Lasers in Manufacturing Conference 2021

Laser texturing of heat exchanger tubes for nucleate boiling regime promotion

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Abstract

Titanium tubes of 16 mm diameter and 0.8 mm thickness, were textured using a cw, single mode, 1070 nm fibre laser. The laser beam was guided by a galvanometer scanner. Textures of homogeneous, parallel grooves of 60-80 µm width and 70-110 µm depth were generated on the exterior tubular surface. A wide range of parameters: laser power, laser speed, tube rotating speed or focal distance was studied to improve the homogeneity of the generated textures. These tubes were later tested in both controlled and industrial environments, along with non-textured tubes, and their heat transfer behaviour was analyzed under an ammonia nucleate boiling regime. Results indicate that laser textured tubes show a consistent increase of 60 % of their heat transfer coefficient, when compared to original smooth tubes. These results prove that laser texturing is a suitable technique to significantly increase performance of heat exchangers that work under nucleate boiling regime

Keywords: Laser texturing; heat exchanger; nucleate boiling; continuous wave; tubular surfaces; microprocessing;

1. Introduction

A responsible use of the energy is a subject that the global population is more concerned about each day. The position of the European Commission on this topic is clear: saving up to 10 % in energy for 2030. In order to achieve this goal, it is critical to optimize all operations of the industry that involve transforming energy into heat, which implies improving the efficiency of thermal systems. Heat exchangers are devices created

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for transferring thermal energy between two fluids. The most common systems used in the industry are shell-tube heat exchangers, while boiling is often selected as the mode for heat dissipation due to the high rate of heat transfer associated with it. Improving the efficiency of these shell-tube boilers means enhancing the global heat transmission coefficient through the tubes surface.

Depending on the temperature difference between the fluids, the heat exchanger will be working under a certain boiling regime, which significantly affects its efficiency. These regimes are explained below and represented in Fig. 1.

- Pure liquid: in this phase, the liquid close to the wall slightly superheats, evaporating in the interface between liquid and gas. Heat is transferred purely by convection.
- Nucleate boiling: the most important region in technical applications. The superheated liquid forms vapor bubbles that collapse when contacting sub cooled refrigerant liquid. These bubbles generate an additional turbulence that significantly increases the heat transfer, which raises with the temperature difference of the two working fluids until reaching the critical heat flux. In this regime, the heat transfer coefficient attains its maximum value.
- Transition or partial film boiling: large bubbles form partial vapor films on the tubes surface, acting as an insulant. Increasing the temperature difference enlarges these partial films, decreasing the heat transfer.
- Stable film boiling: a vapor film completely covers the overheated wall. Further increasing the temperature difference also increases the heat transfer due to radiation.

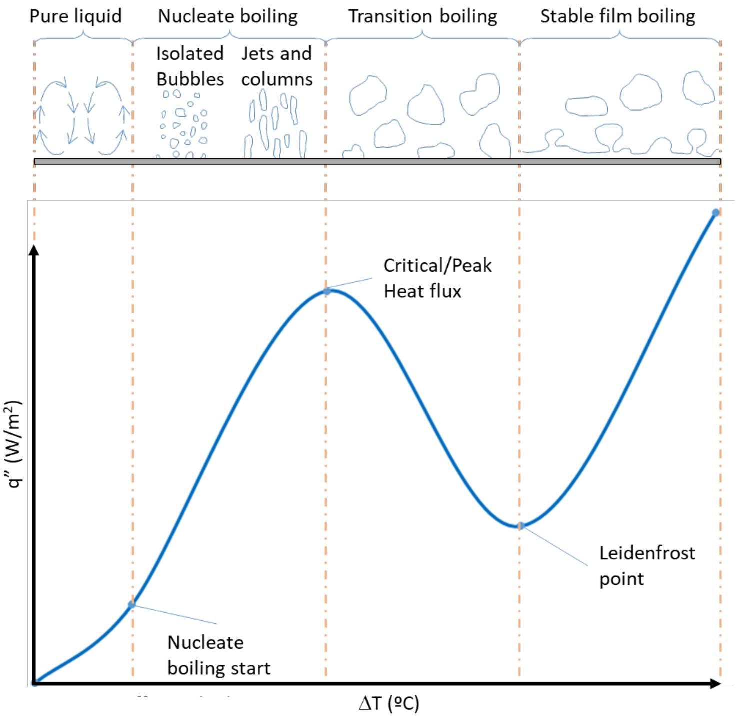

Fig. 1. Different boiling regimes

Due to its high heat transfer coefficient, many researchers have been studying for the past decades finding that mechanically generating artificial microstructures on the heating surface, such as micro cavities or grooves, is a suitable way of reducing the temperature difference required for the nucleate boiling to start [1,2]. Other researchers have already demonstrated the potential of laser textured surfaces for enhanced boiling heat transfer in laboratory environments by using pulsed laser sources [3].

In this work, a continuous wave laser system was used to generate micro grooves on the tubes outer surface in a radial disposition. Grooves generation on metallic surfaces with a continuous wave fiber laser is based on using a combination of a scan head at high speeds and a laser source able to provide enough energy density so the metal melts within the few microseconds that the laser beam stays on the same spot. This can generate an overpressure in the molten pool that causes the ejection of the molten material, creating a groove within the range of several tens of microns depth along the laser beam path and a width larger than the beam spot size. This is the limitation of this system: the size range of the features that can be achieved will be within a few tens to hundreds of microns. However, this limitation is not an inconvenient for the generation of nucleate boiling promotion surfaces, as other authors have already established that grooves with sizes within the range of hundreds of microns or even few millimeters can significantly enhance this boiling regime [4]. Particularly, Okamoto et al [5] have reported an increase of 40% of the heat transfer of titanium plates with 30 µm deep and 100 µm wide grooves working with ammonia and seawater in nucleate boiling regimes. However, the rest of the literature cited in this work seems to indicate that high aspect ratio grooves would yield a better efficiency than wider, more shallow grooves.

The textured areas were evaluated by means of confocal microscopy and scanning electron microscopy in order to determine their depth, width and heat affected zone. Corrosion resistance of the textured areas was also analyzed.

The tubes were later tested in a controlled laboratory environment and in an industrial heat exchanger. In both cases, the heat exchanger was a tube-shell type. The heat transfer coefficient of these tubes was determined and compared to that of non-textured tubes.

2. Experimental method

2.1. Laser texturing

All experiments were performed with a continuous wave fiber laser (Rofin FL 015 C) of 1070 nm wavelength. An IntelliSCAN 25 galvanometer scan head with a 163 mm FL theta objective was used to direct the laser beam, with speeds up to 10 m/s.

The tubes used in the experiments were grade 2 titanium of 16 mm outer diameter, 0.8 mm thickness, 1 m long for the laboratory environment testing and 2 m long for the industrial environment testing.

The tubes were mounted on an aligned system with three self-centered positioners and a spindle motor was used to rotate the tubes at speeds up to 2.000 RPM. The scan head was moved along the tube’s length, at a fixed height, by a REIS gantry robot that provides 35 µm resolution and a workspace of 6x2x1.5 m. Fig. 2 shows a schematic image of this experimental setup.

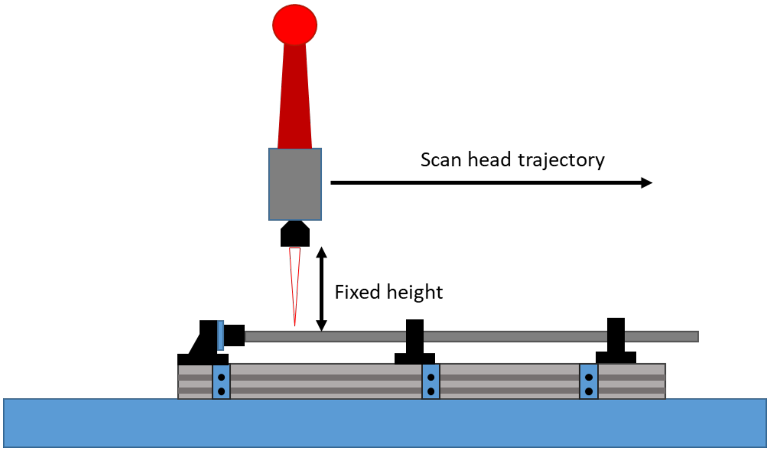

Fig. 2. Laser texturing setup.

A wide range of process parameters was tested in order to evaluate their influence on the resulting micro grooves morphology. These parameters are shown in Table 1:

Table 1. Range of parameters used for micro grooves generation.

Parameter	Value range
Laser Power	500-1,500 W
Relative laser speed	5-10 m/s
Number of passes	1-7
Rotation speed	0-2,000 RPM
Max. defocus due to tubes curvature	0-8 mm

First, we performed a study of the parameter window of laser power and speed suitable for the generation of grooves on grade 2 titanium flat samples.

The selected parameters were later used for generating the grooves on tubular surfaces according to the following procedure: The scan head would scan short lines of a few millimeters length in the direction perpendicular to the tube's length, separated 200 µm from each other. The scan head was synchronized with the tube rotation in such way that every 1, 2, 4 or 8 turns of the tube, one groove would be textured around the perimeter. Depending on the lines length, the maximum defocus due to the tubes curvature varies, increasing with the length up to a maximum of 8 mm, the radius of the tube. Different number of laser passes, tube rotation speeds and length of the textured lines were tested. This texturing method is schematized in Fig. 3.

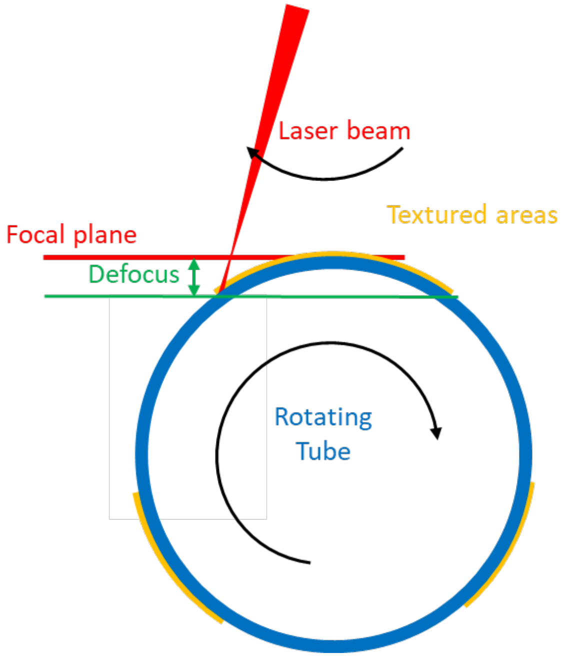

Fig. 3. Laser texturing method for tubular surfaces.

2.2. Surface characterization

A Neox confocal microscope from Sensofar was used to analyze the textures topography, with an objective that provided <1 µm resolution. Nine random measurements were performed per each textured tube, in order

Textured samples were cut and scanning electron microscopy was used to determine any phase change that may happen in the vicinity of the laser trajectory, as well as the depth of the heat affected zone.

Finally, a tube with different textures was introduced into a salt spray chamber for 500 hours. The corrosion of the textured zones was compared against each other and to a non-textured area.

2.3. Heat transfer evaluation

Once textured, the titanium tubes were cleaned with pressurized water, removing the metallic dust that was deposited on them during the process.

The tubes were then mounted in the controlled and industrial test systems with shell-tube heat exchangers. In these exchangers, seawater flows by the interior of the tubes and is cooled by the boiling ammonia in the shell.

The controlled heat exchanger was manufactured by INTEGASA and accommodates 6 tubes of one meter length. Five experiments were performed both with textured and non-textured tubes. This system offers a closed loop control, in such way that the inlet and outlet pressures and temperatures of the seawater are monitored, and the inlet pressure of the ammonia is controlled to keep the temperature difference between the seawater and the boiling ammonia constant, in order to perform each test under stable conditions.

The industrial heat exchanger was manufactured by KINARCA SAU and accommodates 180 tubes of two meters length. Of these 180 tubes, 22 were substituted by textured ones, following the distribution shown in Fig. 4. The experiments consisted in cooling a 20 cubic meter tank full of seawater from 21 ºC to -0,5 ºC, so in this case the temperature difference between the seawater and the boiling ammonia varies throughout the duration of the experiment.

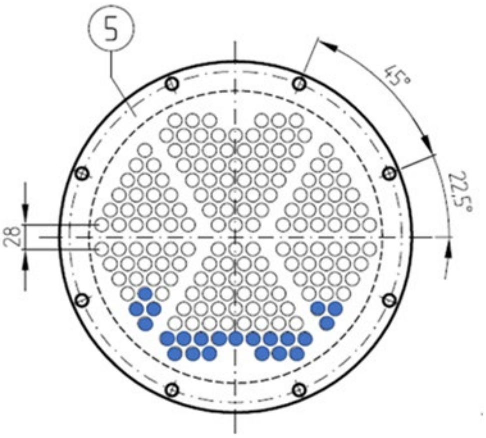

Fig. 4. Distribution of the 22 textured tubes (in blue) in the industrial heat exchanger.

3. Results

3.1. Surface Laser texturing and surface characterization

From the parameter window study, it was observed that proper generation of homogeneous grooves require relative laser speeds of 8 m/s or higher and a minimum of 500 W laser power. Lower values generate grooves with humps and heterogeneities along them or do not generate grooves at all, due to the material not being ejected. Higher laser power increases the depth and width of the generated grooves. An example of these phenomena is shown in Fig. 5.

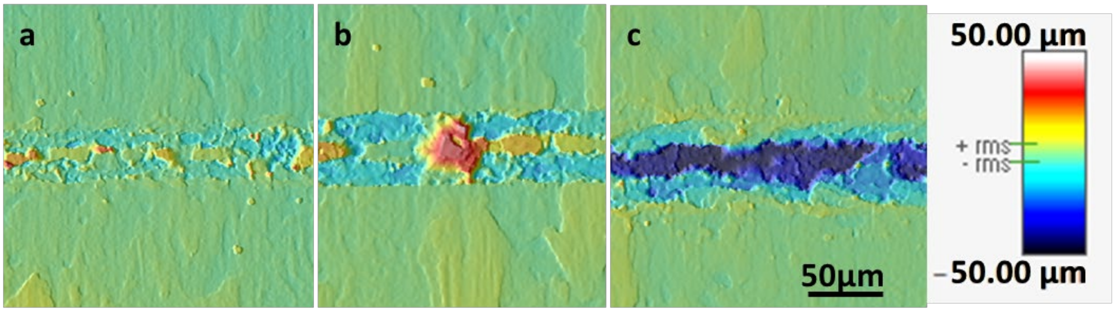

Fig. 5. Grooves generated at (a) 200 W and 9 m/s; (b) 200 W and 5 m/s; (c) 750 W and 9 m/s.

Once it was defined the parameters window for the laser speed and power suitable for the generation on grooves, we studied the influence of the rest of the variables on the tubes texturing process: tube rotation speed, number of laser passes and maximum defocus due to the tubes geometry.

In summary, low rotation speeds, a high number of laser passes and larger defocus increase the heterogeneity of the texture.

Due to the nature of the process, when texturing large areas, a significant amount of molten metal and dust is ejected. When not properly removed, this material is then deposited on the tube surface, solidifying and causing the textures to present heterogeneities. Rotating the tubes at high speeds significantly reduces this effect, as the centrifugal force helps ejecting the molten material, avoiding its deposition on the tube surface, as it can be seen in Fig. 6.

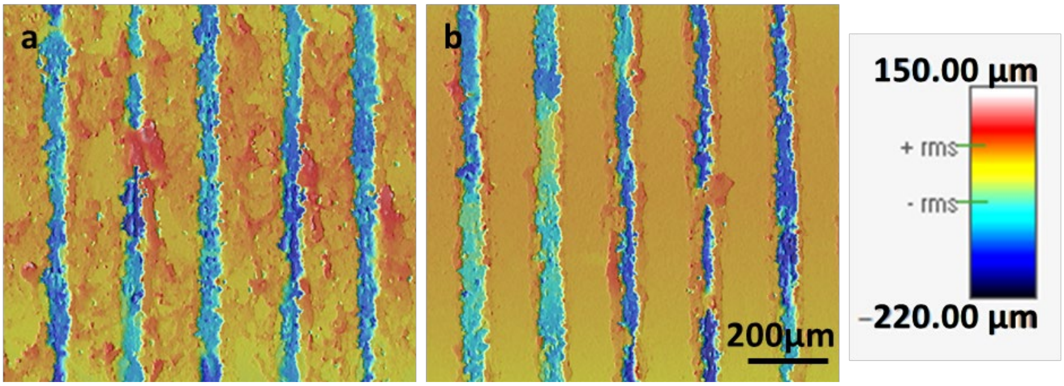

Fig. 6. Grooves generated at (a) 900 RPM and (b) 1800 RPM.

Additionally, increasing the grooves depth by performing more laser passes cause more heterogeneities on the tubes surface to appear. This is due to the molten material not being properly ejected from the bottom of the grooves, and even solidifying before completely exiting the micro channels, closing them, as shown in Fig. 7.

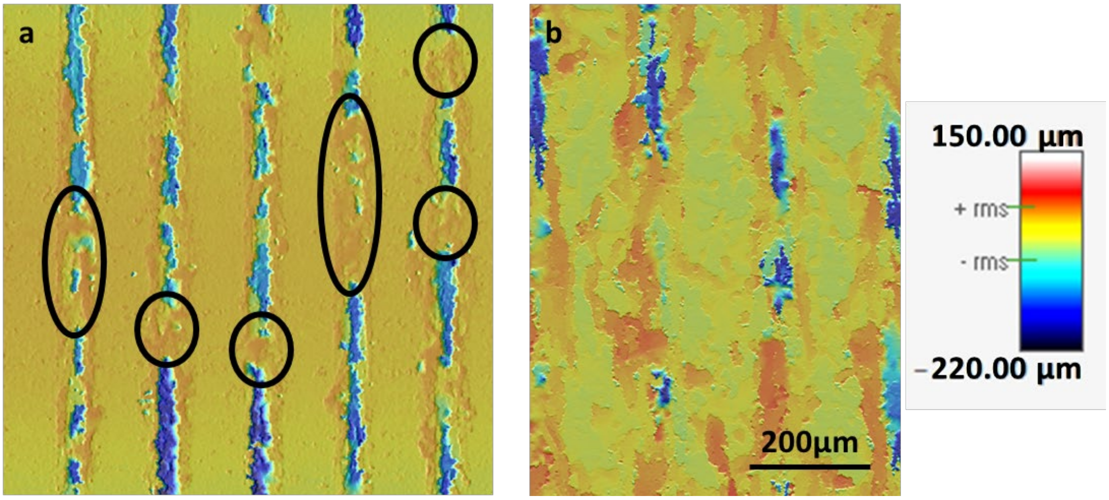

Fig. 7. Solidified titanium within the microchannels at (a) 900 W, 9 m/s and 2 laser passes, and (b) 1000 W, 9 m/s and 3 laser passes.

Next, the effect of defocus on the textures morphology was evaluated. When texturing a tubular surface using a scan head with a fixed focal plane, working without any defocusing conditions is unavoidable. The effect of working out of focus is shown in Fig. 8.

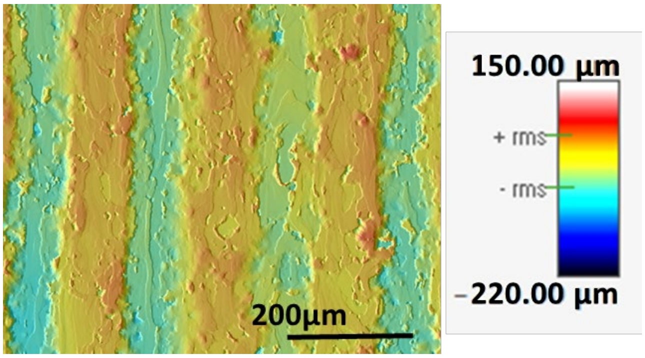

Fig. 8. Effect of defocus on a texture generated 1 mm out of focus.

As it can be observed, working out of focus increases the width and heterogeneity of the generated grooves, while reducing their depth.

From the performed experiments, the set of optimal parameters to achieve the most homogeneous texture with the highest aspect ratio possible were defined. These parameters are 9 m/s laser speed, 800 W laser power, 1800 RPM rotation speed, 2 laser passes and a defocus lower than 500 µm. With these parameters, the generated grooves dimensions are 60 to 80 µm wide and 70 to 110 µm deep. These are the parameters used for generating the texture in Fig. 6 (b).

The texture was cut and analyzed by scanning electron microscopy in order to evaluate the heat affected zone caused by the laser process, however, no heat affected zone was noticeable, as shown in Fig. 9.

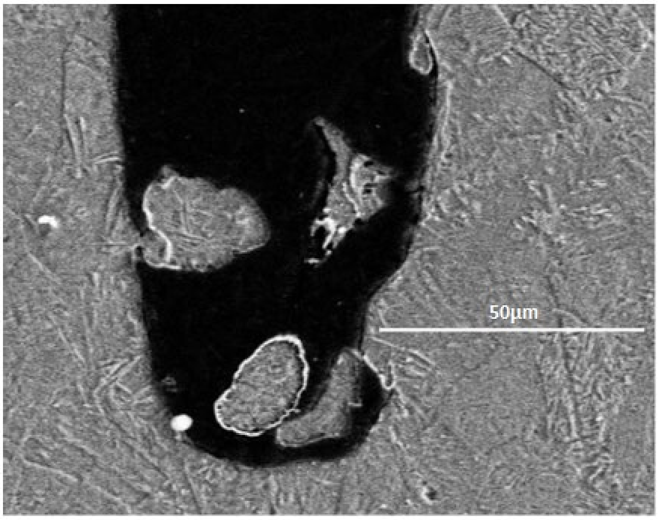

Fig. 9. Scanning electron microscope evaluation of the heat affected zone of a textured groove.

Also, due to the titanium intrinsical resistance to corrosion, the 500 hours test in the salt spray chamber did not have any effect on the textured areas. The results can be seen in Fig. 10.

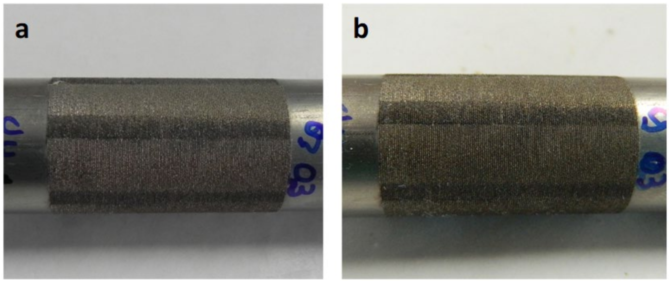

Fig. 10. Aspect of a textured area (a) before entering the spray salt chamber and (b) after being 500 hours inside the spray salt chamber.

3.2. Heat transfer evaluation in controlled environment

A total of 5 tests were done for both textured and non-textured tubes. Each test was performed using different reduced pressure (actual pressure divided by the fluid's critical pressure) and the results were graphed for ease of comparison in Fig. 11, which also shows the equation of the trendlines for both cases. Conventionally, heat flux for enhanced boiling surfaces is calculated based on the equivalent smooth surface [4,6], the same criteria was followed in this study.

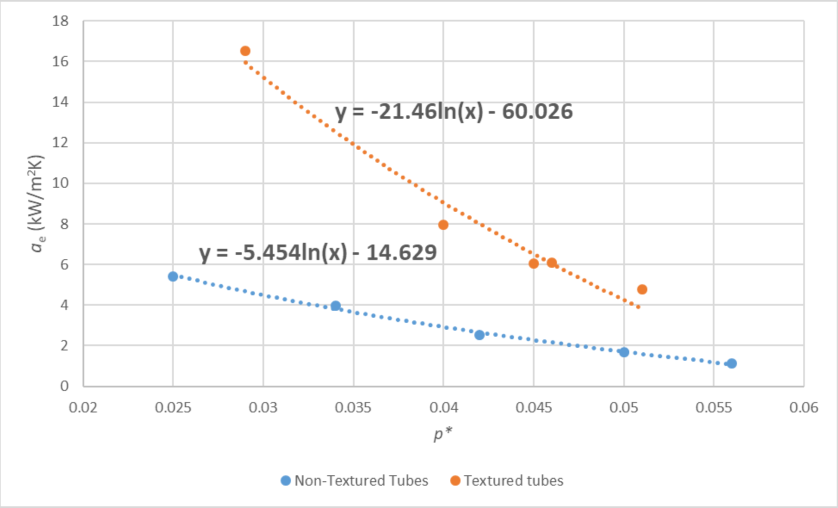

Fig. 11. Heat transfer coefficient against reduced pressure for textured and non-textured tubes.

According to the trendlines equation, the heat transfer coefficient is improved by up to 240% for a reduced pressure of 0,3 or less, while the enhancement diminishes to just 67% improvement for a reduced pressure of 0,56.

3.3. Heat transfer evaluation in industrial environment

In this case, since the experiments were performed in an industrial system, it was not possible to add any more sensors than the ones already present, so the heat transfer was calculated and used for comparison, instead of the heat transfer coefficient. A total of 3 tests were done for both textured and non-textured tubes, the mean values were calculated and graphed in Fig. 12, along with the trendlines equations.

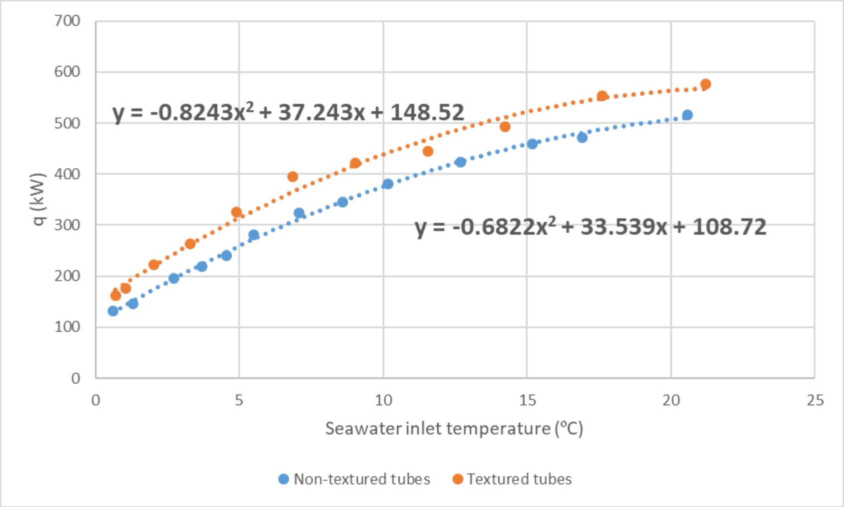

Fig. 12. Heat transfer against seawater inlet temperature for textured and non-textured tubes.

According to the trendlines equations, at 1 ºC of seawater inlet temperature, the overall efficiency of the system is improved by 30%, while it progressively diminishes as the inlet temperature increases, down to 11% at 20 ºC. Taking into consideration that only 12% of the tubes were replaced by textured ones, this means that the efficiency of a single tube is increased between 98% and 250% depending on the working temperature of the heat exchanger.

These results confirm the ones obtained in the controlled environment, where also an improvement of up to 240% in the heat transfer coefficient was achieved but is reduced in certain working conditions.

4. Conclusions

Grade 2 titanium tubes have been successfully textured using a continuous wave fiber laser. It was demonstrated that the textured tubes present an enhanced heat transfer behavior when compared with their non-textured counterparts.

70-110 µm depth and 60-80 µm width micro grooves, with a pitch of 200 µm, can increase by up to 250% the heat transfer coefficient of grade 2 titanium tubes when working under a nucleate boiling regime.

The heat transfer evaluation shows that the temperature difference required for the nucleate boiling to start has been reduced, resulting in a significant increase of efficiency. However, the heat transfer behavior of textured tubes at higher temperature difference should be studied in further investigations.

Continuous wave laser texturing is a suitable method for generating surfaces that promote the nucleate boiling regime. It can become a cost-effective and productive alternative to the mechanical processes that are used nowadays for manufacturing tubes with micro structured surfaces for nucleate boiling promotion.

Acknowledgements

This research was part of the TACTIL project, funded by CDTI within the FEDER INNTERCONECTA program.

Special thanks go to all the members of the TACTIL project Consortium, for their involvement in the research and efforts.

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