Saving Energy in the GFRP Pultrusion Process

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Abstract: This study addresses to the optimization of pultrusion manufacturing process from the energy-consumption point of view. The die heating system of external platen heaters commonly used in the pultrusion machines is one of the components that contribute the most to the high consumption of energy of pultrusion process. Hence, instead of the conventional multi-planar heaters, a new internal die heating system that leads to minor heat losses is proposed. The effect of the number and relative position of the embedded heaters along the die is also analysed towards the setting up of the optimum arrangement that minimizes both the energy rate and consumption. Simulation and optimization processes were greatly supported by Finite Element Analysis (FEA) and calibrated with basis on the temperature profile computed through thermography imaging techniques.

The main outputs of this study allow to conclude that the use of embedded cylindrical resistances instead of external planar heaters leads to drastic reductions of both the power consumption and the warm-up periods of the die heating system. For the analysed die tool and process, savings on energy consumption up to 60% and warm-up period stages less than an half hour were attained with the new internal heating system. The improvements achieved allow reducing the power requirements on pultrusion process, and thus minimize industrial costs and contribute to a more sustainable pultrusion manufacturing industry.

Keywords: Pultrusion process, Die heating system, Heaters position configuration, Energy performance, Numerical analysis.

1. INTRODUCTION

Among the several available methods to produce and manufacture fibre reinforced polymer (FRP) composite materials the pultrusion process is the oldest continuous processing technique and, until now, is still the most cost-effective one at least as regard to the manufacturing process of FRP components with a constant cross-section [1]. One of the main attractions of this manufacturing method is the simplicity of tooling and low labour requirements. Obtained pultruded FRP profiles are widely used in infrastructures of wastewater facilities, as internal or external reinforcement of concrete structures, for retrofitting and rehabilitation purposes of structural elements, and recently, in composite construction systems either with moulded gratings and sandwich panels [2] or in hybrid structural beams jointly with a compression resistant layer of casted polymer concrete [3-4].

Typically, in the manufacturing process of FRP pultruded profiles plain glass (GF), carbon (CF) or aramid (AF) reinforcing fibres, in the form of continuous strands or plys, are pulled through a thermoset resin bath for impregnation (usually a polyester, vinyl ester or epoxy resin). After wetting process, the reinforcement pack is collimated in a progressive manner into a performed shape before entering the heated die where it attains the final form of the die cavity and cures. The tool die may be heated by external or internal electrical heaters, strip heaters, hot oil or by steam; though, external electrical heating systems are until now the most common ones. A programed power controller controls the duty cycle of the heaters, recording real-time measurements through temperatures located at critical points and providing the appropriate temperature profile (TP) along the die required for a proper curing process of the resin matrix. Finally, outside the die, the already polymerized and consolidated composite part (GFRP, CFRP or AFRP profile) is pulled by a continuous pulling system and then a cut-off saw cuts the part into a desired length [5].

Over the last 60 years, the pultrusion manufacturing technique has grown and developed strongly from its conception and first steps in the early 1950' to present as a well-established and efficient industrialized process. The still-developing technologies include, among others, tooling techniques, new combinations of reinforcement and matrixes, hybrid reinforcements and novel positioning of fibre directions. Most of the fundamental research that has also been done in this field is aimed at optimizing, for a given pultrusion profile

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to be produced, the temperature profile (TP) inside the forming die and the other relevant processing parameters (*i.e*., pulling speed, pulling force, die temperature and die length). In spite its relative simplicity, the continuous nature of the pultrusion process lays constraints on the quality control system due to the numerous interdependencies of the processing parameters. For the same product composition and cross-section, pulling speed, pulling force, die length and heating die system are interdependent variables that affect the quality of final pultruded product [6]. To achieve a uniform degree of cure, the TP inside the forming die is a crucial aspect to take into account, and the fine-tuning of this TP according to material composition, composite part cross-section and dimensions, is not a straightforward task. By and large, thermodynamic numeric models based either on finite element or finite difference techniques have been applied for this purpose. An exhaustive review of applied models can be found in Moschiar *et al*. [7] and in other relevant literature available elsewhere [*e.g*., 8-19].

Although the use of environmentally and health-friendly technologies is becoming increasingly important, none of the aforementioned research contributions deal with the optimization of pultrusion process from the energy-consumption point of view. Until now, no significant attention has been given to the efficiency of the die heating system. This fact is supported by the widespread use of external electrical heating systems (*e.g*., the large universal heating platens and the multi-planar heaters), which are associated to large heating losses to the surrounding and to significant energy waste. Also, scarce studies have been published concerning this issue. Some of the few published works are summarized in the following.

Khan and Methven [20] analysed and quantified by thermal simulation the duty cycle of the die heating system of a typical pultrusion process, and thereby, provided an estimation of the Specific Energy Consumption (SEC). The effect of preheating the precursors on line speed was also analysed. For that purpose, different input temperatures of the die were analysed, the heating and cure curves (TPs) were plotted for the composite material inside the die and, then, the simulation was extended for the duty cycles of the die heating system.

Sumerak [21] performed an experimental study undertaken the different conditions at the pultrusion die-planar heaters interface and their effects on process stability and energy consumption. Focused on external heaters system, the study highlights the importance of heaters design, mounting method and routine maintenance on process quality and economics. It was found that the use of conductive heat transfer paste in the heater/die interface, jointly with a heater surface maintenance procedure, lead to the greatest process efficiency, minor heat losses, lower energy consumption (low duty cycle of heaters) and improved product cure consistency.

Srinivasagupta and Kardos [22] used a thermodynamic objective function to minimize the energy consumption during the cure reaction in an injected pultrusion (IP) process. As the same way as the other previous researches in the field, the authors considered that the number, geometry and position of the heaters were predefined and known before the numerical optimization, and the pultrusion process was modelled according to the previous heaters arrangement.

In all of the aforementioned studies, no considerations were done regarding the effects of the heaters relative position on the energy consumption. In order to fulfil this gap, a different approach was used by Santos *et al.* [23-24]. Instead of conventional external heaters, they suggested an alternative die configuration with internal heaters aimed at increasing the number of arrangement possibilities of heaters position. In the optimization process a numerical procedure based on computational fluid dynamics (CFD) technique and on a stochastic optimization algorithm (PSO-Particle Swarm Optimization) was applied. It was found that the optimization with internal heaters was successful in finding a better way to cure the resin in a more uniform way, while minimising the energy rate. Despite the good results and the efficiency of applied model, the published studies do not report on how the optimization process may be enhanced in order to contemplate different relative positions of internal heaters.

Following these studies, the present work is aimed at optimizing the die heating system of a specific pultrusion profile production process. A new internal die heating system is proposed, instead of the existing one of multi-planar heaters, and further, the effect of the number and relative position of the embedded heaters is also analysed towards the setting up of the optimum arrangement that minimizes the energy rate and consumption. Other heating systems, than the large heating platens and the multi-planar heaters, have

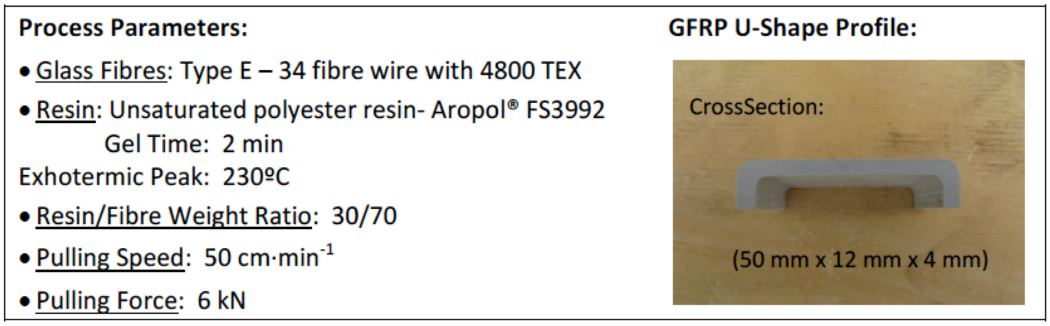

Figure 1: Profile cross-section and control variables applied in the manufacturing process.

already been proposed in the past in order to reduce the heating losses, such as fluid circulation and cartridges heaters. The former solution generally leads to increasing warm-up periods and, additionally, requires the use of pumps that results in added maintenance costs when compared to other solutions [25]. Thus, the electrical cartridge heating system was chosen in this study as it allows higher energy savings, lower set-up periods and enables a better temperature refinement along the die.

Simulation and optimization processes were greatly supported by Finite Element Analysis (FEA) and calibrated with basis on the temperature profile computed through thermography imaging techniques.

2. METHODOLOGIES AND APPLIED NUMERICAL MODEL

The experiments and analyses were focused on the pultrusion manufacturing process of a GFRP U-shape profile, illustrated in Figure **1**, while keeping the other process parameters constant: pulling speed, pulling force, total resistance power of heating system and TP along the die. These control variables, also described in Figure **1**, were already fine-tuned over the years by the large experience of the manufacturer and conduct to a high standard of quality of pultruded part. The length, with and height of die tool used in the manufacturing process of this specific profile were, respectively, 900 mm, 103 mm and 56 mm.

In the first part of this study, the TP along the die for the prior planar heating system was determined by means of thermography measurements and then numerically simulated by FEA with basis on heat-transfer models. After validation of FEA simulation, energy consumption for the proposed new internal heating system was simulated and predicted using the same technique. In order to optimize the heat distribution process and, thereby, to achieve the maximum savings on energy consumption, additional four different relative positions (layouts) for the embedded heaters were considered and investigated.

2.1. Former Planar Heating System and Thermography Measurements

The previous die heating system consisted of four external planar heaters, with 800W each, formed by a Chromium-Nickel spiralled wire embedded in a cast aluminium block. They were divided in two groups ('GH1' and 'GH2'), comprising two heaters each and mounted trough clamps on the upper and lower sides of the tool die as schematically shown in Figure **2**.

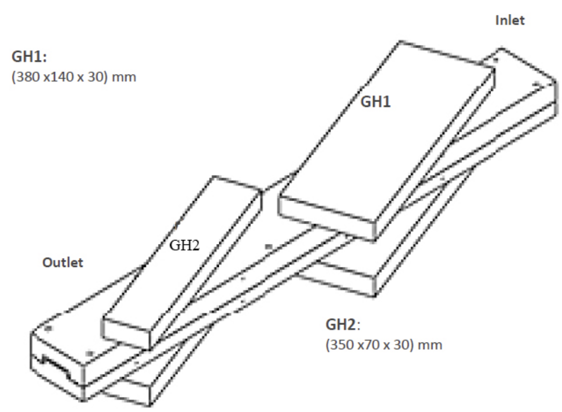

Figure 2: Initial planar heating system with the two groups of heaters (2 x 800W).

All the heaters had the same power, and as such, the size differences only influenced the ratio W/m^3. Two temperature sensors, one for each group of heaters, sent real-time information to a PLC (Programmable Logic Controller), which monitored the duty cycle of the heaters. Set-point temperatures of groups GH1 and GH2 for the production of this specific U-shape profile were 195ºC and 140ºC, respectively, with an allowed temperature variation range of ± 5ºC. This means that the power supply switches between 'on' and 'off' when the temperature is, respectively, 5ºC below or above the reference temperatures.

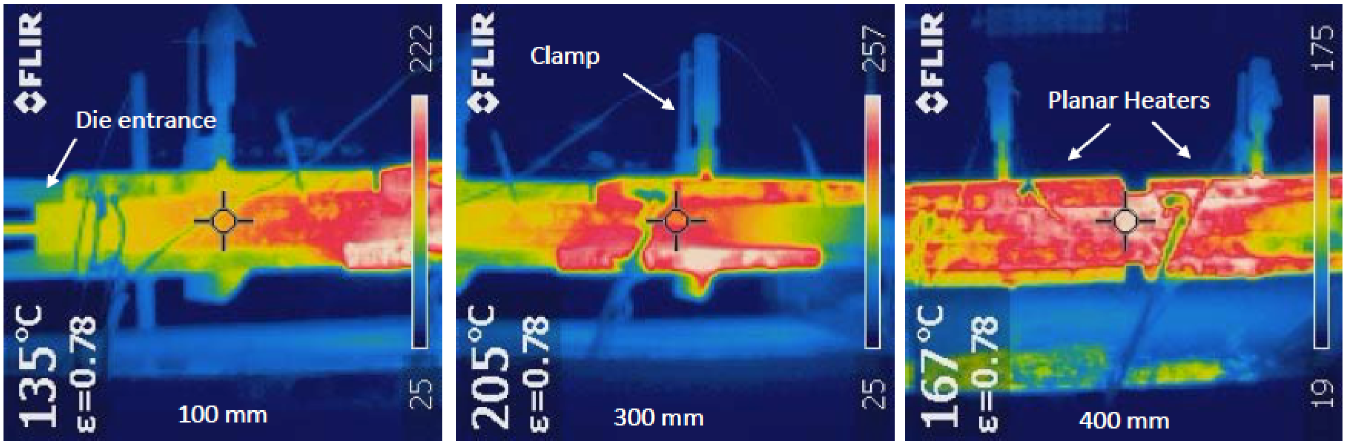

Figure 3: Some examples of thermography images obtained over the initial set-up heating system at different points of die tool.

Thermography images were taken by means of a Flir®i40 imaging camera during a stable manufacturing stage, which allowed assessing the TP along the die. Thermography measurements were made on both lateral sides of the die, as exemplified in Figure **3**, and referred as one single session.

Three sessions were run on three different working days under similar environmental and processing conditions. Each acquired image was divided into 100 different areas corresponding to a matrix with 4 rows and 25 columns representing the lateral face of the die. The Flir® Quick Report software package and statistical tools were applied to all images, and for each image, an average temperature was collected at the interception points of the matrix. Finally, the results obtained from all images throughout the three sessions were averaged to obtain the TP along the die.

2.2. Numerical Simulation Assumptions

FEA was applied to model the die tool-heaters system. The thermal state was assumed to be transient and the following assumptions were presumed: a) all contacts were considered as perfect; b) all bodies were initially at room temperature (22ºC) and remained constant; and c) the convection coefficient and the emissivity were assumed equal to 2 $W/m^2.ºC$ and 0.8, respectively. Die tool was modelled as upper and lower parts and the heaters as independent bodies. A tetrahedral mesh was used, which after convergence resulted in 256975 elements (for half of die tool taking advantage of its symmetry), as shown in Figure **4**.

The reference points chosen for the temperature control (TCP) in the simulation corresponded to those where the temperature sensors of the group of heaters GH1 and GH2 were located on the real die, respectively at 216 mm and 720 mm of die entrance. The temperature at these points was checked with the drawn TP obtained by thermography and was used as a reference to perform the FEA, allowing the fine-tuning and convergence of the analysis. The simulation ran for 4500 seconds (3600 seconds corresponding to a warm-up period and further 900 seconds corresponding to a stable operational phase). At the end of the simulation, both the duty cycle of the heaters and the TP values along the die were obtained and compared with data acquired by PLC and thermography. A good agreement was found between both types of data allowing the validation of the FEA model (as shown ahead in this paper in section 3.1).

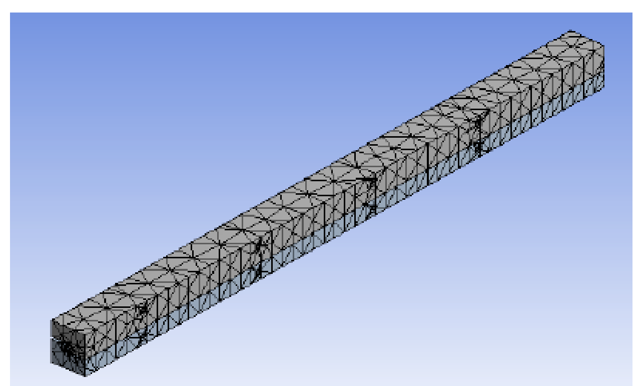

Figure 4: Half of the die tool with the tetrahedral mesh applied for FEA.

2.3. New Cartridge Heating System

The new internal heating system consisted of four independent groups of cylindrical heaters (GH1, GH2, GH3 and GH4), each one comprising two heaters with 400W and a temperature sensor. Total power applied to the system remained equal to 3.2 kW but more distributed along the die, enabling a more precise

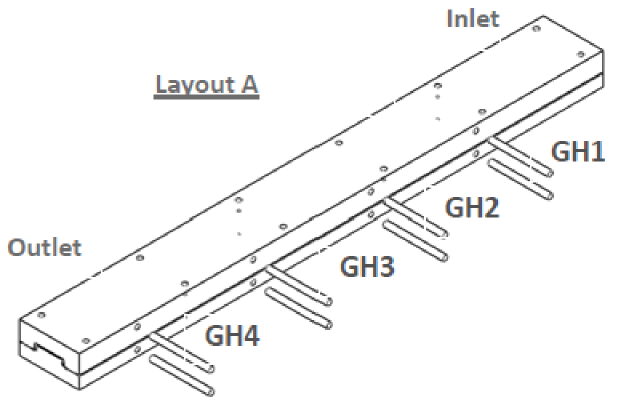

Figure 5: New heating system with 4 groups of embedded cylindrical heaters (2 x 400W).

control of temperature due to its four temperature sensors. The PLC of the pultrusion machine is capable of controlling up to four channels and the resistances were inserted along the die into existing holes formerly conceived and used to accommodate temperature probes (Figure **5**). This location of the heaters corresponds to a specific arrangement hereinafter designated by Layout A.

The new heating system was simulated with the same assumptions used previously for the planar heating system and assuming the same predefined TP. Temperature was controlled at pertinent points near each pair of heaters considering limits of allowable variation of ± 5ºC. A tetrahedral mesh was also used, with edge elements of 0.01 m length, which after convergence resulted in 11089 elements. As the same way as previously, aiming to reduce the computation effort, only half of the die tool was simulated. The duty

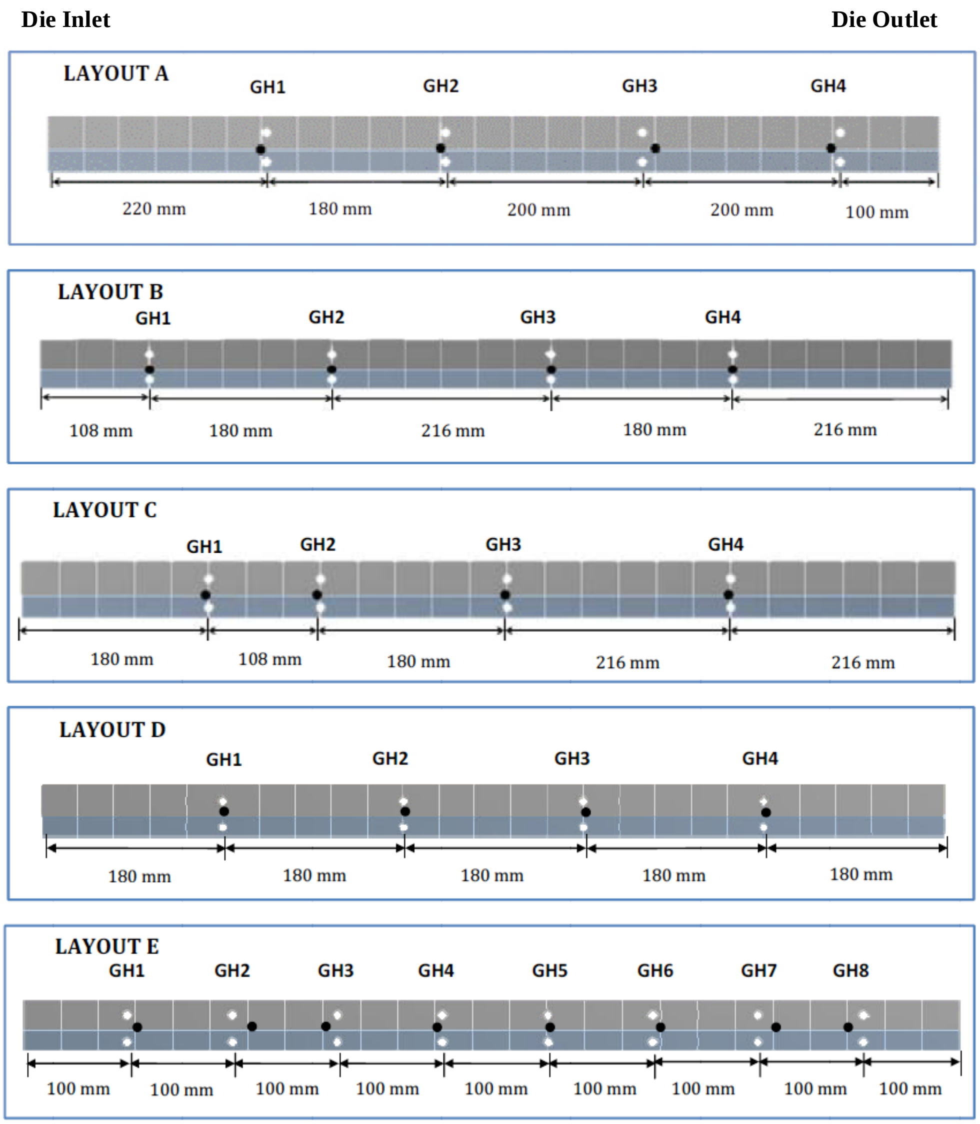

Figure 6: The different analysed layouts for the new heating system: relative position of the heaters (white spots) and temperature control points (black spots).

cycle of the embedded heaters was obtained at the end of the simulation and then, the total power consumptions of both heating systems during an entire working day (8h) were computed and compared. Besides the Layout A, which was experimental implemented taking advantage of the existing holes into the die, more four different configurations of relative position of the heaters were analysed. The correspondent total energy consumptions were also simulated using the same methodology. The different analysed layouts are schematically represented in Figure **6**.

Layouts B and C correspond to relative positions of the heaters in which the TP was taken into account. The criterion was positioning the heaters in correspondence with the TP, more concentrated in the first half of the die where higher values of temperature are required. For defining Layout B, the area beneath the curve of TP obtained by FEA was calculated and divided into four equivalent sectors with the same areas (ºC x mm). For each sector, the abscissa of the centroid was calculated and used as reference for the positioning plan of the groups of heaters. Layout C follows the same principle, but considers the three first groups of heaters (GH1, GH2 and GH3) more concentrated near the peak of TP.

Finally, Layouts D and E correspond to symmetric and homogeneous dispositions of the heaters along the die. Though, whereas Layout D comprise 4 group of heaters as the other prior layouts (A, B and C); in Layout E, 8 group of heaters with the same total power as the previous ones were considered (16 resistances with 200W each). This last layout was justified in order to refine the results obtained with Layout D (see section 3.2).

3. RESULTS AND DISCUSSION

3.1. Validation of the Numerical Model

In Figure **7**, both the TP values obtained by thermography imaging technique and FEA simulation are displayed. The estimated duty cycles of the groups of planar heaters applied in the initial die heating system are also graphically represented in Figure **8** (ahead in this paper in section 3.2).

As shown in graph of Figure **7**, a good agreement between the TP drawn by thermography and the TP obtained by FEA was achieved. The large mismatch observed between the two curves at die entrance was due to operational reasons: this part of the die tool was located behind the fastening elements used to fix the die to pultrusion base equipment, blocking locally the camera's infra-red beam during thermography measurements. After this zone, the maximum deviation obtained between the two curves is around 7%, which is considered acceptable for this kind of analysis. Also a good agreement was attained between estimated duty cycle of the heaters and data collected through the PLC validating thereby the FEA model.

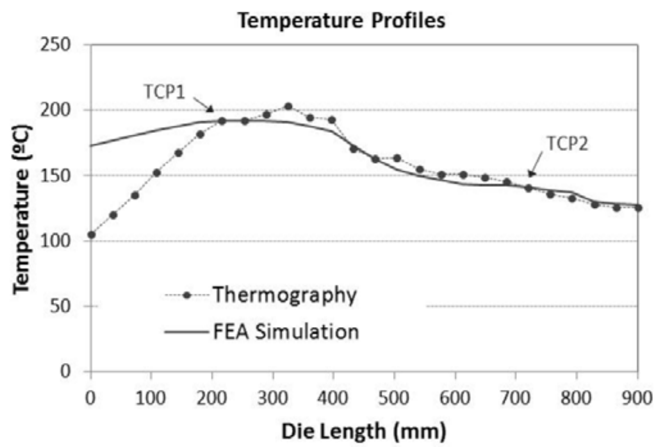

Figure 7: Temperature profiles along the die obtained by thermography and numerical simulation (with both the temperature control points pointed out -TCP1 and TCP2-).

3.2. Numerical Simulation Results for the New Heating System

The duty cycles of the heaters obtained by numerical simulation for each analysed layout of the new heating system are graphically displayed in Figure **8**. Table **1** shows the estimated values obtained for the required warm-up period (T_W), the duty cycle of each pair of heaters in terms of periods of time 'switch-on' and 'switch-off', the power consumption per hour during both the warm-up (PC_w) and the manufacturing (PC_m) periods, as well as the total energy consumption (*TEC*) for a normal working day of 8 hours. The following criteria were followed:

- Warm-up period (T_W) was establish as the period of time after which all group of heaters presented a stable pattern of duty cycle with regular times of 'switch-on' and 'switch-off', as pointed out in graphs of Figure **6**;
- The duty cycles, denoted as 'switch-on/switch-off', correspond to average periods of time computed after the warming period in a stable phase;
- Power consumption per hour during manufacturing time (PC_m) was calculated, for

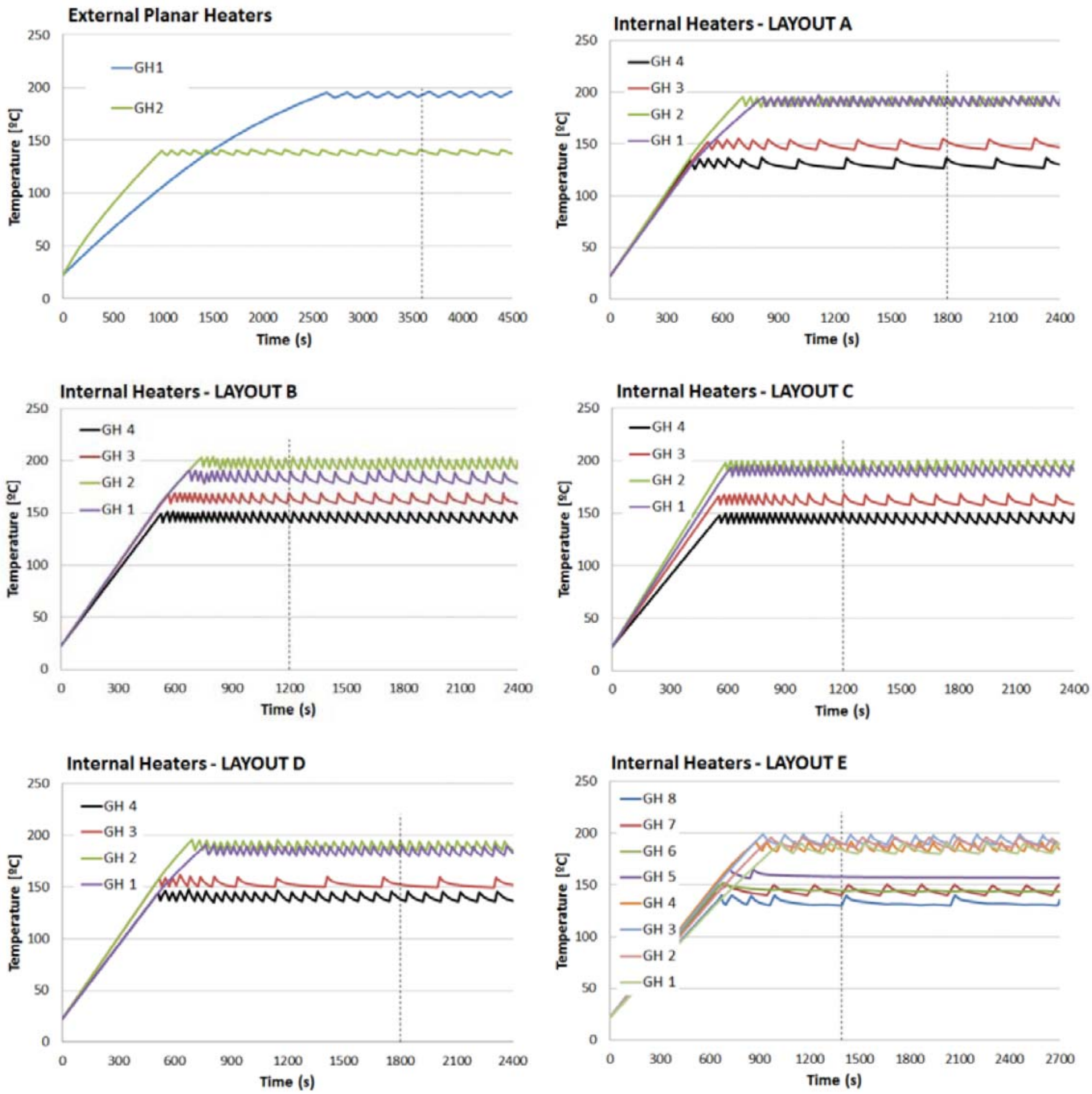

Figure 8: Duty cycle of the group of heaters obtained by FEA simulation for each analyzed layout of the new heating system (internal heaters) e for the initial planar heating system.

each group of heaters, with basis on the average time of duty cycles of the heaters;

- And total energy consumption (*TEC*), in kW, was computed as follows:

$$TEC = PC_W\, T_W + PC_M\,(8 - T_W) \qquad \text{(Eq. 1)}$$

where PC_W and PC_M correspond to the sum of power consumption in kW per hour of all groups of heaters during warm-up and manufacturing periods, respectively, and T_W stands for period of time, in hours, required for heating-up stage.

For comparison purposes, the data obtained for the planar heating system is also presented in Table **1**.

From the results presented in Table **1**, it is clear that significant improvements on energy performance and production times of the pultrusion manufacturing process can be achieved with the proposed new heating system. The cartridge heating system provides significant savings on energy consumption and considerable reductions on warm-up periods, regardless of the number and relative position of the embedded heaters. Reductions of at least 56% and

Table 1: Energy Performance Associated to both Heating Systems and for the Different Analysed Layouts

Heating System	Group Heaters	Power [W]	Duty Cycles [s]	T_W [h]	PC_W [kWh]	PC_M [kWh]	TEC [kW]
External	GH1	800	116.2 / 90.5	1.000	1.412	0.899	9.995
	GH2		28.7 / 176.8		0.722	0.223	
Internal Layout A	GH1	400	12.2 / 35.2	0.500	0.538	0.206	4.350
	GH2		12.2 / 42.2		0.443	0.179	
	GH3		15.7 / 217.0		0.312	0.054	
	GH4		12.1 /241.9		0.258	0.038	
Internal Layout B	GH1	400	9.2 / 67.3	0.333	0.545	0.096	4.451
	GH2		10.1 / 30.7		0.604	0.199	
	GH3		7.8 / 89.7		0.487	0.064	
	GH4		8.9 / 46.1		0.492	0.129	
Internal Layout C	GH1	400	10.2 / 38.4	0.333	0.553	0.168	4.454
	GH2		8.8 / 39.2		0.498	0.147	
	GH3		7.0 / 113.9		0.462	0.047	
	GH4		9.7 / 44.1		0.527	0.144	
Internal Layout D	GH1	400	11.1 / 44.3	0.500	0.485	0.160	3.989
	GH2		10.2 / 40.4		0.438	0.161	
	GH3		10.0 / 290.0		0.288	0.027	
	GH4		9.3 / 83.7		0.348	0.080	
Internal Layout E	GH1	200	31.6 / 210.1	0.386	0.301	0.052	4.128
	GH2		41.4 / 146.2		0.281	0.088	
	GH3		27.9 / 100.8		0.284	0.087	
	GH4		26.4 / 55.8		0.291	0.128	
	GH5		- / -		0.212	0	
	GH6		- / -		0.193	0	
	GH7		38.4 / 171.6		0.220	0.073	
	GH8		25.8 / 620.2		0.218	0.016	

50% on energy consumption and warm-up period, respectively, are attained with the internal heaters when compared with the external heating system (values computed for the Layouts with worst performance in each criterion).

Regarding the different arrangements considered for the position of the heaters in the new heating system some quite significant differences were found between the analysed layouts.

Both configurations that accompanied closely TP (Layout B and C), although providing the lowest warm-up periods, lead to the highest values of energy consumption. TEC associated to Layouts B and C are, respectively, 2.3% and 4.7% higher than TEC induced by reference position (Layout A). The worst energetic performances of these solutions are strongly related to heat dispersion by convection. Although these arrangements were considered in order to concentrate the group of heaters on the areas that require a higher heat supply at start-up period, due to the high temperature differences along the die, the heat is diverted by convection to colder areas and lead to an extra effort of the heaters. This feature is in accordance with the short duty cycles obtained for all resistances in these particular layouts, with periods of time of switch-on and switch-off of similar magnitude.

The relative position of heaters that conducts to the best results is the symmetrical configuration with 4 group of heaters (Layout D), allowing up to 8.3% on energy savings over reference position. This last solution does not shorten the heating-up period, but allows an overall reduction on power consumption per hour during manufacturing stage.

Obtained results for the symmetrical configuration of 8 groups of heaters (Layout E) are quite similar to those achieved with half of the resistances. Total energy consumption is slight higher than that provided by the previous arrangement, leading to minor energy savings with regard to the reference layout (5.1 %), but allows a more accurate temperature profile along the die due to increasing number of temperature controls. For instance, groups of heaters 5 and 6, located respectively at 400 mm and 300 mm of die exit, are only switched-on during warm-up period, which means that the heat produced by adjacent heaters and polymerisation reaction of resin matrix is plenty enough to maintain the temperature, in this region of the die, within the range limits of reference TP. Moreover, due to a more distributed heat power, heating-up stage is reduced up to 23%, which allows an increase on productivity.

Layout E corresponds to the best compromise solution allowing both a reduction of starting-up period and further savings on energy consumption. In addition, the productivity is increased and the control of the process is improved, conducting to a better product quality.

4. CONCLUSIONS

The main outputs of this study allow to confirm that the use of embedded cylindrical resistances instead of external planar heaters leads to drastic reductions of both the power consumption and the warm-up periods of the die heating system. For the analysed die tool and process, savings on energy consumption up to 60% (Layout D) and warm-up period stages less than an half hour (Layout E) can be achieved with the new internal heating system.

It was also found that the relative position of the cylindrical resistances also play an important role on the energetic performance of resultant heating system. A suitable arrangement provides a better distribution of the heat along the die length and, thereby, leads to a reduction of the service time of the embedded resistances.

Regarding specifically the new cartridge heating system, the other results of the experimental and numerical work may be summarized in the following:

- The total energy consumption of the process can be reduced of more than 8% through an adequate location of the embedded heaters;
- The energy consumption during the manufacturing phase does not depend neither on the number of the heaters applied nor on its power. Though, a larger number of heaters allows to reduce the warm-up period, reducing the lead-time and costs of each order;
- FEA is a reliable and not time-consuming method able to predict the power consumption of the die heating systems, allowing the optimization of the relative position of the heaters along the die.

The improvements achieved by this work allow reducing the power requirements on pultrusion process, minimizing industrial costs while increasing the eco-efficiency ratios.

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