DEVELOPMENTS, PERFORMANCE STUDIES AND INTEGRATION OF MULTIFUNCTIONAL COMPACT CONDENSERS IN DISTILLATION PROCESSES

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1. Abstract

This report presents the main results of an European project dedicated to the studies of multifunctional compact condensers in distillation processes. Process intensification is achieved by reducing the size of the equipment and increasing heat transfer, which lead to a higher heat recovery and lower energy consumption.

This project has clear industrial objectives:

- Establish overall performance data for innovative design of compact condensers under actual flow conditions.
- Evaluate new design methodologies by a local analysis (experimentation and modelling).
- Integrate the major results in process simulation software HYSYS.
- Compare technical and economic performances of conventional shell and tube heat exchangers with compact metallic and non-metallic condensers.
- Promote and diffuse the results toward the end-users.

This project deals with compact condensers, under downward or reflux flows and their integration in process units. The aim of this project is to develop and promote the use of compact energy efficient condensers in the process industry by providing heat transfer characteristics, design data, identifying potential market and integrating the design code into a standard process simulation software.

The benefits of process intensification are energy saving, reduced capital cost, improved product quality and intrinsic safety for the process plant. Both systems – reflux and downward condensation – meet the requirements regarding heat exchanged and pressure drop. The predicted data were achieved. The needs in cooling water could be clearly reduced (more than 75 %). Compared to shell-and-tube heat exchangers, they show a significantly lower pressure drop. This means a reduction in energy for pumping the process flow and the refrigerant.

The running cost analysis drive to a decrease of the annual cost more than 65 %.

Overall it seems probable that an increasing use of compact heat exchangers leads to a durable reduction in capital and running costs in chemical industry.

2. Partnership

The objectives have been reached with the active participation of 8 partners including 3 industrial companies (ALFA LAVAL VICARB, BP, LII)

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3. Objectives

Condensation occurs in many industrial processes, but rarely with pure fluid. The fluids encountered are mixtures and often non-condensable gases are present, and this makes the condensation process very complex. In the case of mixtures or in the presence of a non-condensable gas, the vapour condensing must diffuse through the gas to the interface. For this to happen a partial pressure gradient toward the phase interface is required.

The partial pressure of the vapour falls from a constant value at a rather large distance from the phase interface to a lower value at the interface. Correspondingly the accompanying saturation temperature also falls towards the interface Therefore during condensation the condensing vapour arrives by diffusion at the condensate surface it is the thermal resistance in the vapour which limits the process. Hence in order to improve the heat exchange, one must reduce the thermal resistance on the vapour side.

Several factors can enhance the condensation process by reducing the vapour side resistance. During condensation of mixtures or of vapour which contain non-condensable the heat transfer on the vapour side can be improve by raising the vapour velocity. The use of finely undulated surface can also achieve significant augmentations in heat transfer during condensation. It has been shown that corrugation can promote turbulent equilibrium between the phases and thus contribute to the increase in heat transfer.

Compact heat exchangers are characterised by small hydraulic diameters (1-10 mm) and there is no reliable design method to estimate heat transfer coefficients during condensation in such small channel. In the open literature, condensation of mixtures and of vapour in presence of non-condensable have been studied, but essentially for conventional geometry (plain tubes), and only few results have been published with fluids representative of actual process conditions (hydrocarbons).

During the programme, four main tasks have been operated:

Task 1 general coordination

ALFA LAVAL VICARB has taken in charge the general organisation including the internal management and administration of the project. The scientific and technical coordination has been carried out by ALFA LAVAL VICARB.

Task 2 Two-phase flow in compact condensers

This task was devoted to the analysis and modelling of reflux flows. In reflux condensers, the major problem is flooding and the engineers need to have some reliable correlations to estimate the critical gas flow rate. Measurements have been carried out on two basic compact geometries: a plain vertical rectangular channel; and an inclined small diameter tube.

Task 3 Downward condensers

To study the thermal performance of compact condensers under downward flows, laboratory, pilot units and on-site measurements have been performed. For condensation in compact condensers, there are only a few data in the open literature and no general predictive models are available. The aim of the task was to measure the overall performance of compact condensers under realistic operating conditions.

Task 4 Reflux condensers

Reflux condensation is much more complex to analyse than downward condensation. In consequence there was a need to have some information on the basic mechanism of heat and mass transfer in an idealised compact geometry. The next step, in the analysis of reflux condensers, was to obtain some data in the laboratory but with real compact heat exchangers of small size. A prototype compact heat exchanger has been designed and manufactured by VICARB and has been installed in an industrial plant at LII Europe

Task 5 Process integration

The main disadvantage of compact heat equipment was the lack of reliable design methods, which could be introduced in sizing simulation software. The partner UNEW has elaborated some general design methods for compact condensers and has integrated them in process engineering simulation package.

4. Technical overview

Two-phase flow in compact condensers (CPERI)

Experimental conditions and procedures

Task 2.1. Two-Phase Flow in Compact Geometries

Experiments were carried out both in a 70cm high *vertical rectangular channel* consisting of two parallel plates with variable spacing (5 and 10mm) and in 60cm long *small diameter tubes* (i.e. 6 and 7mm) which can be mounted at various inclinations with respect to horizontal plane (30, 45, 60, 80 and 90 deg), in order to investigate the effect of inclination angle on the mechanism of flooding over a fairly broad range of liquid flow rates. Air enters from the bottom of the test section, while liquid is introduced from the top and removed from the bottom of the section. Each flooding test was carried out by pre- pressurising the test section with the gas flowing at a low velocity. Having established the liquid flow, the gas flow rate was then progressively increased until flooding was observed. Using a high-speed camera, fast video recordings were made to elucidate incipient flooding.

Task 2.2. Two-Phase Flow Pattern in Corrugated-Plate Geometries

Experimental data were obtained on liquid distribution and flooding phenomena within the flow channels in novel compact condensers made of *corrugated plates*. Experiments were carried out using a special test section simulating a vertical channel of a corrugated plate heat exchanger. On two plates made of Plexiglas, corrugations were machined at a 45^o angle, as well as *side grooves*, i.e. vertical side channels. Experiments were carried out under adiabatic flow conditions with water, a water/butanol mixture and kerosene. Visual observations of flow distribution were made and fast recordings were taken. The pressure drop was also measured between top and bottom of the channel.

Downward condensers (UNEW, GRETh, LII Europe)

Experimental conditions and procedures

Task 3.1: Effect of geometry and non-condensable gases

Experimental research has been conducted on a compact polymer film cross-corrugated compact heat exchanger. Experiments centred on the performance of the unit for the condensation of water vapour from a humid air stream under various operating conditions. Performance has been quantified in terms of heat transfer coefficients and effectiveness. Significant levels of liquid condensate were found within the gas side of the heat exchanger and the relationship between these levels and the flow rates used is also discussed.
The heat exchanger was constructed from seven layers of corrugated PEEK sheeting of approximately 53µm thickness. These were stacked with corrugations perpendicular to the surrounding sheets. The corrugations were approximately sinusoidal with a peak-to-trough amplitude of 1mm and wavelength of 2mm. The sheets were square with 135mm-side length.

Task 3.2: Overall analysis and modelling on pilot units

GRETh has established the specification of the test section. The sizing and the drawings of the heat exchanger elements have been realised by VICARB. The test section is installed on BUPRO (hydrocarbon test rig) for tests followed by the GRETh.

The test rig BUPRO is devoted to hydrocarbon applications. Fluids such as butane, propane or mixtures can be used. The heat exchangers tested can be either evaporators or condensers. The pressure can be varied between atmospheric pressure and 20 bars with temperatures of up to 80°C. The hydrocarbon flow rate is up to 600 kg/h with a maximal heat duty of 70 kW. A compact heat exchanger has been introduced in this test rig.

Five sets of tests have been performed: three with pure fluids and two with mixtures. For each fluid, the absolute pressure and the mass flow rate on the condensation side were varied. The range covered is presented in Figure 8 for:

- Pentane;

- Butane;
- Propane;
- Butane-Propane (49%-51% in mass);
- Butane-Propane (28%-72% in mass).

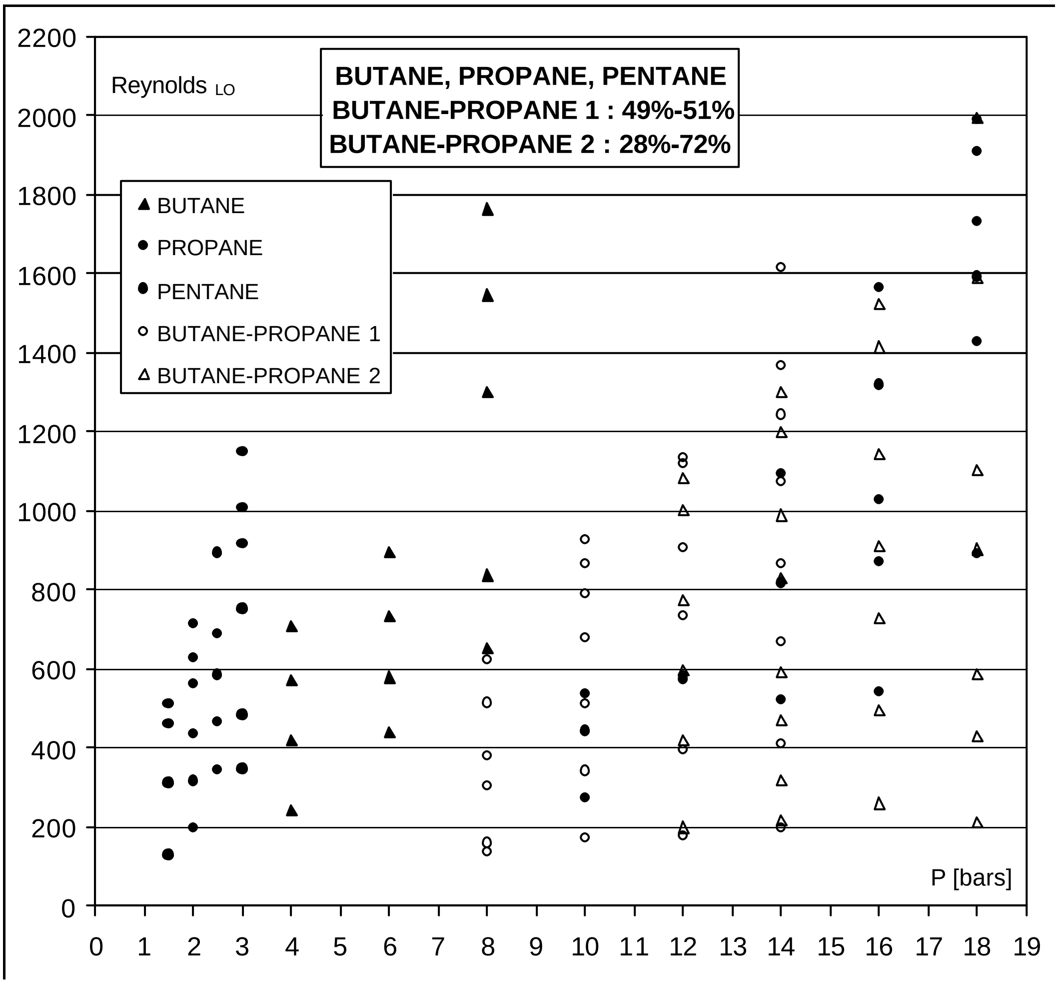

Figure 8: Experimental conditions (all data)

The pure fluids used are of high quality and contain less than 0.1 % of other components. The physical properties have been calculated using the Prophy™ software. For the two Butane+Propane mixtures, the mass fraction has been estimated by measuring the dew and bubble temperatures at different pressures and comparing them with the temperature predicted by the physical properties software.

Task 3.3: On-site measurements and optimisation

Chlorinated hydrocarbons are produced by radical reaction from chlorine and methane. The mass flow leaving the reactor is a mixture of the required products. In order to get commercial products this mixture is separated by distillation in a series of columns. One of these columns is used to separate chloroform and tetracarbon chloride.

A compact heat exchanger has been tested as top condenser on this column and that in parallel of a shell and tube (figure 9 and 10).

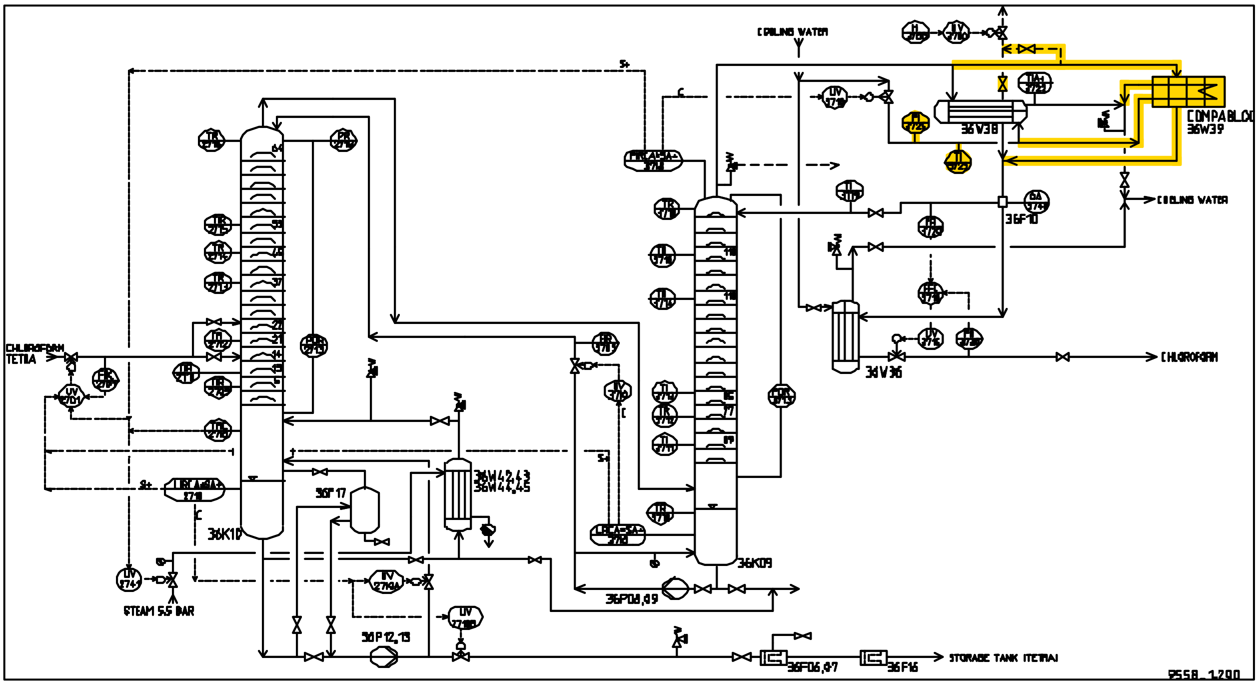

Figure 9: Integration of the downward condenser

Figure 10: Integration of the downward condenser

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Reflux condensers (IET, GRETh, LII Europe)

Experimental conditions and procedures

Task 4.1: Local analysis and modelling

During the first part of the project a literature review on reflux condensation has been undertaken and a test rig has been built. As reflux condensation is much more complex to analyse than downward condensation, where vapour and condensate flow co-currently, within subtask 4.1 of the project the basic mechanisms of heat and mass transfer are investigated in an idealised compact geometry. The test section is a 500-mm long inclined double pipe heat exchanger made of stainless steel. Condensation takes place in the inner tube. The inner diameter of the inner tube is 7 mm and the outer diameter is 8 mm. Temperature controlled cooling water flows in the annulus of the test section counter-currently to the vapour in the inner tube.

Task 4.2: Overall analysis and modelling on pilot units

A test rig has been built by GRETh to measure heat transfer and outlet concentrations of VOCs. For safety reason the test rig is mounted in a separate room and fully automated. The heat exchanger is constructed of stainless steel with a plate thickness of 0.6 mm. The length and width are 300 mm each. The plate spacing is 5 mm at coolant as well as at gas side. The hydraulic diameter, D_H, is 10 mm. Each plate has a wavy configuration with a corrugation height of 5mm and a corrugation length of 15 mm. The corrugation angle is 45° and the coolant is in cross flow with the gas mixture. VICARB supplied this compact heat exchanger.

Task 4.3: On-site measurements and optimisation

An industrial reflux compact heat exchanger has been supplied to LII. The integration of this material in the plant has been made by LII. The production of chlorinated hydrocarbons is a recycling process. This means that non-chlorinated substances are pumped back to reaction. On the other side inert parts cumulate in the process flow. To avoid this, it is necessary to purge. The chlorinated hydrocarbons from this purge (we call it „waste gas“) are condensed and recycled. The rest is burnt in a central incineration plant.

Process integration

Experimental conditions and procedures

Task 5.1: Elaboration of design rules

Task 5.2: Process simulation

HYSYS is a computer program that lets chemical process designers construct a virtual process and examine the effect of changing conditions on the performance of the process. The program consists of a thermodynamic property database and property calculation section allied to a number of unit operation models that calculate how the temperature, composition and pressure of the inlet streams changes as they pass through the unit operation.

The model of the Compabloc condenser within HYSYS is required to calculate the temperature and pressure of the streams leaving the condenser (condensate and cooling water) given inlet streams (vapour and cooling water) whose temperature and pressure are known. Empirical equations are used to calculate the pressure changes in the streams

Two industrial applications of the compact condenser were investigated. The first case study was used to validate the Compabloc model (coming from BP). The second case study is an example of the savings possible when a compact condenser is used (coming from LII).

5. Results and conclusions

For each part of the programme and for each task, some results are going to be introduced.

Two-phase flow in compact condensers (CPERI)

Results

Task 2.1. Two-Phase Flow in Compact Geometries

The visual observations and fast recordings show that the gap size plays a dominant role in flooding **vertical rectangular** channels. For the **5mm** gap channel and relatively high Re_L (>150), “massive” wave bridging is the prevailing flooding mechanism brought about by moderate wave growth on the two films, flowing in close proximity, on opposite walls. For relatively small Re_L (i.e. below 150), with thin liquid films formed inside the test section, flooding is observed to occur at the liquid entry very likely due to growth of disturbances right below the porous section.
In the larger (**10mm**) gap the picture is quite different. For relatively high liquid flow rates (Re_L>500), the critical flooding gas velocity tends to be independent of liquid flow rate, which is difficult to explain. Although some wave “levitation” may take place (in the lower half of the test section), movement upward of “isolated” waves and “localised bridging” seems to be the main flooding mechanisms. The latter is quite pronounced. At smaller liquid flow rates (100<Re_L<~500) the mechanism involving isolated wave movement upward appears to dominate. It is noted that the frequently used Wallis (1969) correlation is inapplicable to the data presented here. Furthermore, no single (all encompassing) model or correlation appears to be capable of coping with the different mechanisms and geometries.

In the **small diameter tubes** tested, the angle of inclination plays a dominant role in flooding as is the case with large diameter pipes (e.g. Hewitt, 1995). The reported visual observations and fast recordings show that the mechanism leading to counter-current flow limitation is different for vertical and inclined tubes. In the former, wavy annular flow prevails prior to flooding. In the latter, stratified flow is gradually changed (with increasing U_G) into a form of annular flow with distinct “ring”–type waves. In both cases, it appears that incipient flooding is associated with transport of relatively large waves upwards. The dependence of critical U_G on liquid flow rate is strongly influenced by the angle of inclination. At small Reynolds number (Re_L<350), in the vertical tube, U_G at flooding is inversely proportional to liquid rate, and a Wallis type correlation is applicable; in the inclined tube, the critical U_G is roughly proportional to liquid rate, something not reported in the literature up to now. The latter dependence may be the outcome of the complicated interaction of drag and gravitational forces prevailing in the descending wave structure. At large Reynolds numbers (Re_L >350) the aforementioned dependence of U_G on liquid rate, for vertical and inclined tubes, is reversed.

In general, for a fixed liquid flow rate, the critical flooding velocity U_G tends to increase with decreasing angle of inclination (with respect to horizontal position), as already observed in previous studies with larger diameter tubes (e.g. Barnea et al, 1986). For small liquid Reynolds numbers ($50<Re_L<\sim400$), as already explained, the mechanism involving isolated wave movement upward appears to dominate. Therefore, as might be expected, the "standing wave" model of Shearer and Davidson (1965), for vertical geometry, seems to perform fairly well. Incipient flooding in inclined (small diameter) tubes seems more complicated and difficult to model.

Task 2.2. Two-Phase Flow Pattern in Corrugated-Plate Geometries

The observations suggest that the side grooves in **corrugated plates** play a dominant role in liquid distribution, allowing the effective "drainage" of liquid moving in the lateral direction, roughly along the valleys of the corrugations. Two critical flow conditions were identified, which are of considerable practical significance:

- At a certain gas flow rate, lateral "drainage " to the side channels is apparently aided by the gas shearing action, thus almost totally depleting of liquid the lower part of the plates. This type of liquid distribution (also referred to as "maldistribution") may be favourable for the operation of such a device as a condenser because of the exposure of nearly 'fresh' wall to the condensing vapours.

- At higher gas velocity, this liquid depletion extends upwards and partial liquid flow *reversal* is observed in the upper part of the plates while drainage continues through the side channels. This is considered as the condition of incipient flooding.

The critical gas velocities of incipient "maldistribution" and of flooding tend to increase with decreasing liquid feed rate, as expected. Concerning fluid properties, significant differences are observed (compared to water) in the liquid film distribution and the flooding velocities with the lower interfacial tension butanol solution and kerosene. A tentative correlation of flooding velocities with liquid physical properties is proposed.

The pressure drop tends to increase with both the air and the liquid flow rates. The occurrence of flooding is associated with a sharp increase in pressure gradient. Moreover, there is also a narrow range of gas flow rates (below flooding) where the pressure drop is weakly dependent on gas flow rate and corresponds to the "maldistribution". Compared to water, a steeper increase of the pressure gradient is evident for the butanol mixture in the same range of flow conditions.

Illustrations of the project

Task 2.1. Two-Phase Flow in Compact Geometries

At present, the graphs presented in Fig. 1 and 2 can serve the purpose of flow regime maps, providing some guidance for the selection of flow conditions to avoid flooding. These graphs are complemented with flooding velocity data obtained with corrugated plate surfaces similar to those of commercial heat exchangers.

A few remarks may be made about the flow patterns:

With regard to *vertical rectangular channels*, it is clear that as the gap decreases the critical gas velocity at incipient flooding would tend to decrease. In general, low liquid loadings (G_L less than 0.02-0.03 kg/m.s) permit smooth reflux operation over a broader range of gas flow rates. Furthermore, it appears that above G_L=0.03 kg/m.s the critical gas (flooding) velocity does not vary significantly over a very broad range of liquid rates. Fig. 3 and 4 show a descending coherent wave, and a typical “wave-bridging” event leading in flooding.

For the *small diameter tube* (7 mm i.d.) the data are replotted in the form of flow maps for vertical and inclined geometries. It is noted that above a superficial liquid velocity $U_L \cong 0.1$ m/s ($G_L > 0.18$ kg/m.s) a nearly constant gas velocity at incipient flooding prevails. It is interesting that beyond that U_L value, the flooding velocities tend to become almost independent of angle of tube inclination (the inclined tubes always associated with somewhat greater critical gas velocities).

Task 2.2. Two-Phase Flow Pattern in Corrugated-Plate Geometries

Fig. 5 includes two pictures of counter-current flow with even liquid distribution before flooding (Fig. 5a), and with “maldistribution” of liquid (Fig. 5b). An attempt to correlate the flooding data for corrugated-wall channels, for the three liquids tested, in terms of the dimensionless gas Reynolds, Froude and Ohnesorge numbers is presented in Fig. 6. It is interesting that the gas Reynolds number, Re_G, at flooding point, is a nearly linear function of the product $Fr_L^{0.15} Oh_L^{0.3}$.

Values of mean (time averaged) pressure gradient, measured between the lower and the upper limit of the corrugated channel are presented in Fig. 7 for various air and water flow rates. As expected the pressure drop tends to increases with the airflow rate. An increase in pressure drop with liquid flow rate is observed as well. The occurrence of flooding is associated with a sharp increase in pressure gradient. Moreover, there is also a narrow range of gas flow rates (before flooding) where the pressure drop is weakly dependent on gas flow rate. This range corresponds to the situation previously referred to as “maldistribution”.

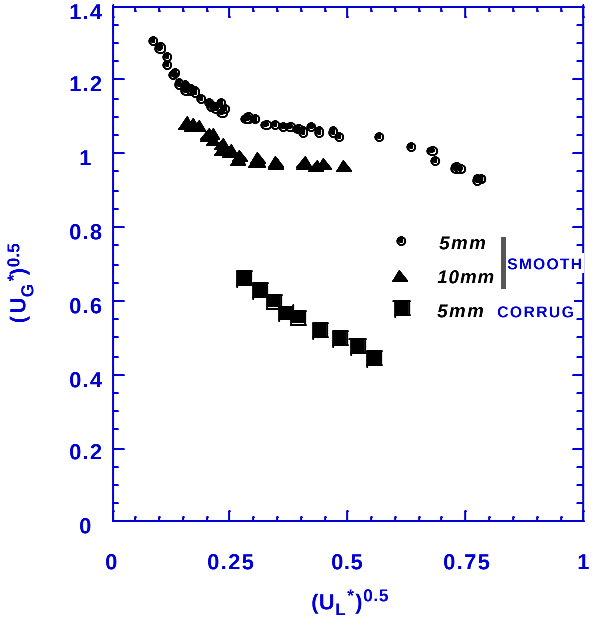


Fig. 1. Experimental flooding data for both types of channels (corrugated wall plates with side plates 9 mm wide)

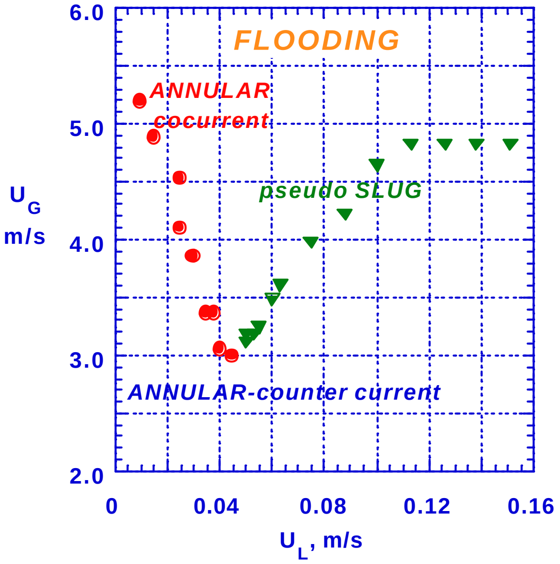


Fig. 2. Typical flow regime map for small diameter *vertical* tubes; counter-current gas/liquid flow.

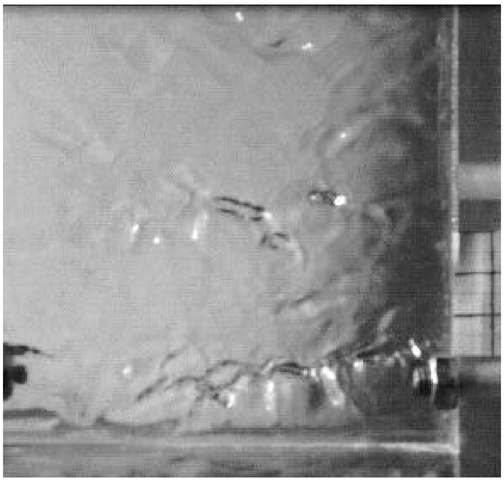
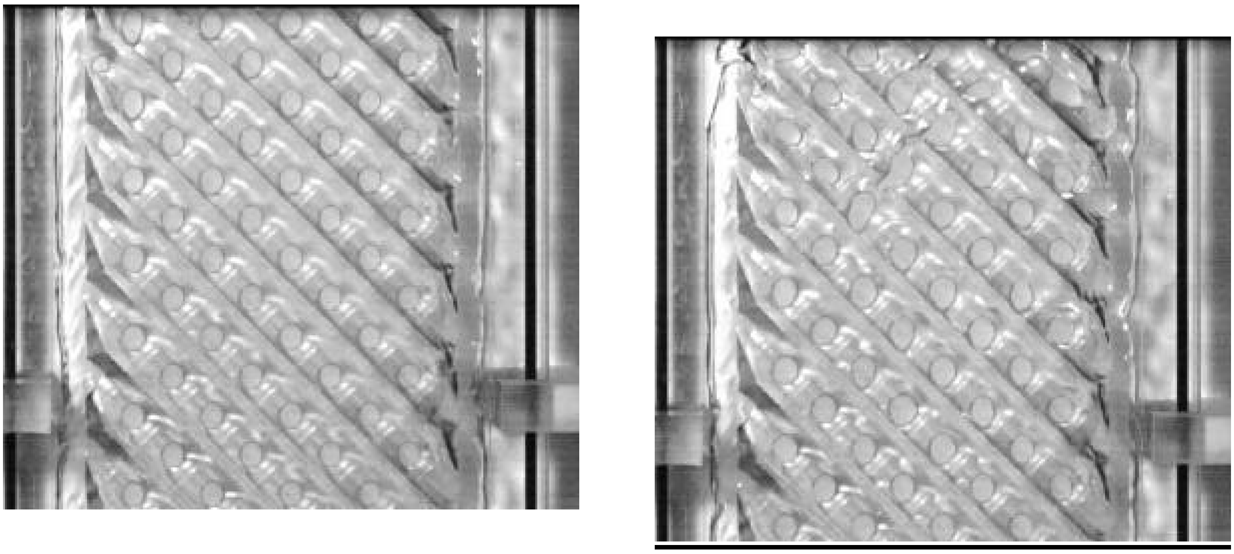


Fig. 3. “Coherent” wave, covering the entire channel width. Side view of the channel (10mm gap).

Fig. 4. The “wave bridging” mechanism. View between the plates, inside the 10mm gap.



a) Before flooding

Q_L= 1.7 l/min, Q_G low

b) "maldistribution"

Q_L = 1.7 l/min, Q_G = 90 l/min

Figure 5. Flow of water and air in corrugated-wall channel: a) counter current flow and b) "maldistribution". Data corresponding to corrugated plates with side-grooves 9 mm wide.

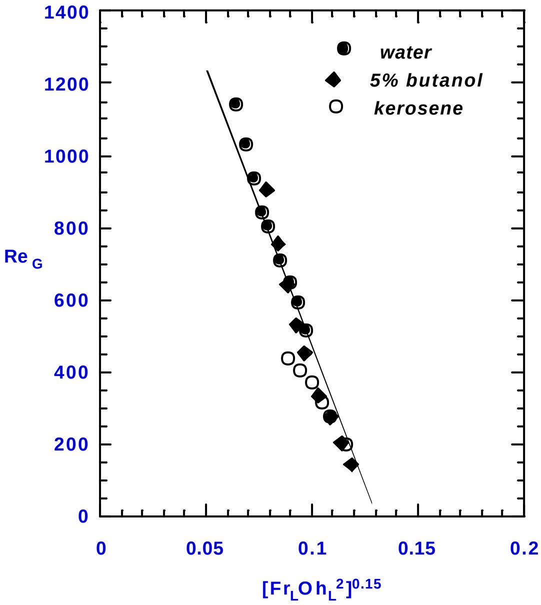


Fig. 6. Flooding conditions for various liquids expressed by dimensionless groups. Data corresponding to corrugated channels with side-grooves 9 mm wide.

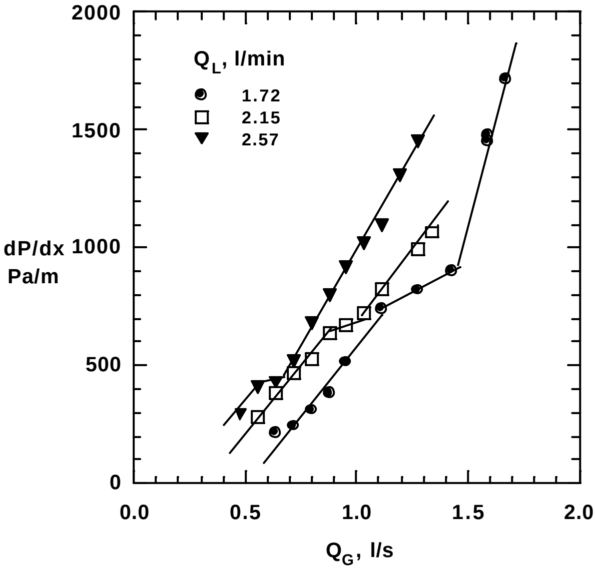


Fig. 7. Mean pressure drop values for counter-current water/air flow and during flooding. Corrugated-wall channel with side grooves 9 mm wide.

Downward condensers (UNEW,GRETh, LII Europe)

Results

Task 3.1: Effect of geometry and non-condensable gases

The performance of a compact condenser constructed from sheets of PEEK has been investigated experimentally using the condenser in a vertical orientation as opposed to the horizontal orientation used for the experimental work. It has been found that

- The pressure drop on the condensing side of the exchanger is 25% less for the vertical configuration and the condensate hold-up for the vertical orientation is smaller. These trends are consistent with the fact that the vertical orientation aids the drainage of condensate from the condenser.

- The rate of heat transfer in the vertical configuration is not noticeably better than that in the horizontal configuration. The values of the heat transfer coefficients are similar but a comparison of the heat transfer rate per unit area shows that as the gas flow rate increases the performance of the vertical orientation is better. As for the pressure drop, the improvement in performance can be attributed to the condensate being cleared more easily from the vertical channels.

Task 3.2: Overall analysis and modelling on pilot units

Three series of tests have been performed using pure hydrocarbons (Pentane, Butane and Propane) and the overall thermal and hydraulic performances have been recorded. The operating pressure ranges from 1.5 up to 18 bars, with Reynolds numbers between 100 and 2500. The results clearly indicate that for low Reynolds numbers the heat transfer coefficient in condensation is similar to that of a laminar falling film and for higher Reynolds numbers turbulent effects tend to increase the heat transfer coefficient. The transition between these two mechanisms occurs for Reynolds numbers between 100 and 1000 depending on the pressure.

For the mixtures (Butane-Propane), the behaviour is quite different. In the first zone, the heat transfer coefficient increases with the Reynolds number, then in the second zone the behaviour is similar to the one of pure fluids.

These observations outline the effect of mass transfer on the overall heat transfer coefficient. For low Reynolds numbers (laminar film) and for pure fluids the heat transfer resistance is mainly in the liquid film and this resistance increases with the Reynolds number (Nusselt theory). For higher Reynolds numbers, the liquid film becomes turbulent and increasing the Reynolds number increases the heat transfer coefficient.

For pure fluids there is no mass transfer effect during condensation (figure 11). On the contrary with mixture, there is a mass transfer resistance due to molecular diffusion in the gas phase. For low Reynolds numbers, the velocity is low and there is almost no mixing in the gas phase, consequently mass transfer effects will reduce the overall heat transfer coefficient. For higher Reynolds number, mixing will occur in the gas phase and will enhance mass transfer; consequently the heat transfer resistance is mainly in the liquid film and the mixture behaves as a pure fluid.

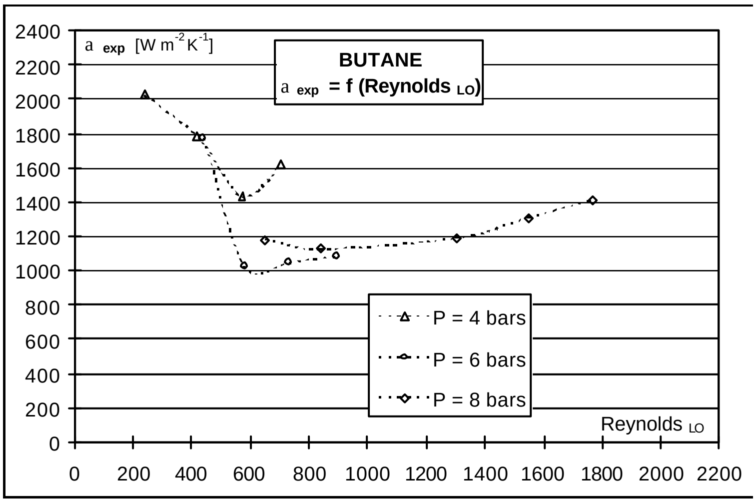


Figure 11: Condensation heat transfer coefficient

Task 3.3: On-site measurements and optimisation

Heat transfer rates between the two units are quite different. The rate of the plate system is about three times as high as the rate of the shell-and-tube heat exchanger. Therefore the surface area of a plate system is only one third of a shell-and-tube heat exchanger – provided that the process conditions are identical.

This results in a reduction in volume and weight of the heat exchanger as well as in a decrease in capital costs. Regarding the Compabloc made of conventional stainless steel 1.4301 and medium size (81 m²) the purchase costs are 65 % of a comparable shell-and-tube heat exchanger. The volume flow of the cooling water is lower. The consumption of cooling water is reduced to a third with the Compabloc (112 m^3/h to 43 m^3/h).

As a conclusion it can be said, that the compact heat exchanger installed at LII Europe GmbH has been successfully tested.

Reflux condensers (IET, GRETh, LII Europe)

Results

Task 4.1: Local analysis and modelling

Film thickness and flooding points have been determined during reflux condensation of steam in a small diameter inclined tube. It has been found that the inclination angle has neither on the condensate film thickness nor on the flooding point a significant effect. A modified McQuillan/Whalley correlation is proposed to predict the flooding point. Flooding experiments were also carried out at higher liquid flow rates with air and water under adiabatic conditions by CPERI in task 2.1 (figure 12). These adiabatic flooding data were in the order of magnitude predicted by the proposed correlation.

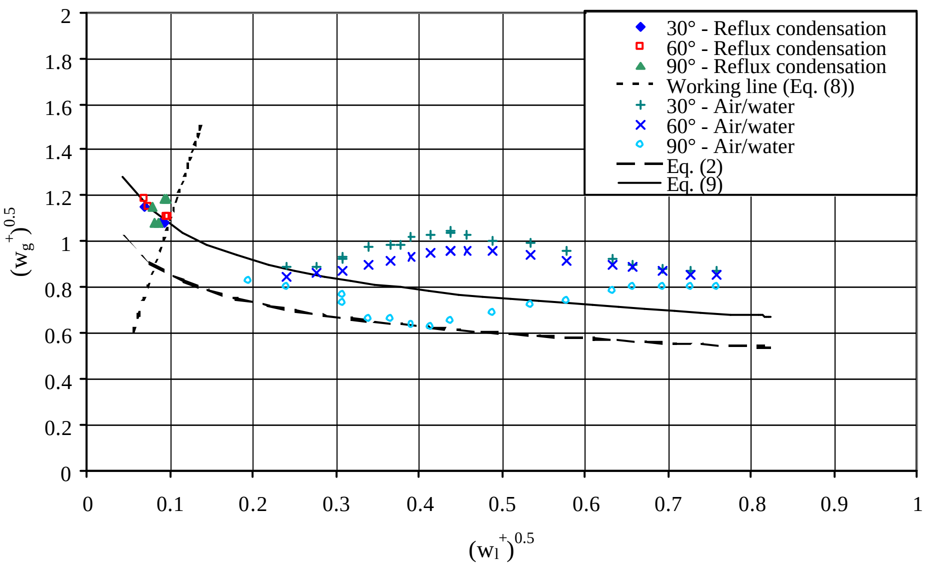


Figure 12: Comparison of reflux condensation flooding data (task 4.1) with flooding data obtained under adiabatic conditions (task 2.1)

Dimensionless heat transfer coefficients have been determined in terms of the average Nusselt number during reflux condensation of pure R134a as well as of R134a in the presence of the non-condensable gas nitrogen in a small diameter inclined tube. It has been found in the experiments with pure R134a that the inclination angle has a significant effect on the reflux condensation heat transfer coefficient. When the tube is tilted from the vertical the condensate film thickness becomes non-uniform around the circumference of the tube, the mean film thickness decreases and the heat transfer coefficient increases. The optimum inclination angle for the heat transfer was found to be close to 45°. A modified Wang/Ma correlation was proposed to predict the heat transfer in dependence of the film Reynolds number and the inclination angle.

Task 4.2: Overall analysis and modelling on pilot units

Experiments have been performed with nitrogen saturated with n-pentane and the inlet parameters, vapour mass fraction, Reynolds number, coolant temperature and coolant mass flow rate have been varied. Two sets of tests have been performed. In the first series, the cooling water flow rate was kept small in order to have a significant temperature difference between the inlet and the outlet. These tests were performed in order to check the heat and mass balance of the condenser. For all the tests, the error in the heat balance between the water and the condensation sides remains below 10%. Therefore the measurement procedure on the process side has been validated. The second series of tests was performed with a high water flow in order to obtain almost a constant water temperature. Furthermore, as the flow rate is increased giving high heat transfer coefficients, the boundary conditions on the condensation side is close to constant wall temperature.

During the reflux condensation tests performed at Greth, the flooding point has been reached increasing gradually the inlet mass flow rate while keeping constant the wall temperature. The flooding point is reached when the condensate flow rate drops suddenly. A correlation was proposed that predicts well the experimental data as a function of the film Reynolds number and the partial pressure of the non-condensable.

The flooding point has been detected and the data compared to the measurements performed at CPERI on a similar geometry (figure 13). Unfortunately the range of operating conditions does not overlap and no direct comparison can be performed. Nevertheless, it seems that the values are in agreement.

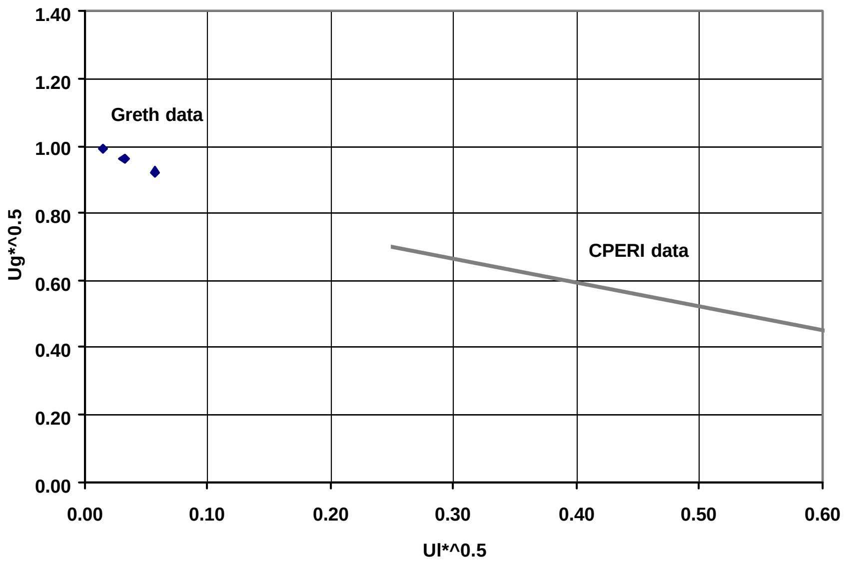


Figure 13: Comparison of Greth and CPERI data for flooding
in cross-corrugated heat exchangers

Task 4.3: On-site measurements and optimisation

The experimental data obtained on the compact heat exchanger have been compared to the previously installed shell-and-tube heat exchanger (S/T). The lower amount of heat exchanged in the shell-and-tube system must be compensated with further heat exchangers. These ones are supplied with an ammonia refrigeration unit. Therefore an additional volume of ammonia is required.

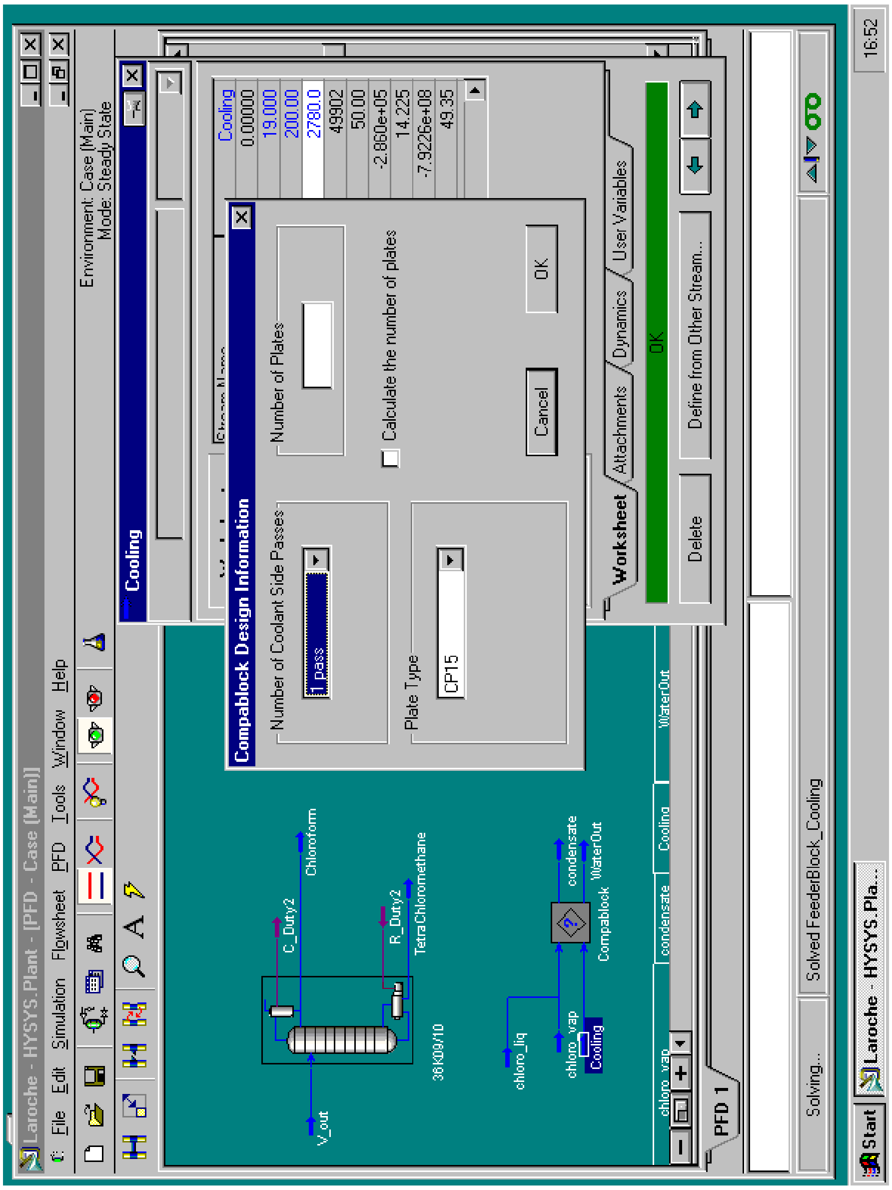
The volume of ammonia required in this case is suppressed with the compact heat exchanger. As a conclusion it can be said, that the compact heat exchanger installed at LII Europe GmbH has been successfully tested.

Process integration

Results

Task 5.1: Elaboration of design rules
Task 5.2: Process simulation

The predictions of the model are compared with measured values obtained by LII (figure 14). It can be noticed from the comparison that the area requirement predicted by the HYSYS model is 9% larger than the actual area of the installed condenser. This is because the experimental measurements used to obtain the heat transfer coefficient equations were made on a system containing C_3 and C_4 alkanes. However the agreement is good enough to have confidence in the predictions made by the HYSYS model.



Compablock Design Information

Number of Coolant Side Passes: 1 pass

Number of Plates:

☐ Calculate the number of plates

Plate Type: CP15

OK Cancel

Cooling
0.00000
19.000
200.00
2780.0
49902
50.00
-2.860e+05
14.225
-7.9226e+08
49.35

Figure 14: HYSYS screen shot

The second case study examined the possibilities for energy saving using a compact condenser on a gas plant. The plant data was supplied by BP Oil. The unit studied condenses a mixture of C_3 and C_4 hydrocarbons at the top of a column used to separate the hydrocarbons from heavier fractions. The data for the simulation of this plant were supplied by BP, and the Compabloc module was incorporated into this simulation. The plant data provided by BP was for part of a gas plant at the Neustadt Refinery. All oil refineries have a gas plant to deal with the overhead vapour streams from the atmospheric crude tower and cracking operations.

6. Exploitation plans and anticipated benefits

By an efficient collaboration between the partners, this project is A GREAT SUCCESS. All the objectives have been reached and several items will be exploited.

No.	**Description**	**Owner**
1	Condensation data bank	GRETh
2	Analysis and predictive model for experiments on condensation of pure fluids and mixtures	VICARB
3	Polymer film unit (patented)	UNEW
4	Flow pattern maps for downward and reflux flow	CPERI

As manufacturer of compact heat exchangers, VICARB will exploit the results by developing innovative heat exchangers for heat and mass transfer in distillation and separation processes. The potential market for such multifunctional units is very wide, and the demonstration of the energy savings obtained with this programme will hasten their marketing.

BP and LII will use the deliverables of task 5 (process integration) to redesign specific processes, which integrate compact condensers. Each company will also assess their design methods by comparing the actual performances of their units with the new design tools provided in task 3 (downward condensation) and task 4 (reflux condensation).

GRETh runs a European club of 100 industrial partners, including SME's to large companies. Through annual meetings and GRETh newsletters, selected information will be provided to the GRETh membership. GRETh carry out consultancy work on heat and mass transfer for their members, and the knowledge and the deliverables developed in this project will be applied for consultancy work with heat exchanger manufacturers and engineering and process companies.

CPERI is cooperating with the major industrial companies in Greece, which are potential end-users of the condensers to be developed in this project. Such firms include the two major refineries (ELDA, Aspropyrgos and EKO, Thessaloniki) as well as the Chemical Companies of Northern Greece S.A. CPERI, as research organisation and training centre and through their participation at this project, will also enhance technology transfer to the Greek industry.

The Technical University of Berlin has strong contacts with the German process industry (HOECHST, BASF, BAYER, etc.). Through training of graduate and post-graduate engineers. IET will disseminate the most advanced design methods, in modelling heat and mass transfer in compact heat exchangers, into EU industries.

At the University of Newcastle, the Department is involved with work in the University's Engineering Design Centre. It is therefore envisaged that the results from this project could be disseminated through the Centre's Technology Transfer Unit. The Centre has several industrial members involved in the process and offshore industry such as Kvaerner, Amec, Shell, Amerada Hess etc.