*Note: There are three additional articles to publish in Volume 26, Number 6, 2005.

Taylor & Francis
Taylor & Francis Group

Volume 26 Number 5 June 2005

heat transfer engineering

AN INTERNATIONAL JOURNAL

Special Issue: Selected Papers Presented at the Sixth Conference on Process Integration, Modeling, and Optimization for Energy Saving and Pollution Reduction (PRES 2003), Held on 26-29 October 2003, Hamilton, Ontario, Canada

Heat Transfer Engineering, 26(5):73–84, 2005

ISSN: 0145-7632 print / 1521-0537 online
DOI: 10.1080/01457630590927390

Taylor & Francis
Taylor & Francis Group

Advanced and High-Performance Heat Exchangers for the Hydrocarbon-Processing Industries

B. THONON

CEA-GRETh, Grenoble, France

This paper presents the results of two projects carried out in Europe that have been supported by the European Commission. These research and development projects were dedicated to advanced heat exchangers for the Hydrocarbon Processing Industries (HPI). Both shell-side boiling and in-tube condensation enhancement technologies have been developed and tested for various applications using pure and mixture hydrocarbons for both boiling and condensation applications. The tests have first been performed at the lab scale and afterward on small pilot units. Based on these results, a demonstration project for a boiler in a polypropylene plant has been realized in 2000, and it has been shown that the minimum temperature approach can be reduced to less than 1°C, thus leading to energy savings. Afterward, the work has been extended to gas liquefaction processes, and an increase of 50–100% can be obtained for condensation/evaporation duties such as those encountered in chilling train for Liquefied Natural Gas (LNG). Technical and economic evaluations have been realized and show that both material and energy could be saved using high-performance heat exchangers.

INTRODUCTION

Heat Exchangers for Petro-Chemical Applications

Heat exchangers are used in several industrial processes, such as refinery, ethylene, gas treatment, gas liquefaction, and polymer, and shell-and-tubes, air-cooler, and compact heat exchangers are the technology the most frequently encountered. Table 1 summarizes the operating conditions of these processes, and Table 2 gives the relative cost of heat exchangers for a new project. Enhancing heat transfer reduces the investment and operating costs and allows higher productivity by either reducing the size of the units or the temperature approach and/or increasing its specific heat capacity (W/m^3). The objectives of these projects were to strengthen the gas and chemical industries and their technology suppliers and introduce innovative technologies and concepts in the process industry. Prior to its introduction and use in the HPI, any innovative technology has to prove that it is valuable at the industrial scale and that sufficient background and basic studies exist to allow its generalization. Nevertheless, a generic and optimal technology cannot be found if the project does not focus on selected industrial separation processes. A technical and economic re-evaluation process between the start-up and the end has established the benefits of these high performances heat exchangers (see Figure 1).

These projects have been partially supported by the EC, within the frame of the non-nuclear energy programme. CEA-Greth was the coordinator of these projects, and their success is greatly due to the excellent collaboration between the partners. The partners are the research centers Sintef (Norway) and the University of Stuttgart IKE (Germany), the tube supplier Wieland (Germany), the heat exchanger manufacturers CIAT and ACM (France), the engineering company Technip (France), and the industrial end-user companies Shell Global (The Netherlands), Targor (Germany), and Statoil (Norway).

Address correspondence to B. Thonon, CEA-GRETh, 17 rue des martyrs, 38054 Grenoble, France. E-mail: thonon@cea.fr

DEVELOPMENT OF A HIGH-PERFORMANCE BOILING TUBE

Industrial Background

The subject of enhanced heat transfer tubes has grown to the stage that it is of serious interest for a whole range of industries. The air conditioning, refrigeration, and automotive industries routinely use enhanced heat transfer tubes in their heat exchangers. The substantial development of low-finned and double enhanced tubes over the years is shown in Figure 2.

Table 1 Application of heat exchangers in the hydrocarbon process industry

Process	Feed	Product	Temperature (°C)	Pressure (bars)	Technology*	Fouling
Refinery	Crude oil	Various hydrocarbons	15 to 550	0 to 200	ST, AC, CO†	High
Ethylene	Propane, butane, and naphtas	Ethylene and polypropylene	−160 to 1125	0 to 130	ST, AC, CO	Medium
Gas treatment	Natural gas	Natural gas purified	15 to 150	1 to 80	ST, AC, CO	Medium
Gas liquefaction	Methane (gas)	Methane (liquid)	−163 to 200	1 to 80	ST, AC, CO	Medium
Polymer	Ethylene, propylene	Polymer (solid)	15 to 110	20 to 3000	ST	Low

*ST: shell and tubes; AC: air coolers; CO: compact.
†Packinox plate heat exchangers.

Overviews on enhanced heat transfer are given by Thome [1–3] and Webb [4]. These enhanced heat transfer technologies rely predominantly on two approaches:

1. increasing the surface area per heat exchanger volume
2. intensifying the heat transfer at the respective surface area

A combination of these two effects can be used as well.

One topic covered in this article is enhanced shell-side nucleate boiling tubes for reboiler within the hydrocarbon processing industry (HPI). The typical process conditions are boiling clean short hydrocarbons (C_2, C_3, BTX, etc.) at low temperature approaches ($\Delta T < 2$ K). More and more, the HPI uses compact and enhanced heat exchanger solutions within revamps, capacity enhancements, and subsequently also in grassroots projects. The reasons for this are increasing demand for energy conservation, competitiveness, and a reduction of maintenance costs, as well as legislative regulations along environmental issues.

The primary application field of enhanced nucleate boiling tubes concentrates on processes with no or only low fouling. The more robust low-finned tubes can contribute in quite a range of cases with severe fouling problems. Further application fields are developing and growing along with the needs of the HPI and first individual successful applications.

Historically, enhancement technologies have been introduced in individual revamps or capacity enhancement situations with high attractiveness versus low risks. In existing plants, the installation of additional equipment is quite expensive due to limited plot space, no additional space for piping, etc. In those cases, existing shell-and-tube heat exchangers (STE) equipped with plain tubes have been conveniently replaced by bundles with low-finned or double enhanced tubes. In the literature, some of these experiences of various oil companies and engineering contractors are given. One of these examples is the application of low-finned tubes in bottom reboilers within a light-end section unit of a refinery [5]. Low-finned tubes have first been tested within various revamp projects, such as a deisobutanizing and pentane splitting service.

Table 2 Relative investment costs of heat exchangers in new projects

Process	Relative cost (%)
Refinery	3.8 to 5.7
Ethylene	8.8 to 12.6
Gas treatment	2.8 to 4.2
Gas liquefaction	1.8 to 2.7
Gas liquefaction using spiral or plate fin heat exchangers	5.6 to 8.4
Polymer	4.8 to 7.2

The application of low-finned tubes in so-called fouling services within a U-tube reboiler for a hydrocarbon distillation unit has been reported [6]. With the low-finned tube replacement bundle using an increased tube pitch and a square tube layout, the operation time significantly increased, and the cleaning time reduced from 300–400 hours to 4–8 hours (!).

Another case is reported for a dehexanizer reboiler [7]. Along with the consideration of pass lanes, an increased tube pitch, square tube layout, and piping reconfiguration, performance improvements are realized for a heavy fouling unit. Low-finned tubes are thereby balancing the reduced surface area due to these means. Further substantial benefits using low-finned tubes can be expected in terms of reducing the wall surface temperature by increasing the surface area and thereby the fouling probability.

Quite a successful enhancement technology established in the HPI since the late 1970s are the porous coated high flux tubes from UOP. These tubes are accepted in a wide range of petrochemical processes. The application fields are within column bottom reboilers and overhead condensers in light-end sections of refineries, air separation plants, olefin plants, and LNG plants. Typical heat exchanger equipment for the reboilers and condensers can be TEMA-type kettle or thermosiphon reboilers, both for horizontal shell-side and tube-side vertical boiling situations. The application of enhanced nucleate boiling surfaces is leading to a significant reduction of required surface area, the required number of heat exchangers per unit, and energy savings [8].

A selection of illustrated case studies and references have already demonstrated the industrial experience with low-finned and double enhanced tubes in the HPI. The primary application concentrates on clean services mostly in refrigeration systems, cold sections of olefin plants, or light-end sections of refineries. Most of these first applications have been realized within revamps and capacity enhancements. The history of references over the last fifteen years proves the successful application of enhanced tubes in terms of thermal performance and especially mechanical reliability.

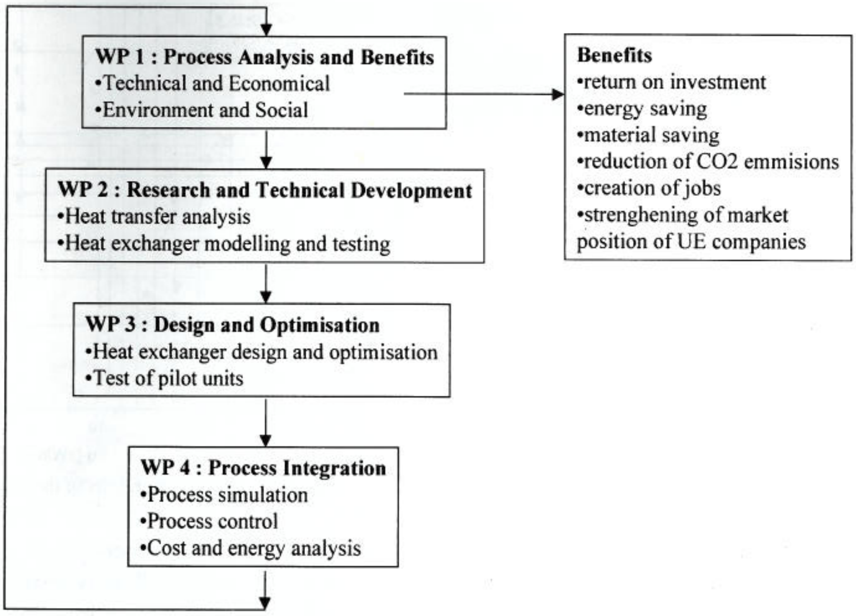

Figure 1 Development strategy.

Tube Structure

The tested structured tubes with re-entrant cavities (outer diameter, 19.05 mm) are new developments of Wieland Werke (Ulm, Germany). The main heat transfer area of these heat exchanger surfaces is located in the tube wall and consists of subsurface channels and cavities (see Figures 3 and 4). These internal structures are connected to the surrounding fluid by small openings (e.g., slits and pores). The dimensions of the subsurface geometries are all in the submillimeter range.

Heat Transfer Performances

Single Tube Experiments

Experiments have been conducted at IKE (Stuttgart University, Germany) with one smooth reference tube and several variations of enhanced tubes with structured surfaces [9–12]. The tubes were made of carbon steel St35.8, and for a working fluid, the hydrocarbon iso-butane, propane, and two mixtures of butane and propane were used. The experiments were carried out with single tubes and minibundles (two tubes inline) at saturation conditions corresponding to temperatures between 253 K and 293 K. The employed heat fluxes ranged from about 2 kW/m^2 to 100 kW/m^2 for single tube experiments and from about 2 kW/m^2 to 70 kW/m^2 for minibundle experiments. The obtained heat transfer coefficients of the enhanced surfaces (see Figures 5 and 6) were compared with the results of the smooth reference tube to calculate the respective improvement factors. For all the tubes tested, the reference heat transfer surface was kept constant and equal to the outer tube surface. The enhanced tube variant 4 shows the best heat transfer coefficients for all tested saturation temperatures. The enhancement factor varies between 1.5 and 2.5, depending on heat flux, operating pressure,

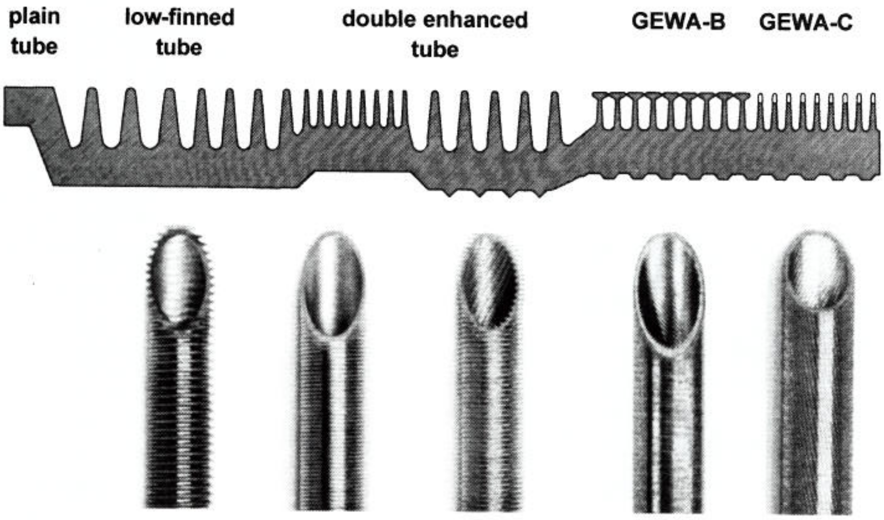

Figure 2 Development of enhanced tubes.

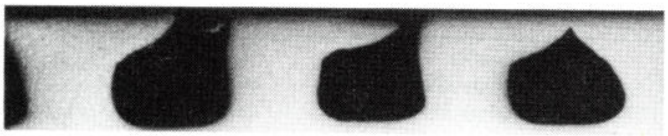

Figure 3 Cross-sectional view of the subsurface structures.

and fluids, with high operating pressures giving the highest values. This variant was chosen used for pilot unit tests at GRETh (CEA-Grenoble, France) on a small bundle of 45 tubes and employed in the shell-and-tube heat exchanger prototype.

Bundle Experiments

Heat exchangers in which an evaporating fluid flows across an horizontal tube bundle, like kettle reboilers and flooded evaporators, are widely used in the chemical and process industry. The design of such equipment requires knowledge of pressure drop, void fraction, and heat transfer for boiling two-phase flow. The available correlations in the literature are limited to some given cases of bundle geometries as well as working fluids (mainly refrigerants) with moderate to high mass velocities. There is a lack of data for industrial equipment for hydrocarbon evaporation, where the typical operating condition is low mass. The present investigation is a part of an experimental program on the two-phase flows and heat transfer characteristics under these operating conditions, concerning the flow boiling of n-pentane, butane, and propane across a bundle of plain tubes. It has been followed by the testing of enhanced tubes under the same conditions [13, 14].

The set-up is representative of an industrial reboiler but differs by the presence of two vertical walls confining the flow. Consequently, the internal shell-side recirculation is avoided, and the mass flow rate through the bundle can be controlled. The operating fluids are pumped as saturated liquid from the shell of the boiler and then subcooled and reentered in the test section in the tube bundle channel. The vapor, which leaves the boiler by the top, is condensed and returned to the shell, where it mixes with the liquid pouring over the wall. This configuration reduces the two-phase flow instabilities and allows us to work with very low mass fluxes, which are typical for industrial reboilers under normal operating conditions. The heating power is

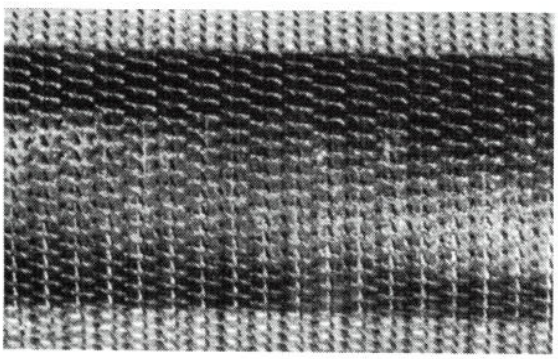

Figure 4 Magnified view of an enhanced evaporation surface.

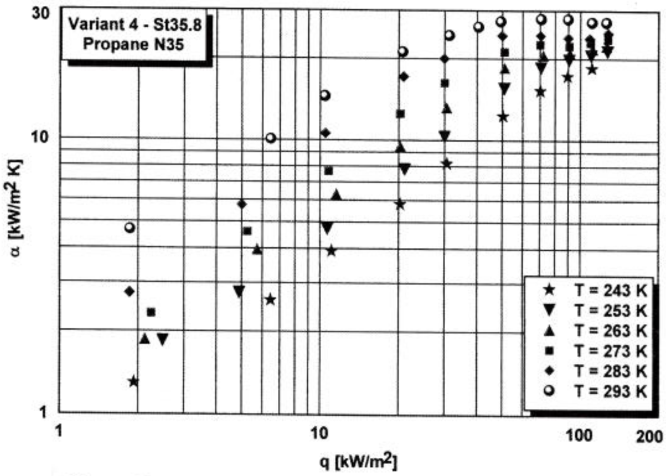

Figure 5 Pool boiling results of the enhanced tube (propane).

supplied by a hot fluid (water–glycol solution) flowing through the tubes. The hot fluid flow is distributed in nine pipes with equal mass flow rates. The hydrocarbon flow rate can be varied up to 3000 l/h (approximately 50 kg/m^{2}s for light hydrocarbons related to the minimum cross-section area). The hot fluid temperature can be adjusted between $-25°$C and 125°C, providing up to 70 kW (52 kW/m^2 related to the outside tube surface). The measurements performed on the test section are aimed to evaluate the outside heat transfer coefficient, the heat flux, and the thermal and hydrodynamic conditions of boiling hydrocarbon at each row.

The present investigation has focused on the characterization of boiling heat transfer of hydrocarbons in a bank of plain and enhanced tubes under conditions of low mass velocity and low reduced pressure. For plain tubes, different flow boiling mechanisms have been identified depending on the fluids and the operating conditions. Increasing the molar mass of the fluid, at a similar boiling temperature shifts the boiling mechanism from pool boiling to convective boiling, and this is in agreement with nucleate and flow boiling models. For enhanced tubes, the heat transfer coefficients (compared to the plain tube) are improved

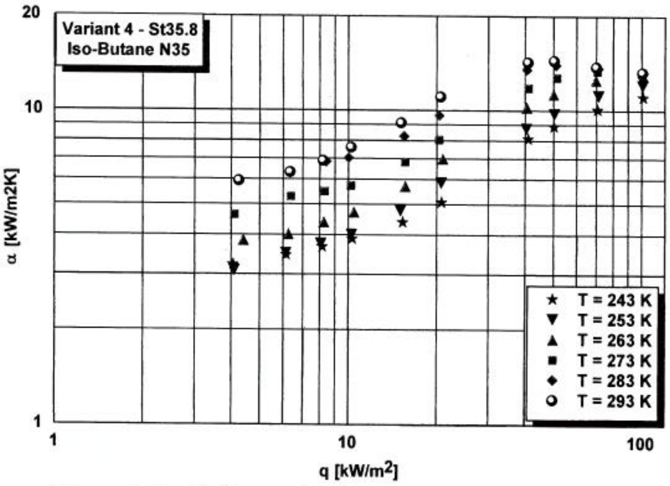

Figure 6 Pool boiling results of the enhanced tube (iso-butane).

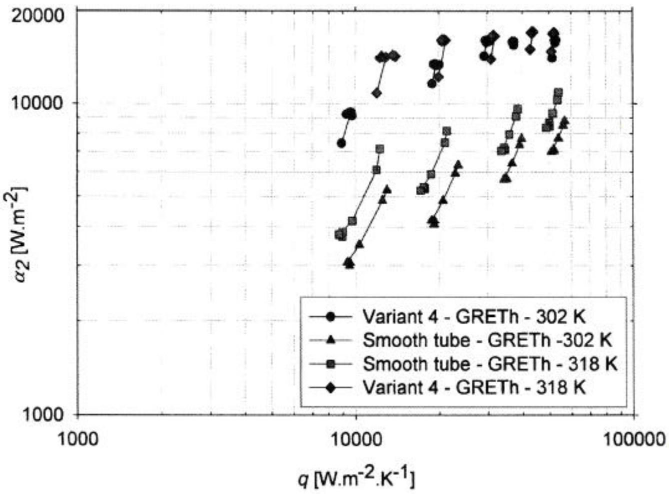

Figure 7 Tube bundle experiments using iso-butane.

by a factor 1.5 to 2 (see Figure 7). The comparison with the data obtained at IKE (see Figure 8) shows that the heat transfer coefficient measured at Greth are higher by 20% that those measured on a single tube at IKE.

Summary

Wieland has successfully developed enhanced boiling enhanced tubes. Four variants and a smooth tube were tested at IKE using pure and a mixture of hydrocarbons. Upon the geometry tested, the variant 4 always shows the highest performance and was therefore selected for tube bundle experiments at Greth.

The results have shown that significant improvement can be obtained using enhanced tubes for shell-side boiling applications. For heat fluxes up to 20 kW/m^2, the improvement factor is between 1.5 and 2.5, and this has been proven for single tube and tube bundle experiments. For mixtures, the enhancement factor for single tube experiments is lower than for pure fluids,

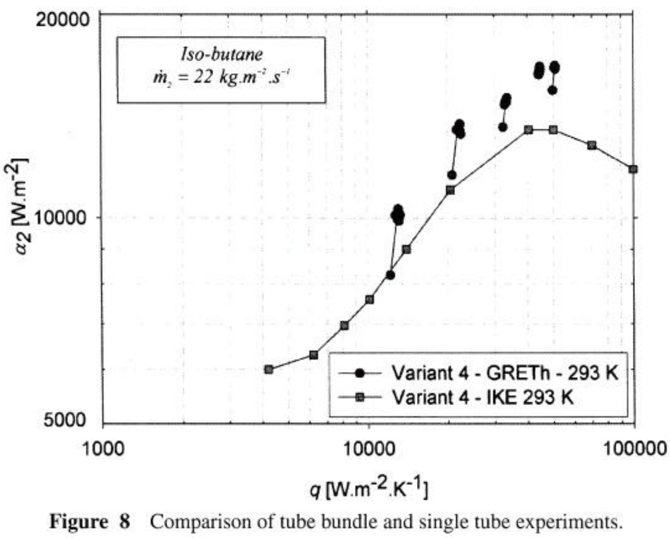

Figure 8 Comparison of tube bundle and single tube experiments.

and an additional mass transfer resistance can explain this. This phenomenon should be reduced for tube bundle applications.

DEVELOPMENT OF A HIGH PERFORMANCE CONDENSATION TUBE

Local Analysis

At a Sintef (Trondheim, Norway), a test plant for measuring local heat transfer coefficients and frictional pressure drops during high-pressure condensation of hydrocarbons has been designed and constructed. Three different test sections with different test tubes—a Wieland smooth tube, Wieland PB-8 microfin tube, and Wieland PB-9 microfin tube—have been installed (see Figure 9).

Measurements have been performed using pure propane and a 50/50 mole % propane/ethane mixture as test fluids. Based on the measurements on the smooth tube, correlations for two-phase frictional pressure drop and heat transfer coefficients are developed. Calculations and measurements for smooth tubes are used in the comparison with the measured data for the microfin tubes [15].

The measurement program has lead to the following results.

Single-Phase Heat Transfer

The PB-8 and PB-9 tubes show an enhancement in the heat transfer coefficient of about 30% compared to the smooth tube. The increase is lower than the increase in surface area (43%). The difference between PB-8 and PB-9 is small, but the performance of PB-9 is somewhat better than PB-8.

Single-Phase Frictional Pressure Drop

The PB-8 and PB-9 tubes show an increased frictional pressure drop of about 60–80% compared with a corresponding smooth tube. The increase is higher for PB-8 than PB-9.

Two-Phase Condensing Heat Transfer

Both PB-8 and PB-9 show enhancement in the heat transfer coefficient compared to the smooth tube. Enhancement of up to

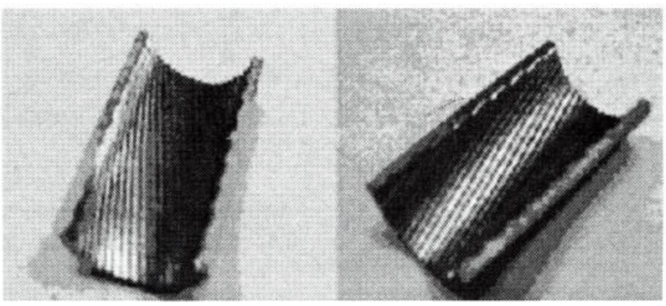

Figure 9 View of the low-finned tubes.

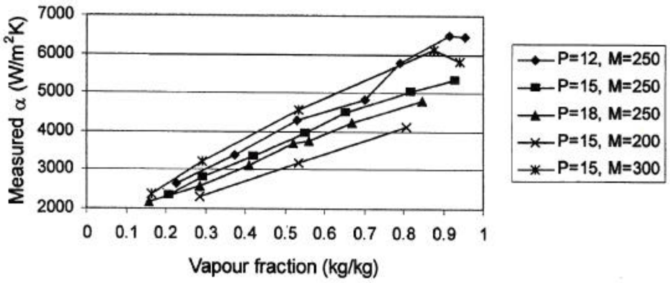

Figure 10 Measured heat transfer coefficients for propane, P[bar], M[kg/m^{2}s].

100% has been observed at low vapor fraction. The enhancement varies between 40% and 100%. The enhancement seems to be larger for low mass fluxes than for higher mass fluxes. The enhancement is larger at a low vapor fraction, decreases to a minimum at a medium vapor fraction ($x = 0.5$–0.7) and increases again at a high vapor fraction (see Figures 10–11).

The average increase for PB-9 is about 70% and about 60% for PB-8, compared to the corresponding smooth tube. The increase for the mixture at 30 bars is somewhat lower than for the propane measurements at lower pressure.

Two-Phase Frictional Pressure Drop

The increase in pressure drop is significant both for PB-8 and PB-9. PB-9 shows a slightly higher pressure drop than PB-8. At a low vapor fraction, an increase of 150% compared to a smooth tube is observed. At a high vapor fraction ($x = 0.9$–0.95), the increase is about 50%. The increase is approximately the same at high and low pressure. For PB-9, an average increase of about 100% can be indicated, while for PB-8 the increase is about 90–95% (see Figure 12).

Enhanced In-Tube Condensation

At GRETh, condensation inside long enhanced tubes experiments have been performed [16]. The tube length was 4 m in order to represent a long chilling train. The test sections were installed on a dedicated test rig for industrial purposes. Experiments with total condensation of pure and mixture of hydrocarbons have been realized.

The overall measured data for a plain tube and a low-finned tube, tested under similar operating conditions, have been compared (see Figures 13 and 14). The low-fin tube geometry provides an enhancement factor (compared to the plain tube) of 30% to 90%, depending on the operating pressure and fluid velocity. These values are in agreement with the local heat transfer coefficients obtained at Sintef on a similar geometry.

Summary for In-Tube Condensation

Microfin tubes developed by Wieland have been tested at Sintef and Greth using pure and mixtures hydrocarbons on a wide range of operating conditions. The results show that the heat transfer coefficients can be significantly increased (up to a factor two), with a pressure drop increase of the same order. Taking into account the enhancement factor obtained for boiling, the overall heat transfer performance of the double enhanced tube is in the range of 1.5–1.9.

DEVELOPMENT OF A PILOT UNIT FOR SHELL-SIDE BOILING

Objectives

In the Targor Polypropylene plant near Cologne (Germany), with an annual capacity of 180 ktons, the E711 reboiler of a propane/propylene–splitter column was chosen for this project. The C3 boiling takes place on the shell side, according to the thermosiphon principle, by operating conditions from about 13.4 bars and 40°C. On the tube side, the reboiler is part of a heat recovering system. The heat of reaction in the polymerization reactor is used for heating the reboiler via a water circulation system. The remainder of the heat that could not be recovered in the reboiler is rejected via a plate heat exchanger to the open re-circulating cooling water system and sent to the atmosphere (see Figure 15). In order to recover heat to the maximum extent, the full circulation water flow is pumped through the reboiler.

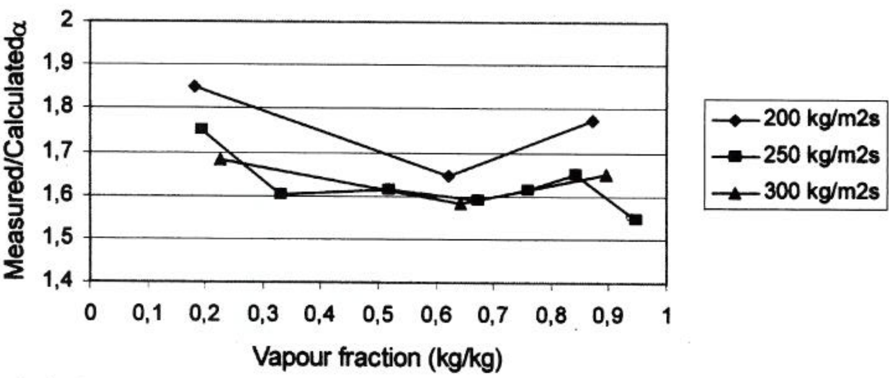

Figure 11 Ratio of measured and calculated (as for smooth tube) heat transfer coefficient for PB-8 using propane as test fluid.

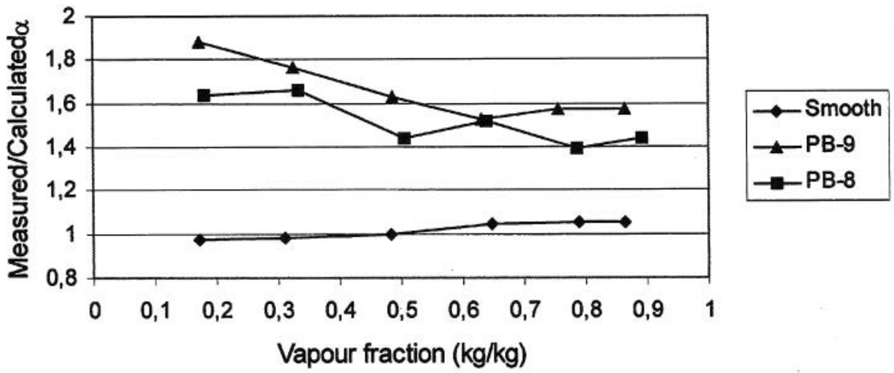

Figure 12 Ratio of measured and calculated (as for smooth tube) heat transfer coefficients for propane/ethane mixture at 30 bar and 250 kg/m^{2}s.

The flow rate and temperature of the circulation water fluctuate, depending on the reaction conditions. The flow rate is between 400 m^3/h up to 455 m^3/h, and the water inlet temperature is between 50°C and 53°C. To guarantee stable operating conditions in the splitter, a second steam-operated, liquid level-controlled reboiler E 712 is installed. In this way, a constant liquid static head for the reboiler is also provided.

The objectives for Targor for taking part in this project result from an increase of the annual production rate from 180 ktons up to 260 ktons. The capacity of the splitter and the reboiler also had to be increased for that reason. Because there was a temperature difference between the circulation water outlet and boiling propane for about 4–5 K, we decided to enlarge the reboiler. Additionally, there will be a saving in energy by reducing the steam consumption in the reboiler E 712. Due to the limited space in the plant, the newly developed "high performances" tubes for boiling of C3 enable us to limit the size of the reboiler so that even the existing pipe couplings could be used.

Heat Exchanger Manufacturing

Concerning the supply of the enhanced tubes for the field test, Wieland has carried out screening tests using prototypes that have been quite successful. It is thus confirmed that the tube structure can be fabricated with the given tools and that the tube dimensions required for the field test can be achieved (10 m-long U-bent tubes). The company Ciat (Culoz, France) has manufactured the heat exchanger according to the Targor specifications.

The general characteristics of the prototype are:

- TEMA type BXU horizontal
- shell diameter: 1.022 m
- number of tubes: 1150
- tube length: 5.25 m
- tube diameter: 19.05 mm
- total heat transfer surface: 360 m^2

Results

To compare the predicted performances made during the design of the new reboiler (based on experimental curves and correlations) with the real performances observed on site, test-run data have been collected during a few days of steady-state operating conditions. The main information is the following:

- C3 temperature: 39.7°C
- Water flow rate: 452 m^3/h

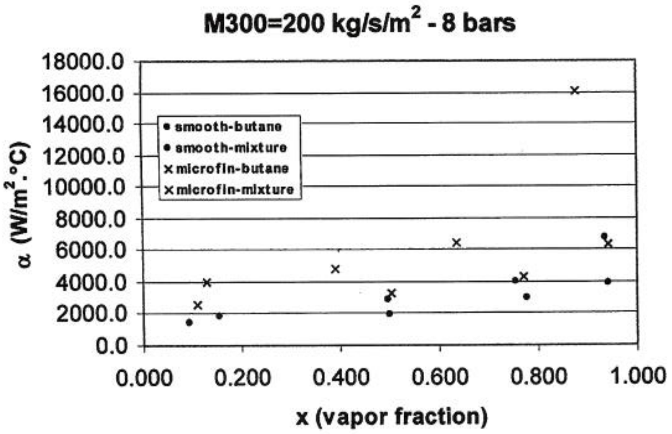

Figure 13 Comparison of the performance (fluid butane and mixture at 8 bar).

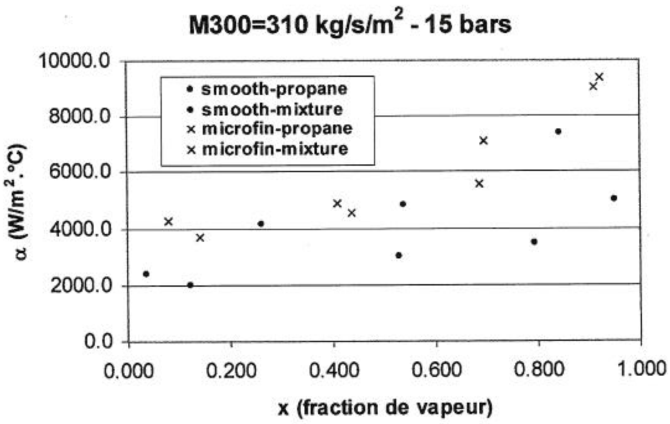

Figure 14 Comparison of the performance (fluid propane and mixture at 15 bar).

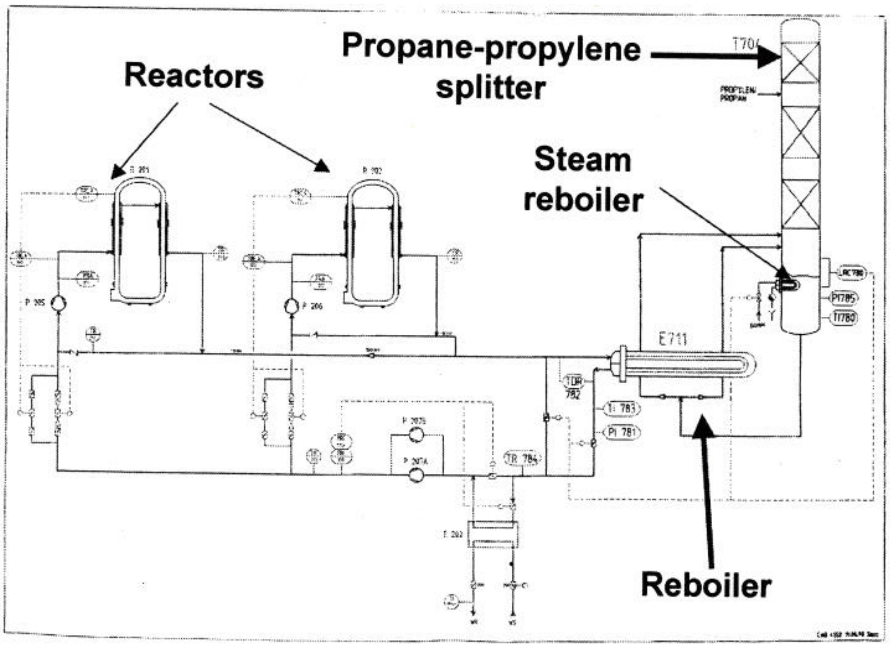

Figure 15 Process description.

- Water outlet temperature: 40.6°C
- Water temperature difference: 9.6°C

A complementary pressure drop measurement was made directly on the reboiler and led to about 0.45 bar (water side). The recorded data are summarized in Table 3. It should be noted that the precision of the temperature measurements has a major influence on the global heat transfer coefficient calculation. In a first estimation, the uncertainty of the global heat transfer coefficient is about ±20%. The recalculated boiling side heat transfer coefficient is in accordance with the GRETh curves, as the range of heat flux of the new reboiler is about 2000 W/m^2 to 40000 W/m^2.

Benefits

To quantify the benefits of the boiling enhanced tubes obtained on the C3 splitter reboiler application, we have simulated the performances of an equivalent bare tube reboiler. The results obtained are presented in Table 4. This comparison shows that the gain obtained on the global heat transfer coefficient (+90%) is dispatched between a bigger duty (+25%) and a smaller LMTD (−35%), which leads to a much smaller cold approach of 0.9°C.

The aim of the replacement of the existing reboiler was to improve the thermal performances without any constraint of size reduction. However, it could be interesting to imagine that the maximum length of the tube is limited, starting with the bare tube solution mentioned here above, which results in 4.0 MW. Table 5 compares the respective sizes of the bare tubes solution and a PB-4 tubes solution designed for the same thermal performances (4.0 MW). The tube length is reduced of 47%. It should be

Table 3 Measured performances

Duty	MW	5.0
Cold approach	°C	0.9
LMTD	°C	3.3
Global HTC*	W/m^2 °C†	3670
Waterside HTC	W/m^2 °C†	10800
Boiling side HTC	W/m^2 °C†	8600
Waterside pressure drop	Bar	0.45

*per m^2 of bare external surface.
†per m^2 of bare internal surface.
†Total equivalent external bare surface = 37 m^2.

Table 4 Data comparison

		Bare tube solution	PB4 tube solution	Ratio
Propane saturation temperature	°C	39.7	39.7	
Water flow rate	ton/h	452	452	
Water inlet temperature	°C	50.2	50.2	
Water outlet temperature	°C	42.6	40.6	
Duty	MW	4.0	5.0	
Cold approach	°C	2.0	0.9	
LMTD	°C	5.5	3.6	
Global HTC*	W/m^2 K	1940	3670	1.9
Waterside HTC†	W/m^2 K	6200	10800	1.75
Boiling side HTC*	W/m^2°C	3800	8600	2.3
Waterside pressure drop	Bar	0.22	0.45	2.0

*per m^2 of external bare surface.
†per m^2 of internal bare surface.

Table 5 Data comparison

Results*		Bare tube solution	PB4 tube solution
Water T° out	°C	42.6	42.6
Duty	MW	4.0	4.0
LMTD	°C	5.5	5.5
Global HTC	$W/m^2{}^\circ C$	1940	3670
Surface required	m^2	377	199
Length required	m	5.25	2.8
Water pressure drop	Bar	0.2	0.2

*Considering that the same number of tubes is kept.

noted that the water pressure drop remains the same at equivalent thermal performances.

Energy and Utility Saving

To increase the duty of the C3 splitter reboiler without changing the water flow rate, it was imperative to decrease the cold approach between water and propane. This was observed during the test-run, with a typical cold approach of 0.9°C. It must be noticed that this approach could not have been possible with bare tubes, as it corresponds to heat flux values less than 1000 W/m^2 for which the onset of nucleate boiling is hardly possible. Before the installation of the new reboiler, Targor sometimes used a second reboiler E712 (on low pressure steam at 4 bar, 152°C) directly inserted inside the column bottom to increase the duty of the reboiler E711. When looking at the typical test-run data, the gain of 1 MW represents 1.7 ton/h of low pressure steam, which can be estimated to $150,000/year (US).

BENEFITS ON ENERGY AND MATERIAL SAVINGS USING ADVANCED HEAT EXCHANGERS IN AN LNG PRE-COOLING PLANT

Introduction

The use of double enhanced tubes for the propane evaporators in a propane pre-cooled MCR® (multi-component refrigerant) cycle will increase the total heat transfer coefficient by a factor of 50–90% compared to corresponding smooth tubes. On the boiling side, the pressure drop is negligible, while for the tube-side condensation, the use of the microfin surface increases the pressure drop by a factor of about 50–100% compared to a smooth tube for the same tube length.

By using the double enhanced tubes, two main different approaches related to the benefits compared with smooth tubes can be indicated:

1. Operating with similar temperature differences as for the smooth tube, obtaining a smaller heat exchanger, or reducing the number of parallel heat exchanger units, giving maximum materials saving and minimum refrigerant inventory.
2. Operating with smaller temperature differences and a similar heat transfer and tube lengths surface area as for smooth tubes, giving the higher energy efficiency. The main savings will be in reduced compressor power and reduced emissions of CO_2 and NO_x.

The optimum design of heat exchangers with double enhanced tubes will depend on the actual performance compared to smooth tubes, as well as the investment and operational cost for the use of such tubes compared to the smooth tubes. In the total evaluation, the reduction of air-polluting emissions as well as material savings are elements to be considered.

Process Calculation by LNG Plant Simulator CryoPro

The precooling section of a four-stage propane-precooled APCI (Air Products and Chemicals Inc.) MCR® plant, as shown in Figure 16, is used as a basis for the process calculation. For the example calculation, the LNG production is about 3.5 mtpa.

Shell and tube heat exchangers are used for precooling natural gas and multicomponent refrigerant. For natural gas precooling, the conditions on the tube side will mostly be in single-phase vapor phase. For these conditions, the heat transfer improvement through microfin tubing is limited, while the pressure drop increase is significant. The conditions on the tube side will control the heat transfer coefficient, and the use of the enhanced surface on the shell side will have a minor effect. For the use of double enhanced tubes for these conditions, another tube-side enhancement method must be applied. (This is not considered in this work.) In the evaluation, double-enhanced tubes are applied only for the MCR® condensers with two-phase flow on the tube side. The first MCR® exchanger is operating at single-phase vapor conditions at the tube side, and microfin tubes are not recommended. The simulation is performed with equal pressure head for each refrigerant compressor in the precooling cycle and for each compressor in the MCR® cycle. The test case data are reported in Tables 6, 7, and 8.

Table 6 Heat exchanger data for base case

	KP-02	KP-04	KP-06	KP-08
U (W/m^2K)	400	750	750	750
DP (bar)	0.35	0.35	0.35	0.35
DT_{min}	6	6	6	6
LMTD (K)	9.98	13.97	13.20	12.10
Duty (MW)	5.79	31.51	34.43	24.91
UA (MW/K)	0.580	2.256	2.608	2.058
A (m^2)	1450	3074	3474	2744
Total A (m^2)	10 742			

Total compressor shaft power: 116.87 MW. Precooling compressor shaft power: 42.44 MW. MCR compressor shaft power: 74.43 MW.

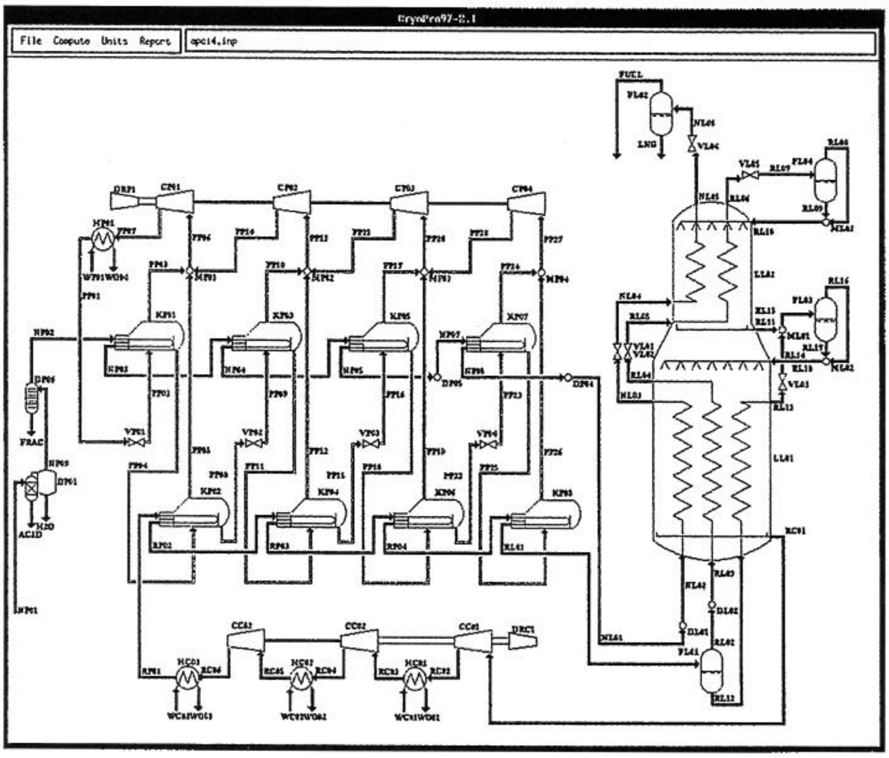

Figure 16 Flow diagram for four-stage propane precooled MCR process (APCI), screen dump from CryoPro.

Evaluation of Calculation Results

By using double-enhanced tubes for MCR condensation in the precooling plant for natural gas liquefaction, the necessary heat transfer surface can be significantly reduced if the heat exchangers are operated at the same overall temperature differences. For Case 1, the total surface area is reduced by about 4000 m^2. Assuming that tubes with an external diameter of 19 mm are applied, this corresponds to 67000 m of tubes. For a wall thickness of 2 mm, this corresponds to 3.8 m^3 of tube material, or a mass of about 30 tons. In addition, the length of the shell will be reduced, also giving significant material savings.

If the heat exchangers are designed to operate at lower temperature differences, both energy and materials saving can be obtained. For Case 2, the necessary compressor shaft power is reduced by about 1.7 MW, and the heat transfer surface is reduced by 1600 m^2. If the power for running the compressors is produced by gas turbines, the efficiency is estimated to 35%, including mechanical losses. This corresponds to a heating value of 4.9 MW or 0.1 kg/s of natural gas. For operation 340 days/year, this gives about 3000 tons of gas. Burning 3000 tons of natural gas will produce about 9000 tons of $CO_2$and about 17 tons of NOx, assuming NOx emissions of 25 ppmv, 0.44 g/kWh. Further, for the same tube dimension as for Case 1, a material saving of about 13 tons can be obtained, assuming that the weight of the enhanced tubes is approximately the same as the smooth tubes.

The conclusion is that substantial energy and material savings can be obtained by using double enhanced tubes instead of traditional smooth tubes.

Table 7 Heat exchanger data for Case 1

	KP-02	KP-04	KP-06	KP-08
U (W/m^{2}K)	400	1350	1350	1350
DP (bar)	0.35	0.4	0.4	0.4
DT_{min}	6	6	6	6
LMTD (K)	9.98	13.97	13.20	12.11
Duty (MW)	5.80	31.47	34.46	24.93
UA (MW/K)	0.581	2.253	2.609	2.060
A (m^2)	1452	1669	1933	1566
Total A (m^2)		6620		

Total compressor shaft power: 117.00 MW. Precooling compressor shaft power: 42.45 MW. MCR compressor shaft power: 74.55 MW.

Table 8 Heat exchanger data for Case 2

	KP-02	KP-04	KP-06	KP-08
U (W/m^{2}K)	400	1350	1350	1350
DP (bar)	0.35	0.6	0.6	0.3
DT_{min}	6	2	1.5	1
LMTD (K)	9.98	9.61	7.31	10.52
Duty (MW)	5.82	39.50	33.46	17.92
UA (MW/K)	0.583	3.045	4.590	1.704
A (m^2)	1457	3045	3392	1262
Total A (m^2)		9 156		

Total compressor shaft power: 115.23 MW. Precooling compressor shaft power: 40.44 MW. MCR compressor shaft power: 74.79 MW.

Table 9 Reference list for GEWA-PB enhanced nucleate boiling tubes

Year of start-up	Plant	Service	Shell-side process	Tube-side process	Material	Number of tubes	Tube length
2004	Ethylene	Ethylene condenser	C3 refrigerant, $T_{boil} = -40°C$	Ethylene refrigerant, $T_{cond} = -35°C$	A-334 Gr1	905 U	6.00
2003	Ethylene	De-ethanizer condenser	C2 splitter draw-off, $T_{boil} = -17°C$	De-thanizer Ovhd, $T_{cond} = -12°C$	A179	1895	7.30
2003	Ethylene	Depropaniser condenser	Propylene, $T_{boil} = 1°C$	Depropanizer Ovhd, $T_{cond} = 5°C$	A-334 Gr1	1467 U	6.10
2003	LNG	C3 chiller	C3 refrigerant, $T_{boil} = -32°C$	Mixed refrigerant, $T_{cond} = -12/-30°C$	A	12563	12.00
2002	Ethylene	Ethylene condenser	Ethane, $T_{boil} = -38°C$	Ethylene gas, $T_{cond} = -35°C$	A-179	2520	7.00
2000	Polyethylene	C3 splitter reboiler	Propane-Propylene, $T_{boil} = 40°C$	Process water, $T_{water} = 50/40°C$	A-179	575 U	5.30

Economic Aspects

LNG projects are always driven by economy of scale and savings in equipment; costs are also drivers, but to a lesser extent. The heat exchanger cost makes up 36% of the total liquefaction unit equipment cost. The liquefaction unit equipment cost is 14% of the total plant cost. Therefore, the maximum impact on overall cost the heat exchangers can have is 5%.

Considering the same compressor shaft power, the use of enhanced tubes in the precooling unit could lead to produce 1.4% additional LNG for a 3.5 MTPA LNG-plant. This translates into the following:

- LNG price $150/ton (US), so 1.4% more LNG production results in $7.35 million/year (US). For a twenty-year plant lifetime, this converts into 0.147 billion US$ additional revenue.
- For a Green-Field LNG plant with a plant lifetime of 20 years, the typical unit capital cost basis nowadays is ~$300/ton, equivalent to $1.05 billion US for a 3.5 MTPA LNG plant.
- The potential "additional" revenue resulting from 1.4% additional LNG production is therefore 14% of the unit capital cost.

This indicates the high technical and economic potential of enhanced tubes for LNG processes.

CONCLUSION

These projects have two main goals: development of high-performance heat transfer surfaces, and testing and evaluating advanced heat exchangers for gas-processing applications. For the first objective, boiling and condensation tests have been performed using fluids encountered in industrial processes in the oil, gas, and chemical industries. It has been shown that the overall performance of enhanced heat exchangers can be increased by a factor 1.5 to 1.9. Then, in 2000, a pilot unit has been designed, manufactured, and installed in a polypropylene plant in Germany. The unit has been operating since and has shown that a low-temperature approach can be achieved, leading to energy savings and better productivity. Afterward, a technical and economic study for the case of an LNG precooling unit has been realized, and the calculations indicate that not only can either investment or operating costs be reduced, but also that the net plant productivity can be increased.

The fruitful collaboration of academia, research centers, and industrial partners has lead to significant scientific and technical advances and innovations:

- Enhanced tubes for boiling and condensation of process fluids
- A database on heat transfer performances of enhanced tubes
- New concept of separation processes
- Advanced and high performances heat exchangers.

To strengthen the technical and commercial use of the results, a technology user group was created, and several engineering and process companies have been informed regularly on the progress made within this project. The technologies and methods developed in this project are currently evaluated for several processes, and some have already been adopted for industrial purposes (see the list in Table 9).

REFERENCES

[1] Thome, J. R., *Enhanced Boiling Heat Transfer*, Hemisphere Publishing Corp., New York, 1990.

[2] Thome, J., Reboilers with Enhanced Boiling Tubes, *Heat Transfer Engineering*, vol. 9, no. 7, pp. 45–62, 1988.

[3] Thome, J. R., Heat Transfer Augmentation of Shell-and-Tube Heat Exchangers for the Chemical Processing Industry, *2nd European Thermal-Sciences and 14th UIT National Heat Transfer Conf.*, Rome, May 29–31, 1996.

[4] Webb, R. L., *Principles of Enhanced Heat Transfer*, John Wiley & Sons, Inc., New York, 1994.

[5] Webber, W. O., Under Fouling Conditions—Finned Tubes Can Save Money, *Chem. Eng.*, vol. 3, pp. 149–152, 1960.

[6] Moore, J. A., Fintubes Foil Fouling for Scaling Services, *Chem Process.*, vol. 7, pp. 8–10, 1974.

[7] Kassem, E., and Mustansir, A. A., How to Design Shell and Tube Exchangers to Reduce Fouling and Enhance Performance, *Convective Flow Boiling Conf.*, Paper III-2, Engineering Foundation, Banff, Canada, 1995.

[8] Kenney, W. F., *Reducing the Energy Demand of Separation Processes*, Chemical Engineering Process, pp. 68–71, March 1979.

[9] Mertz, R., Groll, M., Vasiliev, L. L., Khrolenok, V. V., Khalatov, A. A., Kovalenko, G. V., and Geletuha, G., Pool Boiling from Enhanced Tubular Heat Transfer Surfaces. *11th Int. Heat Transfer Conference*, Kyongju, Korea, 1998.

[10] Chen, Y., Groll, M., Mertz, R., and Kulenovic, R., Comparison of Pool Boiling Bubble Dynamics on Smooth and Enhanced Tubes,

Int. Journal of Heat and Technology, Edizioni ETS, vol. 20, no. 1, pp. 3–13, 2002
[11] Mertz, R., Kulenovic, R., Chen, Y., and Groll, M., Pool Boiling of Butane from Enhanced Evaporator Tubes, *12th International Heat Transfer Conference*, Grenoble, France, 18–23 August 2002.
[12] Chen, Y., Groll, M., Mertz, R., and Kulenovic, R., Bubble Dynamics of Boiling Propane and Iso-Butane on Smooth and Enhanced Tubes, *Experimental Thermal and Fluid Science*, vol. 28, no. 2–3, pp. 171–178, 2004.
[13] Roser, R., Thonon, B., and Mercier, P., Experimental Investigations on Boiling of n-Pentane across an Horizontal Tube Bundle: Two-Phase Flow and Heat Transfer Characteristics, *Int. J. of Refrigeration*, vol. 22, pp. 536–547, 1999.
[14] Aprin, L., Mercie, P., and Tadrist, L., Analysis of Experimental Results of n-Pentane and Propane Boiling across a Horizontal Tube bundle, *12th International Heat Transfer Conference*, Grenoble, France, 18–23 August 2002.
[15] Neeras, B., Condensation of Hydrocarbons in Microfin Tubes, *AICHE spring meeting*, New Orleans, December 2001.
[16] Beaugeois, O., Thonon, B., and Bontemps, A., Condensation of Pure Butane and Propane and a 44/56% Mixture in a Plain and a Micro-Finned Tubes, *Proc. of the IIR Natural Working Fluid Conference*, Glasgow, UK, 29th August–September 1st, 2004.

Bernard Thonon is project manager at GRETh, Grenoble, France. He is in charge of applied and industrial research and development projects on single- and two-phase flows in compact heat exchangers. He holds a degree in mechanical engineering from the INSA—Toulouse in 1985 and a Ph.D. in Mechanical Engineering from the University of Nancy in 1991. He has published in the areas of single-phase, evaporation, condensation, and fouling in compact heat exchangers and enhancement technologies.