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Rapid heating injection moulding: An experimental surface temperature study

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A R T I C L E I N F O

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A B S T R A C T

Rapid heat cycle moulding (RHCM) is a recent set of injection technologies that allow a full temperature control in a mould.

Between all technologies available in terms of heating and cooling, electrical resistance heating and water cooling were chosen for this study.

The mould design has a capital importance in terms of process efficiency. Thermal and mechanical key points must be addressed together. Temperature distribution in moulding cavity and quality part run together.

Before mould machining, a full mechanical, thermal and rheological simulation was carried out. Due to transient thermal complexity, thermal simulation was validated using infrared thermography on a dummy tool fitted with both heating and cooling devices.

All this previous work is usual for each new tool. When a new process is suggested for new part requirements, it is necessary to understand injection physical bases in order to prevent unexpected failures. This work introduces the mould temperature curve to realize how RHCM works, and compare its results with conventional moulding.

The influence of cavity temperature map was studied with a cavity pressure and temperature sensor helped with near infrared thermography. At the same time, the relationship with parameters which control both heating and cooling periods was considering.

Simulation and experimental results are compared, and RHCM process highlights could be well understood to improve future new injection parts development.

1. Introduction

Injection moulding is a process commonly used for complex parts production. Competitive costs dimensional and quality mass production are most remarkable attributes of this technology. A correct tool design and adequate machine setup are essential in achieving these goals.

Plastic material is heated in the barrel due to mechanical work made by the screw rotation and heat flow from surrounding electrical resistances. The polymer flow is forced to get into the mould cavity under flow rate control, and the mould cavity suffers pressures up to 100 MPa. Heat transfer is the most important physical process related with thermal level and distribution reached into the cavity and so in the final both mechanically and aesthetically part quality.

In the injection process, when cyclical stationary status is achieved, global heat put into the system is equal to heat that is going out [1], a called semi-stationary balance during the complete cycle time. The main part of the interchanged heat energy is conducted by cooling system, but is necessary considering other additional mechanisms in heat exchange as heat losses by metal conduction to the plate machine if an accurate study wants to be performed.

During the cooling phase, heat flow rate drives the cooling process. To improve the system design, heat transfer efficiency is the main target pursued by the mould-maker due to its capital importance. The minimum cycle time is highly related with minimum cooling time, usually up to 60% of cycle time comes from cooling time, so, reduce it to the minimum possible, makes a process economically feasible.

Heat exchange between polymeric material and coolant will depend on thermal and geometrical features present in the mould and the part.

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Thermal resistance (as it is explained using electrical analogy) will be dependent on factors [2] such as: steel and water conductivity, water flow rate, location, diameter and/or shape of cooling channels, etc. Heat transfer from part to tempering/cooling system could be divided in two consecutive steps:

Inside the part: heat is transferred by conduction from inside to outer skin through the polymeric material.

From part surface to the environment: it must be divided into heat interchanged with cooling system and with the environment, and the superposition principle could be applied.

Part thickness has been revealed the most influencer factor in cooling time, even further than coolant flow, fluid temperature or cooling 3D layout. It is important to keep in mind that homogeneity in temperature distribution allows quality parameters to be reached, so, an efficient cooling system have to withdraw heat in a double sense: quickly and homogenous way. In any injection moulding process involving heat transfer, shrinkage and warpage are important flaws.

From twenty years ago to now quality requirements in technical plastic parts are growing up and, at the same time, injection technology has developed new processes like sequential injection, in-mould decoration, multimateria technologies, etc. [3,4].

Nowadays the most interesting technology in this field is called “rapid heat and cooling moulding” (RHCM) [5], or simpler, “heat and cool process” (H&C). This technology claims for a full temperature control: in one hand, during filling phase, for better melt front advancement, the cavity is quickly heated, and, in the other hand, when packing phase starts, coolant flow must to reduce mould temperature. That is, the required temperature in the cavity has under control at any injection stage. That is the simple idea for any mould design.

In a conceptual way, moulding cavity is heated up to the right temperature before inject the plastic melt. Temperature gradient between tool and material is significantly lower than measured using conventional technology. In addition, homogeneity in temperature distribution should be better, so that frozen layer become thinner and filling is improved. Near the end of packing stage coolant flow starts and rapidly ejection temperature will be reached, keeping cycle time near to objective value in conventional injection moulding (Fig. 1).

Aesthetical defects such weld lines become hardly recognizable [6], due to the narrow frozen layer during filling phase, so high polished and texturized surfaces will be with high quality, allowing an industrial surface appearance called “black piano” [7].

Main drawback in RHCM technology comes from the fact that energy goes in and out the system each cycle, and any additional time is necessary and operational costs increases. By the same way heating and cooling the tool increases energy costs and required additional investment due to the necessary equipment. The tool material suffers constant temperature variations, so thermomechanical material properties also get critical. If design phase was right, the adverse effects will be minimized without lengthen cycle time in a way that the process become profitable.

In most of cases with careful design, drawbacks could be overpassed by combining materials and designs that optimize heat transfer. In relation with time response, metal volume under thermal cycle must be strictly minimized.

Some design factors are strongly involved:

- Material volume under thermal cycle: time necessary for heating and cooling until the desired temperature is highly related to its global mass.
- Selected tool material: usually steel, good thermal conductivity, good thermal stress and corrosion behaviour but other options could be considered, as aluminium alloys.
- Heat and cold system design: channels closer to the surface improve heat flow and reduce cycle time but this choice affects the mechanical mould strength.
- Heating technology efficiency: induction coils, water steam or resistor elements.

Manufacturers should be keeping in mind new resources must be added to the conventional injection moulding equipment.

- New design capabilities or knowledge
- Heating system using steam, resistors or coils.
- Cooling system, usually treated water.
- If a fluid is used as heating and cooling, a cleaning for heating to cooling change.
- An additional electronic control unit.

Therefore, with the aim of combine main advantages accepting the lowest drawbacks number offered by this technology, some variants have been developed differing each other mainly in heating technology applied. Depending mostly on heating technology it is known using different ways (or trade names) as “heat and cool” (H&C), “variotherm”, “steam moulding”, “rapid temperature cycling” (RTC) or “weldless moulding”, for example.

Although some additional methods have been proposed (even using laser or direct flame as heating source [8], with poor results), the three main strategies for heating are described below:

Convective heating: here, some fluid establishes convective heat flow with channel wall using the cooling lines for both heating and cooling processes. Oil was used at first development stages [9], but was abandoned due to its low boiling point and scarce thermal conductivity. At the same time, hot gases and combustion gases were used but at the end, the process naturally evolved to steam water [10–13] as heat vehicle.

Induction heating moulding (IHM): in this technique, a high frequency electromagnetic field generates heat by means of Joule effect directly into the volume under the cavity surface [14–19]. Coils are installed in channels or cavities made ad hoc between cooling channels and cavity surface. Ferromagnetic material should be used if Foucault currents will be responsible of fast homogeneous heating [20] mainly used in small tools. This technology combines convective steam efficiency with high temperatures not reachable at logic pressures with

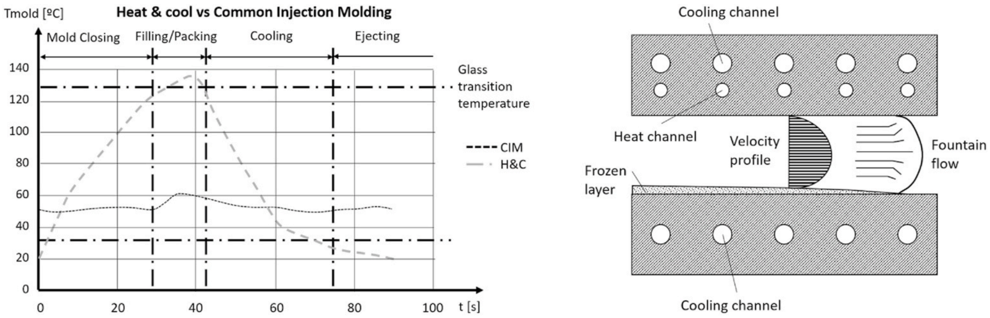

Fig. 1. RHCM vs conventional moulding, a) Cavity temperature and b) melt front advancement and frozen layer.

saturated steam. With induction, heating cost increment have to be carefully studied if project viability should not be compromised. Proximity effect was considered to overcome drawbacks making induction heating affordable but its complexity do not allow until now pass from experimental stage (or simple parts) and more research is necessary [21,22].

Electricity heating mould (E-mould): in this method heat is generated accordingly Joule first law when low frequency current is applied in resistors. In these devices, power density is crucial design factor, nowadays 100w/cm2 is a reliability limit, furthermore, power density around 40 W/cm^2 is considered high density in the industrial practice. An electric resistor is used as heating element placed inside a duct “ad-hoc” practiced between cooling ducts and surface cavity, see Fig. 2. In addition, sealed resistor can be used, and in this case could be placed inside cooling ducts, but water boiling point becomes operational limit [23,24]. Simplicity, low cost and operation until temperatures about 250 °C are main advantages; by the other hand low efficiency and time response are non-negligible drawbacks.

Designers, moldmakers and injection companies are frequently pushed down to introduce these all new technologies in their manufacturing processes, following new trends in quality products but, as it is usual, it is necessary a previous knowledge in order to achieve their benefits. Tool strength and reliability, total process cost, necessary investment and associated defects should be revised just before to change conventional moulding to any other new technology. Authors would like to show some guidelines to illustrate this RHCM process. All experiences are prepared for helping industrial practitioners in their future decisions.

In the present work, an E-mould type system was chosen to study the RHCM process as alternative to conventional moulding. Temperature control was only exerted in the fix half of the tool in terms of heating and cooling, the other half, on the other hand, has no rapid heating but active cooling. Using this arrangement, conventional cooling and RHCM could be compared, and defects when there is no way to achieve a symmetrical part heating and cooling are revealed. In a novel way, fixed half-mould mounted a hybrid sensor allowing pressure and temperature real time measurement.

2. Material and methods

From the multiple ways by which power could be regulated in these resistors, authors preferred on/off triggering using time as a control parameter. This choose was done due to simplicity and improved responsiveness. This allows the study of the relationship between heating time and temperature peak values, mean values and homogeneity in temperature distribution by means an infrared camera, which complement the hybrid sensor data. Part size and geometric simplicity have revealed this type of RHCM technology most suitable having in mind the research work which will be done.

For the study part, a plane frame shape was chosen, a simple geometry in order to reduce unexpected phenomena, and to get simple temperature distribution on the mould halves. Some data about the part designed:

- Maximum rectangular dimensions: 110 × 80 mm,
- Constant thickness: 2 mm,
- Three internal straight sides and a rounded fourth side (Fig. 3 a))
- Two film gates located in the internal part contour (Fig. 3 b))

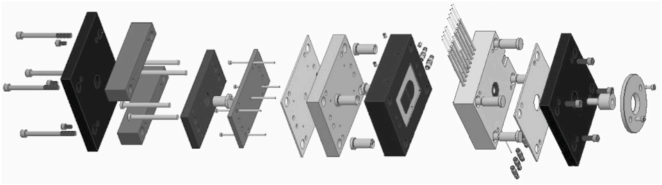

Fig. 2. Experimental tool used in this work, mould with electrical lines used for rapid heating.

Steel was selected as mould material. Heat transfer using steel is lower than using aluminum plates (cause of high density and low conductivity of steel compared with aluminum), but it is much more usual to use steel for large series (frequently up to 10^6 cycles) due to poor mechanical properties of aluminum under injection pressure (not only strength but stiffness too). In the fixed half mould, heating elements are placed just over the part. In order to achieve reliability, power density of heating bars are limited to 60 W/cm^2, in this case we will use 40 W/cm^2, with 4 mm diameter bars. This rate guarantees around 6300 W for the complete half mould. An external timer operated by user will control all resistances. As it was written before, this asymmetrical arrangement was intentionally chosen, because many times it is necessary high quality surface only in the external part face.

Cooling lines are divided in fixed half part, where two U shape independent lines are drilled with 6 mm diameter (Fig. 4), and in the mobile half mould a simple U shape was machined, same diameter. Space rates between cooling lines were stablished following literature design rules [1,2,25,26] searching not only uniform temperature but mould mechanical strength. Water temperature was fixed to 12 °C, and it has been supplied by an external cooler.

After cooling time, pressurized air was used to remove; the coolant remained inside these cooling lines. This action improves heat transfer rate during next heating phase with electrical power lines. Electromechanical valves regulates these movements.

For data recording, a P-T piezoelectric sensor from Kistler was used, with its amplifier and the CoMo Kistler data recorder for measured shots. In this case, cavity pressure and mould surface temperature will be acquired. In the injection machine, a Mateu&Solé hydraulic clamping machine, 55 ton, a thermographic camera FLIR A10 was installed over fixed plate, to capture part temperature at ejection time using infrared technology and Therma Cam Research software. Plastic parts warpage suffered was evaluated using a 3D Faro scanner, and processed by Geomagic Qualify software.

Two different polymers were used, both amorphous: an acrylonitrile butadiene styrene (ABS) grade, Edgetek AS-000 AS from PolyOne, and a polycarbonate (PC), Makrolon 2407 supplied by Bayer. Both materials are frequently used for home appliances and automotive parts, especially for housing and cover TV and other aesthetical components, so it is interesting to inject them with this RHCM process. Their main properties are shown in Table 1.

The injection machine used was a 270/55H from Mateu & Sole, a Spanish trademark made in 2004. Its main characteristics are compiled in Table 2.

All experimental injection results were compared with commercial software Moldflow Plastics Insight, (version 2016) (pressure, temperature, warpage) to aid future designers to understand this technology. That version only allows to use the “variotherm” technique, using water steam for heating, so, it was necessary to run a previous trial test on an individual mould plate in order to test the equivalent power between steam flux rate and heating bars. This study was made using the infrared camera and a finite element code, looking for approximate plate surface temperature results. When this process was finished, time and temperature values for the simulation injection software were fixed and translated to the experimental tool analysis with the necessary precision (temperature differences less than 10% between model and testing sample results). Nowadays, recent software versions include new capabilities for this analysis.

Finally, in order to evaluate warpage under different process and conditions, a laser measurement device was used to compare part deformation, a Faro scan-arm installed in Mechanical Engineering Department of the University of Zaragoza.

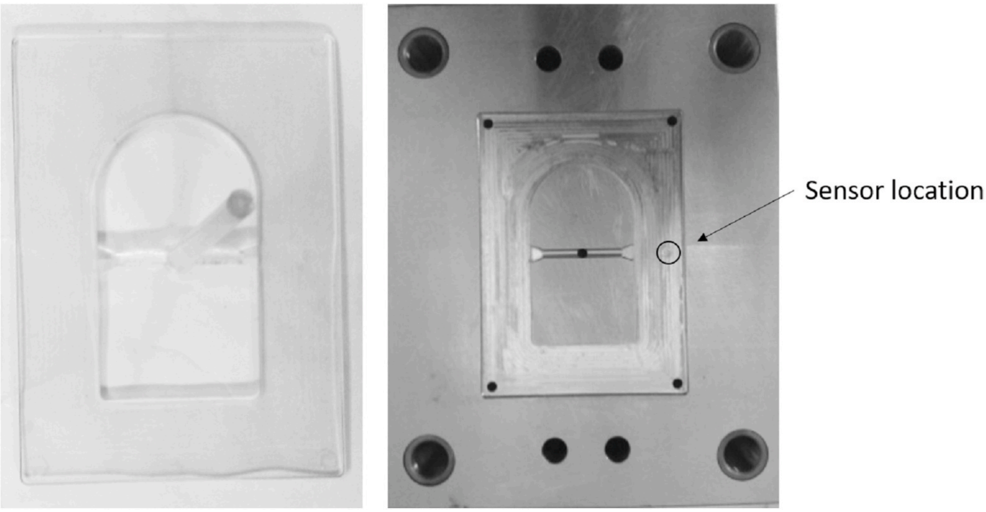

Fig. 3. a) Experimental specimen injected in this work b) Mobile half-mould. Black point shows integrate pressure and temperature sensor location.

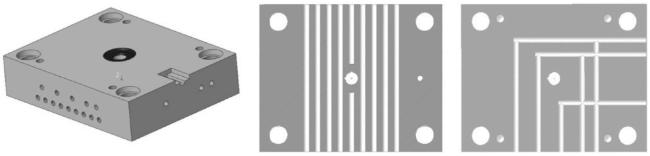

Fig. 4. Heating bars (Ø 4 mm, closed to the plastic part) and two “U” cooling lines Ø 8 mm layout.

Table 1
Basic values for polymers used in this study.

Properties	Edgetek AS 000 (ABS)	Makrolon 2407 (PC)
Density (g/cm^3)	1,05	1,2
Linear shrinkage (%)	0,4–0,6	0.5–0.7
Young Modulus (GPa)	1,8	2,4
Thermal conductivity W/mK	0,20	0,214
Specific heat J/kg K)	1172	2100
Typical processing values		
Drying conditions (°C/hours)	80 °C/3	80 °C/3
Recommended processing temperature. (°C)	220	280
Recommended mould temperature. (°C)	70	80

Table 2
Mateu & Solé 270/55H main characteristics.

Injection unit		
Screw diameter	mm	35
L/D ratio		20,5
Max. Cavity pressure	bar	1735
Max. Injection volume	cm^3	155
Clamping unit		
Clamping force	KN (ton)	550 (55)
Mould height, (min-max)	mm	120–300
Tie bar distance HxV	mm	355 × 355

3. Experimental results and discussion

In order to compare conventional process versus rapid heating and cooling moulding (RHCM), several conditions were setting on the machine control. The temperature response is analyzed in this case, looking for quantifying its value; understand its response principles and stablish some mould design rules and best practices according to previous literature.

Target mould temperature for heating was considered between 90 and 120 Celsius degrees, depending on polymer type (ABS or PC), for RHCM in order to improve surface quality and to reduce welding lines flaw impact on part appearance. When conventional process was made, a typical mould temperature for each polymer grade was used too. It is necessary to consider that this value is not constant along the injection cycle. In the case of injecting ABS, and using infrared thermograph camera, mould surface temperature distribution was supervised, just at the starting cycle time and after heating time (Fig. 5). Each experience was repeated ten times, in order to guarantee adequate statistical values (Fig. 6).

To study the thermal parameter effects on the process, some experiences were carried out using the cited ABS material. In the following case, a comparison between the technology with mould temperature regulation and the conventional was made (Fig. 7), showing the typical heating ramp, the filling phase when plastic melt transfers heat to mould surface, and the cooling time with the surface temperature decreasing. Packing phase almost invisible in both cases, because it is 2 s long and, in fact, under heat transfer laws, it should be considered as the beginning of cooling phase.

The effect of changing cooling time, for example, in the heat and cool process could be appreciated in Fig. 8. The final mould surface temperature is twelve degrees below when cooling time increases 15 s, and it is lower the surface temperature achieved in the next cycle. This effect would be considered for conventional process in the same way, changing part dimensional quality, for example, under PvT diagram and shrinkage rules cited in literature.

Now, when PC is injected and, using H&C process, first basic results is the very important cycle increase required to reach the desired mould temperature, shown in Fig. 9, where it is compared with a conventional process with oil heated at 120 °C. The curve registered by the sensor does not reach this value, but it is equal to temperature level after 45 s with the power lines in H&C process. Therefore, there are important heat transfer effects on these systems, not only dues to power used but to mould diffusivity, its volume, its shape and, specially, time involved.

As it is revealed, H&C process requires almost three times the conventional cycle time in this study for this injection tool. Different authors have written about this, recommended the use of aluminum mould plates and lighter geometries reducing plate height at minimum levels [5,24]. However, it is well known that this reduction produces higher stress values on mould material, when it is under injection pressure, and

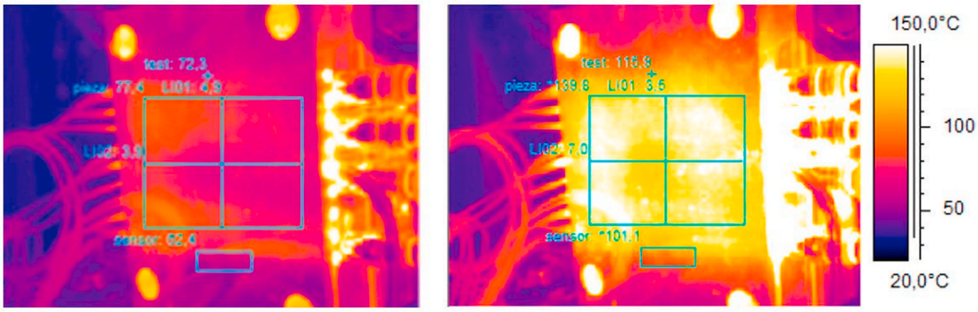

Fig. 5. Infrared mould surface images, fixed half, when the cycle begins and after 45 s of heating with the electric power lines. ABS.

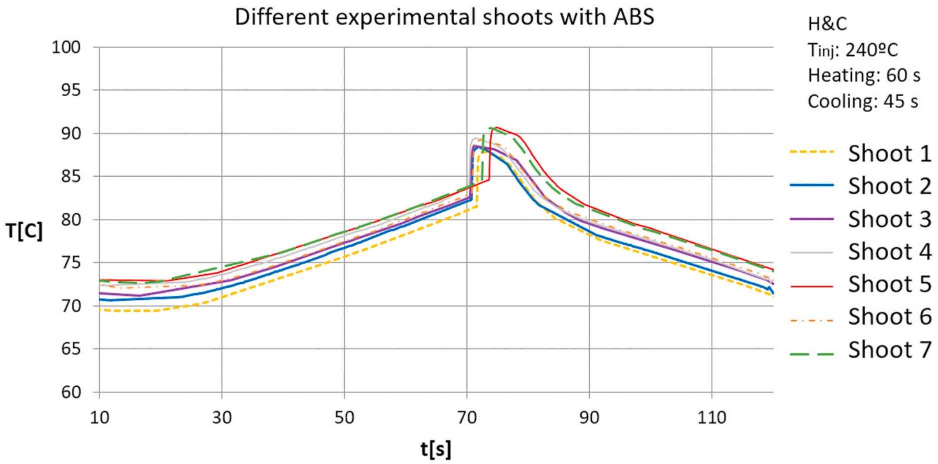

Fig. 6. Sensor temperature curve, H&C process, case with ABS, 240 °C injection temperature, 60s heating and 45s cooling, seven different shoots are shown.

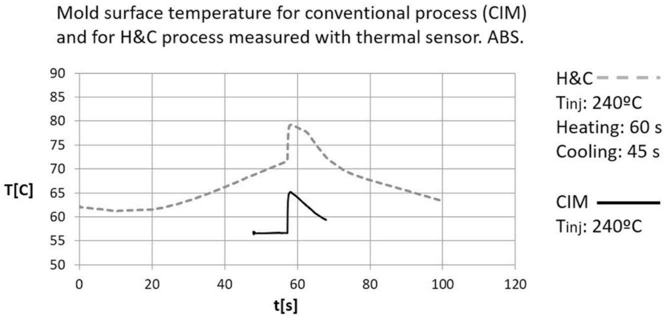

Fig. 7. Cavity temperature curve showing typical injection phase, H&C (discontinue curve) heating 45 s, cooling 45 s; and CIM (continue curve), both for melt temperature 240 °C.

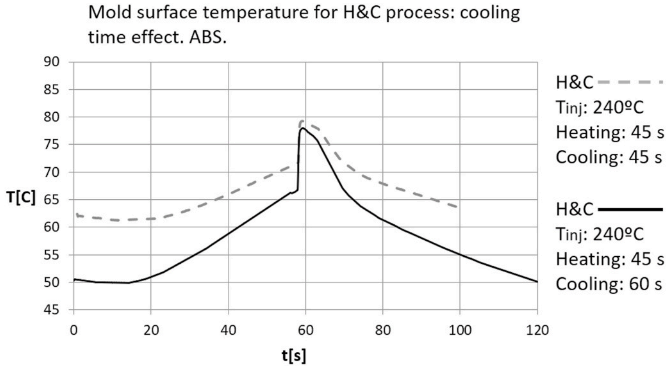

Fig. 8. Mould surface temperature for H&C process: cooling time effect, heating 45s for both curves, cooling time 45 s in discontinue curve, 60s for continue curve.

this promotes unexpected breaks and tool failures. So, designers must consider all these requirements carefully.

Simulation results were compared too, using the cited Moldflow software and the pressure and temperature sensor data obtained. Fig. 10 shows a typical case for this analysis. Qualitative results are similar, and this is illustrative for engineers and mould-makers, but temperature sensitivity should improve in the process modelling and evaluation in author's opinion after this experience, that it is not usual in technical literature.

Warpage is considered a very problematic defect for injection components. Using a no contact measurement technique with the Faro scan-arm, part final deformation was evaluated. For conventional process at recommended mould temperature, non-detectable deformation was encountered. However, for the heat and cool process the heating system is only placed in the fixed mould half, so thermal stresses are induced in the part when it cools down. These results were simulated too, with a qualitative correspondence well defined, in both cases the final concave profile is promoted to the hottest mould side (Fig. 11). Literature explains this phenomenon, and it is illustrated, for example, in Sanchez et al. [27] for conventional samples and Wang et al. [6] for RHCM industrial parts.

Table 3 details values encountered for conventional and RHCM process under similar conditions. The average of the part surface temperature for both processes are also detailed, measured with assistance of the infrared camera software.

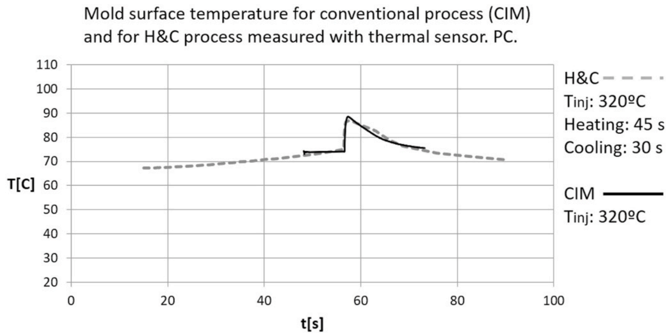

Fig. 9. Comparative sensor temperature curves for conventional process (CIM) and for H&C process. Material: PC.

4. Conclusions

Rapid heating and cooling moulding technique is a new injection moulding process offering new capabilities to plastic converters and part designers. Its driven idea is to adequate the cavity surface temperature to the injection phase, that means to increase temperature just before the melt advancement during filling phase and to cool it down when packing phase stars, as quickly as possible because the imposed gradient is higher than in the conventional process. This is the simple but logical aim for H&C processes.

Several heating and cooling systems have been developed last two decades, using fluids, electrical power lines or induction systems, with different complexity and results depending on part complexity. In this study, an electrical power system was made, for a testing part injected with two amorphous polymers under conventional and rapid heating and cooling systems. A pressure – temperature transducer, not commonly presented in literature, was used to record both parameters in the cavity, and infrared camera and no contact scan-arm were used to evaluate different typical results in injection moulding.

In the same way, an industrial simulation software was used to compare the measured values, adapting the values to the capabilities using a previous mould plate as sample test, because the mathematical model did not support electrical heating in the 2016 version.

Different trials with PC and ABS were made, and the most remarkable values were shown. Temperature is not well studied in the injection moulding technology, even when literature and producers recognize its importance. Usually pressure curves are considered, but temperature ranges and distribution are only supposed under operative or industrial conditions.

After these thermal results obtained, some remarkable results should be considered: the variation of surface mould temperature during the injection cycle offers a set of new possibilities of process control, including the excellent appearance that this new technology exhibits and the improvement of weld line strength also reported, for example in Refs. [28]. Measured values and tendencies were compared with simulation tools, with good correspondence from our point of view, so it is clear that a deep analysis of mould heat transfer in the design phase could improve final production quality.

However, there are some questions without an easy solution: the heating system and layout for complex parts, because heating tools are not easy to locate inside the mould, the thermal inertia in the mould (when steel is used as usual in industrial practice) which increases the cycle time, and the warpage changes that could be promoted if there is only one high quality surface part side required. An important cycle time increase was reported too in this study for RHCM compared with conventional injection moulding, and this fact should be carefully considered if mould long life and large production is needed.

So, authors believe that surface temperature curves, simulated and measured for both processes, and thermal inertia observed in the heat and cool process should be carefully considered from the very beginning in the plastic part project. If not, many industrial problems, defects (as unexpected warpage or unbalanced effects during cavity filling) could appear. The cycle time should be evaluated as well, further from this technique designation, because this is the economical main advantage for injection process, and it could be strongly affected.

Author statement

R. Sánchez: Conceptualization, Validation, Investigation, Data

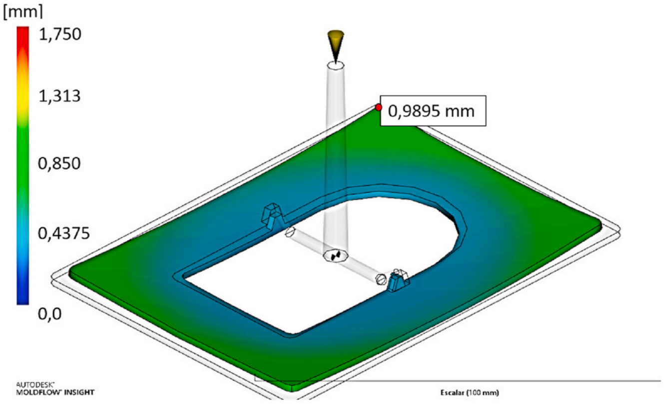

Fig. 11. Warpage tendency obtained by simulation.

Table 3
Warpage comparative between H&C and CIM processes.

Process, melt temperature 240 °C	Maximum Z displacement [mm]	Part ejection average temperature [°C]
H&C sample, 45 s heating, 45 s cooling	0,857	104
CIM, conventional	0,212	115

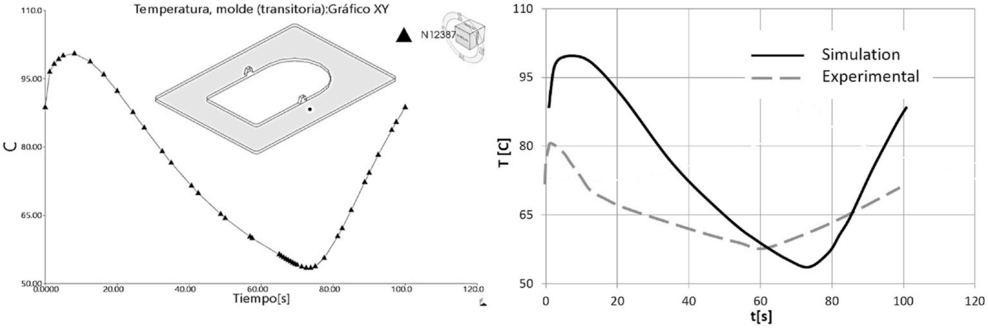

Fig. 10. Mould surface temperature, H&C 240 °C heating 45 s, cooling 45 s, a) Software result b) Comparison between simulated result and experimental result.

curation, A. Martinez: Validation, Data curation, Writing - original draft, Writing - review & editing, Visualization, D. Mercado: Methodology, Supervision, A. Carbonel: Data curation, J. Aísa: Conceptualization, Writing - original draft, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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