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Computational design of mould sprue for injection moulding thermoplastics

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Abstract

To injection mould polymers, designing mould is a key task involving several critical decisions with direct implications to yield quality, productivity and frugality. One prominent decision among them is specifying sprue-bush conduit expansion as it significantly influences overall injection moulding; abstruseness anguish in its design criteria deceives direct determination. Intuitively designers decide it wisely and then exasperate by optimising or manipulating processing parameters. To overwhelm that anomaly this research aims at proposing an ideal design criteria holistically for all polymeric materials also tend as a functional assessment metric towards perfection i.e., *criteria to specify sprue conduit size before mould development*. Accordingly, a priori analytical criterion was deduced quantitatively as expansion ratio from ubiquitous empirical relationships specifically *a.k.a an exclusive expansion angle imperatively configured for injectant properties*. Its computational intelligence advantage was leveraged to augment functionality of perfectly injecting into an impression gap, while synchronising both injector capacity and desired moulding features. For comprehensiveness, it was continuously sensitised over infinite scale as an explicit factor dependent on in-situ spatio-temporal injectant state perplexity with discrete slope and altitude for each polymeric character. In which congregant ranges of apparent viscosity and shear thinning index were conceived to characteristically assort most thermoplastics. Thereon results accorded aggressive conduit expansion widening for viscous incrust, while a very aggressive narrowing for shear thinning encrust; among them apparent viscosity had relative dominance. This important rationale would certainly form a priori design basis as well diagnose filling issues causing several defects. Like this the proposed generic design criteria, being simple would immensely benefit mould designers besides serve as an inexpensive preventive cliché to moulders. Its adaption ease to practice manifests a hope of injection moulding extremely alluring polymers. Therefore, we concluded that appreciating injectant's polymeric character to design exclusive sprue bush offers a definite a priori advantage.

Keywords: Injection moulding; Sprue bush; Apparent viscosity; Shear thinning index

1. Introduction

Contemporary anthropologists assert 1.5 million years of absolute correlation between hominid evolution and manufacturing knowledge reformation; consequently, almost all materials are perpetually enabled to a broad spectrum of application domains inciting stellar functions like greater convenience, compaction, portability, etc. Such scrupulous progression has radically advanced the cognisance of underlying scientific phenomena in pursued techniques, methods, capabilities, tools, approaches, strategies, etc., from both enabled material as well as envisioned application perspective. Liken from a safety perspective[1] plastics characterise mankind's adaptive evolution at the very heart of planet's forthcoming living because they transpire from only 4% of earth's extractions (*natural oil and gas*) compared to 42% for heating and 45% for transportation. Coeval life cycle assessments (LCA)[2] commend plastics as the noblest contributor to ecology, because it absolutely reduces human dependence on fossil fuels like shrinking 150% energy demand [91]. Ever since Alexander Parkes (UK) invented parkesine (*plastic*) in 1855 [97] to substitute dwindling demands of ivory from elephants and whales, tortoiseshells and horns; they are preferred over all other material options [78]. Owing to the accomplished prominence in ambiguous applications, they are eventually turning out to be process migrations destination. Chronologically preceding decennia has witnessed

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[1]United Nations WHO priority concern.

[2]ISO 14000 inter-alia tool to access environmental consequence of a material for production, application and estimate end-of-life aspects including waste, pollution, disposal, etc. [91].

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spectacular evolvements in synthetic polymers to possess appealing degree of aesthetics, functionality, ergonomics, cosmetics, etc. Beyond entwined value, most sensational allure arises from the amazing set of properties polymers contribute to the application. Likewise, from functionality perspective they are deployable to a wide range of applications requiring antistatic, fire retardant, electromagnetic shielding, extreme degree of conductivity to insulation range, etc. properties. Their very high degree of coalescence has further breed a completely new set of materials like composite, hybrid, smart, functionally graded, etc., to contemporary applications.

Due to inextricable key link with civilisation global plastic economy ranks among tenacious sectors [15]; concomitantly that snares a perpetual compulsion to elate sophistication, quality, performance, durability benchmarks, staunch lead-time besides economising [32]. In lieu several polymer processing techniques have transpired under adept commerce patronage; off them injection moulding happens to be at the foremost [45], like one among every third [32% by weight [77]] part is injection moulded [81]. Despite appreciable progresses near net-shape mould making; coherent processing advances like smart set-up or intelligent control; questing product design expectations are yet to synchronise and reconcile enough, because mould designing still amply resorts to heurism [6]. This impuissance frequently evidences as extended lead-time, penalised performance, poor yield and/or compromised quality, hence polymer-processing technology mandates are certainly far ahead of existing capabilities. Principally injection moulding attributes remarkably depend on the combination of in-situ factors {*temperature*: *pressure*: *velocity*}, intrinsic resin properties and configured mould design. These key factors interactively influence the overall thermo-mechanical transformation and ensue performance as well as quality of ultimate moulded products [26,27]

Regardless of exclusive advances in mould design as well as material characteristics, from global resoluteness perspective maturity is still fictive. Severe complexity involved owes relative abstruseness to analyse and inhibit collective decisiveness, so exhaustive simulation, deliberate modifications and multifarious trails are inevitable both interactively and iteratively [85], obviously owing to them uncertainty befalls [82]. Despite higher injection capacity machine being available, its injection pressure gradient rarely suffices progressive energy transformations through nozzle, sprue, runner, gate and moulding impression gap. Recovery quotient of in-mould pressure head from influx kinetic velocity within sprue bush depends significantly on its conduit geometry design perfection. From mould-function assessment perspective this recovery quotient becomes a prominent performance metric as well as conspicuous factor for design perfection. Conscientiously in-situ sprue conduit (*a feed system constituent*) pressure-recovery criteria meticulousness is where performance hearth is for critical insight [19]. Hence embracing fundamental intra-conduit in-situ injection momentum mechanics seems to be a rational approach for efficient mouldability.

2. Literature

Both constraining or liberally expanding sprue conduit invariably hesitate injection, consume more energy or eventually deprive in-mould pressure recoverability [55]. So to design an appropriate feeding system both quality and performance have to be adjudicated as expectant factors. Profound reasons attributed for such ascribes are injectant's characteristic,

1. shear strain along melt-to-conduit wall interface [2]
2. hydrodynamic instability *(a.k.a injection pattern twisting to form spirals or helixes as quantified by Wiesenberger number* [96]*).*

Nevertheless, an in-depth comprehension relating gross defects arousing physics; phenomenal injectant conveyance; pressure recovery; injectant phase transformation; and collimated interactions with sprue conduit expansion [39] is still fictional. Such phenomenal traits should drastically constrain conduit region design *(both cross-section geometry and expansion design)* and its performance,

1. to be wilfully deterministic across melt injection rate adequacy and shear stretching enormity; while ensuring intrinsic uniformity; as well as minimising shear heating. Perhaps this analogy might be complicated, because transit viscosity aggressively reduces *(shear thins)* as injectant traverses through the conduit length and its enormity physically impairs resin properties [12] i.e., *AQL and APL seesaw over design fulcrum.*
2. to essentially accomplish ideal injection. i.e., *injectant's characteristic intra-conduit deformability degree, speed and duration* [9]
3. to intrinsically inoculate polymeric injectant's concurrent in-situ behavioural vitrifications i.e., *non-Newtonian behavioural traits causing premature freezing, impression filling incompleteness,* etc.*, explicitly restrain as ideal sprue conduit expansion design limits* [1]
4. by being imperatively generic, simple, inexpensive and preventive; the criteria would still be applicable to all injectants despite large in variety.

2.1. Acceptable quality level (AQL)

In general, injection moulding involves deformation, transportation, solidification [39] to contrive a polymeric injectant through its aqueous molten state i.e., *above their respective glass transition level* [99]. Invariably such a state excites complex non-Newtonian behaviours that stimulate various erratic unstable mechanical demeanours [51]. Typically, injection-moulding process imperils polymeric injectant to severe physical aggression involving high temperatures, extreme pressures and rapid shear rates [66]. Since most viscoelastic shear thinning thermoplastic melts are vulnerable to aggression magnitude[3] and duration[4] [7]; in-situ chemical transmutations secede most likely phases and eventually

[3]Like to inject long segment block co-polymers (*such as polyurethane, polyetheramides, styrenic SEBS, etc.*) creep level laminar shear rates are required, while significantly immiscible blends like ABS that easily segregate would necessitate rapid laminar shear rate [86].

[4]For instance, polyacetals instantly decompose under excess shear force exertions, especially at higher pressure and temperatures [94].

complicate morphology relative to end group identity (*see Section 2.3.1*).

Above glass transition temperature, most thermoplastic materials are characterised to exist in amorphous state and crystallise upon solidification. If in case vitrifications transpire then amorphousness resides over[5]; post-crystallisation also some class of suspensions still from spherulities and behave as a gel. Such characteristic amorphousness-to-crystallinity quotient of injectant state and its transitioning diversity deterministically constrain the degree of molecular motion, the extent of local rotations, vibration wrangles and translations vs. long-range *(segmental displacements)* mobility of solid state compared to short-range mobility.[6] Accordingly, physiochemical parameters greatly influence injectability, incidentally their exact relationship factoring injectability being still speculative [38] and vague [39]. For the moment, we just recognise that as a potential aspect for future investigation; perhaps, anticipating polymer synthesisers to extensively characterise afore factors [26], [84].

Whilst injection gradient pressure exerts direct mechanical force on injectant molecules, in response they initially deform with sufficient freedom and then gradually displace hesitantly along stimulating force action direction [86]. Principally they relax during filling interval, elastically extend during packing interval and irreversibly stretch during cooling interval. Once stimulating injection force cedes injectant spontaneously relaxes consequent to intrinsic elasticity [38]. Plausibly in a complex mode (*see Section 2.3.1*) relative to characteristic structure, morphology, entanglement, highly localised bonding relenting deformation *(brittleness or stiffness)*, rearrangement easiness *(ductility or toughness)* as well as local bond deformation magnitude and duration [36]. Nevertheless, prolonged injection *(stimulating force action)* irreversibly stretches and conveys injectant far enough such that it will never retrieve required position and shape [86]. The characteristic relaxation–extension–stretch sequel spectrum also depends on the coalesced interactive influence of injectant's phase transformation behaviour and machine's cooling effort; with its diverseness quantitatively exhorting the extent of stress residues and anisotropy, which directly ensues mechanical properties, shrinkage and warpage of finished parts [1]. For same reasons polymeric material's behavioural characteristics should significantly constrain plastic injection mould feed design [12].

Hereby to characterise the importance of sprue-conduit expansion in strain apportioning and diminishing gross melt fracture, shear rate, pressure and temperature effects are reviewed. Especially configuring stress field by exclusively allaying their occurrence and evolution to influence on conduit size design. So from quality and productivity perspective its inference would enable injection mouldability of various polymer melts. However, for ensuring robustness we propose a deeper exploration to reveal the physics associated with gross defects initiation and its quantitative relativity along sprue expansion. Our hypothesis is that viscosity and its gradient at injectant's critical shear rate should bias sprue conduit expansion as a significant spatial factor, irrespective of component/impression and machine/injection effort. Likewise, to assure injection moulding consistency viscosity changing behaviour and its variance at in-situ shear rate *(injection speed)* should significantly constrain sprue conduit expansion as a temporal factor. Therefore, to accomplish AQL feed conduit designs have to endure injection mouldability of chosen individual polymeric injectant.

2.2. Acceptable performance level (APL)

Melt injection problem abstract with empirical relationships appears simple and manageable, but with spatiotemporal non-Newtonian injectant character consideration, it surprisingly culminates to intense computation. While designing appropriate injection mould encumbers imperative manageability anticipation, the challenge surges further to high complexity. Primarily because representing polymer property comprehensively in mould design model would be extremely complicated and resolving it mathematically would be baffling [27] (*see Section 2.3.2*). However, several erstwhile researchers have attempted by adopting inquisitive approaches from multiple perspectives; like by imposing stress gradient, concurrent injectability and solidification.[7] Nevertheless most commercial simulation and analysis packages engaged in practice still presume pure shear flow and largely adopt classical Hooke's shear stress or Newtonian viscosity to approximate some convincing solutions. Although such sceptical approximations fairly correlate with experiments [33], they are mostly confined to extremely far away impression regions from gate locations where polymeric melt injection is almost pure shear flow. Certainly, in-situ polymeric surge can never be a pure shear flow.

While injecting viscoelastic thermoplastic melt through sprue conduit, its elastic energy accumulation and dissipation would diminish influx to efflux pressure gradient, thus modifying injectant's transit state [13]. So in general a conduit design's ability to recover in-mould pressure depends on injectant's elastic and rheological behaviour, hence some relation must exist among them [56]. However, thermoplastic melt's idiosyncratic shear-strain recoverability effect on sprue conduit size being trivial is generally neglected [56]. Because though thermoplastic viscosity increases exponentially with isotropic pressure [58] its scaling intensity is quite mild; so at low in-situ intensity mould designers obviously ignore its effects [53]. Nevertheless such reasoning is untenable for few

[5]Polyethylene terephthalate (PET) as injectant (*melt*) exists in vitrified (*amorphous*) state, but its corresponding injection moulded parts are characterised to exist in semi-crystalline state [18].

[6]Liquid or suspension amorphous state nudge as spaghettic strings crawl, while solidified crystallites slip as discrete chains.

[7]For instance, polystyrene melt was examined experimentally from crystallinity development perspective and then its intent was implemented to distribute in-situ melt streams in an injection mould by adopting linear viscoelastic Maxwell model, Keller model and Janeschitz–Kriegl model in the governing equations.

exceptional instances [21], like very long narrow gap impressions that involve 0.5 to 1 GPa injection pressure exertions. Conversely exorbitant injection pressure causes high stretching rate and as injectant tends to adhere with peripheral surface velocity, its streams fracture. Capricious intra-conduit viscosity adherence rapidly accelerates fractured melt into discrete injection streams [60], however due to phenomenal wall slip in critical shear stress regions, they eventually appear as sharkskin [74]. For a particular combination of machine's maximum injection pressure and impression's recoverable in-mould pressure, the intra-conduit gradient dispersion within diverging sprue region characterise energy transaction consistency [64]. So sprue-conduit expansion geometry design factors together pressure gradient and injectant's in-situ rheological behaviour *(viscous dissipation and shear strain energy dominance* [61]*) a.k.a., sprue-conduit expansion and in-mould pressure recovery quotient have definite relationship and that relativity becomes even more obvious as capillary ratio shrinks to be shorter* [55].

Additives range and their constituent fraction in thermoplastic solvent resin configure injectant's intrinsic properties. So to accomplish proper injection, feeding conduit should synchronise to pertinent all-inclusive rheology[8] [28]. Like to accomplish rapid injection sprue expansion should widen for reinforcement fillers, antioxidants, anti-agers, flame-retardants, colourants, blowing agents, cross-linking agents, UV stabilisers, etc., conversely it should shrink to characteristic rheological promoters like lubricants, softeners, plasticisers, etc. [5].

Likewise, to inject crystalline polymers concurrent appreciation of behavioural mobility and intrinsic phase transformation character persists as a challenge [26], in particular gradually crystallising polymers because several erstwhile peers have observed complicated crystallisation stress distribution with them. Perhaps that is why just 2D injection effort model of crystallisation kinetics was frequently adopted ab initio [27], latter few investigators proffered to appreciate idiosyncratic crystalline polymeric behaviours in gradient models [27]. Recently by adopting power law model in non-linear governing equations, the approach was extended to 3D mathematical formulation was attempted whose solutions were relatively accurate and reliable, besides converged to experimental observations [84]. Thus, offering great potential to design proper mould system even for sophisticated engineering applications. Instead of naive linear relations, Generalised Newtonian Fluid (GNF) constitutive relationship like the Power law model which is extensively employed in finite element approximations would be superior [93]. Because it can even consider residual phase transformation stress [69] *(particularly in amorphous polymers)*.

Hence, to accomplish APL all conforming mould feeding conduit designs should comprehensively appreciate intrinsic non-Newtonian stress distribution pattern besides thermo-mechanical phase transformation behaviour of an injectant.

2.3. Functional assessment

A true feed system design intends to synchronise idiosyncratic polymeric rheology, viscoelasticity and thermo-mechanical phase transformation system behaviour of injectant; confine to contriving impression features; and utilise available injector's injection force exertion and heat extraction capacity for concurrent deformation, transportation and solidification.

2.3.1. Molecular weight perspective

Molecular weight being a prominent morphological factor its de-facto range holistically assorts all polymeric injectants including their blends or co-polymers, besides characterising in-situ behavioural traits and rheological dispersions[9] [22]. So at a particular shear rate the onsets of upper and lower viscous extremities solely depend on constitutive factors like polymer type, concentration, molecular weight distribution, etc.[10] [8]. Hence, heavy molecular weight injectants with finer crystallinity levels necessitate wider sprue expansion, due to higher tensile strength, modulus, toughness, hardness, chemical resistance even at elevated glass transition temperatures. In addition, their dense primary and secondary cross-linking thickens apparent viscosity and strangles shear thinability, which then as implication constrains mobility while risks degradation [11].

In contrast, narrow expansions orient microstructure to abnormal strain intensity perhaps might even yield or deform discretely [62]. Further strictly parallel injection streams exerting enormous compressive shear injection effort [5] on long molecular chains $\left(10^2 \text{ to } 10^6\right)$ cause awkward shrinks [52]. Because most thermoplastics can hardly bear 1 MPa to 10 MPa range in melt phase compared to 10 MPa to 4 GPa in solid state. Also low molecular weight polymeric injectants with severed chains require almost zero shear as their corresponding Newtonian viscosity being almost directly proportional to polymer's molecular weight [22]. But above certain critical molecular weight chains entangle and shear viscosity dependency on molecular weight would become exponential i.e., *exhibiting considerable viscosity changes for*

[8]For instance, unfilled PBT shear thins thrice faster than its mineral filled counterpart. So to abridge cycle time *(relative to the extent of impression volume to be injected within solidification interval of injectant)* slimmer sprue expansion would be necessary. Likewise, engineering plastics are ejectable quickly at 310 K unlike commodity plastics.

[9]Because their chemical structure a.k.a repeating units and end groups (*e.g., polymerisation stoichiometry, mechanistic scales, etc.*); intermolecular forces (*e.g., covalent, ionic, hydrogen bonding, dipole–dipole, dipole-induced dipole, van-der Waals proportional to adjacent surface areas of individual molecules as well as forces adhere to walls*); molecular topology arrangement (*e.g., linear, branched, mono-disperse, star, dendrimeric, cyclic, ladder, comb, supra-molecular, etc.*); physical form (*e.g., higher order intra-chain and inter-chain configuration*) and packing (*e.g., amorphous, crystalline or semi-crystalline depending on molecular and/or molecular fragments array regularity, etc.*) together establish its rheology.

[10]For instance, at any particular volumetric injection (shear) rate available in the machine the corresponding in-situ apparent viscosity's maximum extremity (constant higher altitude) raises further up with injectant's reducing average molecular weight while its lower altitude dives further down with narrowing injectant's molecular weight distribution range.

even small molecular weight changes. Accordingly, in-situ shear thinning behaviour hesitancy also depends on injectant's polymeric structure [41].

Hence, invariably involves complex system of forces to fill *(dominating of intrinsic non-Newtonian factors)* especially into thinner impressions.[11] Therefore average injectant's molecular weight and its corresponding distribution range [17] deterministically cause transit microstructural morphology complexities in conceding component quality *(like mechanical strength (especially impact) and chemical resistance)*. So they are also potential factors ensuing injection. Therefore, the intuitive strategy of having their direct or indirect bias in sprue-conduit expansion design criteria would be quite vigilant [99].

2.3.2. Shear rate perspective

Off the entire feed system diverging sprue-conduit inlet orifice witnesses' swiftest volumetric shear rate along with concurrent heat and mass energy transformations occurring on the shock plane. Although influx shear rate before sprue conduit ingress dominantly influences component yield quality [13] *(especially its thermal characteristics* [70]); sprue conduit expansion also directly adjudicates relative heat developed and/or absorbed past injection shock plane, while its variation depend on Barrel-to-Shot ratio (BSR), whose distribution range approximately exceeds 10% [28]. Accordingly, shock plane orifice inadequacy tempts processors to inject melt at higher undesirable temperature and/or pressure, because both fill time and visible defects *(like short shots, sink marks, ripples,* etc.*)* quickly respond to it [42]. However, such temptation accompanies risks like air entrapment within either conduit or impression, cause burn marks or flash or scratches or loss of transparency or cracks on the parting surface. In addition, defects like differential shrinkage are direct consequences of intra-conduit pressure-gradient vicissitudes. So an appropriate sprue conduit design would enable melt injection rapidly into impression and sustain uniform state *(as much as possible* [5]*)* to mitigate afore risks. Perhaps with available shear injection rate it would be a prudent inevitable judgement across maximum for APL and minimum to retain material at its best characteristics for AQL [46]. Hence to accomplish uniform injection rate at some putative cycle *(filling)* time, traditional wisdom strives to manipulate transit melt state [87]; *like for instance to fill thin impressions before melt solidifies necessitates rapid injection rates*.

Consequent to conduit convergence and divergence on either side of the interface shock plane, greatest restriction to inject melt occurs at the interface between nozzle exit and sprue inlet orifice. So to accomplish ideal throttle action shock section would witness severest shearable rate (*sonic injection perhaps* $M \approx 10^{-1}$ i.e., *injection velocity* $\overline{U}_{Max}$). Convergent nozzle and divergent sprue conduit combination, during filling phase act as nozzle-diffuser intensifying downstream pressure at the expense of upstream melt velocity i.e. *expanding injectant's discharge rate increases from higher subsonic* *(*$M<10^{-3}$*) nozzle velocity to lower subsonic (*$M<10^{-5}$*) sprue filling velocity*. Again the same combination acts as diffuser–nozzle increasing melt velocity at the expense of pressure during packing phase i.e., *injectant compresses from lower subsonic* ($M<10^{-3}$) *nozzle velocity to higher subsonic (*$M<10^{-2}$*) sprue compensation velocity*. Therefore, perfect Mach number at injection shock plane for an injectant depends specifically on its rheological and shear degradation characteristics. That is why in actual injection moulding situations few injectants exhibit varied peculiar instability phenomena, though contentious yet they extensively cause several defects and processing imperfections (*like wall interface instability, undesirable layer distribution, injection stream segregation, pattern distribution,* etc.*)*; and/or their combinations. Popular melt instabilities are generally attributed to anomalous injection stress patterns that typically occur beyond their respective critical shear rates [29,43,100], especially for engineering applications. Because most polymers exhibit distinct viscosity and limiting shear rate magnitude ranging from 10^2 to $10^5\ s^{-1}$ respectively as illustrated in Fig. 1 [14].

Injection moulding seldom involves shear rates lower than $10^{-2}\ s^{-1}$ because at such rates ramping time to attain steady state would be too long and probably by then intra-macromolecular structural defects dominate for most thermoplastics [3]. Contrariwise injection moulding seldom involves shear rate more than $10^6\ s^{-1}$, because injection force action duration should at least be long enough to irreversibly stretch entangled chains far enough as it displaces through conduit [86]. Otherwise exorbitant deformation amplitude exceeding viscoelastic limit would reorient and/or reorganise entangled molecular chains along the injection direction, thus disrupting melt's chemical structure [1].

Indeed few reliable and unequivocal examinations advocate that extremely gentle shear rate encounter almost constant high magnitude viscosity; in contrast terribly intense shear rate encounter almost constant low magnitude viscosity. Interpreting it contextually both minimum and maximum injection efforts attain corresponding higher and lower viscosity thresholds irrespective of shear intensity. Appropriately, these two characteristic extremes corresponds to lower and upper or first and second Newtonian regimes respectively for a polymeric injectant [8], beyond them classical Newtonian constitutive apprehension cease to represent [76]. Interpreting this intuit from an esoteric perspective at almost zero injection effort thermoplastic injectants offer infinite magnitude viscosity whereas at terribly severe shear injection effort they offer almost zero magnitude viscosity. The contingent range across both extremes unequivocally constrain injection mouldability and is very wide in variety discriminating injectants; while for most thermoplastics de-facto injection moulding shear rate range being 10^{-1} to $10^4\ s^{-1}$.

Accordingly sprue bush conduit should be comprehensively designed wide enough to (a) utilise rated injection capacity of available machine; (b) leverage highest melt injectable rate of a thermoplastic material; (c) mitigate melt/gas entrapment, abrupt streaming, pressure/temperature variance, vortexing, undue turbulence, discontinuous splashing of streams, self-

[11] e.g., Shear thinning PMMA viscosity approximately leaps by 6 times to corresponding consecutive shear rate increments [28].

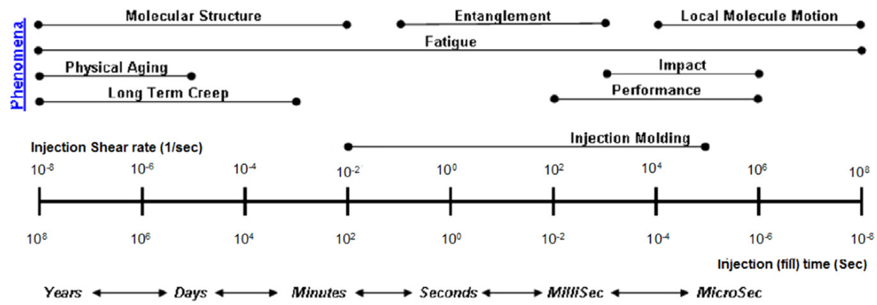

Fig. 1. Shear thinning viscoelastic thermoplastic material's characteristic phenomena across shear rate spectrum [22].

tumbling and dynamic challenges relative to instantaneous rheological characteristics like melt kinesis dissonance to conduit. Eventually enable confirming mould feeding to continuously inject into impression for complete contrivance of parts that are (1) wholly filled (2) superior surface finish (3) undistorted (4) denser *(minimum voids, pores and bubbles)* (5) flexible (6) superior stream mesh weld (7) dimensionally precise (8) uniformly shrunk [16].

Hence to constrain consequent shear rate well within respective critical degradation limit [7] macro-theory of rheology professes that polymer's characteristic factors influencing in-situ net shear strain should be key determinants in designing sprue conduit expansion [55,64]. While true shear degradation threshold is still being debated for most polymers, our proposition emphasises establishing a critical limit exclusively for every injectant; which would be of immense value to both mould designers and processors. With this, a designer can judiciously specify a sprue-conduit expansion angle amidst adjudicating shear to elongation deformation quotient and diminishing gross severity of melt fracture as in Eq. (10). Similarly, a processer would also be well aware of injection rate restriction for the processed injectant beyond which shear splay might occur. Therefore the characteristic dimension[12] of sprue bush geometry through which melt gets injected should be constitutive ratio determinant *(*i.e.*, acting injection force to the product of shear rate and average injectant thermoplastic melt viscosity)* [21]. So transit shear rate would be stable irrespective of influx Reynolds number or sprue capillary ratio [71,75]. Hence for successful injection moulding sprue conduit geometry has to be designed meticulously [21] by traversing shear stress vs. shear rate ratio into distortion free zone [55].

2.3.3. Temperature perspective

Intrusive probes within a sprue system region have revealed that injectant temperature rises sharply during filling followed by gradual declination during packing and significant decay during cooling. Probably concurrent intra-conduit occurrence of volumetric injection dynamics [34], adiabatic compression and shear friction; imperil transit state to severest volatility [28], particularly during filling. Accordingly, intra-conduit temperature gradient influence on efflux shear strain [55] should also be a key factor to determine sprue conduit expansion.

Apparently, sprue-bush heat conductivity exceeds approximately 100 times more than injectant, so approximately 90% of the intra-sprue system mechanical injection power drift would be around its interface. Similarly, mould-cooling systems dominate to such an extent that they completely mask potential sprue conduit design flaws (i.e.*, most probable hot spots in head zone or around injection shock plane or sprue conduit orifice or in base zone)* that surge or disrupt the injection pattern by unduly expanding retributive power. So prominent unrealised, yet most imperative concept being viscous heat dissipation or acquisition i.e.*, transit entropy* along the stationary divergent conduit interface.

Most thermoplastics are typically injected in the range from 100 °C to 500 °C just above their respective glass transition temperature i.e.*, intermittent Newtonian region*; where injection activation energy as a coefficient of viscosity can determine volumetric expansion [92]. Although this relativity decreases as injection temperature raises and increases with thicker viscosity injectants; at lower injection temperatures sprue-conduit expansion sensitivity is highly vulnerable to melt state variations [55]. Nevertheless, the act of shearing itself generates heat between melt layers enough to subjugate its viscosity. The rate of energy dissipated per unit volume of shear melt would be product of shear stress to shear rate *a.k.a., the product of the viscosity and the square of shear rate*. Hence, heat extraction depends on conduit cross section dimensions and heat convection depends on conduit expansion. Therefore melt injection significantly depends on injectant's heat content, interface conduction and transit convection characteristics. So to accomplish in-situ uniformity as well as rapid mobility, conduit expansion design becomes very much critical. Herein concentric conical linear expansion along with its ensuing capillary ratio is obviously key determinant and essentially designed with best accuracy.

Sprue conduit roughness and aspirate geometries also affect laminar melt convection and subsequent stem freezing considerably, because pressure gradient, local Nusselt number as well as Reynolds number stability along the conduit differ from smooth to rough interior surfaces. Probably because flow over rough surfaces strongly recirculate, separate injectant streams, surge wall heat absorption less than its corresponding impression besides necessitate more pressure gradient [101]. Hence to avoid these, conduit interior surface should be designed smooth ($R_z = 2.5\ \mu m$), furrow-less and polished to

[12] i.e., Sprue conduit radius or sheared layer thickness.

facilitate frictionless laminar melt impulse streaming [101] as well as clean sprue stem stripping out with minimum drag, sticking, friction [16] besides nozzle tip to break off. Corresponding co-efficient of friction loss ($C_{\text{Friction Loss}}$) can also be computed as:

$$C_{Friction\ \text{Loss}} = \left(1 - \frac{U_{Sprue\ \ \text{exit}}}{U_{Nozzle}}\right) \quad (1)$$

where $U_{Sprue\text{exit}}$ and U_{Nozzle} being injection rates across sprue conduit exit orifice and injection nozzle tip exit orifice cross-sections.

2.4. Potential design factors

Reportedly contemporary researchers have been widely investigating both experimentally [83,40] and theoretically to locate exact most favourable in-situ state for injecting with a reasonable degree of confidence; that certainly depends on apparent viscosity and shear thinning behaviour. Likewise appropriately appreciating these key factors to design conduit or to remediate configured conduit size might also enable precatory sophistication. Recent inquests on diverging non-Newtonian thermoplastic melt injection deliberated for their relativity with conduit size in complexity and form [48]; critical expansion flow instability prodigies [72]; and several other paradigms. Some of these were outright classical curve fitting attempts to relate shear stress with shear rate over logarithmic scale, while others embraced statistical mechanics theory [44] by applying kinetic theory or theory of rate processes to aqueous state injectant mobility. Whilst the focus here being a priori sprue conduit design to immunise undesirable defects inception, its divergence ought to synchronise afore factors [7]. Nevertheless determining sprue expansion from shear thinning index and apparent viscosity is still a potentially novel outlook and that has been pursued here by.

2.4.1. Apparent viscosity perspective

To accomplish desired intra-conduit extensional strain (*as explained in Section 2.3.2*) conduit divergence should be determined from injectant's characteristic apparent viscosity[13] [55]. Surface defects and awkward distortions abruptly occur for strange reasons [25] even if established they persist inevitably [89] regardless of their root cause mechanism. They are very wily to fix [39] or rather impossible to eradicate [21]; characteristically in-situ apparent viscosity is a prominent design factor responsible for their onset. Potential factors significantly influencing in-situ thermoplastic steady-state apparent viscosity are shear rate *(injection pressure capacity of machine)*; temperature and pressure *(thermoplastic melt state characteristics)* [3]; time interval *(component volume);* and paired {AQL: APL} [44]. Hence, by perturbing it over de-facto range of interest its influence on shear rate depth *(or conduit size)* could be appreciated to endure idealistic sprue-conduit expansion design [4].

[13]Like for instance highly viscous polycarbonate melt requires wider conduit expansion than polyamide melt that comparatively has a thinner viscosity.

2.4.2. Shear thinning perspective

Aggressing injection declines concurrently both viscosity and elasticity by accelerating individual macromolecular chain mobility [57], this in-situ phenomenal behaviour should necessarily be salient factor for designing feed conduit. Correspondingly, peers in practice also apprehend narrow conduit design would suffice for injecting aqueous injectants, while wide conduit size is appropriate for aspic injectants.[14] Although few experimental evidences of aspic injectants being injected through very nominal conduit expansion are also reported, perhaps AQL and/or APL might have been compromised.

Intense shear effort in succession expands influx *(polymeric melt into sprue region from nozzle tip of the barrel)* with almost constant axial velocity or almost constant volumetric injection rate [37]. Obviously initial melt streamlines are highly linear, however as injection pattern gains momentum from any applied shear rate *(injection pressure of available machine)* injectant's behavioural viscosity, elasticity and shear-thinning character characteristically inflects across and along feed system [14]. This synergic phenomenon is unique for each polymer and very closely related to its polymeric chain branching type, molecular chain structure, consequent to co-existent viscosity and elasticity quotient, composition-constituting ratios (*as explained in Section 2.3.1*). Therefore, efflux shear thinning coefficient should essentially be a potential factor to determine sprue-conduit expansion angle perhaps computational theory of elasticity and melt mechanics together would be appropriate to deduce this comprehensive analogy.

The phenomenal time-independent apparent viscosity decline with reviving shear rate character is generally attributed as "shear-thinning" *for a vast majority of thermoplastics.* Along with other analogous terms like temporary viscosity loss and pseudo-plasticity [14] i.e., *viscosity reduction per unit raise in injection shear rate*. Transient in-situ shear thinning behaviour significantly characterise non-linearity educed by the combinational set {machine, material, moulding} and predominate during transit *(filling)*. However contextually in injection-mould design to overcome the characteristic shear thinning behaviour's wide ranging challenge of polymeric injectants; most erstwhile researchers have often quantified it by extensively adopting the power-law or Ostwald de Waele model. That relates shear stress with shear rate on a log–log relativity by approximating linearity within de-facto injection moulding range as illustrated in Fig. 3 [53]. The applicable expression for this would be,

$$\text{Apparent viscosity}, \mu = \frac{\tau_{yx}}{\dot{\gamma}_{yx}} = k(\dot{\gamma})^{n-1} \quad (2)$$

where "*k*" and "*n*" are empirically curve-fit parameters popularly representing injectant's hesitancy *(coefficient)* and behavioural changes *(exponent)* respectively with unit values

[14]As for instance mildly shear-thinning polycarbonate melts having comparatively high index requires larger conduit expansion than rapidly shear thinning HIPS melt having low index that requires little conduit expansion.

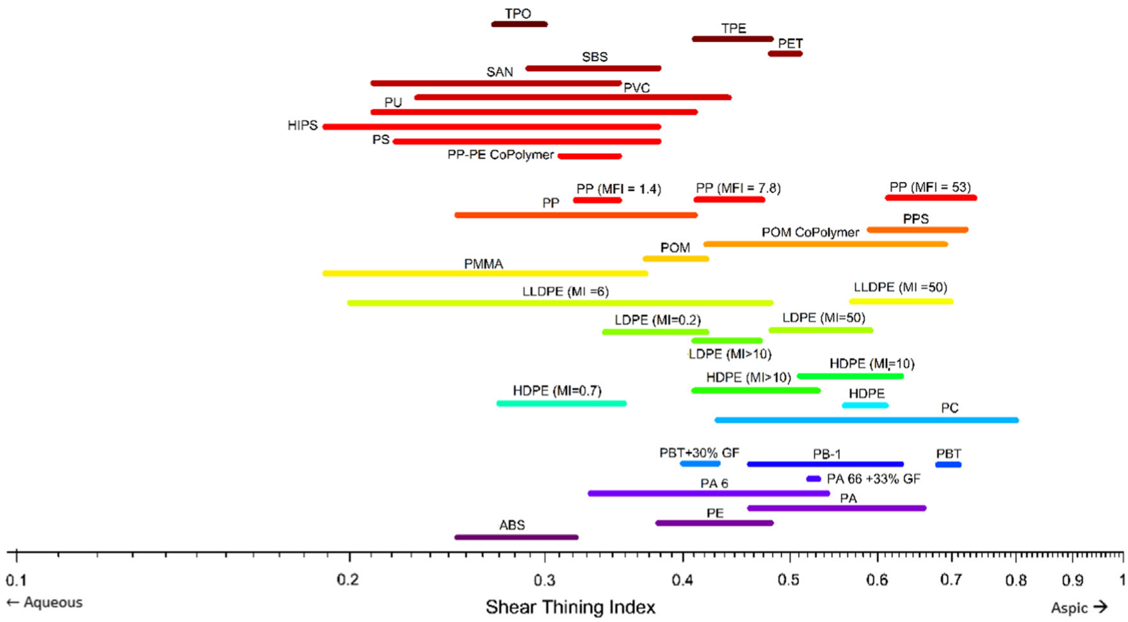

Fig. 2. Illustrative assortment of shear thinning behaviour in polymeric (*thermoplastic*) injectants.

corresponding to referential Newtonian model. Although complete spectrum of pseudo plastic behaviours of all polymeric injectants would be quite exhaustive and arduous to list, yet Fig. 2 attempts to representatively assort de-facto shear thinning index range for popular thermoplastics between ($0.1 < n < 1$). Herein its intensity reduction depicts shear-thinning aggressiveness towards aqueousness.

The power-law model being a simplest representation has several inadequacies like,

1. For a particular polymer its fitted values are pertinent only within its characteristic ranges of upper and lower Newtonian viscosities (*as explained in Section 2.3.2*) and shear thinning intensities, which mostly includes de-facto injection moulding range (*as illustrated in* Fig. 1).
2. It is inept to represent hypothetical zero and infinite viscosity extremes *(as explained in preceding para).*
3. Since n is dependent function of k, it cannot be sensitised arbitrarily without perturbing k, although it could be attributed independently as shear thinning index for unit shear rate magnitude.

2.5. Design scope

Afore review clearly establishes that presuming all polymers at par to design moulds would be a crudest discern, because each polymer behaves quite uniquely and exhibits specific behaviours. For that reason even if all other factors are invariants, each injectant hesitate peculiarly; diversify or heterogenise melt streams[15]; cause different dead-flow zones; distinctly consume extra energy; and discretely deprive in-mould pressure recoverability within their respective stem regions [55]. Similarly, sprue conduit expansion designs accelerate melt extending strain energy and dispense additional energy by inciting vortex streams [61]. Principally too wide expansion conduits rapidly diverge injection streams, accumulate excess melt that delays solidification and deteriorate at low heat extraction regions, thus predating melt fracture. In addition, accumulated melt along conduit walls, intermittently detaches and gets dragged away by succeeding injection action [30].

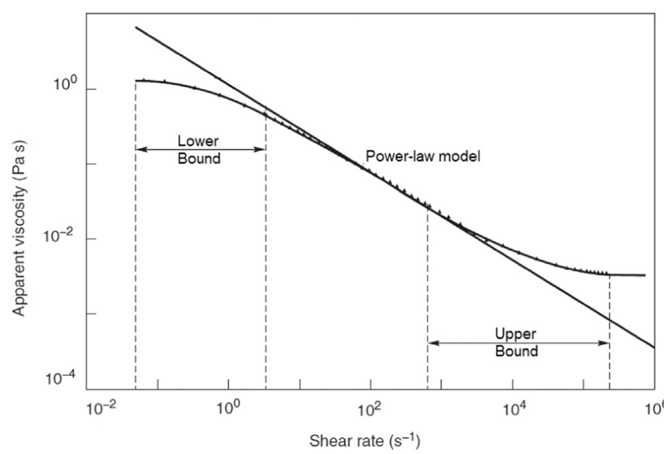

Fig. 3. Illustration of shear rate effect on apparent viscosity for a typical shear thinning thermoplastic melt [8].

Primarily because sprue conduit expansion approportionates extensional stress component along injection direction [24] and shear stress component across its cross section [98] relative to its interface area [59]. Moreover, their coexistence typically causes rheological complexity [24]; sometimes even inertia also appends to complicate it further [4].

[15]For instance PP shear thins instantly and gets rapidly injected even through narrow conduit expansion irrespective of melt to mould temperature gradient, outrageously to inject PC large ridiculous expansion are required with extremely low temperature gradient and almost uniform melt state (*viz., viscosity and shear thinning*), where melt stability being significantly dependent on impression's cosmetic features.

2.6. Design synthesis

Based on contemporaneous review of erstwhile investigation to achieve afore stake, this manuscript systematically accords a renewed succession in our perpetual attempt [49,50] by appreciating ensuant melt injection mechanics [87] with pristine extension, impeccable discussion besides substantiating with pragmatic arguments. Herein a conduit-expansion design criterion is deduced analogous to conical flow mechanics by appreciating injectant's polymeric character as potential design factors (*see Section 2.4*). It serves as a basis to determine exclusive expansion angle, without manipulating operating conditions or impression features, believing such criteria might augment overall confidence *(*i.e.*, anchoring machine and moulding).*

2.7. Design objective

Functionally sprue bush engages cold mould to hot barrel for conveying impinged molten melt from nozzle tip to sprue well over the parting surface [20] at minimum mechanical and thermal energy outlay [79]; with its conduit feature deliberately configured to accomplish acceptable level of impression contrivability [90]. Therefore, its design perfection is crucial to inject, distribute melt and eject moulded part. Essentially ensure continuity to fill impression, balance injection rate; equilibrate energy transactions to rapidly solidify for ejection [63]. Obviously for ideal contrivance sprue conduit topology design criteria should sustain almost even melt state; moderate shear heating; accomplish almost uniform transit pattern; and desired degree of homogeneity, despite discretely fragmented periodic stage vacillations [48]. So it should,

a. convene with injectant's rheology to leverage highest in-situ shear rate [47] *(*i.e.*, maximum shear injection rate being reciprocal of minimum fill time would raise mould performance*);
b. concede intra-conduit transit phase transformation with injection effort;
c. and contain shear heating for desired impression *(volume and depth below parting plane)* and interface area consequent to assembly configuration [23].

These were never thought over and are the prime focus of this research effort.

In pursuit as schematised in Fig. 4, exterior head, shank and base section that integrate to form internal conduit geometry whose expansion design is apparently enabled from injectant's characteristics [47],

1. **Head:** Sprue head is a positive feature possessing negative inlet orifice region to receive melt [90] with hemispherical recess to accommodate abutting nozzle tip [47]. Its inlet orifice size exceeds available machine's nozzle tip size by 20% to drape over [65]. Nevertheless gradient pressure, shear heating and melt-wall interface cooling collectively confine its feature design as well as operating temporal settings [68].
2. **Shank:** Sprue shank is a tubular transition feature forming an internal conical conduit linking head to base with an axisymmetric region for coercing the extent of impression volume *(a.k.a. desired component features below parting plane along with interface area)* as well as mould assembly configuration [73], while its axial length (L) has to flush with *(cavity + bottom)* plate thickness. So providing excess metal stock (zIT12) at component level compensates finish grinding after final assembly. Long sprue bush lengths expand thermally causing far enough "growth" past parting surface that eventually cause flashes. Further nozzle contact forces exert that such protrusion over the moving side of the mould, acting to burst open clamping. So for non-sprue-gated moulds, designers should restrict sprue bush length to be within or just off parting plane, even at highest operating temperature.
3. **Base:** Sprue base with exit orifice region delivers melt into sprue well harmonising feed system continuance along the parting plane. Its design has never been given due consideration although it deserves much (*as explained in Section 2.4.2*).

3. Design criteria

Analytical solution to non-trivial viscoelastic shear thinning thermoplastic injection mould design problems is inimitable owing to complex non-linearity of conservation, state and constitutive equations. Even slight progress surge as a valuable contribution. To realise sprue conduit design we hypothesise it analogous to conical capillary tube subjected to machine's rated injection pressure at inlet end and required injection in-mould pressure at the exit end. Then the ratio of maximum injection effort available in the machine to the extreme injectable extent of the chosen injectant gives its capillary ratio as:

$$\frac{L}{R} = \frac{\nabla P}{2\tau} \tag{3}$$

where

∇P represents maximum injection pressure gradient between nozzle *tip exit or sprue bush entrance orifice* and sprue well or sprue bush conduit exist orifice

τ represents true shear stress *(injectable extent)* of chosen polymeric injectant

L represents length of sprue bush conduit (*explained in Section 2.7 above (2)*)

R characteristic radius of sprue conduit cross section profile.

Since as sprue shank conduit expands linearly, its nominal diameter would be an arithmetic average,

$$\text{i.e.,} R = \frac{\overline{D}}{2} \text{then,} \quad \text{shear stress}(\tau) = \frac{\nabla P \overline{D}}{4L} \tag{4}$$

From trigonometry, linear conduit expansion nominal diameter is obtainable as follows:

$$\overline{D} = \frac{(D_s + D_s + 2L \tan \alpha)}{2} = \frac{2(D_s + L \tan \alpha)}{2} = D_s + L \tan \alpha \tag{5}$$

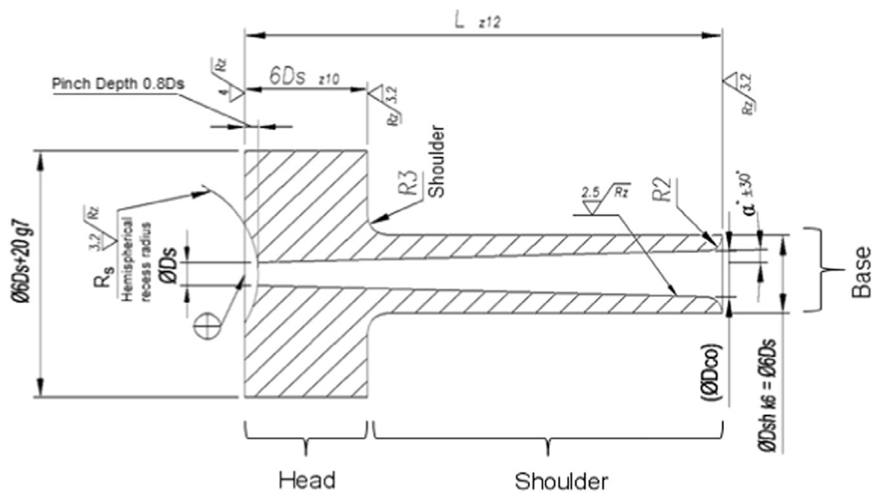

Fig. 4. Schematic representation of typical sprue bush [31].

So by substituting Eqs. (5) in (4) we get,

$$\text{Shear stress}(\tau)=\frac{\nabla P}{4L}(D_s+L\ \tan\ \alpha) \tag{6}$$

Similarly, for injecting melt through capillary conduit its apparent shear rate (γ) could be obtained as follows [25]:

$$\gamma=\frac{4Q}{\pi R^3}=\frac{32Q}{\pi \overline{D}^3}=\frac{32Q}{\pi(D_s+L\ \tan\ \alpha)^3} \tag{7}$$

where volumetric injectionrate,

$$Q=\frac{\text{Shot volume}}{\text{Fill time}}=\frac{V_{Shot}}{t_{fill\ \text{time}}} \tag{8}$$

$$\text{but } t_{fill\text{time}}=\frac{\text{Stroke volume of } M/c}{\text{Injection rate}}=\frac{V_{Stroke}}{U_{Injection}} \tag{9}$$

$$\text{then, so } Q=\left(\frac{V_{Shot}}{V_{Stroke}}\right)U_{Injection} \tag{10}$$

Now to design a specific sprue conduit feature, its operational character should be represented as afore functional metric. Duly melt's characteristic resistance to diffuse through sprue conduit has been quantified with apparent local viscosity (*as explained in Section 2.4.1*), more specifically ensuing melt strain rate for an applied effort viz shear *(injection)* stress [64]. Also thermoplastic melt viscosity being a true fluid property describes spatiotemporal melt state transitory. Therefore based on Sir Isaac Newton's 1687 resistance postulation, its capillary rheologic formulation for injecting polymeric melt injection neglecting strain angle $\theta(t)$ would be [76],

$$\text{Sprue exit viscosity}(\mu)\neq\frac{\text{Shear stress}(\tau)}{\text{Shear rate}(\gamma)} \tag{11}$$

Here shear stress being maximum at the peripheral wall gradually declines towards its central core synchronous to corresponding velocity profile slope, so substituting Eqs. (6) and (7) in (11) we get,

$$\text{Apparent viscosity}(\mu)\neq\frac{\left(\frac{\nabla P}{4L}(D_s+L\ \tan\ \alpha)\right)}{\left(\frac{32Q}{\pi(D_s+L\ \ \tan\ \alpha)^3}\right)}\neq\frac{\nabla P\pi}{128QL}(D_s+L\ \tan\ \alpha)^4 \tag{12}$$

Eq. (12) inequality represents non-Newtonian melt injection across nonlinear viscosity distribution and could be equated adopting Weisenberg–Rabinowitsch correction [76] as follows:

$$\mu=\frac{\nabla P\pi}{128QL}(Ds+L\ \tan\ \alpha)^4\left(\frac{4n}{3n+1}\right)=\frac{\nabla P\pi}{32QL}(Ds+L\ \tan\ \alpha)^4\left(\frac{n}{3n+1}\right) \tag{13}$$

where n representing injectant's shear-thinning behavioural index, that is determinable in accordance with power law as first derivate slope of viscosity vs. shear stress curve on a log–log scale for a particular injection moulding case [59] (*as explained in Section 2.4.2*).

$$n=\frac{d\log_e\mu}{d\log_e\tau} \tag{14}$$

However as a prominent characteristic factor it concocts various processing techniques. Since it attributes non-Newtonian shear thinning viscoelastic thermoplastic melt behaviour to processing rate. Like moderate viscosity at moderate shear-rate for injection moulding; while high viscosity at low shear rates for blow moulding; and low viscosity at high shear rates for extrusion [67]. So for rapidly filling thinner impression high shear rates would be required [13]. Since injectant's shear thinning behaviour at purge shot temperature prior to sprue conduit being almost equal to sprue conduit exit [9] $\left(\frac{d\mu}{dx}\approx 0\right)$ at $x\in[0,L]$ instantaneous viscosity change would be bare minimum $\left(\frac{d\mu}{dt}\neq 0\right)$. However consequent to viscosity change, melt's shear rate fluctuates violently particularly across filling and packing stages, also significantly vary over the cycles [9]; typically, injection shear rates range from 10^1 to 10^4 per second. Since conduit feature being rigid

Table 1
Features of impression.

Shot volume of mould impression	V_{Shot}	2500 cc
Sprue bush length	L_{Sprue}	80 mm

with fixed size, transit viscosity (μ) should to be adapted. So logically, to maintain utmost possible uniformity through the conduit, sprue-conduit expansion design should be specific for rapid shear rate. Accordingly rearranging Eq. (13),

$$(Ds+L\ \tan\ \alpha)^4=\frac{32\mu \mathrm{QL}}{\nabla P\pi}\left(\frac{3n+1}{n}\right) \tag{15}$$

Now resolving for conduit expansion slope,

$$\tan\ \alpha=\frac{1}{L}\left[\sqrt[4]{\frac{32\mu QL}{\nabla P\pi}\left(\frac{3n+1}{n}\right)}-Ds\right] \tag{16}$$

Substituting from sound velocity definition $\nabla P=C_P P_{Max}$, where C_P is thermoplastic melt's characteristic co-efficient representing the extent to which sprue conduit should recover pressure and P_{Max} is rated injection pressure available in the machine [95]. Hence, substituting ∇P and Q into Eq. (16) resolves sprue conduit expansion as,

$$\tan\ \alpha=\frac{1}{L}\left[\sqrt[4]{\frac{32\mu L}{\pi C_P \mathrm{P}_{\max}}\left(\frac{V_{Shot}}{V_{Stroke}}\right)U_{Injection}\left(\frac{3n+1}{n}\right)}-Ds\right] \tag{17}$$

Based on Eq. (17) sprue conduit expansion has been proposed as:

$$\tan\ \alpha=\frac{(E_r-D_s)}{L} \tag{18}$$

where expansion ratio (E_r) being a vital quadrupled parametric ratio concerts conduit space, geometrical attic between nozzle tip and sprue well base and is obtainable by comparing Eqs. (17) and (18) as:

$$E_r^4=\left(\frac{32}{\pi}\right)\underbrace{\left(\frac{3n+1}{n}\right)\left(\frac{\mu}{C_P}\right)}_{Material}\underbrace{\left(\frac{U_{Injection}}{P_{Max}V_{Stroke}}\right)}_{Machine\ \mathrm{Setting}}\underbrace{\left(L_{Sprue}V_{Shot}\right)}_{Moulding}$$
$$=\left(\frac{32}{\pi}\right)\underbrace{Poly}_{Material}\ \underbrace{Ms}_{Machine\ \mathrm{Setting}}\ \underbrace{Comp}_{Moulding} \tag{19}$$

As per Eq. (19) sprue, conduit expansion geometry is specifically sensitive for a particular combinational set {moulding, material, machine}; with its relativity being categorically quantified, the criteria would certainly be highly reliable.

4. Illustration

Both conventional pragmatic examination [90] and classical philosophical inquest [85] of sprue-conduit expansion design criteria stumble. Because with them design factors are at some discrete levels just enough to predict dependent taper angle [10] and persuade on interpretive mode. While the Continuous Sensitivity Method (CSM) contrasts by adopting illustrative intervention to strategically sensitise across infinite scale with broad scope for inquisitiveness, deliberate on wisdom mode and its intervention compliments a unique perspective over prevalent myths and wonted analytical inferences. Sprue-conduit expansion sensitivity over de-facto polymeric character or specific in-situ behavioural range endures judicious decision on appropriate expansion angle design relative to their distinct extent in a chosen injectant. Thereon sensitivity intellect being highly valuable enables configuring conduit expansion angle to stabilise streamlines in design stage or diminish defects amplitude during processing. Such a priori association of intrinsic polymeric material characteristics to sprue conduit expansion would benefit tremendously [55] like rather than remedying various defects after occurrence.

Table 2
Specifications from Windsor Sprint 650T machine.

Injection pressure	P_{Max}	147 to 211.5 MPa
BSR	C_P	50%
Barrel stroke volume	V_{Stroke}	(3.77to543) × 10^6 mm^3
Injection rate	$U_{Injection}$	483 to 720 cc/s
Nozzle orifice	D_n	2.5 mm

Assumptions

1. Apparent viscosity and shear thinning interactive influence is neglected.
2. A relatively very high altitude is hypothetically featured and that accompanies convergence subjectivity for a particular or individual case.

Thermoplastic melt being a viscoelastic shear thinning fluid in pursuit of afore apprehension, we representatively perturb apparent viscosity and shear thinning index[16] [38] exclusively over infinite scale for perspiring their individual bias on sprue conduit taper, while holding all other factors at certain level as below,

a. A typical injection moulded part has been representatively adopted with following hypothetical features,
   Let us consider the material term of Eq. (19),

$$\mathrm{Comp}=\left(L_{Sprue}V_{Shot}\right) \tag{20}$$

Substituting V_{Shot} and L_{Sprue} values from Table 1 in Eq. (20) we get,

$$\mathrm{Comp}=80\times10^{-3}\times2500\times10^{-6}=0.2\times10^{-3} \tag{21}$$

b. Windsor Sprint series horizontal injection moulding machine has been representatively adopted,
   Let us consider machine term of Eq. (19),

$$Ms=\frac{U_{Injection}}{P_{\max}V_{Stroke}} \tag{22}$$

[16] They are easily obtainable from rheology studies of that particular polymer [7,67].

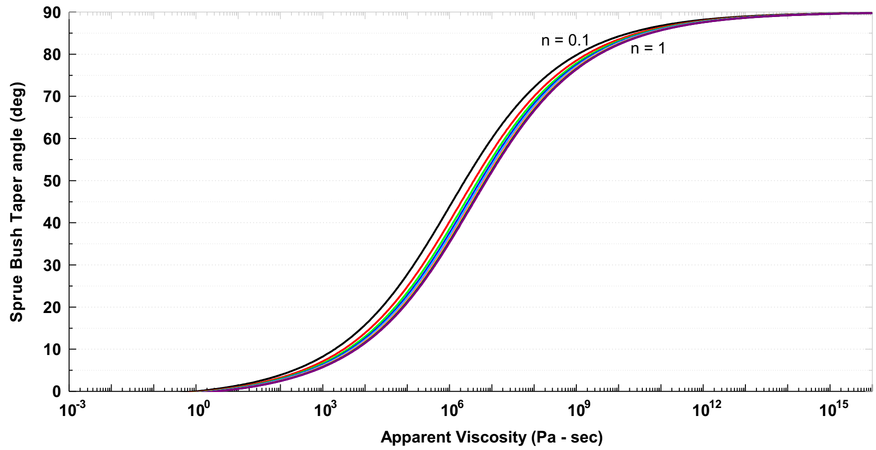

Fig. 5. Apparent viscosity influence on sprue taper expansion.

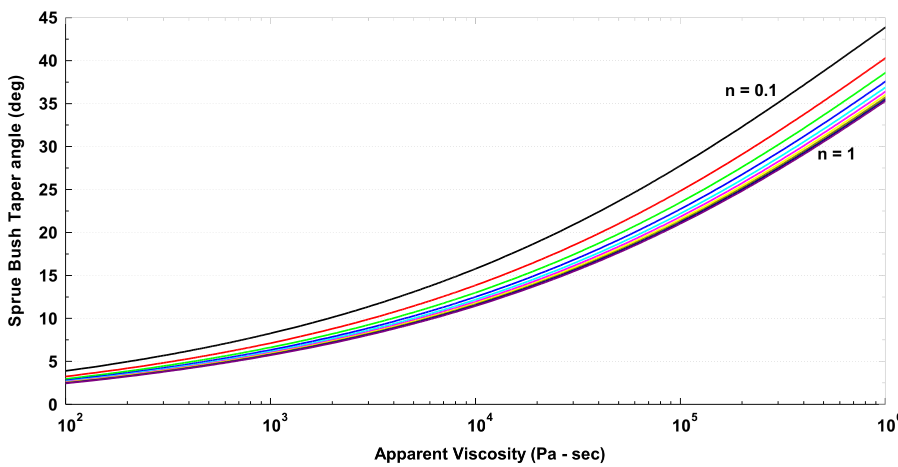

Fig. 6. Apparent viscosity influence on sprue taper expansion within its de-facto range.

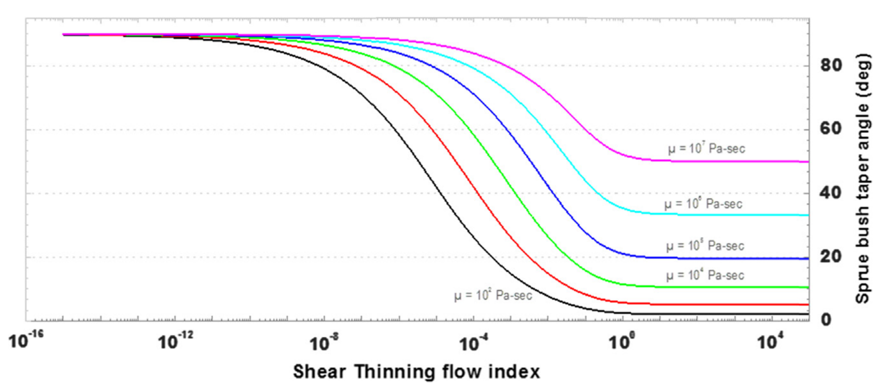

Fig. 7. Shear thinning index influence on sprue taper expansion.

Now substituting Table 2 ranges in Eq. (22) we get,

$$Ms = \frac{\{483, 720\}}{\{147, 211.5\} \times 10^6 \{3770, 5430\}} = \{\{0.627, 0.872\}\} \times 10^{-9} (\mathrm{Pa} - s)^{-1} \quad (23)$$

Accordingly, we opt anchoring Eq. (23) machine setting term range at a nominal value as:

$$Ms \approx 0.749 \times 10^{-9}\ (\mathrm{Pa} - s)^{-1} \quad (24)$$

4.1. Sensitivity to apparent viscosity

Graphical trends of Fig. 5 are very much in correspondence to that in the literature (*as in Fig. 3*) because injectant's apparent viscosity influence ceases at both extremely wide or narrow sprue conduit expansions *(natural bounds* $\alpha \in [0^o, 90^o]$*)*. However its

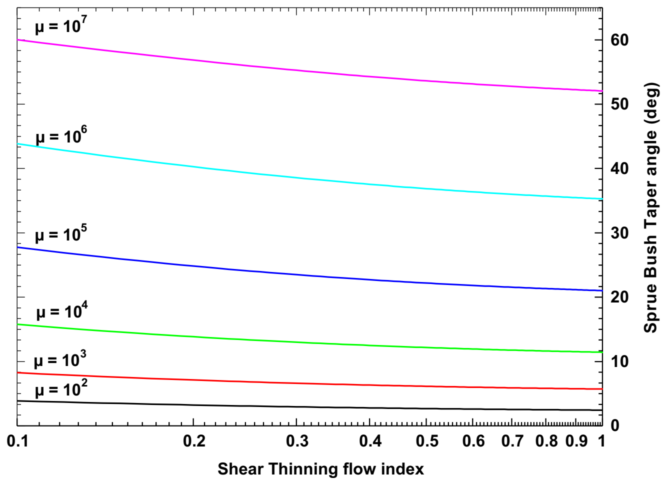

Fig. 8. Shear thinning index influence on sprue taper expansion within its de-facto range.

influence is aggressive amidst de-facto thermoplastic range, incidentally this extends most erstwhile researchers' presumption that sprue expansion relation with viscosity might be linear; perhaps within short injection moulding process range they might have revered such linear pretence. Certainly having known polymeric materials behaviour pure straight line elude is oblivious. Nevertheless, either excess expansions *(relative to aspic hypothetical injectant)* or too narrow expansions *(relative to aqueous hypothetical injectant)* are detrimental because severe orientations transpire and amplify stresses cracking susceptibility[17] (*as explained in Section 2.3.1*). Further as in most real mouldings with exorbitant heavy viscosity, transverse melt injection superimposes subsurface orientation over primary orientation resulting in multiple orientations [5]. Similarly ostensibly very low apparent viscosity magnitude at any given shear rate would excessively orient along longitudinal injection direction, thus predating melt fracture [14]. According to Fig. 5 sprue conduit expansion has an exponential sensitivity with apparent viscosity irrespective of its shear thinning behaviour; implying just nominal widening would suffice even large viscosity leaps. So the tempting practice of just manipulating pressure and/or temperature (i.e., *in-situ viscosity)* cannot abridge overall sprue-conduit expansion design incongruity [66], implying even a large in-situ viscosity tweak can hardly rectify defects as well as eventual processing consistency.

For better perspiration, the relationship was further sensitised in Fig. 6 across de-facto apparent viscosity range of thermoplastics, where slope and altitude dispersion for shear-thinning character was relatively little in comparison to apparent viscosity perturbation. Also the traditional practice of prudently using default taper angle i.e., $1^\circ \le \alpha \le 5^\circ$ *to conserve sprue system volume expense* [31,35] appears to be subjectively justifiable for less viscous commercial polymers, while certainly fallacious for thick viscous and diversely non-Newtonian engineering polymers.

[17]For instance, ABS mouldings are often exposed to acidic solutions for electroplating, so to control functional viscosity in any particular orientation they have to be injected at very nominal sprue conduit expansion [80].

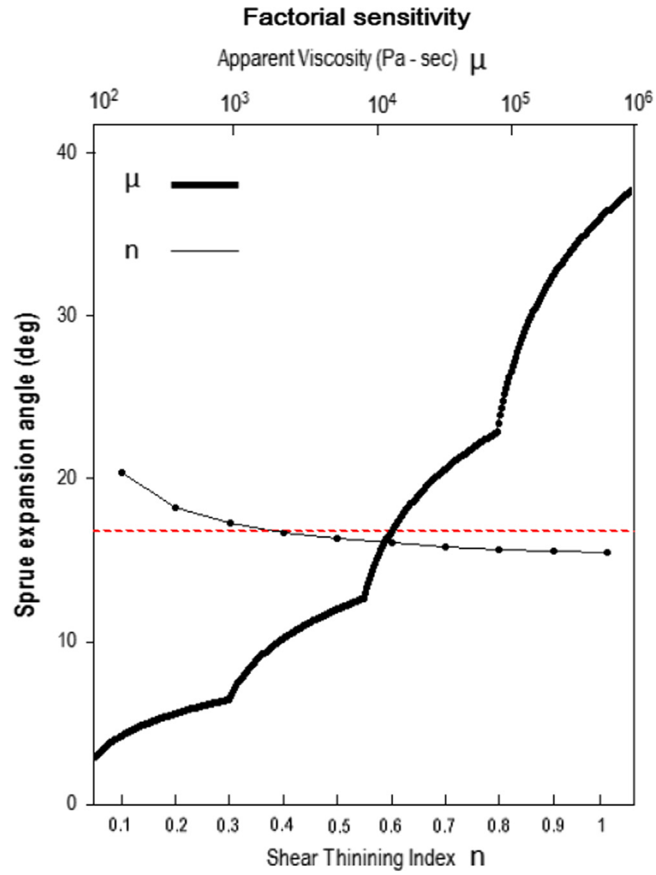

Fig. 9. Sensitivity of injection behaviour and hesitancy within their respective de-facto range.

Should a mould designer intend to accomplish best feasible performance then for afore illustrated hypothetical injection situation *(machine and component)*, from Fig. 6 curve trend we infer that a lowest viscosity tractile injectant at $100(\mathrm{Pa}-s)$ would approximately need $2.8^o \pm 1.36^o$ sprue conduit expansion. In contrast a highly viscous stubborn injectant of $1,000,000(\mathrm{Pa}-s)$ would approximately need $37.6^o \pm 8^o$ sprue conduit expansion. Accordingly, we summarise that ideal performance can only be accomplished with sprue bush conduit expansion design being contingent upon injectant's relative apparent viscosity.

4.2. Sensitivity to power law index

We infer from Fig. 7 that in-situ shear thinning behaviour vividly influences injection mouldability, especially within narrow and wide conduits (*as explained in Section 2.3.1*). Clearly, shear thinning flow index accords a logarithmic relationship with sprue-conduit expansion angle consistent with pragmatic belief [54]. Hypothesising natural extremity if power law index reduces describing significant shear thinning intensity in correspondence expansion angle has to widen irrespective of injectant's intrinsic viscosity. Because scaling hype severely aggravates such that sprue bush conduit existence itself ceases (*at its natural limit* (90°)) as shown in Fig. 7. Hence to sustain APL an extremely shear thinning injectant would invariably need a wide expansion relative to its apparent viscosity. While an extremely stubborn injectant with almost nil shear thinning behaviour ceases its relativity with conduit expansion irrespective of its apparent viscosity i.e., *its expansion design becomes solely viscosity dependent*. For instance, rapidly shear thinning commodity resins like PP, PS or LDPE *(having low shear thinning index)* are readily injectable even through wide conduit expansion. While reluctantly shear thinning engineering resins like ABS, PBT, PC *(having high shear thinning index)* cannot be injected through ridiculous expansions, instead they require meticulously designed expansions at an unimaginably gentle shear rate; else defects like blemish would be obvious.

For better perspiration, the relativity is further sensitised in Fig. 8 across de-facto power-law index range for thermoplastics (see Fig. 2). Wherein slope and altitude dispersion for intrinsic apparent viscosity were relatively significant compared to shear thinning perturbation. In addition, characteristic dispersion broadly encompasses the entire range across both shear thinning behavioural index as well as natural expansion angle bounds. So to overwhelm sprue conduit flaw the tempting practice of spontaneously manipulating pressure and/or temperature (in-situ *apparent viscosity)* might reasonably remedy. Like shear thinning behavioural influence could be regulated by adopting following strategies: (1) maintaining melt temperature uniformity, (2) controlling melt injection rate steadiness, (3) adjusting pressure and injection rate amplitude and (3) stabilising melt injection consistency *viz time interval*.

In relevance to our objective (*in Section 2.7*) of contemplating holistic thermoplastics range for injection moulding, Fig. 9 factorial sensitivity of afore hypothetical case. Hypothesising apparent viscosity as random parameter and shear-thinning index as relatively nested parameter (*as deliberated afore in Section 2.4.2*), Fig. 9 curves trends establish that apparent viscosity slope overtly exceeds shear thinning index's. So we infer it relatively more influential that was also consistent with wide pragmatic belief [61]. However, despite such implicit relativity of salient factors to sprue expansion, fundamental description is still unheard. Similarly contemporary endeavours depicting conduit design sensitivity at either extremities i.e., *rapid and gradual shear thinning rate* is still daunting [88]. Therefore, the current endeavour reveals an altogether first-hand insight to enhance sprue design robustness. Whereas myriad solitary pragmatic endeavours might have, necessary to either contemplate or establish any other arguments.

5. Conclusion

Attributing the series of arguments extensively justified above, it deduces that by designing a sprue bush conduit very specifically for any particular polymer exemplary performance as well as superior characteristics are certainly accomplishable. A collective design criteria model proposed for sprue-conduit expansion to inject broadly all thermoplastic melts was pertinent with wide-ranging application (*machine and impression*) possibilities. The results thus obtained from an illustrative hypothetical case were fully continuous with de-facto range of all thermoplastics as illustrated in Fig. 9. Therefore a polymeric injectant's in-situ ability to remain consistent *(represented by apparent viscosity)* renders almost direct logarithmic proportionality; while its in-situ phenomenal behaviour *(represented by shear thinning index)* has a mild inverse logarithmic proportionality to conduit expansion. Hence we conclude that polymeric injectant's intrinsic hesitancy has more significant influence than its corresponding non-Newtonian behaviour. Nevertheless, both being aggressive in nature, so injectant character and its interactions are certainly significant impelling factors to design sprue-conduit expansion. This intuit also asserts the ability to compliment many other determinates through extended analytics; affective synchronisation and cognising in-situates like injection fill time; injection ramping speed for packing, operating temperatures, compatibility, etc.

6. Contribution

Above proposition contributes new outlook to assess resin's injection mouldability particularly those categorised as reluctantly mouldable, despite possessing excellent properties or involving severe injectability.[18] The criteria thus proposed might augment overall confidence of designed moulds to inject highly challenging injectants in the future, neither swapping machine nor altering component being necessary. Because, the present endeavour extends resins selection liberty upon designing moulds relative to a chosen thermoplastic along with its constituent additives. Furthermore, the present endeavour promises even for injection moulding of conventional thermoplastics to engineering applications like optical disk moulding [90], reflectors for lighting systems, laptop casings, etc. So forth products with improved quality in addition extend their design freedom can be easily moulded.

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