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PAPER TITLE: **3, 2, 1 … K, nucleation! or recent improvements in enhanced heat transfer is further reducing temperature approaches in LNG pre-cooling heat exchangers**

Abstract:
Since the first greenfield deployment for Qatargas II in 2005, the authors' dual enhanced tubes[a] have gone on to equip the precooling shell and tube exchangers for 160 Mtpa of LNG plant capacity in operation or under construction, demonstrating highest level of reliability and outstanding performances. All applications to date have been on APCI's propane precooled MR processes. In a world, which suddenly became thirsty of LNG, existing and new facilities are looking for any opportunity to push further efficiency, offering highest production rate at lowest power consumption, while decreasing carbon footprint and achieving attractive CAPEX. Wieland and Technip Energies[b] (T.EN) have engaged in a state-of-the-art development programme including a unique test bench (KoMeT-1), that can evaluate boiling performance of new surfaces at very low heat flux, particularly tuned to C3/MR precooling conditions and liquid vapor separation within the evaporator shell, generally upstream the compressor which helps to reduce the chiller size and the fluid inventory.

The paper will use operational feedback to explain how enhanced tube technology supports heat transfer performance maximization at the lowest heat flux, followed by enhanced chiller design, including entrainment. Finally, a real case study targeting to maximize LNG production will show for a C3/MR precooling chilling train, the advantage to reduce the cold approach from 3°C to 1°C. The presentation will also detail the impact on CO_2 emissions.

Paper: MLMYJPPBLR

1. Introduction

Since the first greenfield deployment for Qatargas II in 2005, the authors' dual enhanced tubes have gone on to equip the pre-cooling heat exchangers of 160 Mtpa of LNG capacity in operation or under construction, demonstrating highest level of reliability and outstanding performances. All applications to date have been on APCI's propane pre-cooled MR processes. In a world, which suddenly became thirsty of LNG, existing and new facilities are looking for any opportunity to push further efficiency, offering highest production rates at lowest power consumption, while decreasing carbon footprint and achieving attractive investment decisions (CAPEX).

To reach this level of expertise, Wieland Thermal Solutions and Technip Energies have engaged in a state-of-the-art development program that includes scientific work and dedicated product development, highly accurate test equipment with specifically adapted procedures in combination with feedback from existing operations in the field of LNG and other industrial size equipment such as e.g., Ethylene Plants and others.

This paper will describe the test equipment used and achievements made in developing dual enhanced tubes with specific heat transfer surfaces for shell and tube heat exchangers, used in the liquefaction process of LNG plants. Special attention will be paid to optimized equipment design and its positive impact on CO_2 emissions. Finally, a case study will demonstrate the advantageous impact on production capacity and beneficial operational efficiency (OPEX) by minimizing the approach temperatures.

2. Fundamental Process Scheme

The APCI-C3/MR ™ liquefaction process from Air Products combines a precooling section using propane (C3) as refrigerant with a mixed refrigerant (MR) for liquefaction. The precooling cycle ensures natural gas (NG) cooling down to approximately – 35°C while liquefaction operates from -35°C down to -160°C. The precooling cycle represents about 30 – 35% of the total refrigerant compressor shaft power and any kind of reduction or increase in efficiency would be of interest [1]. One major portion of this precooling equipment are large propane evaporators, often referred to as chilling trains, removing heat from the NG and from the condensing MR, which will be used in the liquefaction part. Typically, a chilling train is composed of three or four kettle type heat exchangers installed in series. This equipment can be very large and heavy. Every action to achieve a more compact or more efficient process will be beneficial for all actors: to the manufacturer by proposing a lighter heat exchanger with a reduced need of steel reducing the equipment carbon footprint, to the engineering, procurement and construction company

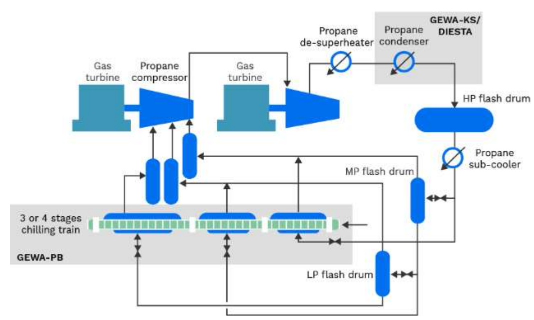

Figure 1: C3/MR Process Scheme

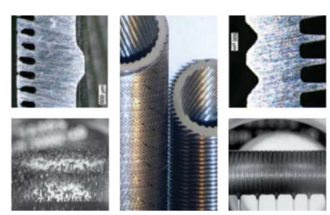

Figure 2: Enhanced Boiling & Con. Tubes

by delivering a more compact heat exchanger reducing all surroundings weight (piping, concrete, steel structure, etc.) resulting in a cheaper transport and installation and lower overall CO_2 emissions and, finally, to the operator by proposing a more efficient process scheme, i.e. a low carbon footprint per ton of liquefied natural gas.

The application of enhanced heat exchanger technology, using dual enhanced nucleate boiling tubes[a] by T.EN and Wieland has been an enormous success since the first installation in 2005. Once Qatar North Field East (NFE) will move to operation, the global LNG capacity will be more than 160 Mtpa of NG that will be precooled thanks to this technology.

3. Test Equipment at Wieland Thermal Solutions

With the support of T.EN, a unique test bench has been designed, built, and commissioned at Wieland Thermal Solutions in Germany to carry out shell side heat transfer measurements with hydrocarbons, called “KoMeT-1”. This hydrocarbon evaporation and condensation test facility is used for pool boiling measurements at very low heat fluxes, particularly tuned to the operating range of C3/MR pre-cooling conditions. Since it is not easy to receive feedback from the field, this equipment nicely allows to have an additional source of information.

3.1. Goals and Challenges

The purpose for carrying out boiling tests and collecting measurement data with hydrocarbons is:

- To describe fundamental heat transfer characteristics of enhanced nucleate boiling surfaces[a],
- To incorporate know-how in specific heat transfer correlations,
- To benefit from the use of heat transfer correlations in the design of heat exchangers for LNG pre-cooling heat exchangers,

By designing and building a unique test equipment like “KoMeT-1” several challenges had to be met. First, the safety requirements in handling explosive fluids in a factory environment had to be considered in the test rig design, building and construction and in all test procedures. Second, with the highly enhanced surfaces and the corresponding high heat transfer coefficients, measurement accuracy became more challenging than ever. In this case, electrical heating was evaluated, installed and used, which has been proven to be a reliable and practical way of heating.

3.2. Test Capabilities and Test Conditions

To comply with actual operating conditions in LNG and Ethylene production, KoMeT-1 has been setup to handle the following test range:

Fluids available:	pure fluids (C2 to C5) and mixtures with two components
Temperature range:	-30°C < T < 70 °C
Operating Pressure:	maximum of 50 bar

Table 1: Test Conditions

3.3. Safety


Figure 3:KoMeT1 Test Facility

Based on many years of experience with pressurized test facilities using synthetic refrigerants, which are widely used in Air Conditioning and Refrigeration applications, the new challenge was to deal with flammable and potentially explosive atmospheres. For that reason, the test concept has been designed to a fluid volume of less than 500 g of hydrocarbons. The entire test facility is positioned in a dedicated room with additional precautions, e.g. an encapsulated “bell”, which covers the test chamber and is working under vacuum conditions. Additional equipment is in accordance with the European Directive to work with “Equipment for potentially explosive atmospheres (ATEX). If there is an issue with any kind of leakage or a too high system pressure, the safety procedures will immediately release an acoustic alarm and an emergency program will be initiated. Amongst other aspects, this includes a controlled release of the test fluid and purging with nitrogen before opening the test chamber. The equipment and test procedures have been certified by an independent third party, TÜV Süd in Germany.

3.4. Procedure of Experimental Measurements

To achieve accurate test data, it was mandatory to work on a dedicated procedure for preparing test specimen and to ensure repeatability regarding all operating conditions, particularly when measurements at low wall to saturation temperature differences are conducted. To support this, measurements have been fully automized and the data acquisition and software has been tailored to the necessary requirements. Thus, the following parameters are safely collected for boiling tests:

- Wall temperature (PT-100) in several locations
- Liquid and gas phase bulk temperature (PT-100)
- Pressure in gas phase
- Electric power to calculate heat flux

3.5. Test Results for Shell Side Boiling

The following paragraph will briefly describe propane shell side boiling characteristics of plain and enhanced surfaces.

Initial measurements have been carried out with plain tubes and results have been thoroughly reviewed and compared with literature, confirming proper functioning of KoMeT-1 test facility. An important lesson has been that experimental data and available correlations from literature vary significantly. One main reason for this is the tube surface roughness, which depends on the material and on the manufacturing process. The heat transfer performance measured for plain tubes met expectations and it has been proven that the shell side pool boiling heat transfer coefficient (ho) versus heat flux is dependant of the saturation temperature – test results are shown in **FIG 4**. It has been confirmed that "ho" increases steadily with increasing heat flux. When the saturation temperature is increasing, the curve shifts to higher levels. This behaviour is in well agreement with experimental data and correlations from literature.

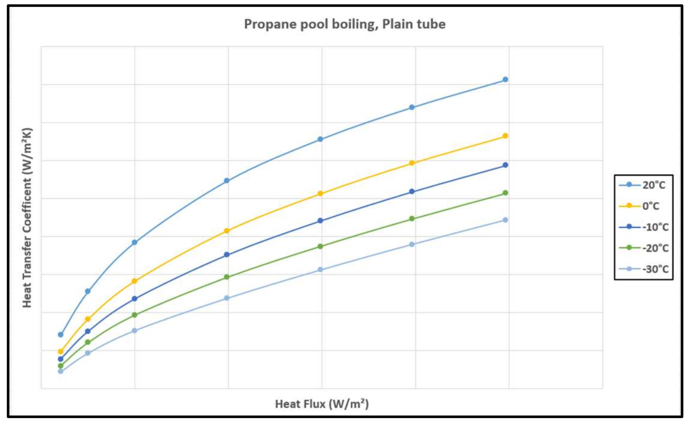

Figure 4: Pool Boiling of Propane on Carbon Steel Tube

FIG. 5 compares propane pool boiling heat transfer coefficient of a carbon steel plain tube to a carbon steel dual enhanced nucleate boiling tube[a] at the same test conditions. With specific enhancements for boiling, the shell side heat transfer can be substantially increased. One key advantage of Wieland enhanced surfaces is the specific improvement of the boiling heat transfer coefficient at low heat fluxes (respectively wall superheat temperatures). This is very important for the design of most compact and efficient refrigerant chillers and reboilers.

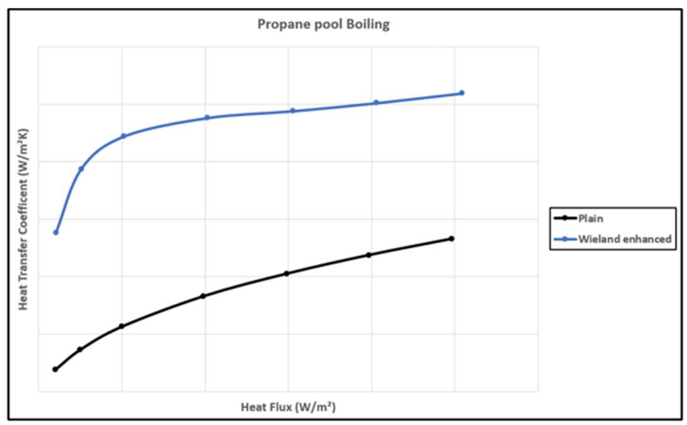

Figure 5: Pool boiling performance of plain tube vs. Wieland enhanced nucleate boiling tube (GEWA-PB)

FIG. 7 shows nucleate boiling characteristics of an enhanced boiling tube[a] versus a low fin tube at the same wall superheat of 2K. It is well noticeable that enhanced surfaces have significantly better performance, and the number of nucleate boiling formation is by far higher than for low fin surfaces. Even at extremely low wall to saturation temperature differences the enhanced surfaces still perform, and nucleate boiling is still active at a wall superheat of as low as 0.16 K – see **FIG. 6**.

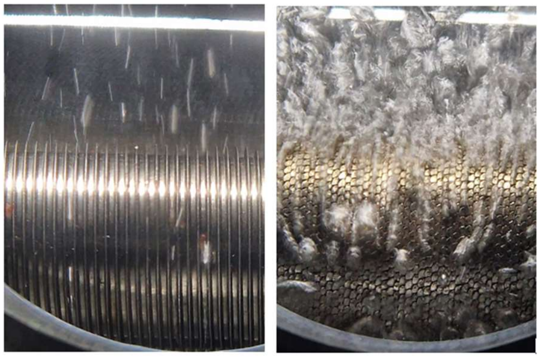

Figure 7: Boiling at 0°C of propane with 2K wall superheat. Left 30fpi low fin tube, right Wieland enhanced boiling tube (GEWA-PB)

Figure 6: Boiling at 0°C of propane with 0.16K wall superheat on Wieland enhanced boiling tube (GEWA-PB)

3.6. Tube Side Heat Transfer

For a balanced heat transfer characteristic between shell- and tube sides, an additional tube internal enhancement for gas cooling, condensation and subcooling is the most preferred if not mandatory option. Although this paper focuses on shell side heat transfer characteristics, it should be mentioned that tube side enhancements further improve the overall heat transfer coefficient by a more balanced distribution of the heat transfer resistance between the out-and inside.

4. Heat Exchanger Design Aspects

Propane chillers are one pass design as the tube side stream (NG or MR) operates in series. On the kettle – shell side, different levels of pressures will set the corresponding propane boiling temperatures.
Because of this, the heat flux will vary from tube inlet to outlet. For instance, considering a high pressure (HP) stage propane chiller for a project located in Gulf of Mexico environment, we have the following conditions:

Propane boiling temperature = 17°C	**NG temperature (°C)**	**Temperature difference (°C)**
NG Inlet side	33	16
NG outlet side	20	3

Table 2: Operating Conditions

Considering the difference in heat flux from inlet to outlet, the vapour production is directly proportional to the temperature difference, thus about five times more vapour will be generated at the heat exchanger inlet. This will also result in a very heterogeneous entrainment behaviour, which raises the question of how to manage liquid carryover issues. Typically, the following methods are used to avoid difficulties:

- Divide the kettle length into different parts and determine the diameter based on the most stringent portion. This method relies on gravity only and is very conservative.
- Adapt the nozzle sizes and locations along the kettle to the local vapor production to perform efficient vapor removal and avoid local congestion. This method can help to prevent from generating overloading zones versus underloading zones and avoid transversal vapor acceleration due to congestion. An average behaviour can then be considered to determine the kettle diameter based on average actual and critical entrainment velocities. Nevertheless, this method results in complex and non-symmetrical piping connections to the kettle with complex stress analysis.
- Consider the use of mist eliminators, installed horizontally and perpendicular to the ascending to the ascendent vapor flow. This presents the advantage of forcing the vapor along the kettle prior to reaching the exhaust nozzles. The definition of wire mesh design as well as the need of a perforated plate are based on the local vapor flow velocity. A Computational Fluid Dynamics (CFD) study may be required to confirm the right positioning of the mesh. A point of attention is also the disengagement space above the wire mesh to the nozzle to limit pressure drop and ensure the best efficiency of the wire mesh. This method is interesting as it makes the nozzle location independent from the vapor flow generation because of to the wire mesh stabilization effect.

Moving from plain to low fin tubes and finally to dual enhanced nucleate boiling tubes[a] results in lighter and more economic chillers by making them substantially (up to 50 % shorter). When entrainment control relies on gravity only, it would mean that the volume for liquid vapor separation shall be maintained to keep ascending velocity at the same level, but as the heat exchanger length decreases, diameter shall be increased. The diameter increase has a direct consequence on the inventory and the safety of the equipment. Reducing the diameter will ensure a limited propane inventory as well as a safer design as the size of the pressure vessel is smaller.
Furthermore, using dual enhanced nucleate boiling tubes[a] in a kettle, designed with separation methods based on gravity only, would be like installing a formula one motor in a car designed half century ago. This is why T.EN and Wieland developed enhanced chillers to combine the best in class boiling tube technology with the best in class kettle design and achieving the most compact technology resulting in a very low weight and associated CO_2 emissions.

4.1. Liquid Separation in Chillers With Mist Eliminators

Chillers used in propane precooling cycles of an LNG plant are based on shell and tube heat exchanger technology known as kettle type (K type as per TEMA nomenclature). The purpose of a kettle is to vaporize a liquid but also to ensure the elimination of a portion of droplets in the produced vapor to ensure proper and safe work of the associated compressor. Thus, a maximum quantity of liquid per unit mass of vapor is requested to the kettle designer. This defines the entrainment which is given either in percent or in kg of liquid per kg of vapor (1% means 0.01 kg of liquid per kg of vapor at exhaust). It should be noted that entrainment deals with total quantity of liquid only, not with the size of droplets.

The entrainment phenomenon will thus play an important role in designing a kettle and shall be well understood.

As described in **FIG. 8**, a kettle reboiler is composed of a tube bundle, with the hot fluid flowing inside of the tube, inserted into an enlarged shell that serves as a reservoir and boiling pool of the cold fluid (the refrigerant) and as a disengaging space for large liquid droplets. When the fluid in the tubes is hot enough, the liquid in the shell boils and vapor is generated. Because of the density difference, the two-phase mixtures circulate across the bundle, the liquid flowing downward in the shell and the wet vapor rising in the vapor space.

When the two-phase flow arrives near the pool surface, "splashing" phenomenon throws liquid droplets into the vapor space. One part composed of large droplets falls back into the pool due to higher gravity force and another part composed of smaller droplets is taken away by the vapor phase, this last phenomenon is called "entrainment".

Nowadays, the entrainment prediction is very complicated because a lot of research deals with the forming of liquid droplets but only a few studies treat the droplet mass distribution measurement and droplet initial velocity over the phase separation from the vapor-liquid interface.

Among several references, e.g., HTRI®, a very well-known research organization in the energy field, has developed proprietary correlations [2] & [3] to predict the entrainment ratios. They explain the relation between the entrainment ratio and the vapor velocity. This vapor velocity is a combination between the produced vapor flow and the actual kettle geometry.

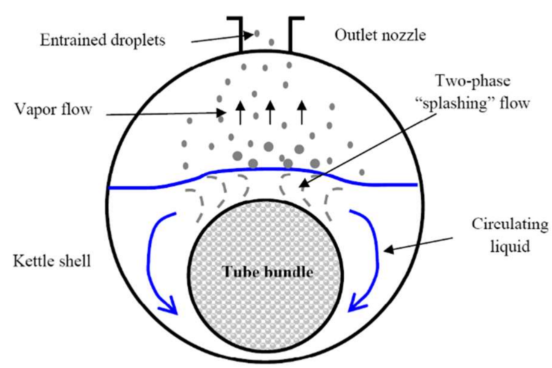

Figure 8: Cross section of kettle reboiler

This velocity is compared to the critical entrainment velocity (V_{cr}) which was obtained by semi-empirical and theoretical approaches. This critical entrainment velocity defines a velocity threshold above which, shear forces balance gravity force and droplets are entrained by the vapor flow. To calculate this critical entrainment velocity, entrainment ratio, vapor flow rate and physical properties are required. The kettle diameter is determined by iterative steps.

Many heat exchangers have been designed with these methods. However, small droplets are very difficult to remove with the gravity settling only because they are entrained with a very low vapor velocity. Therefore, if a very low entrainment ratio is desired, volume must be increased until phase separation is ensured. If the tube length of the tube bundle is fixed by the heat transfer, then the diameter of the kettle will have to be increased.

To reduce the kettle diameter, mist eliminators are usually used. Two types of mist eliminators are applicable in such case, called wire mesh and vane. Wire mesh and vane devices employ the same mechanism known as inertial impaction and thus are subject to the same basic design rules. Inside wire mesh and vane, little droplets coalesce to form droplets large enough to separate from vapor by gravity settlement.

Koch-Glitsch DEMISTER® style 709 [4]

Figure 9: Typical mesh-type mist eliminator pad.

Koch-Glitsch FLEXICHEVRON® style VIII [4]

Figure 10: Mist eliminator with chevron type vanes.

The throughput capacity of a wire mesh or vane mist eliminator is limited by balancing two related phenomena: flooding (choking with liquid) and re-entrainment (dislodging, suspension, and escape of coalesced droplets).
The gas-liquid separation is guaranteed by maintaining the gas velocity below the maximum recommended gas velocity. The Souders-Brown equation is widely used in sizing a wire mesh or vane mist eliminator.

$$V_G = K\sqrt{\frac{\rho_L - \rho_G}{\rho_G}}$$

V_G gas velocity (m²/s); K vapor load velocity (m²/s),
ρ_L liquid density (Kg/m³), ρ_G gas density (Kg/m³)

Standard K values (m/s)	Vertical flow	Horizontal flow
Mesh	0.107	0.128
Vane	0.152	0.198
Vane double pocket	0.305	0.305

Table 3: Standard K values

The removal efficiency of mist extractor is typically 99% of liquid droplets larger than 3-10µm for wire mesh and 10-40µm for vane types. For wire mesh, efficiency can be achieved by changing the mesh thickness, the density of the pad and the diameter and material of the wire. For vane mist extractor, plate depth, spacing, number of turns and material can be varied to meet the required removal efficiency.

4.2. Smart Enhanced Chiller (S.E.C)

S.E.C. designs represent the most compact heat exchanger design with the lowest charge of refrigerant as well as the smallest volume to ensure specified entrainment behaviour to protect the compressor. The patented S.E.C design relies on a smart use and positioning of mist eliminators combined with a deflector plate. This design presents several advantages compared to standard horizontal mist eliminator installation:

- The needed space to meet the Souders-Brown velocity is now optimized within a smaller volume.
- The combination of the two main types of mist eliminators, wire mesh with vane pack proposes higher efficiency compared to single wire mesh in horizontal installation. Furthermore, coalesced droplets are directed downward to the deflector plate and the liquid propane is drained back to the pool. Thus, the coalesced droplets are not drained counterflow of the ascending vapor stream, reducing the risk of re-entrainment.
- Finally, a deflector plate is installed at the bottom to drive the vapor all around the mist eliminator and ensuring that vapor flow is well distributed. CFD studies were conducted to secure the design which has been confirmed by several mist eliminator vendors. It shall be noted that, compared to standard plain or low finned tubes, dual enhanced nucleate boiling tubes[a] do not need to be flooded to operate at the maximum efficiency, they just need to maintain a wet surface, which can be ensured by being in the foam region. Liquid level can thus be set up lower than for a standard kettle without impacting the cooling effect on tube side. This has been confirmed by numerous site references.
- Applied mist eliminator technologies are well known and proven technologies already in service in our industries. Depending on process conditions, the S.E.C. may reduce the number of inlet and outlet nozzles on the shell side to one each.

Ultimately, S.E.C. designs lead to compact heat exchangers with economic advantages and reduced carbon footprint by reducing the material used, e.g. piping, steel construction, foundation etc.

The design of a S.E.C. solution is done using CFD performed by T.EN. All in-house designs are validated by a recognized manufacturer of mist eliminator. To illustrate today's CFD capabilities, **FIG. 11** shows the velocity field in the dome of a chiller equipped with a horizontal mesh and an inlet distributor.

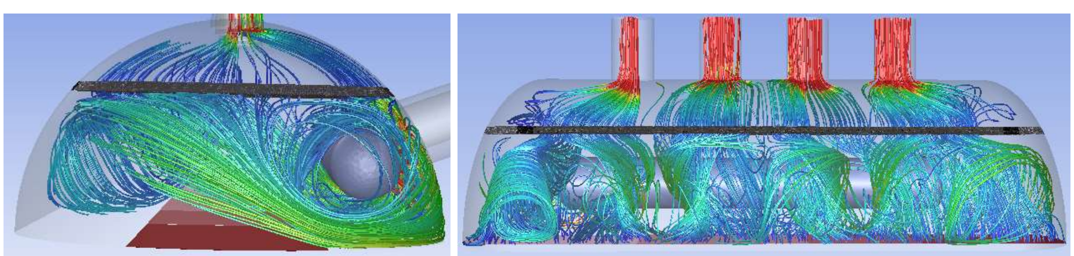

Figure 11: CFD study results on horizontal mesh.

FIG. 12 compares the conventional sizing method with a smart enhanced chiller design for a MR train with a 2K approach temperature. The kettle diameter reduction can be up to a factor of two for the stages at the highest pressure.

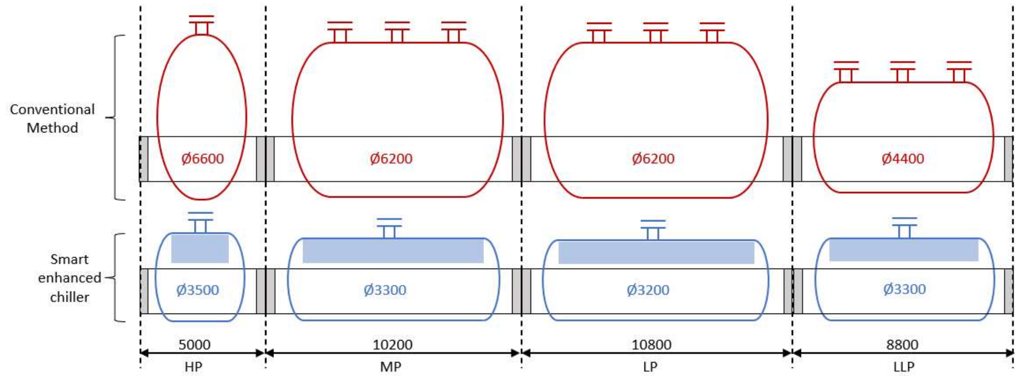

Figure 12: Impact of disengagement method: "Conventional method" vs "Smart Enhanced Chiller" (e.g. MR Chilling train at 2K approach design with GEWA PB tube)

5. CASE STUDY – FROM 3K TO 1K TEMPERATURE APPROACH

Main precooling cycles in operation in the world have been designed using 3K temperature approach, meaning the difference between the outlet FG or MR temperature and the propane boiling temperature of the corresponding chiller.

A generic case has been developed to evaluate precooling cycle performances for three different temperature approaches on propane vaporizers (3K, 2K and 1K), to demonstrate the capability and to show the advantages of the dual enhanced tube technology[a] combined with the S.E.C. design in the improvement of performance of a LNG plant, the efficiency saving on the refrigeration loop and the positive impact on the CO_2 emissions. The generic case is based on a single LNG train of 5 Mtpa LNG production using C3/MR technology, refrigeration compressors being lined-up as per the split-MR configuration (HP compression stage of the MR cycle being on the same shaft as the propane compressor to have the same drivers on the two different shafts, **FIG.13**).

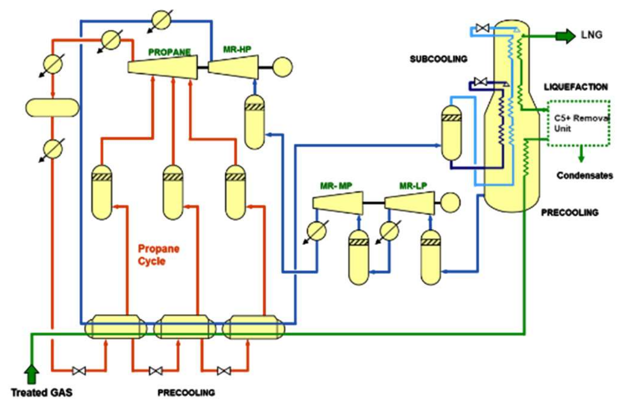

Figure 13: Split-MR liquefaction typical configuration.

The propane loop (precooling cycle) is composed by 4 stages (HP, MP, LP and LLP stages) on both natural gas and mixed refrigerant circuits. The LNG train is air cooled and ambient conditions are based on US Gulf Coast.

Several aspects have been studied first, a technology comparison based on identical refrigeration cycle performances at 3K approach, second, a propane compressor power evaluation at 3K/2K/1K temperature approach with propane vaporizers based on S.E.C. concept and equipped with dual enhanced nucleate boiling tube technology[a], and finally, an LNG production capacity assessment combining propane compressor power saving and dual enhanced nucleate boiling tubes[a] applied to grassroot and revamp projects.

5.1. From Conventional to Smart Enhanced Chiller Design

The first study, based on 3 K approach temperature, confirms the already well-known benefit, with numerous references worldwide, on the chilling train characteristics of using S.E.C. equipped with dual enhanced nucleate boiling tubes[a] compared to the conventional low finned tube-based design (26fpi low fin tube), see **FIG. 14**.

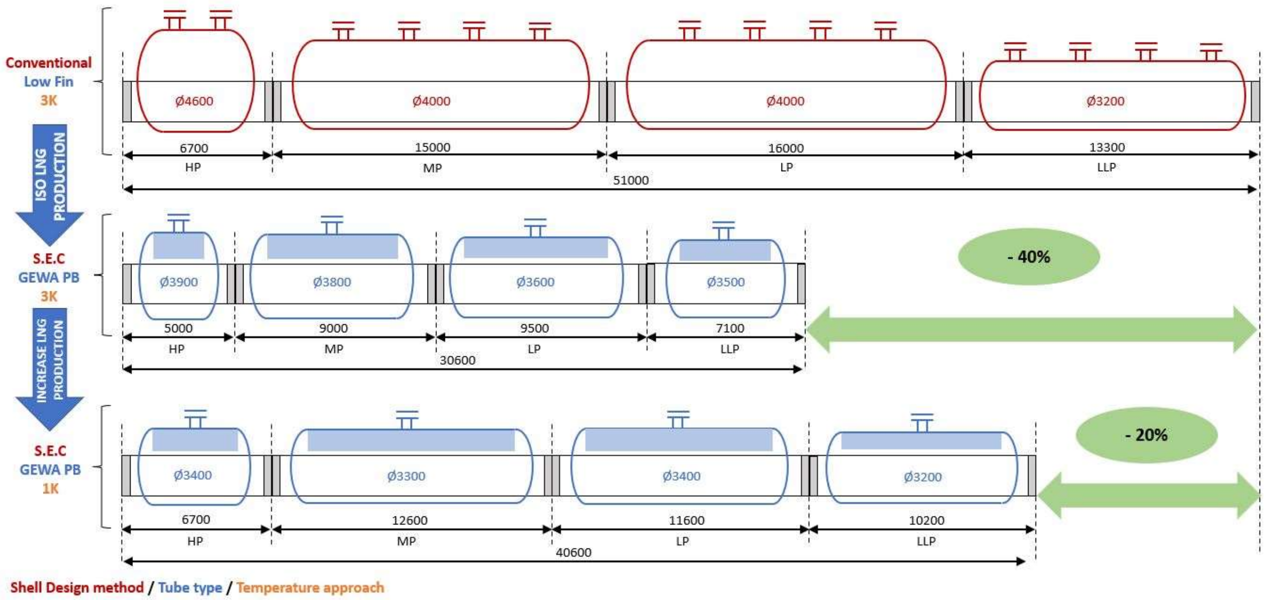

Figure 14: MR chilling train: dimensions comparisons between low fin tubes at 3K approach vs GEWA PB tubes at 3K and 1K approaches; carbon steel tube material

For identical operating process conditions, C3 vaporizers of FG and MR trains, designed with S.E.C. and dual enhanced nucleate boiling tubes[a], are shorter by about 40% and lighter with a direct positive impact on the weights of piping, concrete for foundation, and steel for structure. Furthermore, the size reduction of the exchangers results in a CO_2 emission reduction during the manufacturing phase of about 40% compared to standard low finned tube chillers carbon footprint; additional savings of CO_2 for surrounding equipment can be added to this value.

Focusing on the chiller dimensions, the compactness of the dual enhanced vaporizer has an impact on the kettle size for a same liquid/vapor entrainment ratio, leading to higher kettle diameter when it designs with the industry conventional method. Smart Enhanced Chiller design gives an advantage on the kettle diameter, reducing considerably the dimension compared to conventional method as detailed in **Table 4**.

Pressure Level	Industry conventional design Low Finned Tubes		Smart enhanced chiller design GEWA-PB tubes	
	Kettle diameter, mm	Tube length, m	Kettle diameter, mm	Tube length, m
HP	4600	6.7	3900	5
MP	4000	15	3800	9
LP	4000	16	3600	9.5
LLP	3200	13.3	3500	7.1

Table 4: Kettle diameter comparison at 3K approach for C3/MR chilling train

5.2.Lowering Temperature Approach to Temper Energy Consumption and CO_2 Emissions

As already shared, in a liquefaction unit, 30 to 35% of the total power of refrigeration is dedicated to the precooling section. Duty of propane compressor being defined by the temperature approach on both propane vaporizers and propane condenser, one way to improve the efficiency of the refrigeration cycle is to reduce compression ratio by reducing these temperature approaches.

Nowadays, the industry is moving to 2K temperature approach in the chilling trains. Nevertheless, with conventional "Low Fin Design", the heat transfer performance decreases substantially and the use at temperature approaches lower than 3K becomes inefficient. Dual enhanced nucleate boiling surfaces[a] become a mandatory technology to enhance nucleation as shown on **FIG. 6 & 7**.

The changes from 3K to 2K and from 3K to 1K approach on propane vaporizers, with identical LNG production capacity, improve the propane refrigeration cycle efficiency by 2.2 % and 4.4% respectively, reducing the CO_2 emission by the same amounts by reducing the fuel gas consumption.

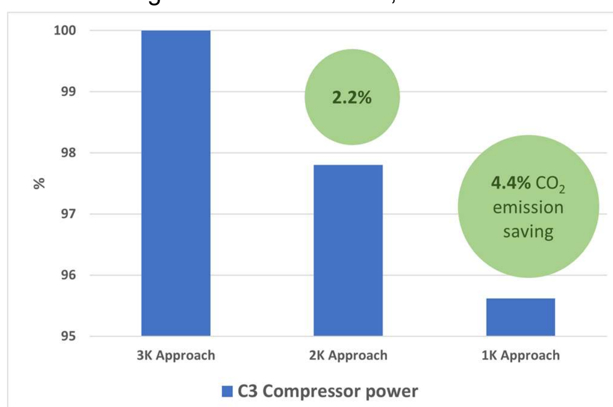

Figure 15: C3-Compressor power and emission savings

5.3. Applications to the Revamping of a Chilling Train

Two configurations were studied:

- Replacing the chilling trains with new and more compact chillers to increase LNG production by lowering the temperature approach or,
- Replacing the chillers but maintaining their overall dimensions and increasing the LNG production by lowering the temperature approach.

Both routes are explored here after.

5.3.1. Combination of Compact Chilling Trains With Low Temperature Approach

In paragraph 5.2, the reduction of temperature approach to 1K allows a power reduction of the propane compressor by 4.4%. This available extra power can be used to increase the LNG production and in the frame of that study case, this corresponds to an increase in the range of 1 to 2% of the LNG production. This is due to the split-MR configuration (**FIG.13**), additional power from the MR compressor is transferred on the propane compressor shaft line. From a geometry point of view, considering the dual enhanced tube technology, the needed heat transfer area for 1K approach is logically higher than to 3K approach due to a lower mean temperature difference (MTD) and a lower heat transfer coefficient as the heat flux is decreased too. Nevertheless, overall chilling train length still remains 20% lower than the conventional finned tubes design which produces less LNG at 3K approach (**FIG. 14**).

5.3.2. Maintain Chilling Train Dimensions With Low Temperature Approach

The second option that was explored is to maintain the overall length of the former chilling train which has been exploited by a tube-to-tube replacing and to apply a reduction of temperature approach in the range of 1K.
By adjusting temperature approach on propane vaporizer based on the maximum available efficiency of propane cycle, about 1% additional LNG production is expected with smaller or close kettle dimensions compared to conventional low finned solution (**Table 5**). This will minimize the impact on the surroundings.

Pressure Level	Industry conventional design Low Finned Solution		Smart enhanced chiller design GEWA-PB solution	
	FG	MR	FG	MR
	Kettle diameter, mm	Kettle diameter, mm	Kettle diameter, mm	Kettle diameter, mm
HP	2500	4600	2400	3400
MP	2400	4000	2400	3200
LP	2300	4000	2300	3200
LLP	2200	3200	2300	3100

Table 5: Kettle diameter comparison at identical length for FG and MR chilling trains

5.4. Overview of Carbon Dioxide Emissions

Carbon dioxide emissions during equipment manufacturing is mainly proportional to the material weight: less material there is, less CO_2 emissions there are. Based on former studies [5] the CO_2 emissions of heat exchangers has been focusing on scope 3 emissions, according to the Greenhouse Gas Protocol [6].

For an expected LNG capacity production at identical temperature approach, the change from conventional chiller design equipped with low finned tubes to S.E.C. design equipped with dual enhanced nucleate boiling tubes[a] leads to a vaporizer weight reduction close to 45%, reducing manufacturing CO_2 emission by about 40%. Considering a reduced temperature approach from 3K to 1K, if the material weight and CO_2 emissions from exchanger manufacturing remain lower from conventional chiller design equipped with low finned tube solution at 3K temperature approach by 15% and 8% respectively, it shall be noted that propane compressor energy consumption is lowered by 4.4%.

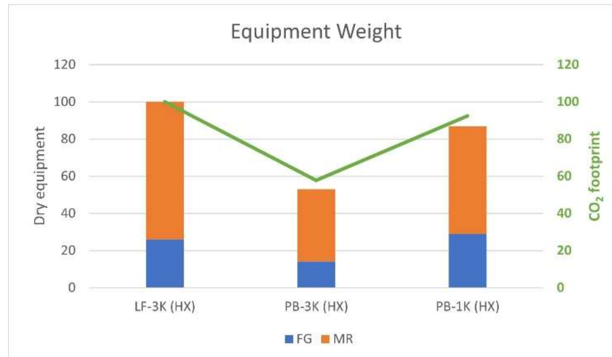

Figure 16: Compressor power and CO_2 emissions saving by using GEWA PB at different temperature approaches.

In the case that this compressor is driven by a gas turbine without CO_2 capture, it is about 4.4% less CO_2 emissions that are recorded. At the liquefaction unit level, it is a CO_2 emission reduction of 1.1% considering that propane compressor power represents 33% about of the whole energy consumption of this unit.

6.TAKEAWAY

Over the last 25 years, Technip Energies and Wieland Thermal Solutions have pursued a constant effort to bring the most energy efficient technology to the propane precooling cycle of LNG plants. This effort was converted in success by numerous trains in operation all around the world.

First, the development of a deep knowledge in boiling mechanisms was supported by the two actors by continuous technology and research watch and, mainly by the decision to get an independent and unique asset for pushing in their limits the developed technologies. This was the funding of the KoMeT-1 test loop. Being able to perform measurements at very low heat fluxes, in a safe and controlled environment, and to complement them by site information have strengthened the dual enhanced tube technology[a] as well as its acceptance by the market.

Second, Smart Enhanced Chiller concept has been progressively developed to ensure the most efficient liquid vapor separation in the smallest volume. Over the years, the design was patiently shaped and carved combining the best separation technologies, numerical simulation tools such as Computational Fluid Dynamics with site feedbacks.

Finally, all these technologies and concepts are combined in a unique high performing heat exchanger dedicated to propane precooling cycle. The reduction of the temperature approach is a key parameter to save energy and to reduce CO_2 emissions of the cycle. Whether with a temperature approach of 3K, 2K or 1K, dual enhanced tube performances allow to get a more compact design than with conventional low finned tubes, in terms of overall dimensions and weight to produce the same LNG capacity.

Temperance of the CO_2 emissions of the liquefaction unit or additional LNG production are both paths that become available by considering lower temperature approach on propane vaporizers. If an optimization is envisaged on other loop locations (e.g air coolers), total refrigeration loop performance can still be pushed to a higher efficiency level.

7.NOTES:

[a] Wieland GEWA-PB enhanced nucleate boiling tubes

[b] Technip Energies and Wieland Thermal Solutions: https://www.wieland.com/en/solutions/energy/cooperation-technip-energies-wieland

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