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Micro-cooling Constructal Design: An Application to Mold Inserts Thermal Management

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Abstract. Mold thermal performance has a direct influence on part properties, quality and defects, and mold productivity. Through additive manufacturing, inserts can be developed with features that respect the necessary high complex geometries the part requires and that increase thermal performance. Constructal design is explored as a design tool to produce guidelines for cooling channels development.

INTRODUCTION

Mold cooling stage is one of the most important stages in the molding cycle. It plays a crucial role in injection molding by taking more than half of the molding cycle time and affecting the part final quality and mold productivity. It begins when plastic at entry point solidifies and plastic flow into the mold stops. How long the stage lasts depend on the desired ejection bulk temperature for the part and the cooling channels heat removal capability [1]. Therefore, cooling channels are essential to ensure a reduced cooling stage, an increase of productivity and to minimize undesired effects obtaining quality plastic parts.

One of the most challenging issues in plastics injection is the hardening of small thin wall plastic parts with complex geometries that increase the difficulty in designing appropriate cooling channels. The use of *Additive Manufacturing* grants a more precise approach to mold design, allowing a better adaptation of cooling channels to highly complex geometries, resulting in a more uniform part cooling, which in turn reduces cooling time [2].

Inserts manufacturing should be achieved by additive manufacturing, capable of producing highly complex geometries. The fundamental purpose is to increase inserts thermal performance to increase part quality and mold production rate.

When minimizing systems or components, methodologies should be developed to potentialize mold inserts cooling without affecting part characteristics. The tendency to miniaturization in flowing systems points towards vascularization, as seen in nature. Through the application of constructal design, vascularized channels can be developed to better suit the inserts complex geometries and achieve the intended thermal management effects that the combination of these technologies allows.

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THERMAL MANAGEMENT IN MOLD INSERTS

Conformal cooling is an approach to the thermal management of molds by designing cooling channels which follow the part's contours. This path adjustment facilitates a faster and more uniform cooling of the mold. However, given the variation of the complexity degree of a part, the implementation of this approach is not straightforward through traditional machinery. Therefore, additive manufacturing represents a step forward in the availability of conformal cooling to mold designers.

There are several research works showing the effectiveness of this approach and a particular concern about the design of the channels [3, 4, 5]. Park and Pham [6] distinguish three types of conformal shapes: zigzag; parallel; and spiral. Each configuration has a purpose, but the optimization of channels sizes, distances and other lengths scales depends on numerical simulations. There is no optimization based on flow or heat transfer constraints. In this sense, a constructal design follows an approach driven by thermal optimization in the design phase, prior to any numerical simulation.

CONSTRUCTAL DESIGN APPROACH

The use of a *Constructal* principle is the design of configurations in thermal systems minimizes trial-and-error approaches while increasing a system's performance. The principle predicts and explains how nature evolves and designs systems to perform with reduced resistance to the flow. Thus, its basis is to optimize the system to provide an easier access to flows from one point to another, being the points either singular or infinite (line, area or volume).

The application of the constructal design does not eliminate imperfections, but aims at minimizing their impact by distributing them along the flow. Pressure drops or temperature differences usually quantify these imperfections.

In a flow, there are external and internal scales, and the *Svelteness* which corresponds to the relation of both becomes a property of the global flow architecture within the constructal principle. In internal flows, the *Svelteness* describes the relative importance between localized and distributed losses along the flow, commonly neglected when calculating the global pressure drop. By showing that this simplification is not always true, the *Svelteness* becomes a potential design parameter helping engineers to evaluate flow efficiency. Additionally, the importance of *Svelteness* is highlighted in systems miniaturization [7].

The following sub-section presents a flow configuration developed for micro-cooling in mold inserts designated as *Umbrella*, and a synthesis of the theoretical grounds of the geometrical relations which minimize the currents that flow through the channels.

The Umbrella Method for Micro-cooling of Mold Inserts

The *umbrella* method consists in cooling the insert volume through a primary channel until a tip where *n* secondary channels depart making the fluid flow return through divergent channels.

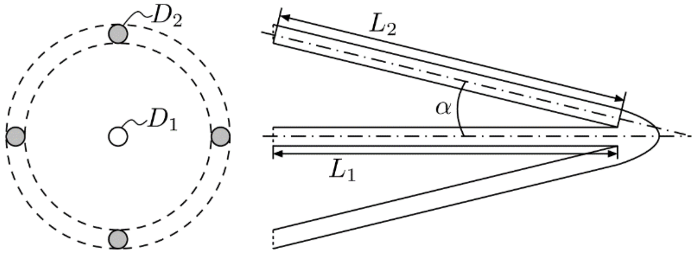


FIGURE 1. Scheme of the umbrella geometry with $n = 4$ secondary channels and the relevant geometrical parameters.

Through mass and momentum conservation and by minimizing distributed friction losses in each channel a geometric constraint relating the size of primary and secondary channels is determined:

$$\frac{D_1}{D_2} = n^{1/3} \tag{1}$$

The *Svelteness* relates external and internal length scales, which are the area occupied by the geometry and the volume of primary and secondary channels, respectively. For the Umbrella configuration, it can be expressed as:

$$\mathrm{Sv} = \Gamma(n, \alpha)\left(\frac{L_1}{D_1}\right)^{2/3} \tag{2}$$

where Γ is a function of the number of secondary channels n and the return flow angle α. The relevant geometrical parameters of the Umbrella are clearly related to *Svelteness*.

The ratio between local and distributed head losses is the criterion used for optimizing the flow resistance. The physical modeling considers a laminar regime, since the risk of phenomena, such as cavitation, is higher in the turbulent regime. By ensuring that local losses are much lower than distributed losses due to friction, $\frac{\Delta p_{local}}{\Delta p_{distr}} << 1$, in practice, their effect becomes negligible. In this sense, local losses should be an order of magnitude lower than distributed losses, expressed as $\frac{\Delta p_{local}}{\Delta p_{distr}} = \Delta p^*_{crit} < 0.1$

According to the physical modeling of the Umbrella configuration, the head loss ratio expresses as

$$\Delta p^*_{crit} = \frac{\Lambda(n, \alpha)}{64\psi(n, \alpha)}\left(\frac{\mathrm{Re}_{D_1}}{\mathrm{Sv}^{3/2}}\right) \tag{3}$$

Since the *Svelteness* is a geometrical property of the flow related to pressure losses, we use it as the criterion to evaluate the efficiency of the flow and the corresponding effect of geometric parameters.

RESULTS AND DISCUSSION

The two independent geometric parameters investigated in the work presented here are the size of secondary channels (D_2) and the return flow angle (α). The size range for D_2 lies between $50\mu m$ and $500\mu m$ with $5\mu m$ steps, and the return flow angle varies from 1° to 10°.

To evaluate the Umbrella method applied to micro-cooling of mold inserts, several assumptions are made:

- A Reynolds number of 2300 in the primary channel.
- The order of magnitude for primary channel length, L_1, is 10^{-2}, or centimeters.
- The number of secondary channels the maximum possible under the criterion of a minimum distance between secondary channels equal to their diameter. This relation is expressed as $n_{\max} = floor\left[\frac{\pi L_1 \tan\alpha}{D_2}\right]$ where floor rounds the result to the nearest integer less than or equal to that element.

Linking these assumptions to the head loss criterion $\Delta p^*_{crit} < 0.1$ helps establish a minimum value for *Svelteness* (Sv) above which we can neglect local head losses.

The size of secondary channels is an essential input parameter. Mostly due to its relations to other geometric variables, such as the primary channel size and maximum number of secondary channels, but also because it is the smallest dimension in the umbrella configuration with serious implications for the manufacturing process.

Figure 2 shows the results for Sv obtained through Eq. (3) solved for this parameter, considering the effects of the return angle α and D_2. In practice, higher angle values represent an increase of the external flow length scale, while increasing the size of secondary channels represents an increase of the internal length scale. This relation explains the result depicted in Fig. 2.

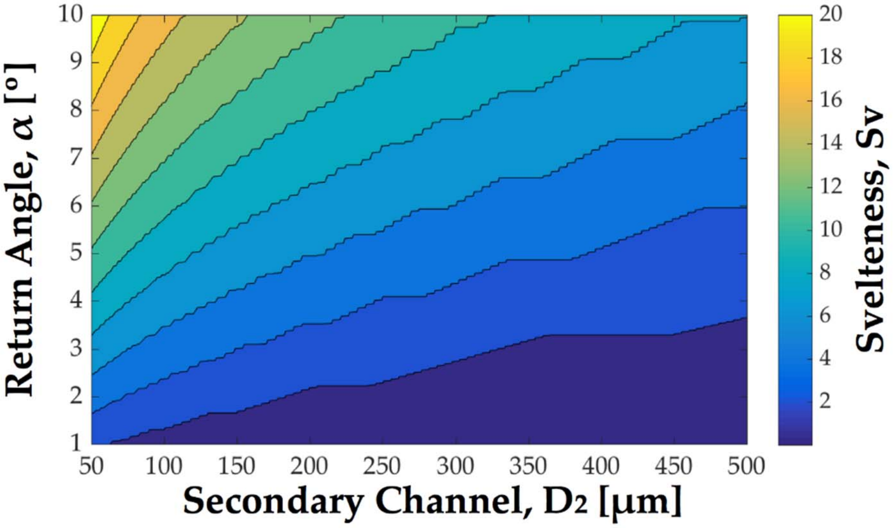
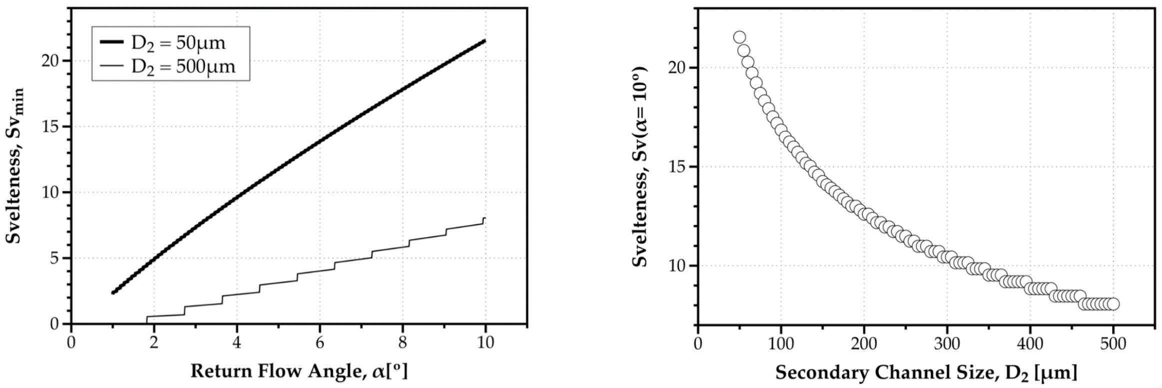


FIGURE 2. Minimum *Svelteness* value for several return angles and several secondary channel sizes.

The results show how the Svelteness is more sensitive to the return angle α with smaller secondary channels (Fig. 3b) and to secondary channels' size with higher return angles (Fig. 3b).



(a) (b)

FIGURE 3. (a) Minimum Svelteness value for several return angles with $D_2 = 50\mu m$ and $D_2 = 500\mu m$; (b) Minimum Svelteness value for $\alpha = 10^{o}$ and several secondary channel sizes.

One of the usual metrics regarding the Svelteness in inner flows is to set it to 10. But this depends on the the flow architecture as Fig. 2 shows. Therefore, if we fix the Svelteness at 10, what would be the best return flow angle depending on the secondary channel size? This is the result depicted in Fig. 4. The non-linear result is interesting because it provides a guideline for choosing the best angle for the minimum size that additive manufacturing can produce.

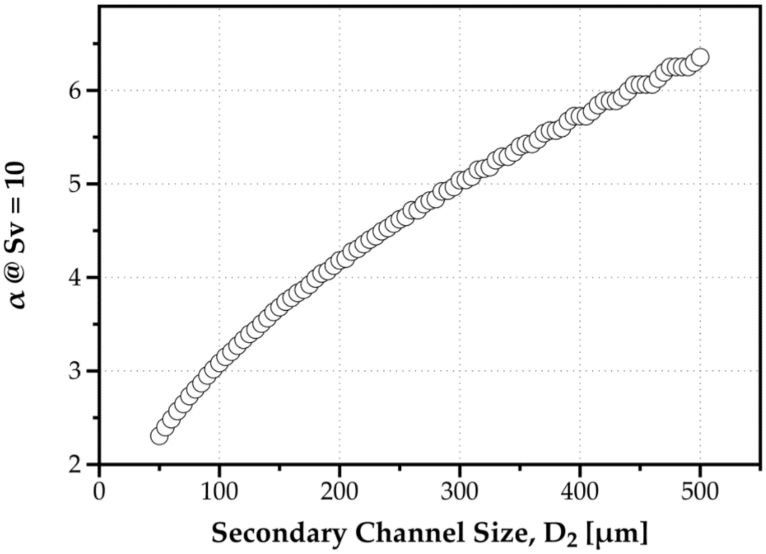


FIGURE 4. Best return flow angle α , for a fix Sv = 10, as a function of the secondary channel size D_2 .

Finally, these results demonstrate the flexibility the Umbrella method has to maintain local losses negligible and benchmark the geometry at its maximum capacity to do so, allowing it to be further constrained while predicting the effect it will have on to ensure an optimized flow.

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REFERENCES

1. D. O. Kazmer, Injection Mold Engineering (Hanser Publications, Cincinnati, 2007).
2. T. Wu, S. A. Jahan, Y. Zhang, J. Zhang, and H. Elmounayri, Procedia Manufacturing 10, 923–934 (2017).
3. S. J. Park and T. H. Kwon, Journal of Manufacturing Science and Engineering, Transactions of the ASME 120, 296-305 (1998).
4. X. Xu, E. Sachs, and S. Allen, Polymer Engineering & Science 41, 1265–1279 (2001).
5. D. E. Dimla, M. Camilotto, and F. Miani, Journal of Materials Processing Technology 164-165, 1294–1300 (2005).
6. H. S. Park and N. H. Pham, International Journal of Automotive Technology 10, 87–93 (2009).
7. A. Bejan and S. Lorente, Design with Constructal Theory (John Wiley & Sons, Inc., Hoboken, 2008).