PROCESS INTENSIFICATION OF LIQUID-LIQUID NON-ISOTHERMAL PROCESSES BY USING CHEMICAL REACTOR - HEAT EXCHANGERS (L/L HEX)

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1 ABSTRACT

The prime objective was to develop through a total Process Intensification (PI) approach, validated design tools and guidelines for aiding the design and operation of intensified chemical reactor - heat exchangers (HEX reactors) for the energy-efficient, clean processing of two-phase, liquid-liquid (L/L) fast non-isothermal reactions.

A liquid-liquid chemical reaction scheme has been developed to assess heat and mass transfer rates within HEX reactors. This chemical probe has been used to characterise the performance of commercial designs of compact heat exchangers and mixers as chemical reactors. Selected industrial liquid - liquid reactions have been studied and their sensitivity to various parameters including heat and mass transfer rates assessed.

Mathematical models, both generic and specific, have been developed, allowing simulation of the results from exothermic liquid - liquid reactions, and providing information on the interrelationships between chemistry, physical properties, and heat and mass transport. Experimental studies to provide visualisation of 2 phase flows, give droplet size distributions and quantification of heat transfer within HEX reactors have been completed.

Guidelines for the selection and design of intensified liquid-liquid chemical reactor-heat exchangers have been produced. A first paper design for a multichannel heat exchanger reactor, incorporating direct injection of reagents into the zones of optimum mass and heat transfer has been produced, with the unit being manufactured and trials performed.

Excellent results from the operation of two industrial chemical reactions in HEX reactors have been obtained. Reaction times have been dramatically reduced, the safety of the processing operation increased, and in one case byproduct levels reduced by 99%. Evidence for significant potential energy savings has been produced.

The economic and environmental benefits resulting from this project include:

- i) reduction in the amounts of byproducts from industrial processes
- ii) reduction in energy usage for the separation and disposal of waste products
- iii) lower CO_2, NO_x and SO_x emissions
- iv) recovery of high grade heat available from HEX reactors
- v) lower plant capital and operating costs for smaller, safer, continuous operation

Keywords: **liquid-liquid reaction, chemical reactor, compact heat exchanger, process intensification, heat and mass transfer**

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3 OBJECTIVES

The objective was to develop through a total Process Intensification (PI) approach, validated design tools and guidelines for aiding the design and operation of intensified chemical reactor-heat exchangers (HEX reactors) for the energy-efficient, clean processing of two-phase, liquid-liquid (L/L) fast non-isothermal reactions.

The main driver for the project was marked improvements in energy-efficiency of chemical reactors in the EU's process industries. Energy savings through uptake of HEX reactors are estimated to be around 76,000 TJ per year, resulting in a reduction in CO2 emissions of 4.8 million tonnes per year.

Savings could be achieved through optimising use of energy by converting from stirred vessels to in-line reactors, and by recovery of waste heat from chemical reactions. Priority reactions were identified and reactions considered having high potential for Process Intensification are as follows, with typical values of their exothermicities (kJ mol^{-1}) given in parentheses: nitrations (-400); sulfonations (-150); halogenations (-100); polymerisations (-200); oxidations (-150); hydrogenations (-500); aminations-(120).

Implementation of a new strategy, based on continuous integrated chemical reactor- heat exchangers, will significantly reduce running costs, energy consumption, pollution and unwanted byproduct formation whilst markedly improving product quality, safety and profitability of the EU's chemical industry.

Safety is a very important consideration in the design of new chemical plants. Owing to the inhomogeneity of species and of temperature within stirred tank reactors (STRs) the possibility of thermal runaway is greatly increased. By combining the technology of high intensity in-line mixers with that of compact heat exchangers (CHEs), such inhomogeneities may be removed, thus eliminating the possibility of runaway reaction.

4 TECHNICAL DESCRIPTION

The chemical process industry is dominated by processes operated in stirred tank reactors. These units are flexible but have a number of significant drawbacks, particularly when performing reactions that have the potential to be completed in times shorter than a few minutes. These drawback, such as poor heat transfer, low average mixing intensity, inhomogeneous distributions of reactants, temperature and mixing energy, can lead to reductions in yields, energy efficiency and profitability.

It was the aim of this project to develop and implement a continuous reactor, based on compact heat exchanger technology and demonstrate its suitability for fast exothermic chemical reactions. The approach to be applied in this project was Process Intensification. This type of unit had previously been tested for reactions between miscible liquids, it was the aim of this work to apply it to industrial reactions between immiscible fluids. In such liquid- liquid systems the mixing processes are different and heat transfer may be affected by the 2 phase flow.

In order to be able to design reactors and liquid-liquid reaction process better it was necessary to develop a number of tools and increased expertise and understanding. The main technical objectives of the project were to:

> Develop a the chemical probe which could be used to characterise Compact Heat Exchangers (CHEs) as chemical reactors,
>
> Develop a mathematical model which could be used to interpret results of reactive studies in commercial CHEs and for parameter-sensitivity studies (chemical probe and industrial schemes).

Once these were achieved it was possible to better design appropriate reactors and operate them in industrial trials.

Successful completion of the project required the following workplan objectives to be achieved:

i. Development of a L/L chemical reaction scheme, termed a "chemical probe", for use as a diagnostic of both mass and heat transfer rates. Implement of the probe allowed characterisation of CHE units as reactors.

ii. Development of a mathematical model to simulate the results of L/L exothermic reactions. This was subsequently used to plan and guide the industrial trials and for interpretation of the results from the CHE characterisations.

iii. A better understanding of the influence of mass and heat transport on the rates and selectivity's of typical industrial L/L reactions, and of the interrelationships of the chemical, physical and transport processes, has been developed;

iv. From the information and expertise gained during the project it has been possible to produce guidelines for the design of intensified L/L chemical reactor- heat exchangers;

v. A first design of a multi-channel heat exchanger – reactor has been produced, constructed and tested. Information from the industrial trials of this unit allow an improved design to be prepared.

vi. Successful demonstration of the HEX reactor technology on 2 industrial processes. Results indicate how increased safety and energy efficiency can be achieved while still increasing yield, productivity and profitability.

5 RESULTS AND CONCLUSIONS

5.1 The Chemical Probe

BHR Group has developed a set of liquid liquid reactions that act as a chemical probe, exhibiting sensitivity to both heat and mass transfer. An explanation of how the two-phase chemical probe works is described below:

$$A_{(x)} + B_{(y)} \xrightarrow[\text{v. fast}]{} P_{(x/y)} \qquad \Delta H_{r1} = \text{highly exothermic} \qquad \textbf{(1)}$$

$$A_{(x)} + C_{(y)} \xrightarrow[\text{fast}]{} Q_{(x/y)} \qquad \Delta H_{r2} = 0 \qquad \textbf{(2)}$$

The two reactions (1) and (2) form the two phase chemical probe. B and C are reactants in phase y competing for reactant A in phase x. When all the reactants are mixed together A will form a dispersion in phase y.

Since reaction (1) is virtually instantaneous, this means that the reaction is limited by mass transfer and therefore dependent on k_L**a**: k_L is the liquid side mass transfer coefficient for the diffusing species and **a** is the specific surface area per unit volume of the dispersion. The higher the mass transfer rate the faster the apparent rate of reaction.

Reaction (2) is slower and it is kinetically limited. Its reaction rate is given by the product of concentrations of A and C multiplied by the rate constant for the reaction. This rate constant is temperature dependent through the Arrhenius expression. The mass transfer rate of the diffusing species is postulated to be faster than the chemical rate of step (2), which will therefore not be affected by changes in mass transfer.

When all the reactants are mixed together, a dispersion of A is formed. Good mixing generates a fine dispersion, i.e. a high specific mass transfer area and hence a high rate of mass transfer. This means that reaction (1) will be favoured and therefore more P and less by-product Q will be formed. Poor mixing will result in a coarse dispersion, i.e. a low specific mass transfer area and hence a low rate of mass transfer. In this case reaction (1) will be retarded thereby increasing the lifetime of A, allowing it to contact more C and produce more by-product Q. Through chemical analysis of the product distribution (P/Q) a sensitivity to mass transfer can be quantified and possible to comparison of the mixing capabilities of different HEX reactors made.

The thermal sensitivity of the chemical probe is provided by the fact that reaction (1) is highly exothermic and reaction (2) is kinetically limited. In the normal course of the reactions between A and species B and C, an overall exotherm will be generated. Any moderate increase in temperature of the system will not affect the rate of mass transfer, so the rate of reaction (1) will be unaffected. However, an increase in temperature will increase the rate constant of reaction (2) and hence increase the actual rate of reaction (2). As reaction (1) proceeds it will evolve heat to promote reaction (2) and generate more Q. If this exotherm is removed as soon as it developed then this thermal feedback will be retarded. Again, by analysing the product distribution P/Q, the sensitivity to heat transfer can be quantified.

BHR Group has identified a set of chemicals and reactions that will perform in this way. These have been tested in simple beaker experiments and the effects described above observed. The chemical probe was then used to characterise the performance of 2 HEX reactors.

5.2 Study of Dispersion Formation

In order to increase understanding of the mechanisms by which dispersions are formed in two phase liquid - liquid flows ETEC undertook and completed characterization of such a system in an HEV geometry. First, Particle Image Velocimetry (PIV) was performed in single phase flow at Reynolds numbers of 1500 to 8000. These measurements provide maps of the velocity field in a symmetry plane of the HEV and allow mean velocity data and turbulence intensity fields to be determined. An extensive analysis of laser Doppler velocimetry data has also been performed to provide a description of turbulent energy dissipation distribution in the HEV geometry

A new experimental apparatus was established for the study of two phase liquid-liquid flows which allowed experiments with mixing ratios of oil in water of up to 30%, and Reynolds numbers from 500 to 25000. An encapsulation technique was developed to provide stabilization of the droplets formed in the HEV. The encapsulation technique was integrated with the study of liquid/liquid flows in the HEV system to produce encapsulated dispersions

A newly developed binocular system was used to observe and photograph the encapsulated dispersions. Measurement of the droplet size and the size distribution were made, in order to allow determination of some characteristic numbers. Figure 1 below shows a photograph of an encapsulated dispersion illustrating the capabilities of the apparatus and techniques developed in this project.

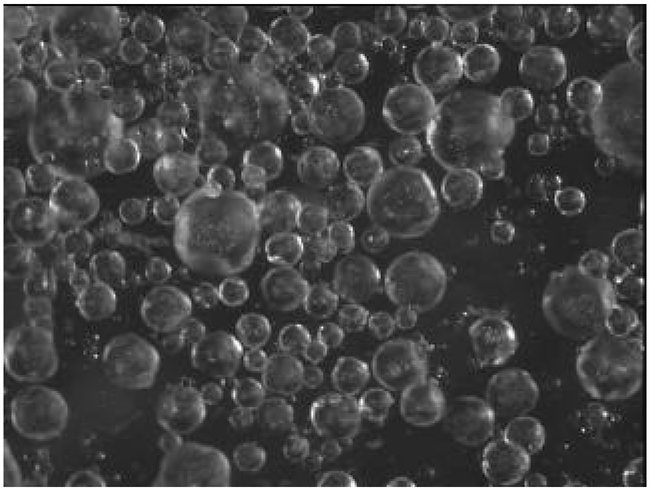

Figure 1. Droplets from 95% water : 5% oil system at a Reynolds number of 15,000.

Droplet data is most commonly reported as the Sauter mean diameter d_{32}. Results show that increasing the turbulent energy of the system (larger Re) causes a decrease in Sauter mean diameter, and that there appears to be a constant of proportionality in this relationship

5.3 Experimental and Numerical Study of CHEs

The development of integrated Chemical Reactor-Heat Exchanger requires sizing tools for aiding the design and operation of the process. The thermal performance of heat exchangers is of prime importance for a global analysis of energy efficiency. Furthermore, a local analysis of flow and heat transfer conditions is also required for a better characterisation in terms of chemical reactors (mixing intensity and residence time distribution).

Two heat exchangers (plate-fin heat exchanger and Marbond heat exchanger) have been studied by GRETh through experiments and numerical simulations. The local heat transfer coefficient on the process side of a Plate fin heat exchanger have been measured and indicate that for low Reynolds number ($Re < 40$) the flow is purely laminar as the Nusselt number is constant. For higher Reynolds number ($40 < Re < 600$), the Nusselt number increases with the Reynolds number ($Nu \propto Re^{0.4}$).

Dye injection was used to characterise the flow structure inside a single channel of the Marbond heat exchanger. The visual observation revealed little mixing between the sub-channels. By injection of salt water at the inlet of the device and measurement of the thermal conductivity of the water at the outlet mean residence time and residence time distributions have been determined. These tests also show that there are no major dead zones within the reactor that could affect the efficiency of the reaction. Pressure drop measurements have been performed in various locations in the channel and a correlation established for sizing the required pumping capacity for the HEX reactor.

Numerical simulations on the two types of compact heat exchangers selected for the project have been performed to produce information on dynamics inside a sub-channel (flow, heat transfer and mixing efficiency between 2 liquids) for different flow regimes.

The results are in a good agreement with experimental visualisations and consistent with well-known correlations for straight channels. Simulations of injection of a second fluid directly into the flow channel have shown that in a laminar regime (Reynolds number less than a few hundreds), the mixing of the two fluid will not be efficient. To obtain good mixing with the help of eddies of different size, it is necessary to be in a turbulent regime.

5.4 Modelling of fast exothermic liquid-liquid processes

The mechanism and kinetics of the chemical probe that was developed by BHR Group were implemented into a generic model of reaction between immiscible fluids. Initial values of unknown parameters in the model were selected through a series of preliminary parameter sensitivity studies and subsequent fitting of parameters until the model was capable of predicting the trends that were measured experimentally by during l/l exothermic reactive mixing studies.

The model qualitatively experimental observations when total energy dissipation rate is varied (i.e. corresponding to change in flow-rate for the experimental situation). However, the quantitative difference between the simulated and experimental results is significant, and is wider for the Marbond than the Kenics device.

The results show that the model is a useful tool for reactor design and parameter-sensitivity studies (further optimisation, but outside the scope of the current project, be beneficial). Models have been used to interpret results from the CHE characterisation studies and to guide the design and implementation of reactors and tests in the industrial trials. An interesting observation from this work is that there is little difference between adiabatic and isothermal operation up to values of f ~ 1 W/kg, but at values of f ≥ 1 W/kg the benefits of removing the heat of reaction become significant

Characterisation of CHEs

A direct comparison of the two CHE reactors, the Marbond and Kenics devices was undertaken. Their performance as chemical reactors under single phase isothermal reaction conditions (i.e. virtually no heat of reaction), allowed estimation of their efficiency for micro mixing, Figure 2.

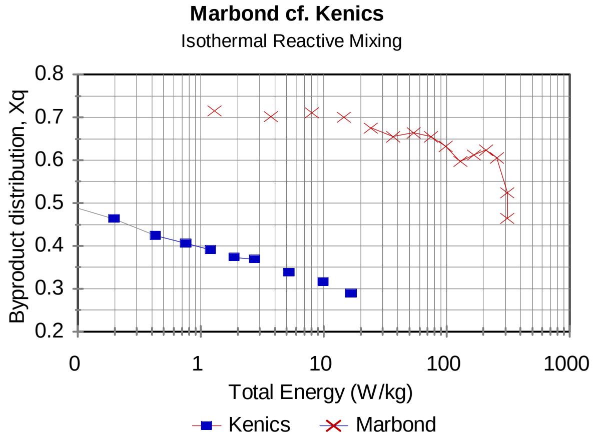

Figure 2. Comparison of micromixing performance of Marbond and Kenics units

This difference in the efficiency of the two devices reflects the fact that the Kenics was designed to be efficient at generating turbulence at the micro scale of mixing, whereas the Marbond is developed from an original unit which was designed to be efficient at convective and turbulent heat transfer - i.e. at the macro scales of mixing. Thermal characteristics of the Marbond and Kenics devices was also performed.

The new L/L chemical probe developed in Task 1 has been operated within HEX reactors over a range of process side flowrates and under cooled and non-cooled conditions. The results, in the graphs below, for both reactors show that increasing the process flowrate gives:

an increase in the extent of reaction completed

a reduction in the amount of byproduct formed

and that the removal of the heat of reaction, by cooling the reactor, also results in a decrease in the amount of byproduct.

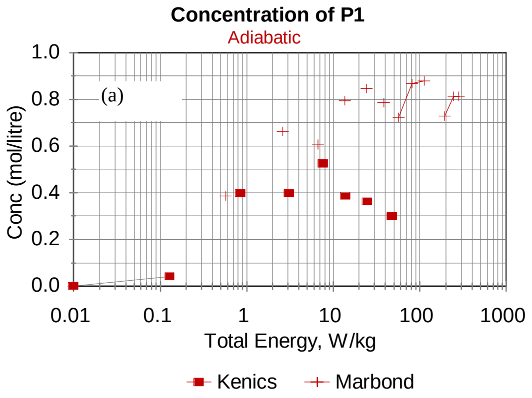

Figure 3. Comparison of performance of Marbond and Kenics reactor units with L/L probe without cooling

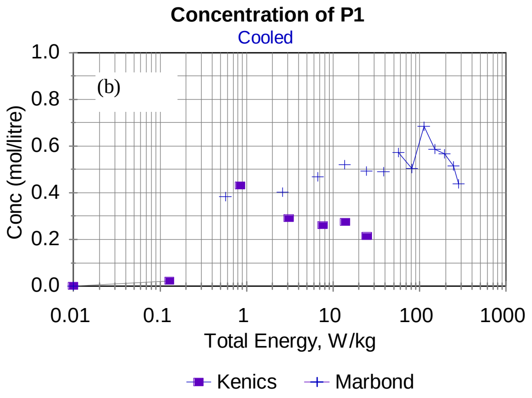

Figure 4. Comparison of performance of Marbond and Kenics reactor units with L/L probe with cooling

The adiabatic or uncooled results shown in Figure 3 indicate that the Marbond reactor performs less well as a mixer for reaction, higher levels of byproduct are formed. However comparison of the adiabatic and cooled modes of operation show that the Marbonds cooling and heat transfer capabilities have a much greater impact than those of the Kenics, which is a less efficient cooling unit.

Accordingly, there remains plenty of scope for optimising the flow path geometry of the Marbond with the aim of achieving the compromise required between efficiency at the micro and macro scales of turbulence.

5.6 Selection and Characterisation of Industrial Processes

The first step in design of a chemical process is the collection of design data. This collection has been successfully performed for the two industrial processes outlined below using standard chemistry equipment and approaches. For each of the industrial chemical reactions, the collection of data exceeded that which is normally made for development of a batch process. The PI approach involves the design of a reaction environment and consequently a reactor. To do any design a number of inputs are necessary. This is an important point and reveals the price to pay for a better PI process – the cost of obtaining detailed process information. Quantification of kinetics, thermodynamics, mixing needs is the necessary first step to (re)designing processes, given that extrapolation will be necessary for operation in PI kit.

Diffusion bonded compact heat-exchanger reactors were fabricated by Chart Marston for the industrial trials. Designs were produced by BHR Group and NIMIX using information from both chemical reaction modelling and fluid dynamic modelling of the process as the design basis as well as the specific process details supplied by the chemical companies.

5.7 Industrial Trials

The Hickson & Welch “FAST” process is a two-stage oxidation, by hydrogen peroxide, of a thioether to a sulphone.

$$R - S - R^1 \xrightarrow[catalyst]{Aqueous\ H_2O_2} R - SO - R^1 \xrightarrow[catalyst]{Aqueous\ H_2O_2} R - SO_2 - R^1$$

Thioether (oil in water)	Sulphoxide (homogeneous mixture)	Sulphone (oil in water)

Results from the kinetic studies showed that this reaction is slow in terms of the rates ideally suited to the HEX reactor. It was anticipated that only the first stage of the reaction would be completed. However trials using a series of 5 HEX reactors were extremely successful. Once the optimum conditions had been determined it was possible to achieve a 100% reaction of the thioether. The particular process has been studied over a wider range of operating conditions than previously, culminating in a reduction in batch time from 18 hours to 30 minutes, with at least as good as batch yield. A final run in which the product was isolated gave a yield of at least 93.4%.

The industrial chemical process chosen by Dow Corning is based upon the hydrosilylation reaction which is ubiquitous within the silicone industry. It is a simple addition. A side reaction can occur and the reaction is catalysed.

The designed and tailored reactor unit had a small internal volume (21 mls). Instrumentation enabled a heat balance to be completed around the unit so heat transfer coefficients could be calculated. An in-line dynamic mixer was placed as close as possible to the inlet of the reactor and used to ensure mixing the two immiscible reactant streams. On operation without the pre-mixer a lower, but still significant, extent of reaction was completed.

High heat generation rates (1.2 kW) are capable of being generated without excessively high exit temperatures. Degree of conversion can be estimated for this reaction based on the standard 380 kJ/kg heat of reaction (or 1.22 kW) heat generation and suggest that near complete conversion was attained at rates of up to 12kg/hour at a variety of temperatures and catalyst concentrations. Product appearance was actually better than the corresponding batch-made material.

Best results were obtained at reactant flowrates of about 10 kg/hr at 130 °C, ie a residence time of about 10-12 seconds essentially consistent with the earlier kinetic modellingChemical analysis of the product from the HEX trials has been performed. This showed a dramatic decrease in the levels of impurity, as predicted by the modeling of NIMIX. Reductions in the levels of impurity of up to 99%, compared to traditional pilot scale stirred tank preparation, have been achieved. This improvement is a consequence of operating safely at temperatures well in excess of those accessible in a str, and with the material exposed to elevated temperatures for a much shorter time. The semi-batch str approach took 2 hours compared to a residence time of the order of 10 seconds in the HEX reactor.

Whilst outside of the Joule III contract, work has continued at both chemical companies to examine the HEX reactor on other chemical process.

5.8 Conclusions

This project has been successfully completed. All of the workplan objectives have been achieved:

i. The L/L chemical reaction scheme, termed a "chemical probe", has been developed which can and has been used as a diagnostic of both mass and heat transfer rates;

ii. A generic mathematical model capable of simulating the results of L/L exothermic reactions has been developed and applied. Specific models of the chemical probe and industrial processes were produced and used to guide HEX pilot trials and in interpretation of CHE characterisation studies.

iii. Through the combine application of models and experiments the partners have gained a better understanding of the influence of mass and heat transport on the rates and selectivity's of typical industrial L/L reactions. The interrelationships of the chemical, physical and transport processes have been studied and understanding of their implications for reactor and process design increased.

iv. The results of the project tasks have been captured and are available for dissemination throughout the project partners, and in some cases are available to the wider scientific and engineering communities. The results have been used to improve guidelines for the design of intensified L/L chemical reactor- heat exchangers.

v. A first design of a multi-channel heat exchanger– reactor has actually been produced, constructed and tested within the current project. The results have shown the suitability of such a unit to chemical reaction processes. In addition information for improving the design and application of heat exchanger – reactors has been generated

vi. The results from the industrial trial has been successful and will provide strong evidence of the applicability of HEX reactors to the chemical industry.

The success of the project was dependent on achievement of the following critical deliverables:

- Development of the chemical probe
- Development of the mathematical model.

Both of these critical deliverables have been achieved and implemented.

The chemical probe has been used in characterisation of Compact Heat Exchangers (CHEs) as chemical reactors. The project has demonstrated the feasibility of the probe as a design tool.

The mathematical model has been used for interpreting results of reactive studies in commercial CHEs and for parameter-sensitivity studies (chemical probe and industrial schemes). The simulations are however only qualatitative at this stage.

The overall objective of the project was to develop through a total Process Intensification (PI) approach, validated design tools and guidelines for aiding the design and operation of intensified chemical reactor- heat exchangers (HEX reactors) for the energy-efficient, clean processing of two-phase, liquid-liquid (L/L) fast non-isothermal reactions. This has been achieved as demonstrated by the results presented within the reports produced.

6 EXPLOITATION PLANS AND ANTICIPATED BENEFITS

6.1 Benefits

This successful project will contribute significantly to overcoming the perceived risks associated with new or different technology and approaches. Everyone wants to see a working demonstration of PI before buying in. The continuous operation of PI kit on three (two industrial and one ‘invented’) processes will go a long way towards providing this confidence in PI.

In the case of the industrial partners the investigation of PI processing options within the new product development cycle will mean that PI can be considered for production scale operation alongside traditional stirred tank processing. This evidence and experience increases the chances of PI making an impact and being implemented.

The reaction processes studied in this project are typical of a number of processes operated by the chemical companies. Therefore there is a large opportunity for duplication of the implementation of this technology and of the savings it can bring. Exploration of these opportunities is ongoing at Dow and also at Hickson & Welch and will probably continue for a number of years.

There is a long list of potential benefits from Process Intensification, a number of these may be possible or of specific interest in connection with any individual chemical process or company:

- Higher productivity
- Higher purity product
- Smaller plant
- Cleaner
- Inherently safer
- Increased energy efficiency
- Lower capital costs
- Lower running costs
- High pressure capability

The main driver for this project was marked improvements in energy-efficiency of chemical reactors in the EU's process industries. Energy savings through uptake of HEX reactors are estimated to be around 76,000 TJ per year, resulting in a reduction in CO2 emissions of 4.8 million tonnes per year.

The specific industrial results demonstrates the improvements which Process Intensification can produce. The observed increase in product quality will substantially reduce the downstream processing costs and energy requirements associated with removal of impurity’s. In addition there is opportunity to recycle the high-grade heat removed from the reacting fluids and collected by the HEX coolant. This energy could be used to preheat the fresh reactants to reaction temperatures before introduction in to the reactor. The savings in energy consumption are estimated at 15 – 25%

In-line operation may also be a license to operate, either commercially or from a safety viewpoint. The greater heat transfer area per unit volume and the reduced plant size and reacting inventory at any given time minimize the potential for runaway reaction, making many in-line processes inherently safer.

A growing awareness of pollution and environmental issues means that chemical companies are coming under ever stricter legislation regarding their discharge of effluent. It was estimated in 1993 that pollution costs the EU 9 billion ECU per year (3% of turnover for that year). This figure could be more than halved through reducing the reliance on stirred tank technology and by moving towards cleaner and more efficient in-line reactors. It is reported that bulk chemical processes generate 1-5 kg of byproducts per kg of product and fine chemicals and pharmaceuticals considerably more. By improving mixing and removal of the heat of reaction as it is generated and by using a CHE reactor, the formation of byproducts could be substantially reduced. With replacement of refluxing reactors with HEX reactors the emissions of volatile organic solvents could be significantly reduced

6.2 Exploitation Plans

Detailed plans for exploiting the results and knowledge produced by this work are include in the Technology Implementation Plan. A breif indication of the areas where the partners will actively seek to gain commercial benefit from the project are outlined below.

BHR Group will directly exploit the deliverables of the project through its large client base of process companies throughout Europe. The design tools will be applied to the solution of process problems through consultancy and process partnering. In addition, members of the Club Projects at BHR Group will be given access to results through the HILINE Dissemination programme. Upon completion of the project, the flow loop will be used commercially as a facility for the characterisation of existing and new designs of CHEs and for process trials for process companies who are exploring the potential of CHEs as reactors for their processes.

GRETh, as a research organisation, will exploit the deliverable in a similar manner to that of BHR Group. They also run a European Club Project, and carry out single client consultancy work in the field of heat transfer. In addition, GRETH has created a group to take charge of technology transfer and R&D dissemination. Expertise and deliverables developed through the project will be applied to consultancy work that is carried out with process industries and manufacturers of heat exchanger devices.

Dow Corning and Hickson & Welch, as end users, will initially exploit the deliverables of the project by applying the tools to the redesign of the specific processes under consideration in the project. Each chemical company will also aim to apply the generic tools and design guidelines to the redesign of their other L/L exothermic processes at production sites throughout the EU. For Hickson & Welch, advances such as those offered by the project will enable them to attract growing business in pharmaceutical and agricultural products. Dow Corning's business revolves around highly complex silicone chemistry, with numerous reaction routes leading to different products of reaction depending on the reactor conditions. As different products are required by the market at different times, it is essential to beable to direct the reaction in favour of the desired product by changing reactor and/or flow conditions of operation. The deliverables of the project should enable Dow Corning to produce the products that are required by the market whilst minimising the use of starting materials and production of byproducts, both of which represent considerable savings in energy and reductions in pollution.

ETEC, which is a part of the University of Nantes, carries out industrial contracts with companies from the European process industries. The results of the project will enable ETEC to build its portfolio of project and consultancy activities. For example, the flow loop and the measurement techniques developed, will be used for testing new geometries of compact equipment developed by manufacturers of heat exchangers.

Chart Heat Exchangers will exploit the results of the project by developing their heat exchanger equipment as novel, efficient, intensified chemical reactors. As the market for *HEX reactors* is at an embryonic stage, the demonstration of the industrial, energy and environmental benefits of *HEX reactors* to EU process industries will hasten bringing their products to market.

NIMIX Limited will exploit the results of the project through its business with industrial customers such as ICI, Zeneca, Akzo Nobel, Kodak, Agfa, Du Pont and the Dow Chemical Company. In addition, NIMIX Limited will work closely with manufactures of mixing equipment and compact heat exchangers, and will partner these companies in the development of their products as compact chemical reactor - heat exchangers.

6.3 Target Groups for Dissemination

The main beneficiaries of the expected deliverables will be process industries and manufacturers of CHEs. Process sectors to be targeted specifically include: (i) fine chemicals, (ii) intermediate chemicals, (iii) bulk chemicals, (iv) polymers, (v) other organics, (vi) pharmaceuticals.

Information will be fed to these sectors via the following organisations and activities.

6.4 Organisations

CEFIC (European Chemical Industries Federation)
SUSTECH (Sustainable Technologies Initiative)
Chemical Industries Association
Royal Society of Chemistry
Society of Chemical Industry
SOMER (Society Organic Manufacturers Eastern Region, UK)
NOWSOC (North West Society of Organic Chemical Manufacturers, UK)
IChemE (Institution of Chemical Engineers, UK)
EFCE (European Federation of Chemical Engineers)
AIRTO (Association of Independent Research & Technology Organisations, UK)
HEXAG (Heat Exchangers Action Group, DTI-sponsored, UK)
National bodies for best practice

7 Photograph

Illustration of HEX reactor concepts

Feed of reactant streams, mixing, chemical reaction and heat transfer all occur within the heart of a HEX reactor