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CONCEPT EVALUATION AND LAYOUT DESIGN OF A PISTON MOULDING MACHINE

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ABSTRACT
Lomolding is a piston moulding process, similar to injection moulding in some respects, aimed at making thermoplastic parts. A life cycle cost model is being developed to optimise lomolding machine designs and to investigate the range of products suitable for profitable application of lomolding. Several machine layout concepts were generated and evaluated to optimise the lomolder life cycle cost. This paper describes the concepts that were evaluated, why the final concept was chosen and ends with an outline of a parametric model that can be manipulated to generate different sized machines of the final concept. The key elements focussed on are the metering- and moulding unit assemblies, as well as the runner system between them. The material plasticiser and clamp unit are excluded since they are similar to those found on injection moulding machines. The parametric model is the starting point for estimating the contribution to the life cycle costs of the machine's purchase and operating costs and the energy consumption.

Keywords: Injection moulding, piston moulding, thermoplastics, parametric design, machine sizing

1 INTRODUCTION

1.1 Lomolding machines
Lomolding is a piston moulding process aimed at making parts similar to those produced by injection moulding. Its main operational sequence (illustrated in Figure 1) starts by measuring off in the metering cylinder the exact amount of molten thermoplastic (melt) required for a part (the shot), transferring the melt to the moulding cylinder and then pushing the melt into the moulding cavity by the moulding piston. During solidification, the moulding piston holds the cavity under pressure and the piston face forms part of the cavity wall.
The area where the melt enters the cavity, here referred to as a ring gate, is much larger than the sprue typically encountered in injection moulding, which is anticipated to bring advantages such as moulding of longer fibres, lower material shear rates, and lower clamping force requirements.
A life cycle cost model is being developed to optimise lomolding machine designs and to investigate the range of products suitable for profitable application of lomolding, with a focus is on the capital-, maintenance- and operating costs. Typical issues that must be addressed are the optimum ratio of moulding piston area to part projected area (considering life cycle cost and part quality), the choice between electric and hydraulic actuators, the choice between a single piston and multiple piston arrays and the effect of design and process choices on energy consumption. The life cycle cost and the issues just mentioned are strongly influenced by the machine layout concept.
Many subsystems in lomolding machines are practically the same as those in injection moulding machines, e.g. the clamping unit (the part of the machine that opens and closes the mould halves) and the platens (the stable structures that support the moulds). The plasticising unit for a lomolder can be an extruder, as used in an injection moulder, but a lomolder can alternatively receive the melt directly from a compounder since it does not impose a significant backpressure on the plasticising unit. The design and lifecycle costs of the subsystems shared with injection moulders have already been optimised through many years of development, therefore these subsystems could be excluded from the work presented here. The focus in this paper is on the metering unit (where the exact amount of material to fill the cavity is measured off), the moulding unit (which pushes this material into a part

cavity) and the hot runner used to convey the melt from the former to the latter. These three subsystems are referred to as a lomolding unit.

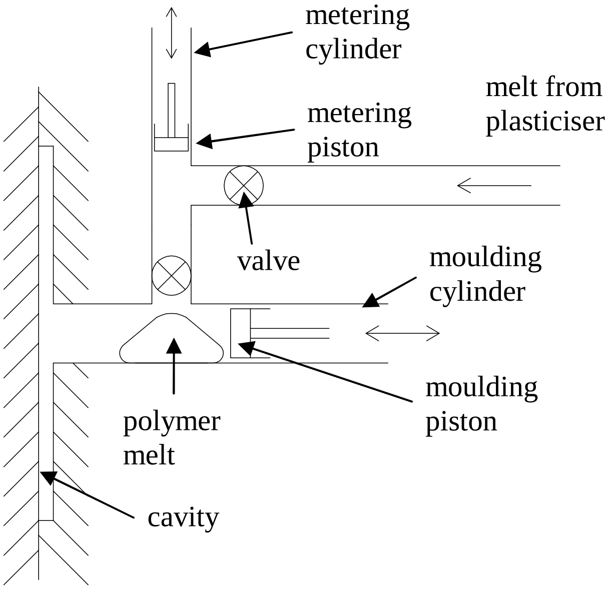


Figure 1. The lomolding process

1.2 Main design requirements

When the work presented here started, two experimental machines had already been built and used for investigations of the lomolding process [1]. The experience gained in these experiments aided in formulating and evaluating machine layout concepts presented in this paper. The following requirements were formulated from this experience for evaluating the concepts for the metering unit, hot runner configuration and moulding unit:

- The exact amount of molten material has to be measured off. This is challenging, since thermoplastic materials expands and shrinks considerably with changes in temperature [2].
- To keep both the cycle time and the backpressure imposed on the plasticising unit low, metering should preferably be done in parallel with the part cooling phase.
- When the melt has been pushed into the part cavity and the piston face forms part of the cavity wall, it is essential that the face must be cold enough to ensure even cooling of the part. To prevent premature solidification when the measured amount of material is transferred in front of the moulding piston, Dymond [3] showed that the time that the material is in contact with the piston face, before it has pushed the material into the cavity, should be kept short.
- The moulding cylinder temperature must transition from melt temperature (>200°C) where the melt is received, to mould wall temperature (<55°C) at the junction with the part cavity. The region below melt temperature should be kept as short as possible and the time that the melt is in contact with cold parts of the cylinder should be kept as short as possible to prevent premature solidification.
- Fibre breakage must be minimised since moulding long fibres is potentially a significant advantage of lomolding over injection moulding. Fibre breakage occurs in regions of high shear rate which causes bending moments on the fibres [4][5]. Therefore these regions of high shear rate are evaluated using equations published by Richardson [6] to determine the pressure drop in runner sections.
- The size of the opening in the stationary platen required by the lomolding unit, must be kept small to minimise the weakening of the platen. Also since it may be preferable to place an ejection system on the same side as the moulding piston (for cosmetic reasons), the lomolding unit should be compact.
- The changeover and maintenance cost must be minimised, e.g. by providing effective purging and minimising the replacement or refurbishment of complex parts.

1.3 Life cycle cost model development

The life cycle cost model is based on the parametric machine model, which can be configured to generate different sizes of piston moulding machines. Once the machine's main component sizing is done, capital costing can be done for the different components, and maintenance- and operating cost can be estimated at component level as well. The parametric model concentrates on the design of the components of the lomolding unit, i.e. the metering- and moulding cylinders and the flow channels between them, since these components differ significantly from those found on general injection moulders. As mentioned above, the plasticiser and clamping unit are essentially the same as in injection moulders. Published life cycle costing research in injection moulding concentrates on part features and mould design [7][8], presumable since research related to machine costing and optimisation is usually proprietary to machine manufacturing companies (and therefore rarely published).

In the next section the different concepts developed are discussed. This is followed by a discussion of the main machine design issues during the design development of a parametric machine model of the chosen concept.

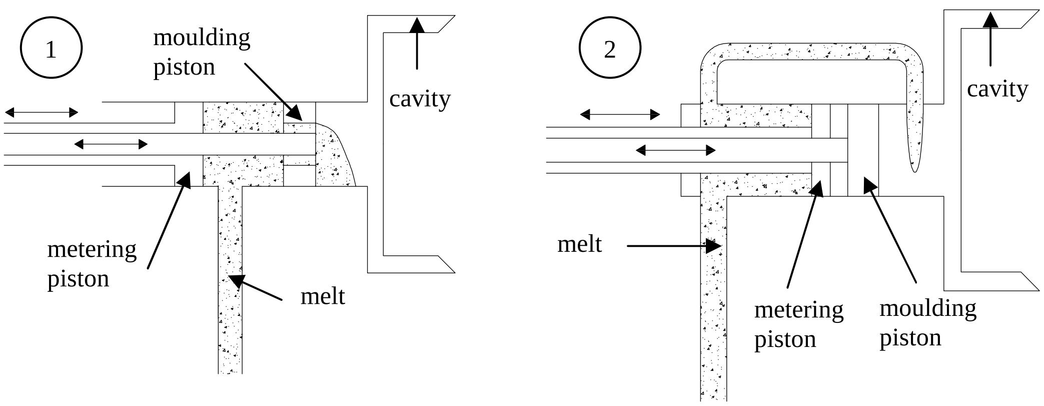
2 CONCEPTS DEVELOPED

This section explains the different concepts for lomolding units that were developed to fulfil the requirements stated in the introduction. Each concept is described in terms of how it works, its advantages and disadvantages, as well as why it was considered for further development or not. The concepts focus on two distinct aspects that were found lacking on the machine that Johnson [1] did his experiments on. Firstly, the melt measuring time overshadowed the cycle time of the part with a volume of 589 cm^3. The transfer unit runners were too small and this led to high pressures required to transfer the melt from the metering cylinder to a position in front of the moulding piston. It also led to high melt velocity speeds and therefore unnecessary high strain rates developed in the material. This aspect needed to be improved.

Secondly, all parts produced on this prototype machine had a defect at the periphery of the moulding piston. Analysis [3] showed that the defect was caused by material that solidified against the moulding piston wall, near the cavity, being pushed into the part at the end of the moulding piston stroke. Concepts developed here tries to minimise the time that the melt spends in contact with the moulding piston (before completing mould filling) and the moulding cylinder respectively.

Section 2 ends with concepts that were developed to try and eliminate the need for an accurate metering phase. These concepts provide the opportunity for adding or removing molten material after crude measuring is done.

2.1 Concepts developed to transfer melt

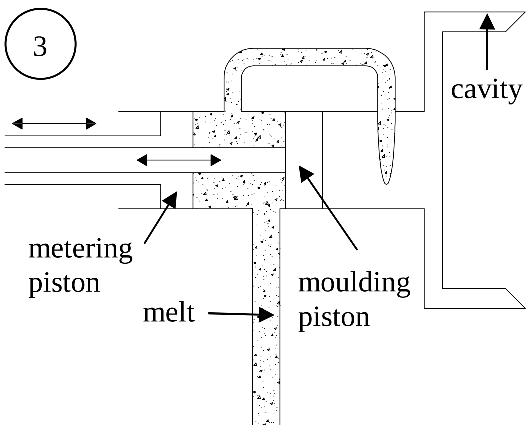


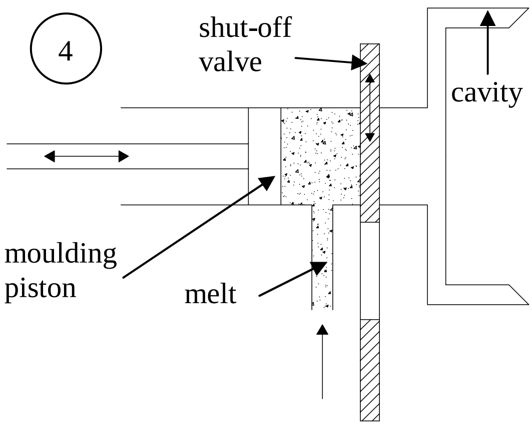
Concept 1: Inline pistons where melt is fed through the moulding piston

Concept 2: Inline pistons where melt is measured behind the metering piston and fed around the moulding piston

Concept 1 shows an inline metering piston and moulding piston. The melt is moved by this double piston configuration and is measured between the two pistons. Once the correct volume of molten

material has been measured, the melt is pushed through a valve in the moulding piston head and transferred to the front of the moulding piston. The valve in the piston then closes to prevent back flow of the melt and the moulding piston pushes the melt into the cavity to the point where its face forms part of the cavity wall at the end of the filling phase.
The concept's advantages include the compactness of the design and that material metering can be done in parallel with the part cooling phase. The concept's main disadvantages are: The valve in the moulding piston creates a high melt velocity section, with high shear rates; This smaller area may also be blocked by material with high fibre content; The inline metering piston and moulding piston leads to a complex mechanical design with increased maintenance times and maintenance difficulties expected; Insolating the hot side of the moulding piston while metering from the cold side required for part cooling, also poses difficulties; The valve in the moulding piston head will result in an extra piston mark on the moulded part; Uniform cooling of the moulding piston on the cavity side will also be difficult to achieve due to the valve in the piston. Due to these disadvantages, Concept 1 is not attractive.
Concept 2 also has an inline metering piston and moulding piston, but the melt is measured behind the metering piston and pushed in front of the moulding piston via a bypass runner. Once the shot has been transferred in front of the moulding piston, a valve in the bypass runner closes to prevent backflow of material during the moulding phase. Next, the moulding piston pushes the melt into the cavity and its face forms part of the cavity wall at the end of the filling phase.
The main concept advantages include compactness of the design, although less than Concept 1. Also, metering can be done while the part is being cooled. The hot melt is not in contact with the moulding piston during the measuring phase. Therefore, cooling of the moulding piston is less of a problem than in Concept 1. The disadvantages of concept are: The inline metering piston and moulding piston leads to a complex design as in Concept 1; Leakage of melt past the metering piston will accumulate between the metering piston and moulding piston, from where it will be very difficult to purge and this will lead to increased maintenance times. Concept 2 is therefore not attractive.



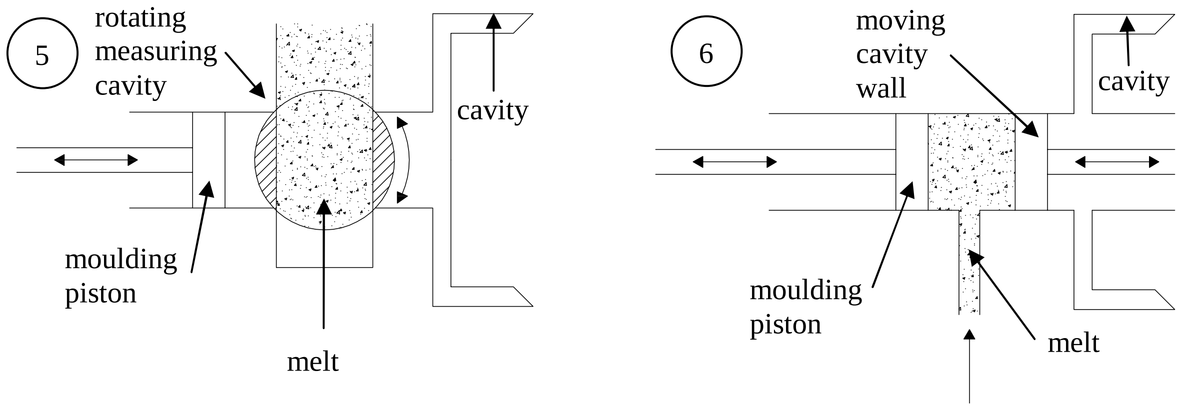


Concept 3: Inline pistons where melt is measured between the pistons and fed around the moulding piston

Concept 4: Inline moulding piston and shut-off valve

Concept 3 is similar to Concept 2, except that the melt is measured between the two pistons. It retains most of the disadvantages of Concept 2, as well as the added complication that the moulding piston has to be hot on the metering side and cold on the cavity side. This concept holds no advantages above Concept 2, except that the problem with melt leaking past the moulding piston in Concept 2 has been eliminated.
Concept 4 shows a moulding piston and a cross-fed shut-off valve. The melt is measured between the moulding piston and the shut-off valve and, once the correct volume of molten material has been measured, a valve closes in the melt inlet to prevent back flow of the melt during the cavity filling phase. After the shut-off valve opens, the moulding piston pushes the melt into the cavity and its face forms part of the cavity wall at the end of the filling phase.
The concept's advantages include the elimination of the metering cylinder. The shut-off valve does not need accurate position control over the range of movement, except that a precise stopping position is

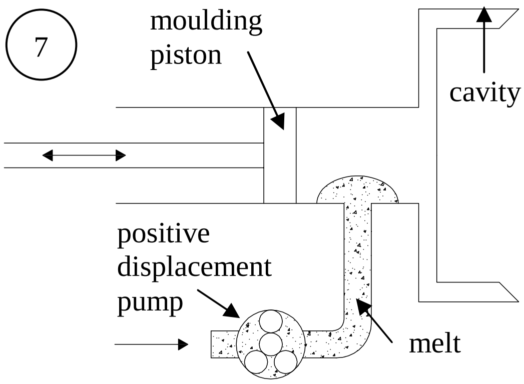
required, but this can be achieved with a mechanical stop. The concept's disadvantages are: Metering cannot be done in parallel with the part cooling phase and the moulding piston head is in contact with the melt during the whole metering phase. This concept is therefore not attractive.

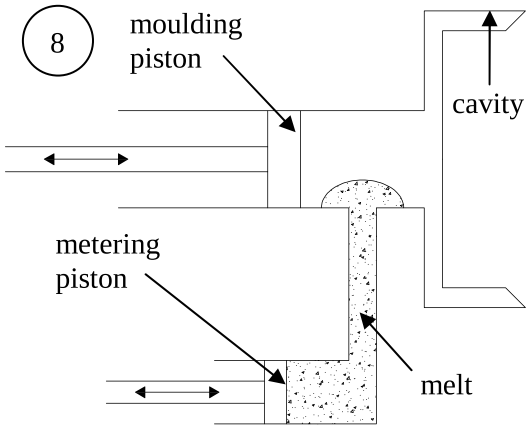


Concept 5: Inline moulding piston and rotating measuring cavity
Concept 6: Inline moving cavity wall

Concept 5 shows a moulding piston and rotating measuring cavity. Melt from the plasticiser fills the fixed volume measuring cavity. Once filled, it rotates through 90° and this allows the moulding piston to push the material shot into the cavity. The moulding piston face forms part of the cavity wall at the end of the filling phase. The concept's advantages include the elimination of the metering cylinder. The rotating measuring cavity does not need accurate position control, except that the stop position before the moulding piston moves forward must be very accurate. The concept's disadvantages are: The shot is a fixed volume and cannot compensate for density changes due to inevitable melt temperature variations; Only parts with one volume can be made on the machine; Metering cannot be done in parallel with the part cooling phase; Heating the rotating body to prevent melt solidification is also difficult. This concept was implemented in the first experimental lomolding machine, but was found unattractive for the reasons given above.
Concept 6 shows a moulding piston on the stationary platen side and a metering piston on the moving platen side. The melt is measured between the moulding and metering pistons. Once the shot is measured, the metering piston retracts and the moulding piston pushes the melt into the cavity. The moulding piston face forms part of the cavity wall at the end of the filling phase. Concept advantages include the inline replacement of the metering cylinder (compactness). However the design on the moving platen side will be complex. Further disadvantages included that metering cannot be done in parallel with the part cooling phase, that the cool moulding piston and the moving wall are in contact with the melt for the whole metering period and that both the moulding piston and the moving wall will leave marks on the part. The concept was discarded for these reasons.
Concept 7 shows a configuration where metering is done with a positive displacement pump. The pump is heated to prevent melt solidification. The melt is transferred to in front of the moulding piston and then pushed into the cavity. The moulding piston face forms part of the cavity wall at the end of the filling phase. Whether replacing the metering cylinder with a positive displacement pump will increase the cycle time, is not certain. However, fibre attrition is likely to occur in the pump when fibre reinforced material is processed. The accuracy of the metered shot is difficult to determine. This concept was deemed unattractive since it replaces a relatively simple and controllable metering cylinder with a more complex pump.
Concept 8 has a separate metering cylinder and moulding cylinder. After the melt is measured off in the metering cylinder, a valve closes in the melt inlet runner (not shown) to prevent back flow of the melt during the moulding phase and a valve between the metering and moulding cylinders (also not shown) opens. The shot is then transferred to the front of the moulding piston. The moulding piston pushes the melt into the cavity and forms part of the cavity wall at the end of the filling stroke.
The concept's advantages include that metering can be done during the part cooling phase and that the moulding piston is not in contact with the melt during the metering phase. The main disadvantage is that this concept is less compact than the previous inline concepts. This concept was however chosen for further development since it best satisfied the requirements listed above, had the simplest

mechanical design (thus reducing development risks) and the space considerations could be addressed as described in section 3.2.
Variations and combinations of the above concepts were also considered but, due to length restrictions, they are not discussed here.

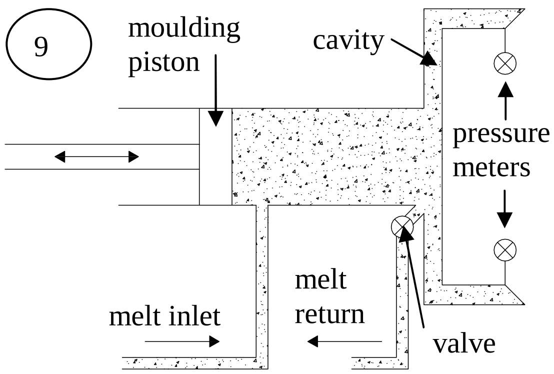


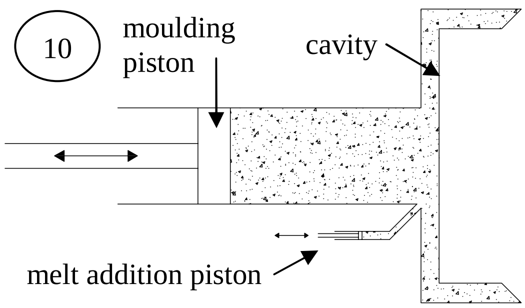


Concept 7: Positive displacement metering
Concept 8: Separate metering and moulding cylinders

2.2 Concepts developed to eliminate accurate metering

The cost associated with accurate metering, in particular the accurately controlled actuator and the close tolerances required for the piston and cylinder, lead the authors to consider concepts that eliminate the need for accurate metering. Those concepts are described in this section.





Concept 9: Pressure metering to replace accurate melt metering phase
Concept 10: Melt injection after moulding piston reaches required position

Concept 9 shows a moulding piston with a melt filling port and melt return port in front of the piston. The volume in front of the piston is larger than the part volume. This entire volume is filled with molten material and accurate melt metering is replaced by measuring the pressure at predetermined points in the part cavity during the injection phase. Once predetermined pressures are reached in the cavity the valve in the melt return line opens and the excess melt is transferred back to a melt accumulator until the moulding piston reaches its stopping position. This concept was discarded, since accurate pressure measurement during the rapid mould filling phase is particularly challenging. Also, the melt may block the metering points after some time. The repeatability of the process is a further point of concern.
Concept 10 shows a smaller additional moulding piston added to the machine configuration. Melt is fed in front of the moulding piston and then pushed into the part cavity. This initial material shot has a volume slightly less than needed to produce a part. Once the moulding piston reaches its intended position, the cavity is completely filled by the additional piston. More than one secondary injection point can be used. When the part is removed after the cooling phase, it breaks off at these secondary filling gates similarly to injection moulding. This concept was discarded as it becomes complex with

too many parts, especially if more than one secondary injection point is used. Also, the small secondary injection points may block if fibre reinforced material is processed. This will result in machine down time.

3 LAYOUT DESIGN

This section further develops Concept 8 and outlines the main machine design issues that strongly influence the cost of the Iomolding unit.

3.1 Computation of forces

The piston moulding process is performed by the actions as described in the introduction (refer to Figure 1). A semi-analytical model [9] was developed to estimate the cavity pressures encountered while filling the part cavity. It was validated by comparison with commercially available numerical simulation packages [10]. The injection pressure, i.e. the cavity pressure under the piston, is an important machine design parameter. The idealised change in the injection pressure and the corresponding flow rate during the mould filling phase are shown by the solid and dashed lines, respectively, in Figure 2.

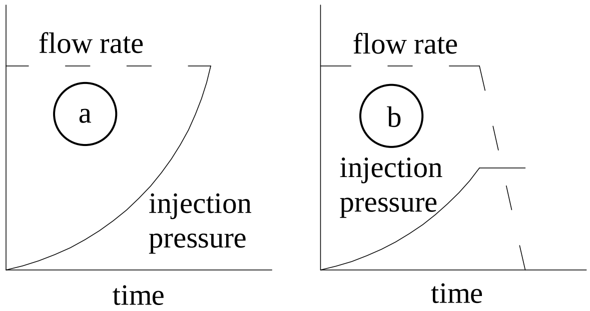


Figure 2. Injection pressure and flow rate during mould filling

Figure 2a shows a constant flow rate and increasing injection pressure over time due to the progression of mould filling. The profiles would give the minimum fill time (which would give a cycle time advantage), but the machine would have to be able to deliver high moulding pressure and flow rate simulataneously. Also, controlling the machine when the shot is even slightly too large or too small, would be very challenging. Injection moulding is therefore not normally done in this manner and instead a constant flow rate is prescribed for only a certain part of the filling phase (80% to 90% of the injection stroke), followed by filling under constant pressure until the cavity is completely filled (as shown in Figure 2b). The change over point between the constant flow rate phase and the constant pressure drop phase is something the designer has to select for a particular layout design.

Once the cavity is completely filled the part is packed under constant pressure. This step is necessary to minimise warpage and to avoid sink marks resulting from the material shrinkage during solidification.

It can be deduced from Figure 2 that a specific machine may be able to produce larger parts than it was designed for by just lowering the material flow rate (keeping in mind that a minimum flow rate is required to avoid a short shot due to premature solidification in the mould). Lowering the flow rate will increase the cycle time per part, but the filling phase is often not a large part of the total cycle time.

The calculated maximum injection pressure is used to determine the maximum force on the moulding piston and the force that the clamping unit has to withstand. The metering piston does not have to exert a pressure as large as that of the moulding piston since it only has to cope with the earliest part of the filling phase and then only when the shot volume exceeds the swept volume of the moulding piston.

The moulding and metering pistons can be driven either by hydraulic cylinders or electric servo motors with ball screws. In both cases the following aspects have to be kept in mind:

- The shaft of the hydraulic actuator or the rotating ball screw must withstand the maximum axial force without buckling.

- The actuator must be able to deliver the required linear speed (determined by the required flow rate) combined with the required force (determined by the injection pressure and a friction allowance) at the point in Figure 2b where the change over from constant speed to constant pressure occurs. This point typically constitutes a critical design point, since the maximum energy transfer from the actuator to the piston occurs at that point in the filling phase.

3.2 Flow areas required

Concept 8 was identified above as the most favourable for further development. The layout shown in Figure 3 is a refinement of that concept. To avoid requiring a large hole in the platen, the metering cylinder is placed behind the platen. Even though Figure 3 shows the metering cylinder to be perpendicular to the moulding cylinder, they could also be placed parallel.

The melt flow path is strongly influenced by the machine layout details: molten material is pushed from the plasticiser through a round hole (part of the runner block, Figure 3:e) upwards into the metering cylinder. The material cannot flow into the moulding cylinder at this stage, since the ports in the moulding cylinder wall are closed by the moulding piston skirt during the packing phase. After the part has solidified, the mould opens, the part is ejected, the mould closes again, and the moulding piston withdraws to its rear position. Then the melt is pushed by the metering cylinder through the runner block circular opening (Figure 4:a), through the semi-annular runner (Figure 4:b) and into the moulding cylinder through two ports in the moulding cylinder wall (Figure 4:c).

The semi-annular runner (Figure 4:b and Figure 5, where the hatched area on the left shows the net flow area) is included in the layout to minimise the swept volume of the moulding cylinder, the time that the melt is in contact with the moulding cylinder, and the length of the moulding piston skirt. The melt enters the moulding cylinder through the two ports in the moulding cylinder wall (Figure 6). The land between the ports helps to ensure concentricity of the moulding piston when it starts moving forward.

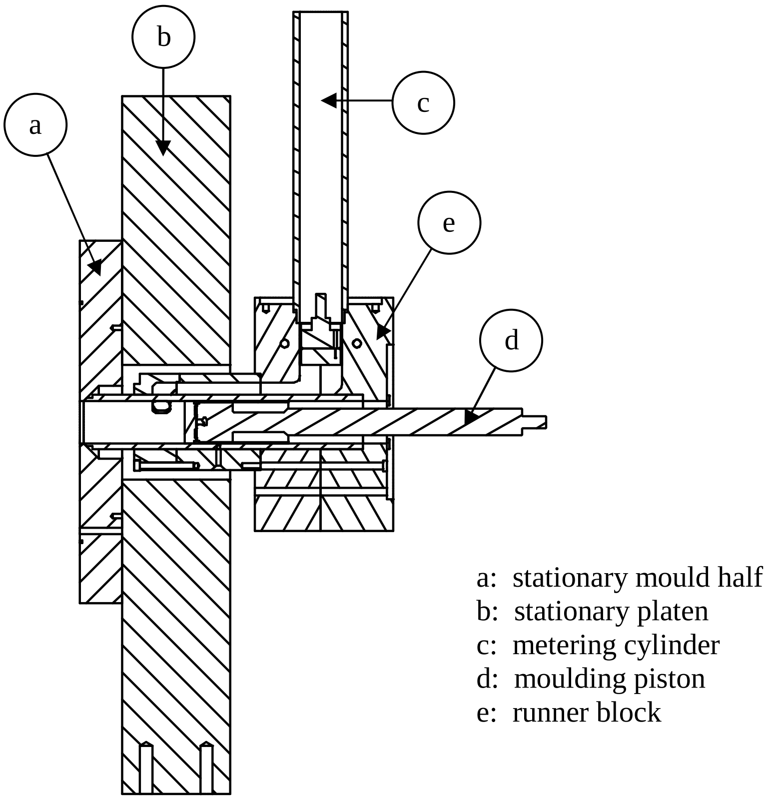


Figure 3. Metering- and moulding unit layout

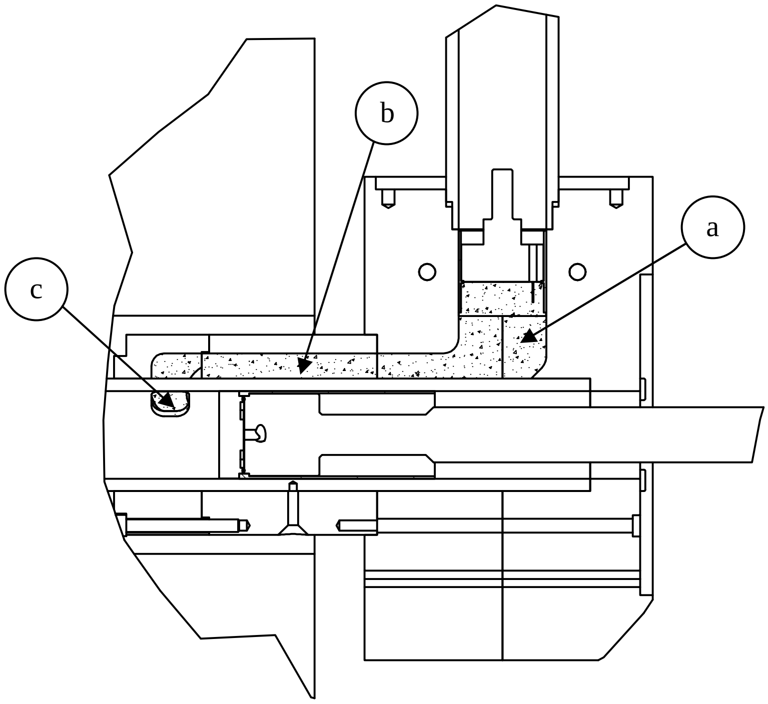


Figure 4. Material flow areas (enlargement of Figure 3).

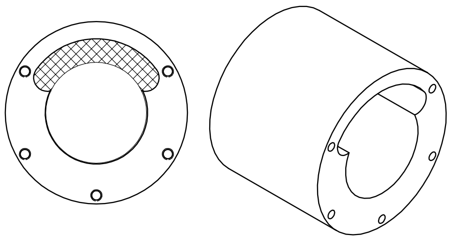


Figure 5. Semi-annular runner

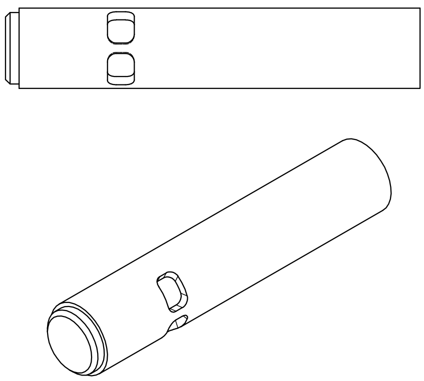


Figure 6. Moulding cylinder

Since many of lomolding's advantages are derived from keeping the shear stresses that the melt is exposed to well below that encountered in injection moulding, the main flow areas described in the previous paragraphs have to be sized in such a way that the melt shear rates in them are significantly less than where the melt enters the mould cavity. The shear rate at that point is controlled by the cylinder diameter, part thickness and fill rate. Richardson [6] published the following formulae that relate the pressure gradient to the material flow rate for non-Newtonian fluids in round tubes and between parallel plates:

$$\frac{\partial p}{\partial z} = 2\mu^* \left[\frac{Q(m+3)}{\pi R^{(m+3)}}\right]^{\frac{1}{m}} \quad \text{(flow in tubes)} \tag{1}$$

$$\frac{\partial p}{\partial x} = \mu^* \left[\frac{Q(m+2)}{2wh^{(m+2)}}\right]^{\frac{1}{m}} \quad \text{(flow between parallel plates)} \tag{2}$$

The viscosity at unit shear rate is given by μ^*. Q is the material volume flow rate, m is the viscosity shear rate exponent (in a power law viscosity model), R is the radius of the tube, w is the width of the flow channel between the parallel plates and h is half of the channel height. Equation 2 applies to cases where h is much smaller than w.
These equations take into account the total flow area as well as the shape of the flow area. In the parametric model, since the real flow areas do not exactly correspond to either equation's geometry, half of the hydraulic diameter is substituted for R in the case of non-round flow areas and the pressure gradient given by both equations are evaluated for each part of the flow path. The largest of the two pressure gradients is compared to the pressure gradient at the entrance to the mould cavity to decide whether the flow area is large enough. The shear rate is directly influenced by the pressure gradient. Fibre breakage due to bending (one of the reasons for fibre attrition) occurs as the fibres rotate against the material flow direction. These bending forces are proportional to the material shear rate [4]. The retention of longer fibres is expected to be one of the advantages of lomolding and therefore it is important that shear rates are lower everywhere in flow path upstream of the injection line.

3.3 Thermal considerations

The material selection for some critical parts of the lomolding unit is strongly influenced by thermal expansion considerations. Almost all parts are made from tool steel except for the parts described below. Significant temperature changes occur from start-up to normal operation. The mould cavity is ideally cooled to a temperature in the range of 30°C to 55°C, while the moulding- and metering cylinders are kept at temperatures above 200°C to prevent melt solidification. These large temperature differences, compared to ambient, will lead to significant thermal expansion and must be accounted for.
Figure 7 shows some details of the moulding cylinder and piston. The cylinder is typically made from honed hollow bar and hardened to resist frictional wear as a result of the piston skirt. The moulding piston and piston face are made from unhardened tool steel so that they will wear rather than the cylinder (the piston is easier to replace), but are strong enough to withstand the cavity pressures. Care must be taken to ensure that all the parts shown in Figure 7 should have approximately the same thermal expansion coefficient, otherwise the piston skirt (the solid black part in Figure 7) might get stuck in the moulding cylinder which will result in machine failure, or it might become too loose which will result in melt leaking past the sleeve. Therefore, the piston skirt is made from cast iron which has the same thermal expansion coefficient as mild steel [11] and some lubricity properties due to its graphite content. Large differences in thermal expansion coefficients is the reason why phosphor-bronze was not selected, even though it reduces frictional wear excellently in many applications.

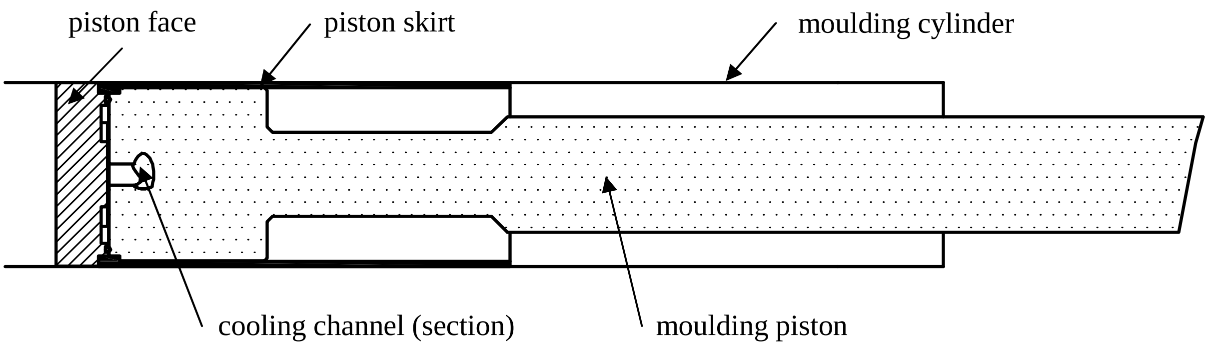


Figure 7. Moulding piston parts

To minimise heat transfer from the hot moulding cylinder to the mould cavity (with a temperature difference close to 200°C), the contact area between them is kept as small as possible. A heating band around the end of the moulding cylinder can be used to keep its temperature above the melt solidification temperature.

3.4 Layout sizing procedure

A summary of the different designer decisions and parametric design calculations are given in Figure 8. The material properties and process parameters mentioned in the figure include:

- melt viscosity at unit shear rate, μ^*
- melt viscosity shear rate exponent, m
- melt inlet temperature, T_i
- cavity wall temperature, T_w
- melt solidification temperature, T_m
- thermal conductivity of melt, k_m
- melt density, ρ
- melt thermal diffusivity, α

The part volume and material injection profile (Figure 2) are specified by the user, while the injection pressure is calculated using the semi-analytical model.

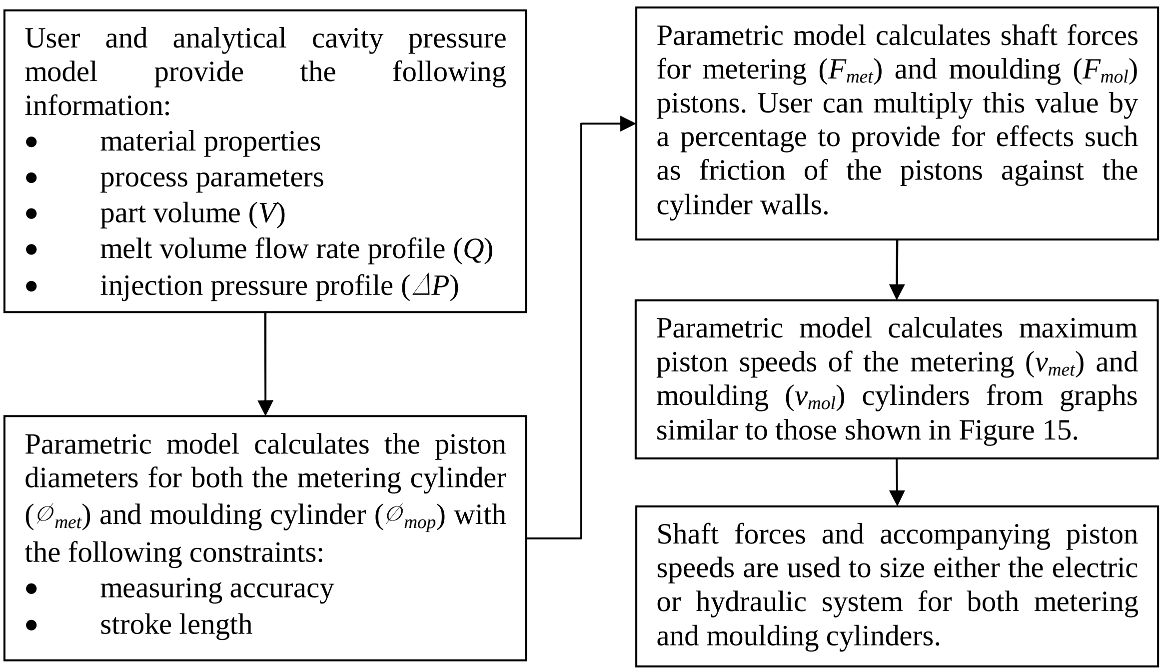


Figure 8. Parametric design flowchart

The parametric model was applied to two case studies to show the versatility of designing machines at extreme scale ends [12]. One machine was aimed at parts with a diameter of about 150 mm and thicknesses from 1 to 3 mm, while the other was aimed at a pallet-sized part, with a shot size of 20 L and a projected area of about 1 m^2.

4 CONCLUSIONS

Various machine concepts were explained and evaluations were given for their suitability as candidates for further development. The chosen concept was refined and a parametric machine model created to assist in layout design. Thermal effects considered in the machine layout and component material choices were highlighted. The parametric model is suitable for layout and sizing studies of lomolding units, which is an important step towards predicting their life cycle costs. The next step in the research is to link this parametric model to an optimisation package and adding the cost components for the different life cycle phases. It will then be possible to compute the best (in terms of life cycle cost) configurations and sizes of the moulding and metering units to manufacture a specific part.

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