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SPECIAL FOCUS: PETROCHEMICAL TECHNOLOGY (/MAGAZINE/2022/MARCH-2022#SPECIAL-FOCUS-PETROCHEMICAL-TECHNOLOGY)

Enhanced reboiler for C3 splitter heat pump improves energy efficiency and reduces CO2 footprint

Energy efficiency, carbon dioxide (CO₂) footprint reduction and the minimization of material requirements are becoming key drivers of our daily decisions in all industry sectors.

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Energy efficiency, carbon dioxide (CO₂) footprint reduction and the minimization of material requirements are becoming key drivers of our daily decisions in all industry sectors. With the example of a successful process integration of a propylene-propane splitter unit in an existing refinery and petrochemical plant environment, the authors would like to demonstrate the benchmark capabilities of a combination of sophisticated technologies for enhanced heat exchanger design, as well as distillation and vapor recompression technologies. The authors' focus is on a case study and the implementation of an enhanced thermosiphon reboiler/condenser heat exchanger for polymer-grade propylene production. Startup data from the field has proven the successful operation of this highly efficient unit.

This evaluation will focus on an open heat pump C₃ separation unit. The design concept of the enhanced thermosiphon reboiler, along with a cost evaluation of an economical and low-CO₂ footprint basis, will be presented. In the latter case, Scope 1–3 emissions¹ will be considered.

Background

According to the International Energy Agency (IEA), energy efficiency is “the first fuel of a sustainable global energy system.”² Nevertheless, the agency noted that “global improvements in energy efficiency since 2015 have been declining.” This is a reason for concern, as the IEA's Sustainable Development Scenario relies on an energy efficiency of 40% to ensure meeting international climate and energy goals in the next 20 yr. One of the causes of climate change is linked to the low cost of energy sources such as oil and gas. The COVID-19 pandemic has also strongly impacted recent investments in energy efficiency. While we have a good understanding of this global threat, and are increasing our control over it, the negative impact of climate change on our planet remains and proposing solutions that improve energy efficiency to reduce greenhouse gas emissions is the most economic means to reduce carbon intensity, according to the “Industrial Energy Transition Manifesto” of KBC, a Yokogawa Company.³

For more than 20 yr, in accordance with environment, social and governance policies, the co-authors' companies have jointly developed, and supplied to the energy industry, enhanced heat exchanger solutions that reduce unit size and improve energy efficiency. These solutions rely on dual enhanced tubes dedicated to the Tubular Exchanger Manufacturers Association (TEMA) type of shell-and-tube heat exchangers, especially for large heat duty services in the LNG and petrochemical sectors.

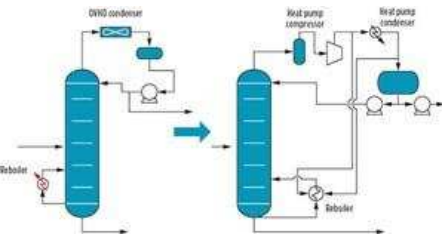
Borealis—one of the world's leading providers of advanced and circular polyolefin solutions and a European market leader in base chemicals and the mechanical recycling of plastics—has made energy efficiency a major axis of its strategic sustainability framework for energy and the climate.⁴ It even goes further when energy efficiency is combined with the use of locally produced renewable electricity, as in its petrochemical facility in Porvoo, Finland, where energy efficiency actions are combined with a long-term power purchase agreement to supply the site with renewable energy.

This article will present the technical basis of a heat pump system applied to a distillation column that helps improve energy efficiency and minimize carbon footprint. The importance of the heat exchangers that are part of the heat pump system, the overhead condenser and the bottom reboiler will be presented. Technologies developed by the co-authors' companies will be described.

Lastly, the authors will demonstrate the successful implementation of a heat pump equipped with proprietary reboiler technologies for the upgrade of Borealis' C₃ splitter unit in Porvoo.

Heat pump principle

The heat pump principle in the frame of a distillation column (**FIG. 1**) targets the recovery of a part of the condensation duty released in the overhead condenser to be used for the boiling service at the bottom of the column.⁵ The overhead vapor will be compressed at a preßure level allowing the overhead vapor to be condensed in the column reboiler. This requires products having close boiling temperatures (typically leß than 45°C) and column bottom temperatures below 100°C. A prime example widely used in refining and petrochemical operations is the propane-propylene splitter column.



(/media/16485/ronka-fig-01.jpg)

FIG. 1. Example of a heat pump implementation on a distillation column.

Energy savings are expected on a heating medium for the reboiler and in a reduction of the cooling water flowrate for the condenser. However, additional power is required to drive the compressor by using either an electric motor or a steam gas turbine. This additional power demand should be considered in the energy balance and carbon footprint.

The vapor compressor discharge preßure is directly linked to the reboiler boiling temperature, where the minimization of the temperature approach in the reboiler will allow for the minimization of the compressor work.

The major part of the gas overhead stream is routed to the reboiler. A trim condenser is required to condense the remaining vapor for reflux and other purposes.

Condenser and reboiler of a distillation column

If we focus on the heat exchangers associated with the distillation column, we must manage—on one side—the overhead condenser, which is generally water- or air-cooled, depending on the operating preßure of the distillation column. On the other side, the reboiler is generally heated by steam, but other sources can be used, such as a liquid heating medium (e.g., hot oil, quench water or hot process stream) or even electric heaters.

The most common exchanger type for these two services in the energy industry remains the shell-and-tube heat exchanger. Depending on the service, its orientation and fluid side allocation can differ. An overview of a typical condenser and reboiler arrangement is detailed in **TABLE 1**. The fouling propensity of each stream will play a key role in finalizing side allocation. Tube-side allocation for cooling water from the open loop is common to manage a minimum water velocity in tubes and to maintain a good shear rate to minimize fouling.

TABLE 1. Typical condenser and reboiler arrangement				
Service	Hot fluid	Cold fluid	Insulation	Remarks
Condenser	Overhead vapor	Cooling water	None/Thin	Tube side
Reboiler	Heating medium (e.g., steam, hot oil, quench water, or process stream)	Bottoms liquid	None/Thin	Shell side
Reboiler	Heating medium (e.g., steam, hot oil, quench water, or process stream)	Bottoms liquid	None/Thin	Tube side

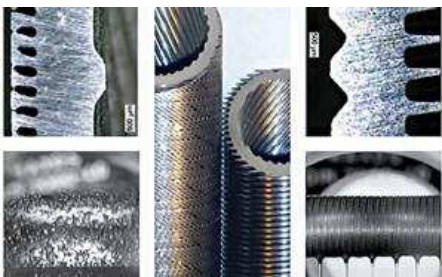
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Depending on fouling and the associated cleaning requirement, the TEMA type of shell-and-tube heat exchanger will be defined. Horizontal NXN-type exchangers will perform well with a clean overhead vapor to be condensed, while horizontal AES-type exchangers will be recommended in the case of a fouling liquid boiling on the shell side heated by quench water, with both sides requiring mechanical cleaning.

The heat duties can be large in this service (several tens of MW are common), and several shells operating in parallel are usually required for the reboiler. Therefore, technologies that can improve the efficiency of the exchanger are of high value. Plain tubes can be replaced by externally finned tubes, which will help to increase the heat transfer area by a ratio of 2–3. Ultimately, dual enhanced tubes will provide the necessary heat transfer intensification, along with an increase in surface to maximize the heat transfer for both sides of the tube.

Proprietary heat transfer solutions

For the past 20 yr, the co-authors' companies^c have jointly developed technologies to serve the energy industry. These technologies primarily target the light hydrocarbon boiling and condensing services. Propane chilling trains on propane/mixed-refrigerant LNG trains or C₂/C₃ fractionations and splitting services and C₃ refrigeration units are good candidates to benefit from the proprietary enhanced nucleate boiling tube technology^a. This technology^a is a dual enhanced tube promoting nucleate boiling on the shell side, while inner microfin grooves increase surface area and promote turbulence, increasing the heat transfer on the tube side (**FIG. 2**). Typical fluids are light hydrocarbons such as ethylene, ethane, propane, propylene and butane.



(/media/16488/ronka-fig-02.jpg)

FIG. 2. View of two types of proprietary heat exchanger tubes: Enhanced boiling tubes^a (left) and enhanced condensing tubes^b (right).

Case study: C₃ splitter reboiler/condenser–Open heat pump loop

A C₃ splitter unit—more accurately referred to as a propylene/propane splitter unit—is used in the separation of propane and propylene. The difference in the molecular weights of propylene and propane is small (42.08 g/mol vs. 44.1 g/mol), as is the difference in their liquid-vapor equilibrium temperatures. For example, at 12 bara, the boiling point of propane is 34.3°C, while the boiling point of propylene is 26.2°C. The difference of 8.1°C is well below 45°C, and the boiling points are also lower than 100°C. The fractionation column of such a unit will receive a feed stream where the two molecules are mixed with potential traces of heavies. The propylene will be separated from the propane and will exit in the gas phase at the top of the column, while the propane-concentrated liquid stream will leave at the bottom of the column. A reboiler will partially vaporize the stream, starting the propylene/propane separation and heating the column. Because of the very close volatility of the two components, the separation is difficult and will require many trays in the column and even several columns in series.

The propylene gas phase will generally be condensed with cooling water, and a part of the condensate will come back to the column as reflux stream. The main part of condensate will leave the unit as propylene product. The heat available in the vapor is lost to the environment. By directing the vapor to the reboiler, some heat can be saved. Nevertheless, the temperature level of the exhausting vapor is too low to ensure the heat transfer in the reboiler. It is necessary to increase the pressure of the pure propylene stream to increase its dewpoint.

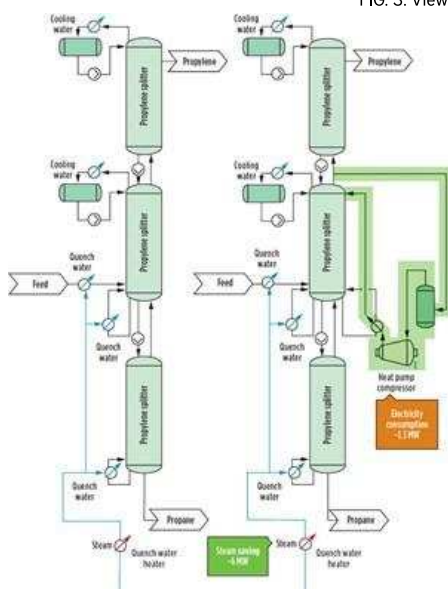
Application of a heat pump to Borealis' C₃ splitter unit at its Porvoo facility

As presented at *Hydrocarbon Processing's* International Refining and Petrochemical Conference (IRPC) EurAsia in June 2019 in Helsinki, Finland, Borealis evaluated several process schemes to upgrade the C₃ splitter unit for additional propylene production capacity at the Porvoo facility (**FIG. 3**), along with changing from chemical grade propylene (98 wt%) to polymer grade (99.5 wt%). The upgrade had to be performed within a given setup and within a limited plot space. As the reboiler and condenser duties will increase significantly, and given the shortage of quench water (already supported with steam in the existing unit) and cooling water (the cold source for the condenser) during the summer season, Borealis selected a vapor recompression heat pump scheme. The former unit was composed of three C₃ splitter columns operating in series to produce a chemical grade propylene product (**FIG. 4**).



(/media/16489/ronka-fig-03.jpg)

FIG. 3. View of Borealis' petrochemicals plant in Porvoo, Finland. Photo courtesy of Borealis.



(/media/16492/ronka-fig-04.jpg)

FIG. 4. Former C₃ splitter unit (left) and the upgraded C₃ splitter unit with a vapor recovery heat pump system (right).

The middle and bottom columns were equipped with quench water reboilers, and the middle and top columns were equipped with cooling water condensers. The middle column is larger than the other two. As mentioned, steam heating of quench water was needed to supply sufficient energy to users and to operate the reboilers.

The vapor compression heat pump had several advantages. A revamp of the existing reflux system was not needed when the heat pump system was designed to provide enough reflux. The existing condenser on the middle column was kept as the trim condenser in the case of the condensing load being higher than the duty released in the new reboiler/condenser reboiler. The existing reboiler in the middle column

required no modification, as the required additional duty is phased in through a new reboiler/condenser within the vapor recompression cycle. This scheme minimized the number of new equipment items. Furthermore, the system was able to operate without the heat pump at reduced capacity. For example, this case could occur during maintenance activities on the compressor.

The first drawback was that the new reboiler/condenser had to be located close to the middle column to allow the reboiling side to operate in thermosiphon mode. Some space was required by the heat pump housing (**FIG. 5**), and it was also necessary to power the compressor.



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FIG. 5. New compressor housing. Photo courtesy of Borealis.

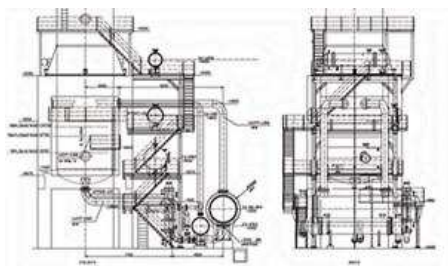
Several design options were considered when finalizing this system. The compressor head was defined to be high enough to provide reflux to the middle column. The heat pump compressor was selected to be an electric motor driven with inlet guided vanes (IGVs). In addition, the compressor design was selected to be as simple as possible. Because of cooling water temperature variation, the system was designed to work with column operating pressures ranging between 12 bara–16 bara.

The new heat pump was commissioned in 2017, with very good results. The targeted product propylene quality (99.5 wt%) and capacity were exceeded. This success was due to a good distillation tray selection and performance, heat pump design and performance, and advanced process control. Part of the heat pump performance is due to the new reboiler/condenser heat exchanger using the proprietary enhanced nucleate boiling tube technology^a.

Challenges of designing a reboiler/condenser. When installing new equipment in an existing facility, compactness is always advantageous. The selection of high-efficiency tubes minimizes the plot space requirements.

A second challenge is the piping, especially for this exchanger, as the reboiler operates in thermosiphon mode. Installation close to the column, along with well-designed piping, secure the level of performance.

Design duty is 37 MW, with a turndown of 10 MW. The logarithmic mean temperature difference (LMTD) is set to 10°C as a compromise between energy savings, compressor load and exchanger size. Using a proprietary dual enhanced tube^a allowed a single shell design to be used with the associated inlet and return piping to the column under a confined space (**FIG. 6**). As the vapor fraction on the boiling side was set to 30 wt%, a horizontal X TEMA-type exchanger was developed by the co-authors' companies (**FIG. 7**).



(/media/16490/ronka-fig-06.jpg)

FIG. 6. Reboiler/condenser installation at the bottom of the column. Photo courtesy of Borealis.



(/media/16493/ronka-fig-07.jpg)

FIG. 7. Heat exchanger leaving the factory in Austria.

When in operation, the heat pump system was reported to show savings in steam production of about 6 MW. This satisfied the goal of minimizing the heating of quench water and to avoid any investment in additional steam usage. Regarding cooling water, no extra capacity was required—thus saving some investment. In the balance, the compressor required about 1.3 MW of electricity.

Shifting energy input from steam to electricity helps in sourcing energy from renewable sources. Borealis will purchase more than 20 MW of wind power over the next decade, enabling a 13% increase in renewable power in its overall electricity consumption at its production facilities in Porvoo.

What would have been the final scheme without the co-authors’ companies technology?

The following will provide a comparison between standard tubes and the proprietary enhanced nucleate boiling tubes^a.

Usually, approved technology for this service is standard low-finned tube technology. This technology requires an increase of the heat transfer area of the tube, typically by a factor of 2–3 vs. a plain tube. If this technology is considered vs. plain tube technology, it is not necessarily better for this application for the following reasons:

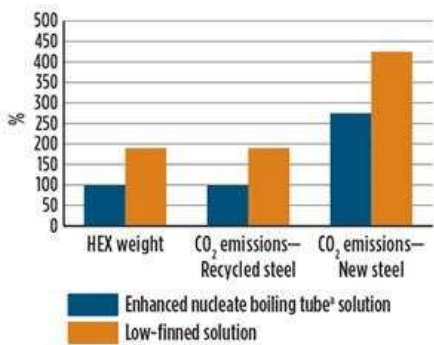
- The shell-side heat transfer coefficient is controlled by the heat flux (i.e., the difference of temperature between the cold and the hot stream). The enhanced nucleate boiling tube^a was specially developed for light hydrocarbon nucleate boiling to generate bubbles at very small temperature superheat, with minimal heat flux. The resulting heat transfer coefficient is 2× higher than the one for a low-finned tube under the conditions of this case.
- The tube-side heat transfer coefficient is the governing coefficient for this application. The enhanced nucleate boiling tube^a proposes an inner groove that increases turbulences to help disrupt the liquid film at the wall, making the area available for new vapor to be condensed. It also provides an additional heat transfer area compared to the smooth internal surface of a low-finned tube.

Because the enhanced nucleate boiling tube technology is more efficient, a design based on low-finned tubes cannot meet the same targets, making it necessary to increase the size of the equipment. TABLE 2 details two design scenarios compared to the installed one. Scenario 1 (iso duty) is a design based on 30 fins per inch (fpi) low-finned tubes, maintaining the same LMTD compared to the actual design. Scenario 2 (iso size) maintains the actual size, replacing each enhanced nucleate boiling tube^a by a 30-fpi low-finned tube and a larger LMTD. For Scenario 2, the lower heat duty must be compensated by the increase of condensing vapor pressure by +1.8 bar, resulting in a larger compression power.

Scenario 1 (iso duty): Larger size means larger CO₂ footprint

In the first case (low-finned design meeting the same heat duty), a 75% increase in tube length is required with the low-fin technology to perform the same duty. As the original solution weight is already heavy (60 t), it was mandatory to add a second shell. For some cases with multiple shell designs, the co-authors’ companies’ solutions can help reduce the number of shells, saving on capital expenditures and meeting space limitations.

For the low fin design, the authors calculated a total dry weight that was 87% higher than the actual design. As these exchangers are made of steel, the manufacturing weight is directly related to the carbon emissions during the manufacturing. The publicly available French database managed by ADEME—the French Agency for Ecological Transition—gathers several pieces of information about carbon emissions. ADEME differentiates between recycled and new carbon steel. The CO₂ emissions by 1 t of steel ranges from 0.938 (recycled steel) to 2.211 (new steel) t of CO₂ equivalent emitted, depending on the final mix of steel sources. In this case, the enhanced nucleate boiling tube^a solution saves 87% of CO₂ emissions. The impact of tube technology—the enhanced nucleate boiling tube^a vs. a low-finned tube—and the origin of steel on CO₂ emissions are shown in FIG. 8.



(/media/16491/ronka-fig-08.jpg)

FIG. 8. CO₂ equivalent emissions on mass of steel and steel mix.

Besides capital expenditure savings and minimizing CO₂ footprint, additional savings in installation costs should also be considered. A larger number of shells results in more piping (for the distribution of vapor from the compressor and condensate reflux to the column), structures and foundation concrete. In addition, for thermosiphon-based heat exchanger units with multiple shells, particular care in designing the cold-side piping to and from the column must be taken to ensure good fluid balance between the shells operating in parallel. This case also assumes that the required space for multiple shells would have been available around the column.

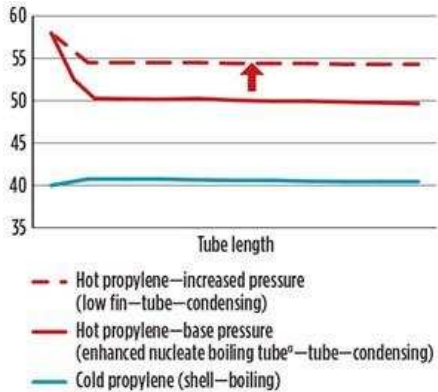
Scenario 2 (iso size): Energy efficiency supports carbon footprint reduction

The second case maintains the existing space, replacing each enhanced nucleate boiling tube^a solution with a 30-fpi low-finned tube. As the efficiency of the low-finned tube is lower, to reach the same level of heat duty, the condensing vapor temperature must be raised by increasing the pressure. TABLE 2 shows a 24% loss of duty due to the use of a low-finned tube. This can be compensated by increasing the pressure by 1.8 bar, corresponding to an increase of tube-side hot propylene condensing temperature of 3.9°C (FIG. 9).

TABLE 2. Technology impact on reboiler/condenser efficiency and size			
	Installed design: Enhanced nucleate boiling tube ^a	Scenario 1: Low-finned tube (iso duty)	Scenario 2: Low-finned tube (iso size)
Heat duty, %	100	100	76
No. of shells	1	2	1
Blank tube area, %	100	175	100
Total dry weight, %	100	187	100
Required vapor pressure increase	N/A	N/A	+1.80 bar

Notes: Basis of 100% corresponds to the values of the enhanced nucleate boiling tubes design.
Low-finned evaluation is based on a 30-Tpa carbon steel low-finned tube geometry.
Dry weights are calculated using HTS1000[®] section of A/Hanger Suite[®] software version 8.2.

(/media/16498/ronka-table-02.jpg)



(/media/16495/ronka-fig-09.jpg)

FIG. 9. Cold and hot stream temperatures in the reboiler/condenser equipped with the enhanced nucleate boiling tube^a (reference) vs. low-finned tubes (increased preBure).

The preBure increase linked to the use of the low-finned tube is proportional to the electric consumption of the comprebBor that must be provided, with approximately 26% more electric power required at the comprebBor shaft (0.34 MWel).

The comprebBor is electric motor driven. The extra carbon emiBions of this additional power when using a low-finned tube instead of the enhanced nucleate boiling tube^a will depend on the fuel mix used to supply the electricity. For various fuel sources and their specific characteristics, the extra CO₂ emiBions are calculated in **TABLE 3**, aBsuming year-round operation (8,640 hr). To make this increase of CO₂ emiBions easier to understand, the authors converted these values into kilometers driven by a car. Converted into Earth rounds, aBsuming a diesel car with average emiBions of 169 gCO₂eq/km (as per the ADEME database), this would range from 3–459 times around the Earth. A significant contributor to reduce CO₂ emiBions in the future is the use of renewable energy sources.

TABLE 3. Carbon footprint comparison vs. electricity production source				
Electricity production source	Nuclear	Gas	Coal	Wind (onshore)
Carbon emissions, kgCO ₂ eq/kWh	0.006	0.418	1.058	0.0141
Extra CO ₂ emissions, tCO ₂ eq	18	1,228	3,107	41
Earth rounds by car ^b	3	181	459	6

(/media/16499/ronka-table-03.jpg)

Takeaway

As the world faces significant environmental challenges, energy-efficiency solutions are necessary to meet reductions in carbon footprint. The co-authors’ companies have worked for more than 20 yr to develop such solutions for the energy industry. By choosing these solutions and engaging in several initiatives, Borealis intends to be a leader in energy efficiency.

The co-authors’ companies’ dual enhanced tube solutions have demonstrated their beneficial impacts vs. low-finned tubes, resulting in savings on the number of shells that must be installed and on capital expenditures. The technology also preserves natural resources, resulting in lower CO₂ emiBions during manufacturing, transportation and installation. The enhanced nucleate boiling tube^a technology has been proven to be successful in supporting the introduction of more efficient proceB schemes with heat pumps, thus lowering power consumption and reducing carbon footprints. Additionally, it fosters the shift from foBil fuels to electricity, further promoting the use of renewable energy sources in proposed solutions.

Through the installation of a vapor recompreBion heat pump system in its Porvoo facility, Borealis and the co-authors’ companies—combining market and carbon footprint objectives—have demonstrated strong capabilities to design, install and operate reliable, mature and sustainable solutions. **HP**

NOTES

- ^a Wieland GEWA-PB enhanced nucleate boiling tubes
- ^b Wieland GEWA-KS dual enhanced condensing tube
- ^c Technip Energies and Wieland Thermal Solutions: <https://www.wieland-thermalsolutions.com/en/industries/proceB-technology/cooperation-technip-wieland>

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