flow than others and fouling mitigation must hence be directly related to the choice of the plate heat exchanger. In order to study in clean conditions the flow maldistribution the TRICOT software developed at GRETh was validated to the configurations to be studied. Then fouling experiments were carried out on a semi-industrial test rig.

Influence of the flow rate: The relative variation of the pressure loss $\frac{\Delta P - \Delta P_t}{\Delta P_t}$ increases when channel velocity decreases. Visual observations of the deposit show that it is located on the active part of the heat transfer surface. Therefore the pressure loss increase is directly related to the deposit growth. By considering $\Delta P$ as a fouling indicator, we can assume being in the adhesion controlled regime if $\Delta P$ is low and in the mass transfer controlled regime if $\Delta P$ is high. So, the higher the velocity in the channel, the lower the fouling. The critical value is about 0.12 – 0.15 m/s.

Influence of the arrangement: Analysing U and Z type arrangement, GRETh found that in the Z arrangement, the flow maldistribution is more pronounced. The $\Delta P$ evolutions indicate that the adhesion controlled deposition flux is more important for the Z arrangement. The effect of fouling is not only an increase in $\Delta P$, but also a drop in the heat transfer performance (i.e. an increase of the fouling resistance). However, the heat transfer rate is affected differently according to the flow arrangement. Indeed, in the Z arrangement the heat transfer rate is nearly constant but lower than in the U arrangement for the first 30 channels. Consequently, for this second reason, the influence of fouling on heat transfer is more pronounced in the Z arrangement.

Influence of the corrugation angle: the asymptotic fouling resistance is lower for the 60° corrugation angle channel than for the 30° corrugation angle channel. Indeed, the flow distribution between the channels is more variable for the 30° (i.e. the number of channels with low velocity and higher deposition flux is greater). This result is the consequence of the flow structure, which is highly three-dimensional for the higher angle (sub-channel flow) and more organised for the lower angle (furrow flow). Besides the critical velocity above which deposition is adhesion controlled, has a higher value for the higher angle: 0.12 for 30° angle and 0.15 for 60° angle.

Subtask 1.2 Flow distribution and precipitation fouling in corrugated HE plates

The main emphasis of these experiments was on the distribution of deposits over the surface of individual plates, rather than on overall performance or performance of individual heat exchanger channels. The distribution of deposit in plate heat exchangers is not only essential for modelling of the fouling behaviour; it is also an excellent measure of the homogeneity of flow and, therefore, of the clean performance of the heat exchanger. To study the effect of flow distribution, flow velocity and shear stress on precipitation fouling on corrugated heat
exchanger plates, experiments using commercially available heat exchanger plates with different corrugation angles have been carried out. The experimental results have been used for a parametric study of fouling and excess heat transfer area.

**Subtask 1.3  PHE design for dairy product**

Due to the complex geometry of the PHE, this device is very sensitive to fouling, especially for dairy products where flow velocity is low and temperature high. The objective of the work is to develop a numerical method for predicting the thermal-hydraulic behaviour of dairy products. To do that, the following steps have been followed:

First, GRETh has developed and validated in simple geometry a numerical model able to predict the non-Newtonian behaviour of dairy products. A good agreement between experiments and computations on a single plate has been obtained.

Then, a 3D model of the inside part of an Alfa Laval Vicarb V2 plate H.E. has been done. For water flow, local information about the flow and the thermal fields has been obtained. Global balance of pressure drops and heat duty has been computed and compared with experimental data. A good agreement has been obtained for the main tendencies: the influence of the Reynolds number, the influence of the corrugation angle.

At least, the 3D model of a dairy product flow inside a PHE has been performed. The fluid properties, given by INRA and DANONE, have been modelled according to non-Newtonian rheological laws. The results obtained give the good tendencies in terms of pressure drops and heat transfer. However, due to the poor amount of data available, it was difficult to validate correctly the approach. Nevertheless, the model is able to give local information, which are very useful for the fouling mitigation.

The tool is able to give information about the region of high cooking risks and is able to simulate some geometrical enhancements.

In the same time, INRA and DANONE have elaborated a Fouling Model Fluid (FMF) which is a quite similar rheological behaviour for both the FMF and the actual product (milky dessert). The major interest of that FMF is to allow reliable and reproducible fouling tests with a cheaper fluid than the actual one. Then, tests on V7 Vicarb plates have been performed.

**TASK 2  Improvement of H.E. surfaces**

**Subtask 2.1  Improvement of heat exchanger surfaces**

This subtask is about the application of electricity in industry and more precisely the use of direct heating of fluids by Joule effect. The main industrial applications of this technology are in metallurgy, chemical and foods industry. Electric tubular heat-exchangers become specially attractive for a precise control of temperature of the product to be heated, and for that reason the technology have been developed in the food industry. GRETh has focused its attention on food industry where the products need a thermal treatment. The heating needs an extreme care, especially for viscous fluids; the final quality of the products depends mainly on the product’s temperature during its heating, when an over-cooking must be absolutely avoided. The temperatures of the product and of the wall, and also a precise density of the food at the wall are determining factors. The general objective of the work consists in a geometrical improvement of electric tubular HX for fluids heating by means of numerical software available at the GRETh’s numerical platform. Several geometries have been numerically simulated: a plane tube and two advanced surfaces. The plain tube is considered as a reference to which the other concept will be compared.
The first advanced geometry presents a kind of wall roughness. It consists in a sudden decrease of the cross section of the tube, followed immediately by a slow increase of the cross section to its nominal value. It is placed two or four times along the tube, with a portion of plain tube between two of them. These kind of improved tubes show clearly their efficiency: the fluid is heated until the centre and wall temperatures are less important. But there is a price to pay: pressure losses are more than three times higher.

The second geometry consists in a regular channel with a non-circular cross-section. This configuration cannot be simulated by a two-dimensional approach. Only half of the tube is simulated for natural and mixed conditions for convection. As for circular plain tube, we can observe a boundary layer development near the wall, but natural convection creates velocities in the cross-section plane with values of about 5% of the entrance velocity in the layer and increases its thickness. Fluid temperatures are globally lower in the mixed convection case, especially near the wall where the maximum value reaches 265 °C against 430 °C for the forced convection case. The hot points are located at the top of the cross-section for mixed convection and at each wing head for forced convection.

From the recommendations coming from the numerical results, 4 four modified tubes have been manufactured by ACTINI Company and tested at INRA. One final industrial configuration has been evidenced.

**Figure 2:** the industrial modified tube. Dimensions are given in mm. The filled circles are representing the location of thermocouples used for wall temperature measurements.

**Subtask 2.2 Development of low fouling surfaces**

The advantages and disadvantages of Plate Heat Exchangers (PHEs) as compared to tubular heat exchangers have been discussed by a number of authors. For example, PHEs can achieve higher heat recovery rates with smaller temperature approaches. Process changes are readily implemented by adding or removing plates. The small liquid hold-up is beneficial when toxic, volatile and temperature-sensitive fluids are processed. Furthermore, PHEs require considerably less space than shell-and-tube heat exchangers and subsequently weigh less. Due to the thin plates, stainless steel PHEs are cheaper than tubular heat exchangers since less material for the construction is needed. It is generally believed that PHEs are less prone to fouling, because they can be operated under fully turbulent conditions at relatively low flow velocities due to the use of corrugated plates. This results in higher wall shear stress, which leads to reduced deposit formation since most fouling mechanisms decrease with increasing wall shear stress. However, the presence of gaskets is a disadvantage for the use of PHEs for...
highly corrosive media and for higher temperature and pressure conditions. The thin walls of the plates are vulnerable if the heat exchangers are used for erosive duties.

One of the main reasons why the installation of PHEs is still limited in many industries is the uncertainty about their fouling behaviour. Due to the small channel width, blockage may occur much easier than in shell-and-tube heat exchangers.

Attempts have been made to either reduce the potential of a fluid to form deposits or to improve the removal of deposits. Methods can be classified into two basic categories; chemical methods and mechanical methods. Chemical methods reduce fouling by the addition of chemical additives to the fluid to be processed. In general, the application of additives is limited, by the high costs of the chemicals, but also because large quantities of added chemicals may require disposal at a later stage in the process, which causes additional costs. Most of the mechanical methods have been developed for shell-and-tube heat exchangers and their application to PHEs is strongly restricted. However, the most effective steps to mitigate fouling are those taken during the design stage. In case of a PHE, an optimum design means the shape and size of the plates, the overall flow design of the unit and the selection of a suitable material with optimum surface properties, i.e. surface energy and also surface roughness.

The successful performance of modified heater rod surfaces in pool boiling and sub-cooled flow boiling has already been demonstrated. The stainless steel surfaces were treated using ion implantation, ion sputtering and coating technologies. It could be shown that due to the lower surface free energy, the amount of deposited salt crystals (CaSO₄ and CaCO₃) onto the heater rod surfaces was reduced significantly as compared to results obtained with untreated stainless steel surfaces. These surface treatment techniques, but also other technologies have now been applied to Alfa Laval stainless steel heat exchanger plates in order to investigate their performance in a commercial PHE.

**Surface Properties & Fouling Behaviour**

It was expected that reduced surface energy would lead to reduced asymptotic fouling resistance, reduced maximum pressure drop, reduced initial fouling rate and increased initial period. Furthermore it was hoped that a correlation between these parameters and the surface properties could be found. In Figure 10, the asymptotic fouling resistances are plotted against the surface energies of the treated heat exchanger plates. There is no obvious correlation between asymptotic fouling resistance and surface energy. The surface treatment with the lowest surface energy in this chart (SiF⁺ implanted surface) does not exhibit the highest reduction in fouling resistance, but the expected trend of the dependence between fouling resistance and surface energy could be shown; lower surface energy leads generally to reduction in fouling resistance.

Boulange-Petermann et al. investigated the influence of metallic surface wettability on bacterial adhesion. They presented the number of adhering bacteria as a function of the total surface energy. A direct relation between the number of adhering bacteria and the total surface energy could not be found, since for a given number of adhering bacteria, a range of surface free energies could be observed. However, when they regarded separately the results obtained on non-polar surfaces and those obtained on polar surfaces, then in both parts it was obvious that the number of adhering bacteria increased with increasing surface energy.

Considering the carbo-nitrated & oxidised, the Amorphous Carbon and TaC sputtered and the ion implanted plates to be non-polar surfaces, and the Ni-P-PTFE coated, the DLC sputtered and the electro-polished and untreated plates to be polar surfaces (refer Figure 1), one can still not detect a clear relationship between fouling resistance and surface energy can be observed. The comparison of surface energy data with induction time in a recently published paper where the influence of surface properties on crystallisation fouling from a pure CaSO₄
solution has been investigated yielded also no correlation between surface energy and the fouling behaviour observed.

**TASK 3  Investigation of key factors in plate H.E. fouling**

**Subtask 3.1  Deposition and removal in precipitation fouling**

Particulate matter can be found almost in all industrial heat exchanger systems and it may cause not only particulate fouling, but it may affect dramatically the precipitation fouling rate as some literature data suggest. In order to clarify this issue, work has been undertaken in this subtask on the effect of commercial particles on calcium carbonate precipitation fouling, in a commercial plate heat exchanger, under isothermal once-through flow conditions. The experiments were carried out by passing a solution supersaturated with respect to CaCO3 through a PHE. Two types of commercial CaCO3 (fine aragonite and calcite) and TiO2 particles were used at various concentrations. The progress of the deposition process was monitored by measuring the increase in the pressure drop inside the PHE. At the end of each experiment the mass of the dry deposits on each plate was measured and visual observations were made regarding deposit patterns and adhesion characteristics.

The presence of aragonite particles exerts a great influence on almost all deposition characteristics (deposited mass, pressure drop, deposit morphology) compared with those of “pure” precipitation deposits. An interesting feature of these deposits is their “rippled” appearance. On the contrary, the use of the relatively large calcite particles and of TiO2 particles did not result in any deposit enhancement. The relative enhancement of deposit formation in the presence of the aragonite particles tends to decrease with increasing flow velocity. This trend may be attributed to the increasing removal rate of deposited particles with flow velocity. It was also found that the higher the added particle concentration the greater the relative enhancement of scale formation. Finally, no difference in the deposit characteristics was noticed when the flow direction was changed from upwards to downwards.

**Subtask 3.2  Deposition and removal in particulate fouling**

The objective of the work undertaken was to study particle deposition under well controlled conditions, both experimentally and theoretically, in order to obtain a better understanding of the key issues in particulate fouling, namely particle transport, sticking probability and removal. For this purpose, an experimental system for direct optical observations of particle deposition was assembled. This system included a narrow channel test section, an optical microscope with video camera, video recorder and a mini-computer for image acquisition and analysis. The major parameters considered in the study were particle size, substrate material, physicochemical interactions and hydrodynamic conditions expressed in terms of wall shear stress. Experimental data were obtained with glass particles of diameter 1.8 and 1.5 µm depositing on glass and stainless steel substrates in a horizontal channel. In addition, data were obtained with silica particles of 0.9 µm in diameter depositing in vertical and horizontal channels in order to assess the effects of gravity forces. The theoretical study included modelling of particle transport and deposition by incorporating the effects of various hydrodynamic forces and the concept of sticking probability. Expressions for the attachment efficiency coefficients were derived.

**Subtask 3.3  Effect of operating parameters on fouling in industrial HE's**

Fouling of cooling water was investigated by running the new fouling test rig that was installed at BASF AG in Ludwigshafen, Germany. The test rig comprised two ALFA LAVAL plate and frame heat exchangers that were run in parallel. Plates of different geometries were provided by ALFA LAVAL.
It was the objective to study the influence of operating parameters and special plate treatment on the fouling behaviour of filtered Rhine water. Most experiments were carried out at one of BASF waterworks buildings, and cooling water was drawn off the cooling water pipeline directly after the sand bed filters. Treated heat exchanger plates were provided by UNIVERSITY OF SURREY. After the second year, the test rig was transferred to a different place at the BASF site at Ludwigshafen to collect more fouling data and to investigate the influence of flow velocity etc. on the fouling behaviour.

Mass flow rates were set constant and controlled by pneumatic valves. During most experiments, mass flow rates were adjusted to realise 0.2 m/s at the hot water side, whereas the cooling water side was adjusted to only 0.1 m/s to accelerate fouling. By means of a computer program, all relevant data like temperatures, mass flows, and pressure drop were recorded to enable data evaluation. The fouling resistance was calculated from the change of overall heat transfer coefficients during an experimental run according to the following equations.

\[
\dot{Q} = k \times A \times \Delta T_{\text{log}}
\]

\[
\frac{1}{k} = \frac{1}{\alpha_c} + R_c + \frac{s}{\lambda} + R_n + \frac{1}{\alpha_n}
\]

\[
R_n \approx 0
\]

\[
R_c(t = 0) = 0
\]

\[
R_c(t > 0) = \frac{1}{k(t = 0)} - \frac{1}{k(t)}
\]

With \(\dot{Q}\), heat flux; \(k\), overall heat transfer coefficient; \(A\), heat transfer area; \(\Delta T_{\text{log}}\), logarithmic mean temperature difference; \(\alpha\), heat transfer coefficient; \(R\), fouling resistance; \(s\), plate thickness; \(\lambda\), thermal conductivity of plate material; \(C\), cold side; \(H\), hot side and \(t\), time.

During the first few hours of an experiment, the plate heat exchangers (PHEs) had to adjust to steady state operating conditions. Therefore, a mean value for the overall heat transfer coefficient, \(k\), was calculated from process data recorded between the 1st and the 10th hour of a run. This mean value was used as a zero value, \(k(t=0)\), to calculate the fouling resistance as a function of time.

During the experiments, different plate treatments were tested, i.e. amorphous carbon, nanocrystalline graphite and silicon ion implantation. Furthermore, the influence of flow velocity inside the PHE’s was studied.

**TASK 4  Data assessment - Modelling**

**Subtask 4.1 Cooling water systems**

Scale formation on heat transfer surfaces for the evaporation of water containing various amounts of dissolved salts is a frequent engineering problem. Nevertheless, only few experimental and theoretical investigations on this subject can be found in the literature. In this investigation the experimental data of previous work (Najibi et al. 1997) were used to develop a mechanistic model for the prediction of fouling rates for calcium sulphate and calcium carbonate during convective heat transfer and sub-cooled flow boiling. The models are able to predict all observed trends correctly.

Scale formation on a heat exchange surface causes degradation in thermal performance and also can have other serious consequences. In many concentration, crystallisation and separation processes fouling of the evaporator heat transfer surfaces is an important problem. The process liquid enters the evaporator at a temperature, which is lower than its saturation temperature causing sub-cooled flow boiling to occur. This mode of heat transfer is characterised by generation of bubbles at the heat transfer surface while the bulk temperature of the liquid is still...
below the saturation temperature of the solution. Bubbles detaching from the heat transfer surface collapse and condense in the sub-cooled liquid bulk. Sub-cooled boiling can occur over a considerable length of the evaporator and may represent up to 50% of the total heat duty.

Fouling is a transient phenomenon. Using a constant value for the fouling resistance at the design stage, which is common practice in designing heat exchangers, can therefore predict what may happen to the boiler performance but not when it will happen. Thus, it is likely that the equipment will have to be taken out of service for cleaning at an inconvenient and economically undesirable time. In order to provide satisfactory surface area for an acceptable period of operation, it is necessary to be able to predict the dependence of fouling resistance on time and also on operational parameters. The ability to carry out such modelling would also aid the determination of optimum cleaning cycles, the evaluation of anti-fouling treatments, and the identification of process control strategies.

The main objective of the present investigation was to develop a mechanistic model for prediction of fouling rates of calcium sulphate and calcium carbonate scale formation during sub-cooled flow boiling using experimental data obtained elsewhere (Najibi et al. 1997). Although fouling is more severe during boiling heat transfer a recent literature review (Jamialahmadi et al. 1993) on the mechanisms of boiler fouling reveals that experimental and theoretical evidence on fouling under boiling conditions in general and under sub-cooled flow boiling in particular is scarce. Several investigators (Lorenz et al. 1974, Mikic et al. 1969) have suggested models for boiling heat transfer in which the total heat transfer surface is divided into two parts; the area affected by active nucleation sites and the remaining area where forced convective heat transfer occurs. Chen (1966) developed an additive correlation by combining the convective and nucleate boiling contributions to flow boiling heat transfer, which has been confirmed as one of the best available prediction methods for pure fluids and mixtures (Müller-Steinhagen et al. 1995). In its basic form it is expressed as:

$$\alpha_{fb} = \alpha_{fc} F + \alpha_{nb} S$$

where $\alpha_{fc}$ is the convective heat transfer coefficient which would be found for the liquid phase flowing alone and $\alpha_{nb}$ is the nucleate pool boiling heat transfer coefficient which depends on the wall superheat. The Gnielinski (1986) and Gorenflo (1988) equations are used to calculate $\alpha_{fc}$ and $\alpha_{nb}$ respectively. In Equation (1) $S$ is a "suppression factor" to account for the decrease in nucleate boiling as forced convective effects are increased. $F$ accounts for the effective increase in liquid velocity due to the presence of the vapour phase and is a function of the martineii parameter. An analogous procedure has been used in this investigation to develop a model for prediction of calcium carbonate and calcium sulphate fouling rates during sub-cooled boiling. It uses the Chen model (Chen 1966) to calculate the fraction of heat transferred by nucleate boiling:

$$NBF = \frac{\alpha_{nb} S}{\alpha_{fb}}$$

This parameter may be interpreted as a measure of the fraction of the heat transfer area affected by bubble growth mechanisms. Scale formation at the heat transfer surface during sub-cooled flow boiling is a combination of the following two mechanisms:

1. In the area which is affected by the vapour bubbles fouling occurs mainly due to the mechanism of bubble formation and micro-layer evaporation.

2. In the remaining area, fouling takes place by forced convection mechanisms.

As shown in Fig. 1 both of the mechanisms occur in separate zones of the heat transfer surface. Therefore, the overall fouling rate can be presented by the following equation:
As the heat flux increases, the number of nucleation sites increases and Equation (3) predicts that the fouling caused by the boiling mechanism will increase.

**Comparison with experimental data and with other models**

The models developed by Chan and Ghassemi (1991) and by Hasson et al. (1968) and the model suggested in this study for prediction of fouling during convective heat transfer have been implemented in Equation (3), together with Equation (4). A typical comparison between the predictions of these three models with experimental data is shown in Fig. 3. There are considerable differences between the experimental data and prediction of Eq. (3) using Hasson's Ionic Diffusion Model (Hasson et al. 1968) for prediction of the forced convective part of the fouling rate.

In Fig. 4 measured fouling resistances for calcium sulphate are compared with the predictions of the model suggested by Bohnet et al. (1987) and Ritter (1983), and the model developed in this work. The proposed model and the Ritter model predict linear fouling behaviour, while the Bohnet et al. model predicts asymptotic fouling resistances.

The suitability of the investigated models for prediction of calcium sulphate and calcium carbonate fouling rates during sub-cooled flow boiling is illustrated in Figs. 5 and 6 where all experimental data obtained under various operational conditions are compared with predicted values. The average absolute error of predictions for calcium sulphate is 25% and for calcium carbonate is 22% which shows the applicability of the suggested models.

**Subtask 4.2 Dairy products**

The main purpose of that task was in a first step to collect a maximum of data (in literature when available) concerning fouling in heat exchangers when treating food products. Both tubular and plate heat exchangers were dealt with.

In a second step, modelling of fouling curves have to be established accounting for the different parameters (temperature level, type of fouling deposit, flow arrangement, geometrical parameters, etc.). The different models (empirical relations or not) have then to be provided to the data bank of Task 5.

Four main representations are commonly used to follow fouling phenomena:

- evolution of pressure drop with time,
- evolution of the overall heat transfer coefficient with time,
- evolution of fouling resistance with time,
- evolution of fouling layer thickness with time.

All these representations are of course quite equivalent and only depend on common use in the different industries.
5. Results and conclusions

**GRETh** is mainly involved in subtasks 1.1, 1.3 and 2.1.

In Subtask 1.1, the flow distribution and particulate fouling in PHE’s has been studied. Indeed, in a plate heat exchanger equipped with a significant number of plates, the fouling behaviour is more complex to analyse. The general trends already described in the literature about the influence on fouling of the velocity and the corrugation angles are still present, but due to the large spread of velocities encountered in the different channels in parallel, these influences are not straightforward. We propose to use the relative pressure encountered during fouling in some channels as a fouling indicator. As its evolution measured in the same heat exchanger increases strongly when the velocity decreases, it could indicate the transition between a mass transfer and an adhesion controlled deposition flux. Moreover limit values of the velocities of about 0.12 m/s and 0.15 m/s respectively for the 30° and 60° corrugation angle appear to characterise this transition. It is also worth noticing the strong effect of the plate arrangement: in Z arrangement the influence of fouling is stronger than in U arrangement because of an accentuated flow maldistribution and a smaller heat transfer efficiency. More experiments are planned at GRETh in the near future: tests with V20 VICARB plates (heat transfer area: 0.2 m²), tests on a single channel in order to explore more precisely the velocity effect on the deposition flux, exploitation of the temperature measurements in the different channels during fouling.

In the Subtask 1.3, The numerical simulation for the description of the thermal-hydraulic behaviour of the dairy product flow inside a plate heat exchanger has been validated on the following points: First, a non-Newtonian model for describing rheological behaviour of the dairy products has been implemented and validated on a simple geometry inside TRIO software. Then, the numerical simulation of a water flow inside a complex geometry of plate heat exchanger has been developed and validated. Next, according to the physical properties of the model fluid given by partners (INRA and DANONE), the thermal-hydraulic behaviour of this flow has been investigated and analysed in order to optimise the process and define a novel heat exchanger geometry. Using the CFD software, we are now able to have a reliable description of the thermal-hydraulic behaviour of dairy products in plate H.E.. The way of reducing the cooking i.e. the fouling is to suppress the low velocity regions by feeding these regions with external devices.

In the Subtask 2.1, the improvement of heat exchanger surfaces has been investigated. Indeed, the development of enhanced surfaces is an important challenge for the food products industry. We presented calculations based on two types of improved geometry. We have shown promising results under the aspect of a better homogeneity of the product temperature. These results have helped ACTINI to choose with more accuracy the final geometry of tube for manufacturing.

**TU-BS** is mainly involved in subtasks 2.2 and 3.1. In both subtasks the main focus is on the improvement of compact heat exchanger with respect to minimum fouling tendency. During subtask 3.1 a review of the key factors influencing fouling is elaborated in order to support a complete understanding of the physical principles. The achieved better understanding of the key factors shows the way to design more efficient compact heat exchangers. The main disadvantage of known models is a lack of a description of the induction time. In this period the adhesion of crystals on the heat transfer surface and their concretion to a compact fouling layer take place. The deployment of new low-fouling surface
materials increases the significance of the induction period since long periods correspond to low fouling costs.

In order to be able to compare properties of heat transfer surfaces to their performance when exposed to a liquid flow of an aqueous salt solution (CaSO\textsubscript{4}-H\textsubscript{2}O) in fouling experiments a test unit was built.

The design of the plate heat exchanger supports a comfortable replacement of its heat transfer surface for the examination of many different materials. Previous fouling test runs show that there is a strong dependence of adhesion on the surface properties of the heat exchanger. These results motivated an extensive measuring program with various surface materials during subtask 2.2.

The materials have been chosen with respect to an expected low-fouling tendency on the basis of DSA (drop shape analysis). Here, images of droplets on heat transfer surfaces are digitised using commercial hardware and software. It is assumed that the physical properties of the test liquids are well known. Then, the measured contact angles can be used to calculate surface energy data. The models used for calculation, especially their restrictions, are examined within the project.

Due to low surface energies it can be expected that coatings made of Ni-PTFE, DLC (diamond like carbon) TiN and TaC-PTFE decrease fouling tendency. The Ni-PTFE coating is determined to have the lowest surface energy.

Besides surface material, also surface contour influences the adhesive strength of the deposit. A rough surface can favour mechanical bonding between deposit and heat transfer surface. The impact of surface contour on fouling has been examined by a topography measuring station.

The comparison between Ni-PTFE and stainless steel yields the conclusion that the characteristics of surface contours are similar. Though the number of profile elements is reduced due to the coating process, the mean roughness resemble each other. Hence, the influence of surface properties on fouling behaviour can be explained referring to energy related characteristics, only. On the other hand, the deployment of a DLC coating implies a significant change in surface topography. The chemical vapour deposition process contributes to a smoothing effect. An improved fouling behaviour of such a surface material can only be explained considering both surface energy and geometry.

Before performing long-term fouling experiments the influence of surface properties on adhesion characteristics have been analysed by means of a ring shear device. Here, deposits of the salt used in real fouling experiments are produced on the heat transfer surfaces by precipitation. Since measurement errors have a crucial impact on the results statistical methods are deployed to determine the medium adhesive strength.

The adhesive strength of crystalline deposits on polymer-based coatings proved to be less than the corresponding value on an untreated stainless steel surface (St). Since the surface topographies of Ni-PTFE and St resemble each other, the decrease of the adhesive strength can be explained by the influence of surface energy, only. Furthermore, the experimental results show that polishing is a promising alternative to reduce adhesion. The adhesive strength for an electro polished steel surface is just about 40\% of the corresponding value for an untreated steel surface.

So far, it is rather complicated to judge whether the decreased adhesive strength of deposits on DLC and TiN is based on surface energy or geometry. The electro polished steel surface also provides a low adhesive strength in comparison to the untreated steel surface. Therefore, long-term fouling experiments have been performed in order to enable one to recommend an optimal choice of surface properties.
The analysis of fouling data proves the expected low-fouling tendency of coatings such as TiN and Ni-PTFE. A remarkable extension of the induction period can also be realised by smoothing surface contour, e.g. by electro polishing. The optimal surface material is Ni-PTFE. Due to a relatively small surface energy the adhesive strength between deposit and heat transfer surface is low resulting in a long induction period. As a consequence, the induction time of Ni-PTFE is about three times the value of the untreated steel surface reducing the cost of fouling considerably.

The main disadvantage of the deployment of some low fouling surface coatings lies in their abrasion characteristics. The low temperature stability of polymer-based coatings is a severe problem when they are exposed to higher heat flux densities. During the fouling experiment with the Ni-PTFE coated heat transfer surface, critical flaws can be detected all over the surface indicating that the destruction of the deposit has been initiated. In contrast, the TiN coating provides the most promising capability to resist high temperature and shear forces. The improvement of the abrasion properties of coating materials is a task for the producers of up-to-date coatings.

**DANONE** is mainly involved in subtasks 1.3. The main objective of CIRDC Danone, in collaboration with INRA, was to understand and then to reduce fouling in Plate Heat Exchangers when heating dairy products (milky desserts were specially examined). To achieve that objective a Fouling Model Fluid (FMF) has been developed. Based on food constituents, this model fluid has the same rheological behaviour than the real fluid (highly viscous shear-thinning behaviour) and also fouling curves in PHE's are quite similar for both model and actual fluids.

This FMF has then been used to optimise operating conditions on a given PHE; an experimental design was elaborated for that purpose. Results are quite promising: influence of parameters such as residence time, mean flow velocity or temperature profiles has been pointed out: fouling can surely be reduced by adjusting these parameters.

Future works will be carried out to go on fouling experiments and finally to obtain the optimal configuration for a given thermal duty.

**CPERI** is mainly involved in subtasks 3.1, 3.2 for experimental studies and 5.2 database development. In subtask 3.1, the main result of this experimental study is that a small concentration of fine aragonite particles can cause a significant increase in the deposited mass inside a PHE (see relevant illustration) and also to induce the onset of scaling at relatively lower supersaturation values, for which no precipitation fouling is observed otherwise. The enhancement of scale formation appears to be independent of the flow direction inside the PHE compartments and it tends to be reduced with increasing flow velocity. The mechanism of this enhancement by aragonite particles is not obvious, but it may be related to an increased mass transfer rate due to roughness caused by the deposition agglomerates of cemented (with precipitating CaCO₃) added particles. In contrast, the addition of TiO₂ particles and of large calcite particles did not show any appreciable increase in the scale formation. More work is required in order to clarify these complex phenomena, although from a practical point of view the solution is relatively easy: filtration and removal of particulates.

In subtask 3.2, a set of experimental data on micron-sized particle deposition under well-controlled hydrodynamic conditions has been obtained, covering a wide range of physicochemical conditions, particle sizes and substrate materials. The experimental results
reveal the important effects of gravity, lift forces and physicochemical interactions. Good agreement is obtained between theory and experiment by incorporating a finite attachment efficiency in a model of particle deposition. It is shown that even with particles in the micron size range the attachment efficiency is limited for hydrodynamic conditions that are similar or less severe than those encountered in industrial heat exchangers. Although a unique expression for the dependence of this attachment efficiency on shear rate has not been derived, the results obtained will be helpful in improving the understanding and modelling of the complex processes of attachment and re-entrainment in particulate fouling.

In subtask 5.2, CPERI is in charge of developing a database software on fouling. The “Prometheus” database was developed for retrieving, screening and organising data and information found in the open literature pertinent to water-side fouling. Prometheus serves also as a tool to identify data sets with certain characteristics. The scope may be extended in the future to assessing predictive models for design and other applications. Up to now more than about 120 papers and conference proceedings on PHE and fouling in general have been incorporated in the database. The number of data sets reaches 200 (coming from 12 papers), the number of images (figures, pictures, schematics) is about 1000 and the number of tables is 200.

**INRA** is mainly involved in subtasks 1.3, 2.1 and 4.2. In subtask 1.3, a Fouling Model Fluid has been developed with reconstituted milk, 5 g/l native $\beta$-lactoglobuline, 10% (w/w) sucrose and 0.15% (w/w) Xanthan gum. This FMF is quite available to simulate the milky dessert of DANONE for the two aspects (rheological behaviour, fouling behaviour in PHE).

The main advantage of such a fluid is that you can simulate fouling behaviour of real products by use of a reproducible fluid with well-controlled physical properties. This fluid should be used in the future to optimise PHE’s (for minimising fouling propensity) or to compare the efficiency of different geometry of heat exchangers. Obviously, validations with real products will always stay essential. Also, an experimental test rig has been installed and tested in the INRA pilot hall. This rig allows to accurately determine the thermal and hydraulic performances of heat exchangers (PHE’s in that program). This rig is obviously still available and could be used for other heat exchangers than those presented in that Joule Program.

In subtask 2.1, The work carried out has allowed the development of a completely new enhanced tube with ACTINI. This tube can be inserted in Joule Effect Heaters and presents several advantages:

- manufacturing this tube is relatively easy,
- when using such tubes, the amount of pressure drop is not excessive,
- the heat transfer coefficient is greater than for classical smooth tubes,
- when handling highly viscous fluids, the modified tubes ensure a better uniformity of heat treatment,
- these tubes are less prone to fouling: experiments on both fouling model fluid and real fluids confirm that point.

These tubes are now industrially available and are recommended when heating food complex fluids.

In Subtask 4.2., some fouling data on food products have been collected. Some of fouling curves have been modelled and provided to data bank of CPERI. The main conclusion was that it is relatively delicate to generalise fouling curves with foodstuff: the number of parameters is important (operating conditions, geometry...), and a lot of criteria have to be accounted for: pre-processing of the product, nature and composition of that product, origin...
UniS is mainly involved in subtasks 1.2, 2.2 and 4.1. In subtask 1.2, according to the work/time schedule in the Technical Annex the work undertaken by UniS referred to the investigation of the effects of flow velocity, temperature and plate design on precipitation fouling, the deposition rate or/and the distribution of CaSO₄ fouling in a PHE. Experiments were carried out with a simulated once-through flow of the solution to determine the pattern of distribution of the deposits over the surfaces of the plates. The overall performance of the CHE was monitored by pressure drop and temperature measurements. The effect of three kinds of solution concentrations, flow velocities and corrugation angles has been tested. This part of the project was progressed as planned and was completed within the time period set at the beginning of the project, although several experimental runs were performed during the last year to clarify some questions raised. So the comparison of stated and planned activities for UniS clarifies that all stated objectives have been achieved in this subtask. The parametric study enables one to give recommendations of the overall design of a plate heat exchanger depending on different fouling mechanisms. Among all the methods investigated for excess area provision including the standard exchanger case where no excess area has been provided for, the addition of parallel plates gives the highest fouling resistance for the two lower-activation-energy cases investigated. It is only at very high activation energies where flow velocity has little or no effect on fouling that pass B#1 which has the average highest wall temperature among all the ‘overdesigned’ exchangers, exhibits the highest fouling resistance. This is reasonable as adding extra parallel plates resulted in the lowest flow velocity among all the exchangers investigated.

The consequences of having a two-pass arrangement are mostly encouraging. The flow velocities are higher for both passes of both configurations when compared with that of the standard exchanger. However, all the corresponding average wall temperatures are higher than that of the standard exchanger, except for pass B#2. Since the flow velocities of all the individual passes are comparable to each other, whether a pass would foul more than another is dependent on the corresponding wall temperatures.

Among all the over-designed exchangers and their individual passes, pass B#2 not only has the lowest average wall temperature, but it also has a relatively high flow velocity. As a result, it has the lowest fouling resistance and highest \((\dot{Q}/\dot{Q}_0)\) for all the three activation energies investigated. Despite its high average wall temperature, pass B#1 maintains a low fouling profile at low activation energies. It is only at very high activation energies that pass B#1 exhibits high fouling resistances and low \((\dot{Q}/\dot{Q}_0)\).

When adhesion-controlled fouling is expected, the excess area is best incorporated by having a two-pass arrangement, or by using plates with half the standard plate width. The occurrence of reaction fouling can be significantly reduced by lowering the prevailing wall temperature on the cooling waterside. Therefore a two-pass arrangement and plates with half the standard plate width should be avoided.

In subtask 2.2, according to the work/time schedule in the Technical Annex the work by UniS consisted of two assignments, namely development of numerous low energy surfaces and experimental tests to evaluate the performance and the influence of those surfaces on Precipitation fouling. Different techniques have been used to develop the different surface modifications. Those treatments have been applied to samples of various geometry for different test procedures and analysis of surface properties. The materials have been chosen according to experience gained by the experimental work during the first twelve month of this project. The experimental work carried out has focused on CaSO₄ deposition and sticking...
probability. The effect of 10 different surface materials has been investigated. The complete experimental and theoretical work has been carried out as planned. It could be shown that using appropriate surface treatment techniques to modify the surfaces of heat exchanger plates is an effective tool to reduce scale formation in plate heat exchangers significantly. The already known general tendency, reduced surface energy leads to less deposit formation, could be confirmed. However, no straightforward correlation between surface energy and fouling behaviour could be found. Smoothening the surface of the heat exchanger plates reduced fouling whereas a rougher surface finish increased fouling. The surface energy alone is not sufficient to describe the fouling behaviour observed. There is no explanation yet for the strongly deviating performance of the $H^+$ implanted plates and the DLC sputtered plates did not decrease fouling to the expected extent regarding the surface energies of both treated plate sets. Therefore, a more detailed understanding of the mechanisms responsible for the adhesion of the deposits on the surfaces has to be gained, which is the aim for future works. This may also lead to the development of an appropriate deposit adhesion model.

In subtask 4.1, the objectives are to assess the experimental data in order to improve or develop predictive tools. Measurements for calcium carbonate and calcium sulphate fouling were used to develop a model for the prediction of fouling rates during sub-cooled flow boiling. The suggested model is in analogy to sub-cooled flow boiling heat transfer. It includes transport and reaction mechanisms of scale formation, as well as concentration effects under the growing bubbles. Obviously, the mechanism of heat transfer should not affect the activation energy of the crystallisation reaction. This has been confirmed by the modelling approach. The model is able to predict all observed trends, i.e. the effect of variation in flow velocity, heat flux and bulk temperature, correctly. The quantitative agreement between measured and predicted fouling rates is good.

**Alfa Laval Thermal** (ALT) is mainly involved in the following tasks:

- ALT designed the field PHE unit that was tested at BASF in Ludwigshafen. AL also helped to design the instrumentation of the rig in which the PHE is installed.
- AL supplied hardware in the form of PHE:s to the test facilities site at INRA. Some simulations were also performed for this unit.
- ALT has participated in several discussions with Univ. of Surrey regarding coating of plates. Test results from Surrey were compared to proprietary information and feedback was given to Surrey.
- ALT has searched for and supplied papers to the database on fouling that was created by CPERI.
- ALT has helped to evaluate the CFD runs that were carried out at GRETh. This pioneering work has led to interesting spin-off projects outside the contract.

The main work for ALT remains to be done as the results from the project are now being evaluated internally. Decisions about implementation of results have not yet been taken, as they will involve major investments in our production methods.

**Alfa Laval Vicarb** (ALV), originally VICARB at the beginning of the contract, is acting as an associated partner of GRETh. The contribution of ALV during the project is covering different activities:
• Define the plate pack arrangements to be tested, representing the usual configurations of the industrial heat exchangers, in order to evaluate the maldistribution and its impact on flow distribution and on fouling.
• Supply, to different partners: GRETh, INRA and CPERI, the heat exchangers or plate pack to be tested with the different configuration selected.
• Be part of the meetings in order to give the point of view and wishes of a manufacturer of heat exchangers.
• Supply the CAD design of the plates in 3D for the CFD thermo-hydraulic simulation and do the comparison with actual plates and previous tests.

The main subjects to implement the project list of Alfa Laval R & D organisation are:
• Modify the internal rules to reduce maldistributions and then decrease the fouling tendency.
• Use the right velocities (when possible) to minimise the fouling limit, keeping in mind that higher velocity increase the power consumption.
• Study the surface treatment as anti-fouling solution.
• Use CFD simulation as an optimisation tool to study the local distribution of the flow, with the objective to increase the thermo-hydraulic performances and minimise the local dead zones and so decrease the fouling.

**ACTINI** is mainly involved in subtasks 2.1. The main objective of ACTINI Company was to determine the 4 types of geometry, to foresee the performance trough a numerical simulation made on the different enhanced tubes by GRETh, then determine the method to build the enhanced tubes (Actini) and install them on the test platform of INRA (Actini).
Tests with model fluids have been performed at INRA in order to determine the overall performance (heat transfer coefficient and pressure Drop), qualify and quantify the treatment uniformity, and foresee the fouling characteristics on these enhanced tubes compared to circular tubes.
Then, tests with real food products provided by DEGUT have been done. First, an analysis of the previous results on model fluids has been carried out to prepare the test with actual food products. Secondly, we have to determine the set of tubes, which could be the best the reach the objective of performance and reduced fouling. Thirdly, this set of tubes have been manufactured and tested with food products.
Exploitation of result:
• Patenting the best shape of tubes if possible.
• To determine the methods to manufacture the tubes in series.
• Commercial Action (communication).

**BASF** is mainly involved in subtasks 3.3, and 4.1.
In subtask 3.3, during the experiments using the new fouling test rig, different plate treatments were tested, i.e. amorphous carbon, nano-crystalline graphite and silicon ion implantation. Furthermore, the influence of flow velocity inside the PHE’s was studied.
Generally, little influence of the plate treatment on the fouling behaviour was found (cf. Figures 2 –6). Therefore, a chlorine treatment of the Rhine water was tested to further reveal the fouling mechanism caused by Rhine water. It was found that the chlorine treatment decreases the fouling resistance by roughly a factor of five (cf. Figures 7-9). Due to the great
influence of the chlorine treatment it can be concluded that firstly bio-fouling occurs, thus preparing a sticky microorganism layer onto which particles can adhere. But as the plate treatments were mainly designed to decrease particle fouling, it is obvious that treatments like amorphous carbon, nano-crystalline graphite and silicon ion implantation as tested in the project only have a little influence on fouling caused by Rhine water. Further investigations in that field will thus concentrate on bio-fouling to avoid the formation of a sticky layer.

In subtask 4.1, experimental data available from Subtask 3.3 were evaluated with respect to fouling resistance. However, the database is still narrow and requires additional data about the influence of flow velocity, temperatures, and residence time of cooling water. From the available measurements, it was impossible to derive a simple model for cooling water fouling. Expecting steady state conditions after a reasonable time of each run, the Boltzman function

\[ R_f(t) = \frac{(A_1 - A_3)}{1 + \exp\left(\frac{t - t_0}{A_2}\right)} + A_3 \]

where \( A_1-A_3 \) and \( t_0 \) are adjustable parameters seems to be applicable to describe the time dependent fouling resistance. It produces a sigmoidal curve as suggested earlier with respect to fouling curve modelling. Due to a shift of fouling data after starting the run, the regular curve fit (solid line) did not reproduce the zero value in the beginning, whereas the asymptotic value was over-predicted by fitting the curve through zero (dashed line). As long as the database is so small, modelling is restricted to empirical correlations. However, with continuing experiments, more data will be available to carry out work on modelling the results.
6. Exploitation plans and anticipated benefits.

Exploitation plans

During the project, several exploitable results have been obtained:

- Design rules for fouling mitigation in PHE (Alfa Laval, GRETh, UniS, CPERI and BASF for cooling water systems);
- Enhanced Tubes (Actini, INRA, GRETh);
- Use of Fouling Model Fluid to model the milky dessert behaviour (Danone, INRA, GRETh, Alfa Laval);
- CFD modelling for CHE design (GRETh, Surrey, Alfa Laval);
- Low fouling surfaces (TUBS, Surrey, Alfa Laval);
- Fouling data base (CPERI, INRA, BASF).

For both of them, exploitation plans concerns various aspects:

- Dissemination of the results through publications, articles and lectures
- Further work in the field of experimental (on low fouling surface) and numerical work (on CFD modelling of C.H.E.)
- Proposal of contracts with the CFD approach in order to enhance the P.H.E. design
- Patent pending in the field of enhanced tube and low fouling surface
- Fouling data base on CPERI web site.

All that points are detailed in the Technical Implementation Plan.

Impacts for industry

The range of investigations of this research programme is centred around the framework of the various aspects of fouling in compact heat exchangers. The outcome aims at providing industry with directly usable results (on a short-medium term basis) while at the same time pursuing structured progress towards more generally applicable techniques and methods. Significant economic and technical benefits are expected from the results of this research programme. The present trend of over-designing heat exchangers to cope with fouling results in often unnecessary capital investment, which substantially increases the cost of process plants. Pritchard (1990) estimated that this cost may be as much as 1400 MECU/year, whereby the relative excess costs for compact heat exchangers are significantly higher than those of shell-and-tube heat exchangers. These potential savings, however, can not be realised before new reliable design methods are developed and widely accepted for use in the rapidly developing area of compact HE's. In addition, there are significant lost opportunity costs where energy savings or new processes have not been realised due to uncertainty about the fouling behaviour of the required compact heat exchangers. In this project, new methods for coping with fouling in the industrially important cases of cooling water and of food products are being developed.

The objective for ACTINI is to be well known in the treatment of viscous product, thanks to our knowledge in sizing the exchanger and to adapt the best shape to the product. The equipment, which are concerned, are pasteurizers and sterilizers on liquid eggs a york, fruit purees, desert cream, sauces, and soups.

The total costs due to heat exchanger fouling for the industrialised world have been estimated as US $ 5x10^{10} per year. While these costs can not be completely eliminated, the results of the present study will identify conditions and design options where compact heat exchangers may foul considerably less. A large portion of the thermal energy used in industrial processes is handled through heat exchangers. Therefore, improved heat exchanger performance through
better design techniques (mitigation of fouling) has a direct impact on overall energy efficiency and energy conservation.

Two main classes of fluids are covered in this project with the following potential benefits:

- In the area of food products, fouling mitigation will lead to a significant increase in operating time and hence to increased productivity. For example, a 2 hours increase of operating time corresponds at least to an increase of 10% in productivity. The consumption of water and cleaning agents is reduced by about the same amount. Energy consumption, which is a stronger function of operating time, is even more reduced. In addition, due to better temperature control, the quality of the product and the functionality of the equipment are improved.

- Cooling water fouling is an extremely important problem in the chemical processing industry which has been compounded by increasing environmental regulations challenging the usage of water treatment chemicals in open systems and the discharge of water with previously tolerated additive levels from closed systems. At the same time, the supply of cooling water has decreased because of increasing costs, leading to lower cooling water flow velocities and higher outlet temperatures. Both trends increase the tendency of deposits to form on the heat transfer surfaces. In addition to the reduced thermal performance, cooling water fouling tends to increase the corrosion of heat exchangers. Compact heat exchangers can usually be built from more expensive materials because of their smaller heat transfer surface requirements. This increases the life span of equipment. In addition, smaller and lighter heat exchangers require less floor space and support.

It has been estimated that the annual penalty for heat exchanger fouling in industrialised countries comes to about 0.25% of the country’s GNP. Even a 1% reduction in fouling costs, which seems to be an achievable target considering the overwhelming application of cooling water and dairy products, will have a significant impact. The application of compact heat exchangers for cooling water duties will reduce the temperature approach by at least 5°C, resulting in cooling water saving of about 20%. If this is accompanied by a reduction in fouling resistance, operating costs can be reduced by more than 50%.

At present, about 80% of all heat exchangers are of the conventional shell-and-tube design. More than 10% of these applications could be better fulfilled by compact heat exchangers, if the fouling problem is better understood. Annual heat exchanger sales in the US alone are about 7 billion ECU.

**BASF** is amongst the 4 largest chemical companies in the world. The Ludwigshafen main site alone employs in excess of 45,000 staff. In addition to European competitors, there is strong competition from the US and Japanese market. Increasingly, European companies are getting under pressure from the developing Asian economies, which can produce chemicals at a more competitive price because of labour and energy costs, and environmental regulations. The outcome of the suggested research project will reduce operating and environmental costs in European installations, and increase the high technology advantage.

For BASF, the present investigation using different plate treatments like amorphous carbon, nano-crystalline graphite or silicon ion implementation has shown little influence on cooling water fouling. Therefore, those treatments will not be used in further investigations or applications on the cooling waterside. However, potential is seen to mitigate or avoid fouling processes on the product side, i. e. polymerisation fouling, crystallisation-fouling etc. Therefore, BASF plans to further investigate special surface modifications to avoid fouling on the product side. However, the strategies for fouling mitigation which have been developed during the project has been integrated into the design rules of the company.
**ALFA-LAVAL** and **VICARB** are the world’s largest manufacturers of plate heat exchangers. There is no doubt that their market share would increase dramatically if novel plate designs for reduced fouling were developed. However, at the moment, Alfa-Laval and VICARB use the new validated tools developed during the project for the design of new heat exchangers under fouling conditions. Furthermore, the company has integrated the results of the project about the fouling mechanisms and the mitigation strategy for the design rules.

For **ACTINI**, the economics gains will be on the cost on the exchangers. The benefit for the client will be to have lower fouling, longer production runs and a better product (Len damaged by heat treatment). The benefit for the manufacturer consists in putting lower surfaces. The first results we have from the test made by INRA shows that we can increase the global heat transfer coefficient with the geometry number 4 by a coefficient 1.3 to 1.5, which means a diminution of the size of the exchanger between 25% and 35%. That means that we can expect a reduction of 5% to 8% of the global cost.

For **DEGUT**, the economics gains are on the exploitation cost of the eggs treatment. Indeed, the new low fouling surfaces reduce highly the cleaning cycle so lead to a longer production runs and a better product.

**Impact on environment, working conditions, society, regional cohesion, norms and standard, and SME aspects**

Related beneficial consequences of reduced primary energy consumption are not only economic but also environmental and social. Indeed, reduced atmospheric pollution can result from the reduction of fossil fuel consumption, associated with energy conservation. The indirect social benefits are also apparent, in that regions with no significant energy resources can more easily pursue their economic development under conditions of industrial energy conservation.

Fouling mitigation can also have very significant economic and social impact in that it leads to reduced cooling water requirements and possibly to cleaner water effluents. Improvement in the thermal treatment of foodstuff affects positively the efficiency in pasteurisation procedures and their effectiveness, insuring product safety by achieving the targeted low microbial count.

Heat exchanger cleaning usually involves acidic and caustic solutions which have to be disposed of afterwards, putting additional load on the environment. In addition, frequent dismantling of heat exchangers operating with potentially harmful substances involves a poses a considerable health and safety risk to plant personnel.

Application of compact heat exchangers in domestic applications (distance heating, air conditioning, heating etc.) with reduced fouling will have an impact on the quality of life and the cost of living.

The results of this research project will give European companies of all sizes wider access to the application of compact heat exchangers, and therefore to more energy efficient and less expensive processes. This is of particular importance for the less technically developed regions where new plants will be installed or less advanced plants up-graded. Food processing is an important industry in all European countries, but a key industry in regions with an emphasis on agricultural products. Fouling-free operation of CHE in the food industry helps to improve final product quality and thus the competitiveness of this industrial sector. Highly
specialised experimental and computational techniques have been developed at the various institutions involved in this project, which will be introduced to the partners, thus enhancing technology transfer.

Following ACTINI, the different impacts are on:

- **Pollution**: we tend to reduce fouling and so to increase the production run from 1.5 to 2. Of course, burns products are commonly put to waste and the users will reduce this waste and save products and proteins.
- **The possibility to have reduced fouling on viscous products enables to treat them at a higher temperature.** That means that for sauces like béchamel, you can have a UHT continuous treatment to have a 6 months like product; and on liquid eggs, the fact to increase from 65 °C to 70 °C the treatment temperature enables to increase the shell life from 2 weeks to 5 weeks.
7. Illustrations of the project.

The following drawings and pictures are represented as indicative of the most relevant results of the project.

- **Fouling resistance evolution for 2 flowrates**
  - \( Q_4 = 15 \text{ m}^3/\text{h} \) \( Q_5 = 20 \text{ m}^3/\text{h} \)

- **Fouling resistance evolution for the two arrangements** (\( Q = 20 \text{ m}^3/\text{h} \))

- **Heat rate per channel in clean conditions** (\( Q = 20 \text{ m}^3/\text{h} \))

- **Fouling resistance evolution for the two corrugation angles** (Tests 1&5, U Type, \( Q = 20 \text{ m}^3/\text{h} \))

*GRETh - (Subtask 1.1 Flow distribution and particulate fouling in PHE’s)*
Comparison of rheological behavior of actual and model fouling fluids

The Fouling Model Fluid (FMF) and the actual fluid (milky dessert) have the same rheological behaviour – INRA and DANONE

(Subtask 1.3 PHE design for dairy product)
Comparison between plain tube and improved tube with 2 and 4 restrictions - GRETh
(Subtask 2.1 Improvement of heat exchanger surfaces)

Temperature fields in the non-circular geometry forced convection and mixed convection - GRETh
(Subtask 2.1 Improvement of heat exchanger surfaces)
Comparison between smooth and modified tubes with eggs

Evolution with time of wall temperatures for both smooth and modified tubes when treating whole eggs - ACTINI and INRA

(Subtask 2.1 Improvement of heat exchanger surfaces)

Variation of Asymptotic Fouling Resistance with Surface Energy - UniS

(Subtask 2.2 Development of low fouling surfaces)
Surface energy of several "low fouling" surfaces compared to stainless steel – TU BS.
(Subtask 3.1 Deposition and removal in precipitation fouling)

Fouling curves for several heat transfer surface materials – TU BS.
(Subtask 3.1 Deposition and removal in precipitation fouling)
Influence of fine CaCO₃ particles (aragonite) on deposit formation at low super-saturation values
(T=40°C, u=0.17 m/s, Cₚ=40 mg/L) – CPERI.
(Subtask 3.1 Deposition and removal in precipitation fouling)

Picture of rippled deposits on a plate after the addition of 40 mg/L of fine aragonite particles
(T=40°C, pH=8.3, u=0.17 m/s, time=170 min) - CPERI.
(Subtask 3.1 Deposition and removal in precipitation fouling)

Deposition coefficients of micron-sized particles on flat surfaces.
(a) Glass particles on stainless steel. (b) Silica particles on glass in vertical (V) and horizontal (H) channels. In the horizontal channels gravity is enhancing deposition - CPERI.
(Subtask 3.2 Deposition and removal in particulate fouling)
Relative pressure drop change – BASF
(Subtask 3.3 - Effect of operating parameters on fouling in industrial heat exchangers)

Cooling waternside of PHE 1 (left) and PHE 2 (right) after run No. 8 - BASF
(Subtask 3.3 - Effect of operating parameters on fouling in industrial heat exchangers)
Empirical correlation of experimental data using a Boltzmann equation – BASF
(Subtask 4.1 Cooling water systems)

View of the main page of each publication in the database as it is shown in the Internet - CPERI.
(Subtask 5.2 Method and general applications software development)
APPENDICES

List of acronyms

P.H.E.  Plate Heat Exchangers
GRETh  Groupement pour la Recherche sur les Echangeurs Thermiques
UniS   University of Surrey
TU BS  Technical University of Braunschweig
CPERI  Chemical Process Engineering Research Institute