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Viscosity

A Challenge for Injection Mould Designer

Muralidhar Lakkanna
Department of Mechanical Engineering
National Institute of Technology
Karnataka, India.

Ravikiran Kadoli
Department of Mechanical Engineering
National Institute of Technology
Karnataka, India.

G C Mohan Kumar
Department of Mechanical Engineering
National Institute of Technology
Karnataka, India.

Abstract- **Mould design is vital activity to injection mould thermoplastics with direct repercussions to yield quality, productivity and thereby frugality. As it involves various critical decisions; one such prominent decision being specifying runner size. Unfortunately mould designers intuitively resort to wisely specifying it and then exasperate to optimize / manipulate through independent control parameters [1]. Hence the manuscript intends to leverage the advantage of computational intelligence through a generic, simple, inexpensive preventive design methodology specifically for a particular thermoplastic. In pursuit an exclusive runner cross section size design criteria was imperatively deduced from first principles, further to enhance comprehensiveness its pervasive empirical relationship was quantitatively concocted as an explicit function of in-situ injectant state for an available machine specifications and desired moulding component features. Reckoning apparent viscosity range's behavioural character to assort almost all thermoplastics relative to in-situ spatiotemporal injectant state perplexity [2]; Continuous Sensitivity Method (CSM) was embraced to sensitise it over an infinite dimensional range. Thereon inferences accorded direct exponential proportionality of runner size with discrete slope and altitude for each thermoplastic behaviour, therefore, we concluded that all thermoplastics are injection mouldable subject to properly design feed system.**

Keywords- Plastic injection mould design, Runner conduit, Melt viscosity

I. INTRODUCTION

Several injection moulding defects and awkward distortions abruptly occur without relevant throughputs [3] or have no easy fixes [4] and prevail regardless of their attributed root cause mechanisms [5]. Even if their contentions are established they would be extremely challenging, impossible to eradicate [6] and off course none have any idea how to fix it straight away! Mobility defects like jetting, silver streaks, shrinks, warps, short shot and flash are basically forfeits of feed system design stumbles, because melt kinesis design lacunae would eventually glare as defect. Similarly constrained runner conduit design would unusually hesitate injection consume energy excessively and eventually deprive ability to hold in-mould pressure [7]. Nevertheless in-depth comprehension accounting gross defects incidence physics to their phenomenal interaction with conduit geometry, injectant conveyance [4], pressure tranferability and injectant phase transformation [8] are still fictional. Inevitably most processors objectively juggle between sluggish productivity and quality compromise; obviously even shrewd optimiser can never afford to negotiate beyond some convincing compromise [9].

Objectively runner conduit design criteria should essentially mitigate melt / gas entrapment, abrupt streaming and pressure / temperature variance, vortexing, local turbulence, discontinuous splashing of streams, self-tumbling, etc., including dynamic challenges relative to instantaneous rheological character of injectant [10]. So for ideal mobility both conduit cross section geometry and size designs should essentially be an explicit function of non-Newtonian behavioural traits like characteristic deformability degree, speed and duration, along with concurrent vetrifications [11]. Despite injectants being large in variety, runner conduit design criteria should imperatively be generic and collective to intrinsically inoculate respective in-situ behavioural characteristics [12].

Functionally runner conduit distributes molten melt from sprue well to gates over the parting surface with minimum mechanical and thermal energy outlay [13] its conduit feature configuration significantly influence impression contrivability [14]. So its design perfectness is crucial to inject, distribute melt as impression occupies and eject moulded part [15]. In pursuit runner conduit size design and its performance has been deduced by restraining consequent shear rate within critical degradation limit [16, 17] in terms of transit melt state [18] parameter (apparent viscosity), as it is a holistic rheological quotient function describing intrinsic cumulative rheological property of all constituents in the injectant [19]. Therefore mould designers could judiciously specify a runner conduit size and processer could be well aware of critical volumetric injection rate restriction beyond which shear splay may occur for a given injectant [20].

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II. RUNNER DESIGN CRITERIA

Analytically solving non-trivial viscoelastic shear thinning thermoplastic injection mould design problem would be inimitable; due to complex non-linear conservation, state and constitutive equations even slight progress itself is a valuable endeavour [21]. For solving runner conduit design problem, we are formulating thermoplastic injection through runner conduit analogous to generic capillary tube; so power law equivalent of the celebrated Newtonian Hagen-Poiseuille equation would be [22],

$$Q[t] = -\frac{n\pi R^3}{(1+3n)}\sqrt[n]{\frac{R}{2\mu}\left(\frac{\nabla P}{L_r}\right)} \tag{1}$$

which could be verified by substituting Newtonian value of power law index n=1. Herein pressure gradience (∇p) between sprue well exit or runner bush entrance orifice and runner bush conduit exist orifice could be expressed as a relative quotient of rated injection pressure P_{max} available in the machine as $\nabla P = C_p P_{max}$, where C_p is injectant's characteristic co-efficient representing required in-mould pressure extent that depends on velocity of sound through its melt. Relative to Hagen-Poiseuille assumptions, instantaneous volumetric injection rate $Q[t]$ in terms of available machine's pressure would be,

$$Q[t] = \frac{n\pi R^3}{(1+3n)}\sqrt[n]{\frac{R\, C_P\, P_{Max}}{2\mu\, L_r}} \tag{2}$$

From machine capacity perspective,

$$\text{Fill Time} = \frac{\text{Shot Volume}}{\text{Volumetric Injection Rate}} \quad \Rightarrow \quad t_{\text{fill time}} = \frac{V_{Shot}}{Q[t]} \tag{3}$$

Similarly from mould design perspective,

$$t_{\text{fill time}} = \frac{\text{Stroke Volume of M/c}}{\text{Injection rate}} = \frac{V_{Stroke}}{Q_{injection}} \tag{4}$$

Since maximum volumetric rate cannot exceed available rated capacity, $Q[t] \le Q_{injection}$ to exploit maximum capacity we equate (3) and (4) so,

$$Q[t] = \left(\frac{V_{Shot}}{V_{Stroke}}\right) Q_{injection} \tag{5}$$

Substituting (5) in (2) to obtain,

$$\left(\frac{V_{Shot}}{V_{Stroke}}\right) Q_{injection} = \frac{n\pi R^3}{(1+3n)}\sqrt[n]{\frac{R\, C_P\, P_{Max}}{2\mu\, L_r}} \tag{6}$$

Now resolving for radius we obtain, $$R = \left(\frac{(3n+1)Q_{injection}}{\pi\, n}\left(\frac{V_{Shot}}{V_{Stroke}}\right)\right)^{\frac{n}{3n+1}}\left(\sqrt[3n+1]{\frac{2\mu L_r}{C_P P_{max}}}\right) \tag{7}$$

Herein Eqn. (7) epitomises runner conduit size specifically for a particular functional combination set of impression, injector and injectant as well as characterise operational dependency. However it is noteworthy to witness that the proposed runner conduit radius criteria is significantly biased by local apparent viscosity; which being a true fluid property varies with spatiotemporal melt state quantitatively discriminating injectant's resistance to diffuse through designed conduit, more specifically accounting melt strain rate for an applied (injection) shear stress [23].

III. ILLUSTRATION

Conventional design analogy typically adopts direct mathematical substitution just enough to specify some discrete or numerical runner size as a dependent parameter; in contrast Continuous Sensitivity Method (CSM) is adopted to examine relative complex parameter sensitivity at infinite dimensional range. CSM intervenes to holistically illustrate conduit design sensitivity over in-situ injectant state at wisdom level much beyond pragmatic experimentation or classical philosophy. Although complete analytical inference is still wonted, CSM intervention compliments a unique perspective over prevalent myths. So as part of a broader investigation scope to perspire further into it we opt to perturb dominant power law parameters apparent viscosity and shear thinning index to cognise its exclusive bias on runner conduit size [24]. According to (7) consecutive injection moulding thermal history over rheological parameters also have deterministic prominence through power law parameters; to illustrate that aspect following hypothetical case is espoused.

a. Windsor Sprint series horizontal injection moulding machine has been representatively adopted,

Now considering machine term of (7) and substituting table-1 ranges, we get

TABLE I. *SPRINT 650T MACHINE SPECIFICATIONS* [25]

Injection Pressure	P_{Max}	147 to 211.5 MPa
Based on BSR	C_P	75 %
Barrel Stroke Volume	V_{Stroke}	3770 to 5430 cm^3
Injection Rate	$Q_{injection}$	483 to 720 cc/sec
Nozzle orifice	D_n	2.5mm

$$Ms = \left(\frac{Q_{injection}}{V_{Stroke}}\right)^{n} \sqrt[3n+1]{\frac{Q_{injection}}{C_P \; P_{max} V_{Stroke}}}$$

$$Ms \text{ Š } \{0.12811671, 0.132596685\}^{\frac{n}{3n+1}} \quad \sqrt[3n+1]{\{9.07029478458, 6.304176517\} \times 10^{-9}} \left(\frac{1}{sec^{n}} \sqrt[3n+1]{\frac{m^2}{N\ sec}}\right) \tag{8}$$

Accordingly, we opt to anchor machine setting term range at a nominal value as

$$Ms = (0.130357)^{\frac{n}{3n+1}} \quad \sqrt[3n+1]{7.68723565079 \times 10^{-9}} \tag{9}$$

b. A typical injection moulded part has been representatively adopted with following hypothetical features,

TABLE II. CHARACTERISTICS PROPERTIES OF ABS [26]

Shot volume of injection moulding component	V_{Shot}	2500 cc
Runner bush length	L_r	80 mm

So upon substituting table-2 values in the component term of (7), we get

$$Comp = (V_{Shot})^{n} \sqrt[3n+1]{L_r \; V_{Shot}}$$

$$Comp = \frac{1}{2^{\left(4n + \frac{3}{1+3n}\right)} 25^{\left(n + \frac{2}{1+3n}\right)}} \tag{10}$$

Now substituting (9) and (10) in (7) we get,

$$R = (0.130357)^{\frac{n}{3n+1}} \quad \sqrt[3n+1]{7.68723565079 \times 10^{-9}} \underbrace{\left(\left(\frac{(3n+1)}{\pi\ n}\right)^{n} \sqrt[3n+1]{\frac{2\mu(3n+1)}{\pi\ n}}\right)}_{\text{Polymer}} \frac{1}{2^{\left(4n + \frac{3}{1+3n}\right)} 25^{\left(n + \frac{2}{1+3n}\right)}} \tag{11}$$

In case n is representatively anchored at 0.33 for ABS, then $R = 0.23681665 \times 10^{-3} \mu^{0.497636228}$ m

In-situ influx injectant viscosity and shear thinning index dominance on runner design criteria is very much evident in (11). Their respective behavioural divergence and uncertainty would evidently disperse efflux state and phase transformation consequently affecting moulding quality [27]. Hence for future (11) mathematical model is proposed to determine ideal runner size.

IV. RESULTS AND DISCUSSION

Error! Reference source not found. sensitises ideal runner size to in-situ apparent viscosity with corresponding shear thinning index curves arrayed in relevance to our objective representing all thermoplastics. Although the curves appear to be linear, actually they are exponential in nature; with differing slopes they intersect at some large viscosity, beyond which their slopes proliferate. Hence shear thinning index and apparent viscosity have cognitively negligible interactive sensitivity towards ideal runner size. Hence for real-world thermoplastic melts having apparent viscosity range from 10^2 to 10^6 Pa-sec [28], within which ideal runner size exists continuously; wherein runner size would be almost directly proportional to in-situ injectant state represented by viscosity. Hence it would be evident to conclude that all thermoplastics are injection mouldable subject to appropriately designed feed system.

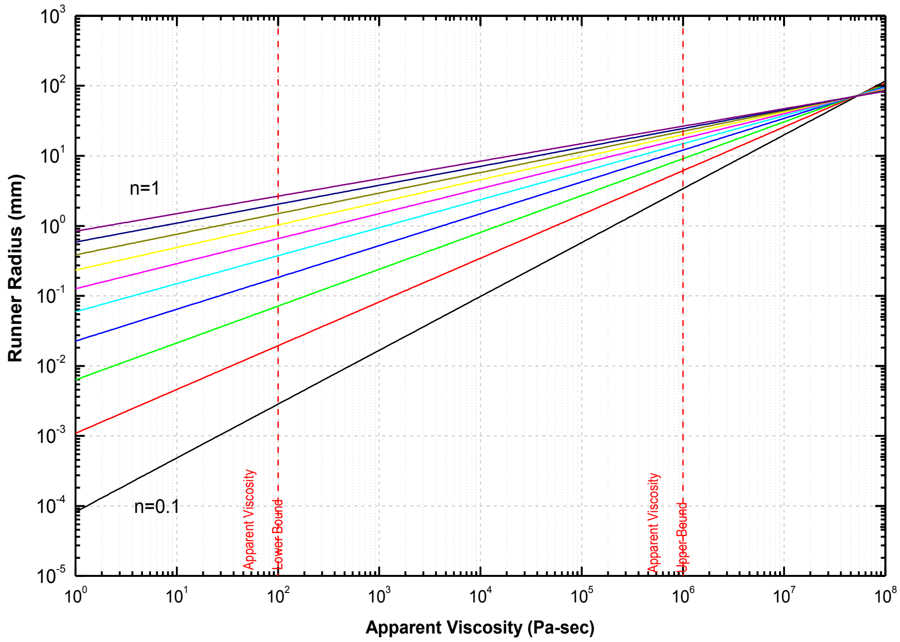

Figure 1 Runner radius relative to apparent viscosity

V. CONCLUSION

Attributing a series of factors deliberated injectant characteristics as well as its interaction have highly complex influence on runner conduit size design. The proposed runner conduit size design criteria model parameters are easily obtainable from exclusive rheological studies of that particular polymer [17, 19] and enable runner conduit size determination conveniently for a wide ranging circumstances arising in actual injection moulding. Further its design sensitivity was illustrated using a hypothetical case for various thermoplastic materials illustrated its consistency with prevalent values in practise. Nevertheless computational intelligence has been intuitively factored to accomplish perfect runner conduit's best performance advantage as well as compliment many other gain able benefits through stretched competence; by synchronising affective and cognitive in-situates like injection fill time, injection ramping speed for packing, operating temperatures, compatibility etc.,

ARTICULATION

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