

# APPLICATION OF FLOW PATTERN CONFIGURATION SPACES TO OPTIMIZATION AND CONTROL OF LIQUID COMPOSITE MOULDING PROCESSES

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**SUMMARY:** Paper [1] in FPCM-9 has proposed a novel approach called *Flow Pattern Configuration Spaces* (FPCS) as a computational framework for LCM process design. The main interesting idea of using these spaces lies in the definition of the coordinate system by means of the process parameters related to the flow, instead of a customary Cartesian coordinate system. In [1] are defined two configuration spaces, one based on filling time, called *Flow Pattern time Spaces* (FPTS) and other based on the distance, called *Flow Pattern Distance Space* (FPDS). The goal of the present paper is to define how to use these spaces in LCM optimization and control processes and the advantages that has the use of these spaces in contrary to use the Cartesian coordinate system.

**KEYWORDS:** configuration spaces, Resin Infusion (RI), optimization, on-line control, Liquid Composite Moulding (LCM)

## INTRODUCTION

The present paper is the extension of [1] where it is introduced a novel filling process representation for LCM processes. It is obtained by the use of a technique called *configuration spaces*. The main property of these spaces is that permits to represent the process to study, instead of a customary Cartesian axis, in terms of process configuration parameters. The use of these spaces in LCM processes is called *Flow Pattern Configuration Spaces* (FPCS). The configuration parameter selection is free and depends on the configuration space application. In the FPCS proposed in [1], one of the parameters is based on the radial flow behavior. Hence, the angle defined by an interest point, such is the nozzle injection or the vacuum vent, to the evaluated point location is selected as a configuration parameter. This parameter is fixed for all the FPCS variants proposed in [1]. The second

parameter is free to choose establishing different possibilities. The first possibility proposed in [1] is based on simulation results, where the normalized node filling time,  $[0..1]$ , of each node is selected as a second parameter. This space is called *Flow Pattern Time Spaces* (FPTS) where the flow fronts are ever represented as circles or straight lines, FPTS-2D and FPTS-1D respectively.

The second FPCS proposed in [1] is based on the distance. The distance configuration parameter selection is due to it is a common concept used in the literature, for LCM optimization [2-3], and control [4-5]. Therefore, the second configuration parameter is the distance between an interest points, such is the nozzle injection or the vacuum vent, and each node. This distance is computed taken into account the mould geometry. Therefore it can be used for real LCM 2.5D moulds. This space is called *Flow Pattern Distance Spaces* (FPDS). The use of the distance instead of time, introduces the contrary concept than FPTS. If in the FPTS the flow front is represented ever as an exact circles and straight lines, in the FPDS it is wished that the flow front has this representation because it means that the flow front has the proper orientation to the vent.

The computational framework proposed in [1] is not limited to deal with the vent and gate inlet shape definition, making it useful for all LCM processes regardless geometrical mould complexity. This paper is focused as follows. In the first section are defined two Process Performance Indexes, one based on the FPTS that measure the proper filling process and other based on the FPDS that measure the proper vent oriented flow. In the second section is used the FPTS to treats to define the optimal gate shape for the optimal filling process using the information obtained through FPTS. In the third section is proposed the methodology of how to use the FPDS defined in [1] for LCM on-line control systems.

## PROCESS PERFORMANCE INDEX DEFINITION THROUGH FPCS

As shown in [1], the FPTS defines the filling process in terms of the normalized filling time. If the mould filling process is perfect, that is, the flow front achieves the vent at the same time; the FPTS contour must be a unit circle or unit straight line, see Fig. 1.

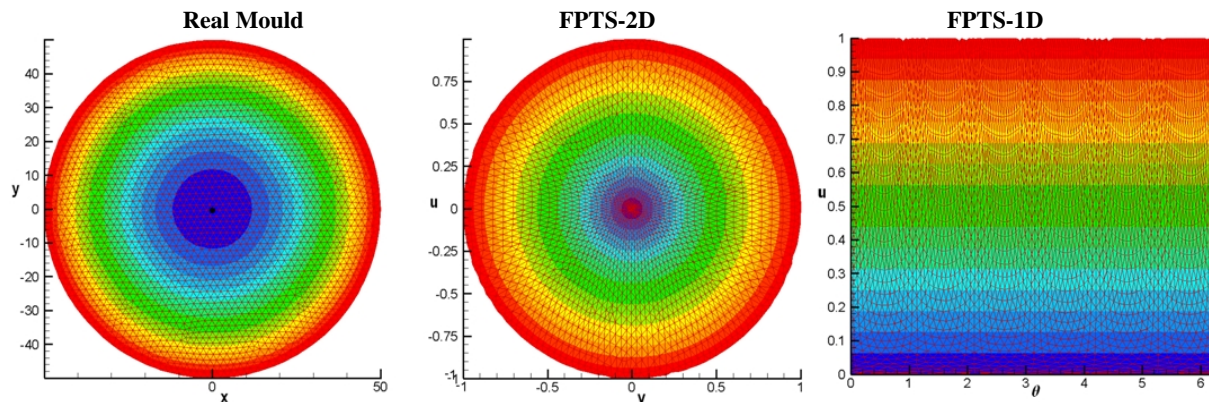


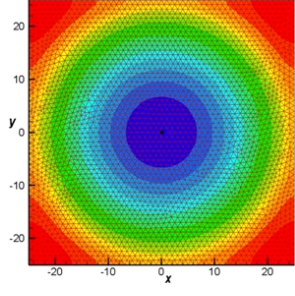
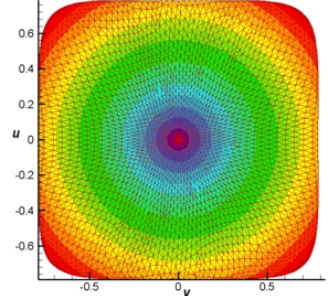
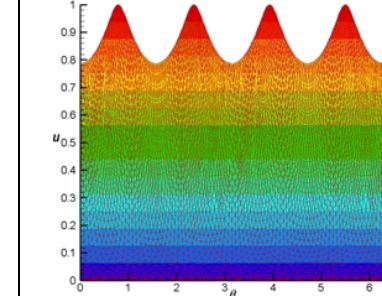
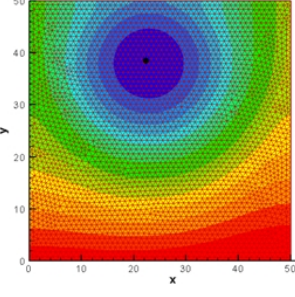
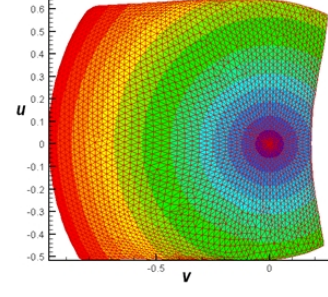
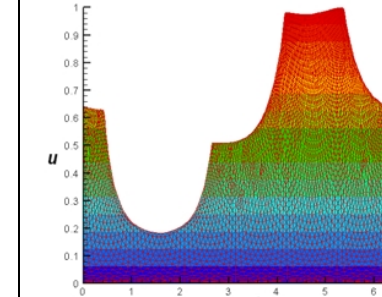
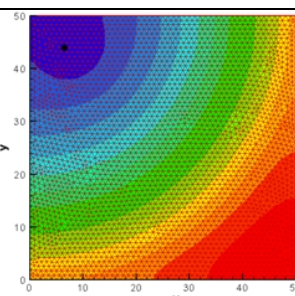
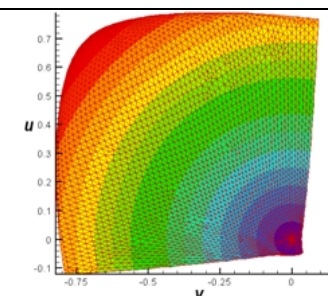
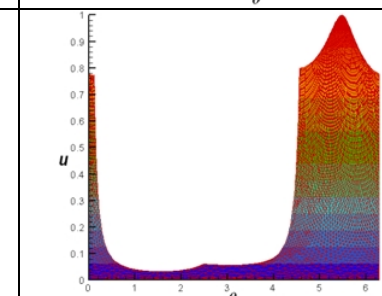
Fig. 1 FPTS when the filling process is optimal.

The FPDS has the inverse concept than FPTS, that is, if the flow front has the proper orientation to the vent, the flow front representation is an exact circle or straight line meanwhile in the FPTS this representation is ever guarantee. Therefore, it is easy to formulae some PPI index as filling factors, that measure this optimization items, that is

$$Q_{fill} = \frac{\sum_{n=1}^{Vn} (1 - \tau_n)}{Vn}, \quad Q_{Shape} = \frac{\sum_{n=1}^{Vn} (\bar{\tau} - \tau_n)}{Vn} \quad (1), (2)$$

where  $Vn$  is the number of nodes,  $\tau_n$  is the configuration parameter of this nodes and  $\bar{\tau}$  is the median of the parameter value nodes. Next table shows an example of the  $Q_{fill}$  evolution in a square mould where the gate inlet is allocated in different positions.

Table 1 Quality fill factor using FPTS

FEM Simulation Mould	FPTS-2D	FPTS-1D	$Q_{fill}$
			0.06
			0.233
			0.3115

Note that in the FPTS,  $Q_{shape}$  is ever 0. It is due to the flow front are exact circles and lines.

## GATE INLET SHAPE DEFINITION THROUGH FPTs

One of the applications of the quality fill factor joined with the FPTs is the optimal gate location for applications where the vent is allocated in the mould contour. The main quality of this methodology is that permits to optimize not only points in the mould, also allows to compute the optimal gate inlet shape for the optimal filling process, that is, the flow front achieves the vent at the same time. Through FPTs it is possible to establish a heuristic methodology to find the optimal gate inlet. In this sense the algorithm proposed in this paper needs to find first the optimal point gate that minimizes the quality fill factor.

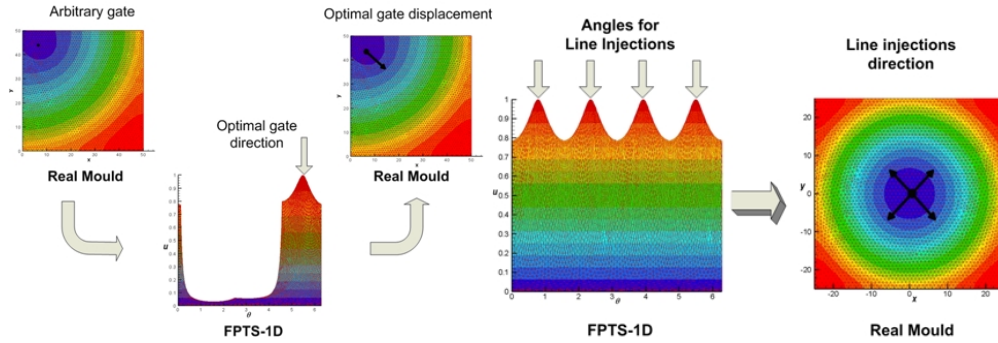
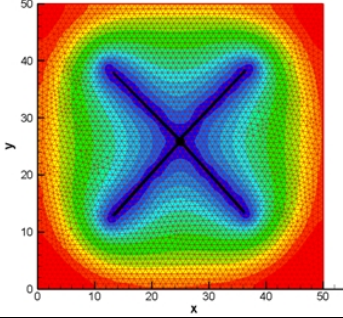
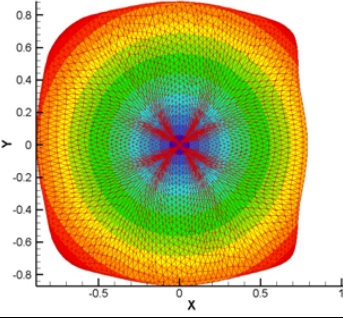
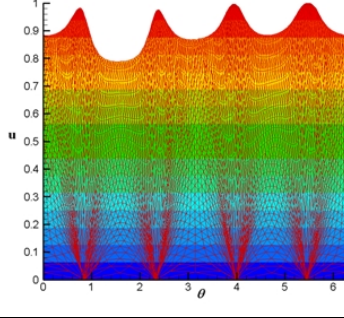
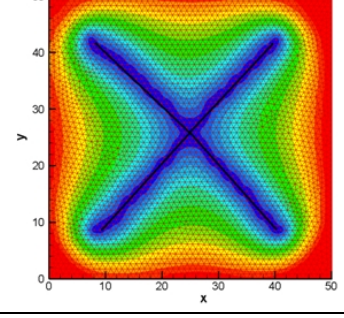
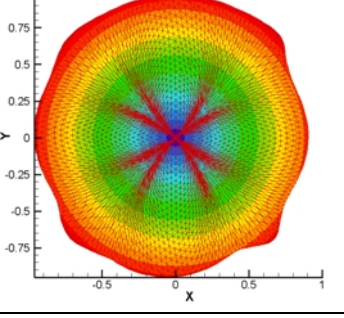
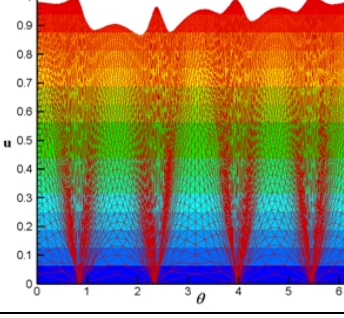


Fig. 2 Optimal gate point location (left). Line injection allocation (right).

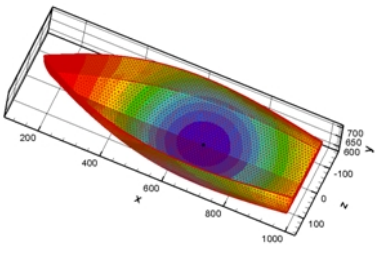
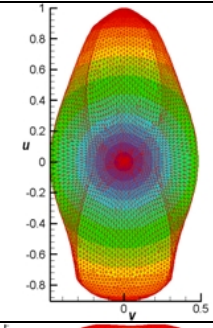
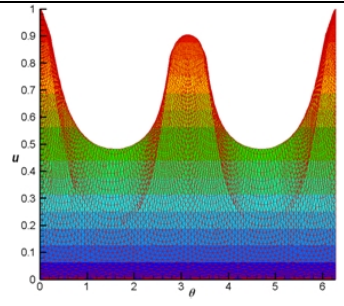
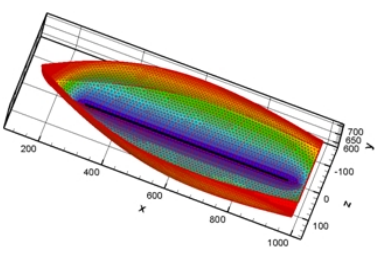
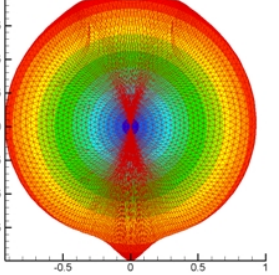
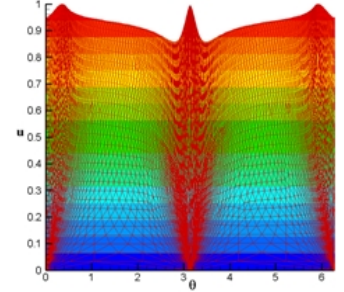
Table 2 Optimization process in a square mould

FEM Simulation	FPTS-2D	FPTS-1D	$Q_{fill}$
			0.047
			0.030

This process can be used for 2D moulds or 2.5D moulds indistinctly, see Table 3.

The process starts for an arbitrary point gate location. After of this, the last node filled in the FPTS defines the angle at which the gate must be moved to find the optimal allocation, see Fig.2 (left). When the optimal gate point is found, line injections are introduced to improve the filling process at the angles that determines the last nodes filled in the FPTS, see Fig. 2 (right). In table 1 is shown the evolution of the Quality fill factor when the gate is moved to the optimal position. In table 2 is shown the evolution of this factor when line injection are introduced in the mould.

Table 3 Optimal gate location (up) and optimal line allocation (down) for 2.5D moulds

FEM Simulation	FPTS-2D	FPTS-1D	$Q_{fill}$
			0.195
			0.043

## LCM ON-LINE CONTROL SYSTEMS THROUGH FPDS

In our previous work [6] is introduced the FPTS and artificial vision for on-line control applications. In this paper, multiple cameras allow monitoring real 2.5D moulds as a FEM simulation does. It is due to the camera pixels are previously associated as Finite Elements. In [6] some different scenarios are previously simulated using the mesh obtained by the camera and translated to the FPTS. The last node filled in each of these simulations is selected as an optimal vent for each case. By the use of each FPTS, it is possible to identify, computing the  $Q_{shape}$ , which scenario is occurred in the real filling process. Therefore, the controller selects the vent that has less  $Q_{shape}$ , because this is the case that is reproduced in the process. This section explains the advantages of FPDS in the control strategy. A square mould with an outlet allocated in the square center and one inlet in each corner is proposed for on-line control, Fig. 3 (left).

As a control criterion, is selected the proposed in [7], where each inlet defines a zone that can be controlled independently (see Fig. 3 right). Therefore, through FPDS, Fig. 3 (center) is very simple to show which inlet requires increasing or decreasing their flow rate. This criterion can be easy formulae through FPDS because allows using the Euclidean distance. It

is due to inherently takes into account the mould geometry, see [1]. Fig. 4 (left) shows an example of filling process. The distance that controls the flow rate of each inlet,  $D_1$ ,  $D_2$ ,  $D_3$ ,  $D_4$ , Fig. 4 (right), can be computed by the Euclidean distance but, as the outlet is allocated in  $u=0$ , just only needs to take into account the  $u$  value of the nearest filled node to the outlet in each zone, because the node value is the distance to the outlet. As the computation is developed in the FPDS, is inherently to the real mould dimension, permitting to control LCM 2.5D moulds in the same manner.

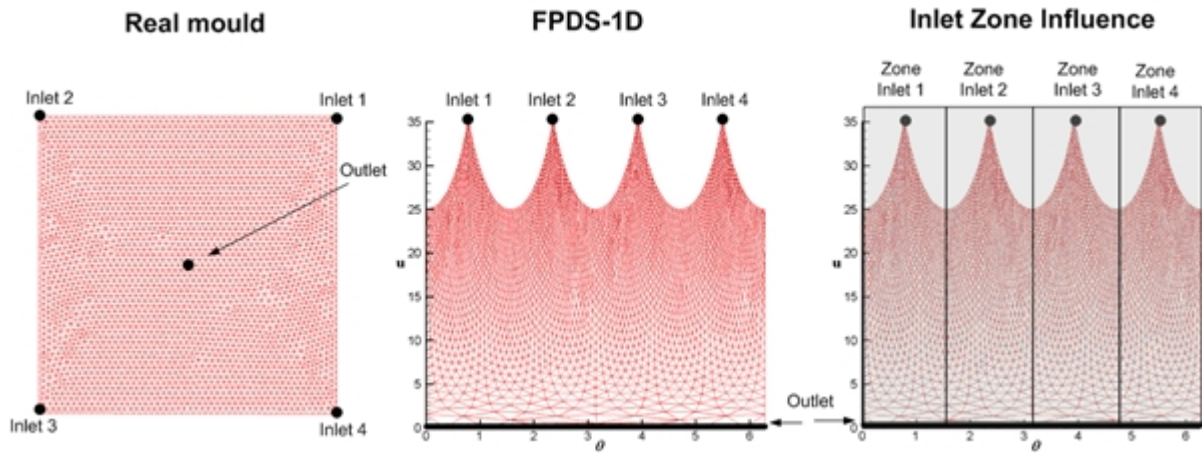


Fig. 3 Mould to study (left), FPDS-1D (center) and inlet influence zone (right).

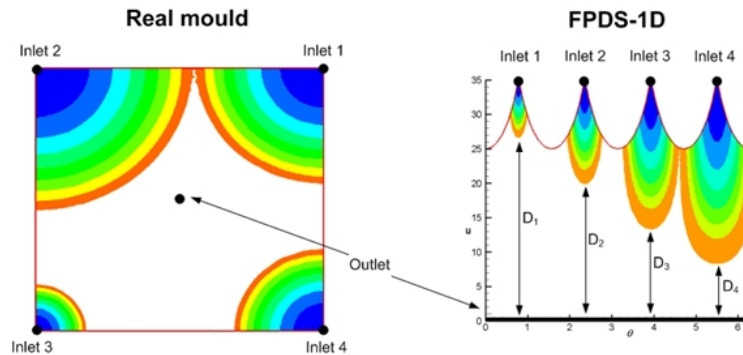


Fig. 4 Example of FPDS applications in on-line control.

## CONCLUSIONS AND FUTURE WORK

In this paper is presented some of the application that have the FPCS proposed in [1] for LCM processes. The FPCS permits an easy monitorization and understanding of the filling process. Therefore the algorithm development for the optimization and control of the LCM processes is also easier than using a complex 2.5D mould. This issue also implies that this algorithm has low computational costs than real mould computation. In this paper first are proposed two process performance indices,  $Q_{fill}$  and  $Q_{shape}$ . The first one permit to measure quantitatively if the flow achieves to the vent at the same time and the second one allows to know if the flow front has a proper vent orientation. These PPI index can be used for optimization and control

of LCM 2.5D processes. If we show the resulting FPTs, seems obvious that, if line injectors are introduced in the angles that the flow achieves the vent later, the filling process should be improved. This criterion is not obvious if we show a complex 2.5D mould. By the use of the  $Q_{fill}$ , this issue is demonstrated. Also is not easy to determine in on-line 2.5D filling which gate must be reduce or increase the flow rate, but showing the FPDS it is quite simple to determine which is the control action to do. The easy criterion permits to develop a control algorithm with a low computation permitting to develop real-time on-line control systems. The use of FPCS has an amount of application in LCM processes; our future work is to use these spaces to define flow front shapes of the optimal filling process through homotopical deformation of the FPCS contour.

### ACKNOWLEDGEMENTS

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