In-line Process and Material Property Measurement in Injection Moulding - a Theoretical Review

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**ABSTRACT**

In running production the measurement of process and material properties in-line, is a requirement to design and implement effective process control in injection moulding. This work presents a structured thorough analysis and review of the research concerned with in-line measurements of selected processes and material properties on the injection moulding machines. This review sets the current state of art within a range of process and material properties, and identifies areas for future research. The process and material property measurements reviewed are: Viscosity, Melt temperature, pvT and Melt density. It is identified that the largest research effort has been placed on the measurement of viscosity and melt temperature, whereas pvT and melt density measurement are less developed. Finally, gaps within the literature are identified and the proposal of a direction within the field is stated.

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1. Introduction

Injection moulding is one of the most popular production methods for mass production of plastic parts (Zhao et al., 2021). It is a continuously growing industry, and around one-third of the plastic products are produced by injection moulding. Plastic parts are being used more extensively for multiple different products, enhancing the requirements for quality and tolerances (Ageyeva et al., 2019). Recently sustainability has become a major topic for consumers, and a topic the manufacturer needs to address to stay competitive (Heidbreder et al., 2019). One of the topics in focus is the utilisation of plastic from sustainable sources or recycled plastics. The reason for variation within the virgin raw material is mainly due to two sources (Heinzler & Wortberg, 2014; Speight et al., 1999, 1995):

1. Variability in polymerisation/manufacturing
2. Subsequent variability due to processing

Variability in the plastic feedstock is inevitable, and depending on the magnitude this will influence the parts produced. Introducing recycled plastic feedstock will at best maintain these variations at the current level.

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The predominant moulding process consists of a fill phase and a hold phase. The parameters are mainly found by time-consuming experimental work for a given injection moulding tool and are not adapted dependent on the material utilised (Agrawal et al., 1987; Hopmann et al., 2015; Speight, Hull et al., 1996). Sustainable materials will challenge this approach, due to the variable nature of the feedstock, making new experiments and mould qualification necessary.

Since the 1980’s injection moulding machine vendors have continuously striven to improve the repeatability in the precision of the injection moulding machines, focusing on the machine parameters (Obendrauf et al., 1993). This will in theory make sure a consistent product is produced if there is no change in the boundary conditions. That is seldom the case in a production environment where the temperature, humidity, and vendors of raw materials, among others, may vary (Gordon et al., 2015). Regarding the process control, a cascade control structure with three cascaded loops is the most frequent control approach in injection moulding (Chen & Turng, 2005). An illustration of the control structure can be seen in Figure 1.

Common for all control loops is that measurement of data will need to be obtained in-line for it to be used in the controllers. The data utilized in each control loop have a different characteristic. Process control requires knowledge about process data, e.g. the material properties, melt temperature, plastic pressure, where part control requires knowledge about the characteristic of the element, e.g., shrinkage, length, or weight.

This theoretical review focuses on the in-line measurement of the process and material properties on the injection moulding machine. Measurement of material properties in-line is a requirement for process control as described above, which is believed to improve process stability in terms of, e.g., element weight or dimensions. The ability to measure material properties in-line will further make it possible to continuously monitor the material, to ensure the material complies with the specification, gain data for simulation software, and utilize, e.g. digital twins.

In the literature, there is a degree of confusion between the terms ”in-line” and ”on-line”. The definitions are according to Coates et al. (1994), that ”on-line” means diverting a part of the melt away from the process to e.g. a rheometer, whereas ”in-line” is defined as the estimation or measurement is conducted in the actual injection moulding process.

Multiple process and feedstock characteristics are of importance in injection moulding. The identified properties of interest in this theoretical review are:

- Melt Pressure
- Viscosity
- Melt Temperature
- Pressure-specific volume-temperature (pvT)
- Melt Density

![Figure 1. General cascaded control structure utilised in injection moulding.](image-url)
The selection is based on the process parameters influenced by the injection system being melt pressure and melt temperature, and the feedstock characteristics related to these parameters. A review of these parameters is not covered in a previously published paper. Remark that thermal properties such as e.g. thermal conductivity, specific heat and transition temperature are also of importance in injection moulding, but are omitted as it is beyond the scope of this review to describe all process and feedstock characteristics.

The melt pressure measurement will not be described in further detail in this theoretical review, due to the availability of sensors directly capable of measuring this. This is well described in a range of studies (Ageyeva et al., 2019; Collins, 1999; Kazmer et al., 2005).

This theoretical review covers the current state of art on how to estimate the identified process and material properties in-line on an injection moulding machine while running with a production mould. Each parameter will be covered separately by reviewing the theory followed by experimental results. The search strategy resulted in the review of 171 scientific papers of which 92 publications are considered core contributions included in this paper.

2. In-line Apparent Viscosity Measurement Methodologies

The materials used in injection moulding are non-Newtonian fluids. The viscosity of a non-Newtonian fluid is shear rate and temperature dependent. The simplest model to describe a non-newtonian fluid that is mainly used in engineering applications is called the power-law model (Coates et al., 1996; Kazmer et al., 2004; Speight, Yazbak et al., 1996). The power-law model is referenced at a specific temperature and given by Eq. (1).

\[ \eta = K \dot{\gamma}_r^{(n-1)} \]  

Where \( \eta \) is the viscosity measured in [Pa·s], \( K \) is a material constant, \( \dot{\gamma}_r \) is the reduced shear rate and \( n \) is the flow behaviour index. There exist multiple models describing the viscosity as a function of shear rate e.g. the Carreau, the Carreau-Yasuda model, the Cross-WLF model, and the Ellis model (Bird et al., 1987; Kazmer et al., 2004). A graphical representation of a selection of the models for polystyrene can be seen in Figure 2.

Bird, Bird et al. (1987) describes how a difference in temperature from the reference temperature also changes the viscosity. The cross-WLF equation is temperature dependent; however, for e.g., the power-law model the change can be calculated using a shift factor. For materials at the glass transition temperature and up to 100°C above the glass transition temperature has the Williams-Landel-Ferry (WLF) equation proven effective (Bird et al., 1987). The WLF equation is given by Eq. (2)

\[ \log(a_T) = \frac{-c_1^0(T - T_0)}{c_2^0 + (T - T_0)} \]  

Where \( a_T \) is the shifting parameter, \( T \) is the current melt temperature, \( T_0 \) the glass transition temperature, \( c_1^0 = 17.44 \) and \( c_2^0 = 51.6 \) K. If data points are available the constants should be \( c_1^0 = 8.86, c_2^0 = 101.6 \) K and \( T_0 \) should be found through data fitting. From the knowledge of the shifting parameter \( a_T \) it is possible to calculate the reduced shear rate as Eq. (3)

\[ \dot{\gamma}_r = a_T \dot{\gamma} \]
The apparent viscosity can now be calculated from data obtained at other temperatures. At this point, there does not exist a single sensor capable of measuring viscosity directly neither in-line or in laboratory equipment. Viscosity can be measured in the laboratory by utilizing e.g. rheometers. A thorough description of rheometers can be found elsewhere (Bird et al., 1987).

The major factors influencing viscosity in injection moulding can be divided into three categories according to Chen et al. (2019); Hopmann et al. (2017).

1. Raw material, e.g. the type, humidity, and batch-to-batch variations.

2. The plasticising effect, e.g., the geometrical design of the screw, the rotational speed of the screw, back pressure, feeding rate and heater band temperature.

3. Injection parameter settings, e.g., the mould temperature, the injection speed, the holding pressure and cooling time.

Several papers deal with the issue of measuring the viscosity of the material in-line. The approach can be separated into two principles, one which tries to measure or estimate the apparent viscosity and one which aims to calculate a viscosity index to track changes in viscosity. Both methods will be presented here starting with apparent viscosity measurement.

### 2.1. Methods and Results to Measure Apparent Viscosity

The measurement of apparent viscosity in-line can be done in multiple positions on the injection moulding machine, e.g. in the nozzle, inlet system, or cavity. Apparent viscosity measurements should be conducted at steady-state conditions. To be able to use regression analysis to find the parameters of Eq. (1), the measurement of the apparent viscosity as a function of shear rate will be required at multiple shear rates and thereby injection
velocities. This is seldom present in running production, due to the aim of zero variation in processing. Instead, the viscosity is calculated at distinct injection velocities and thereby at distinct shear rates. The first principle described utilises two pressure sensors a distance apart, whereas the second principle only uses a single sensor.

Rheology nozzles exist containing two pressure sensors \( p_1 \) and \( p_2 \) a distance apart (see, Figure 3). The wall shear rate and apparent viscosity can be calculated for a flow rate through a cylinder under the assumption that the flow rate is unidirectional, the fluid is incompressible, a large length-to-diameter ratio and the process is isothermal.

The wall shear rate for a Newtonian fluid and the apparent shear rate \( \dot{\gamma}_a \) for a non-Newtonian fluid is given by Eq. (4):

\[
\dot{\gamma}_a = \frac{4Q}{\pi r^3}
\]

\( \dot{\gamma}_a \) being the (apparent) shear rate at the wall, \( Q \) being the flow rate of the fluid, and \( r \) being the radius (Coates et al., 1994). The viscosity for a Newtonian fluid and the apparent viscosity for a non-Newtonian fluid can then be calculated as Eq. (5)

\[
\eta_a = \frac{\pi r^4 \Delta p}{8QL}
\]

Where \( \eta_a \) is the apparent viscosity, \( r \) is the radius, \( \Delta p \) is the pressure difference between \( p_1 \) and \( p_2 \), \( Q \) is the flow rate and \( L \) is the distance between the pressure sensors (Kazmer et al., 2004).

Coates et al. (1994) describe the use of a rheometer nozzle similar to the sensor sketched in Figure 3 with two pressure sensors and two temperature sensors. Experimental results show good agreement between laboratory off-line tests and on-line tests at multiple injection rates utilising the rheometer nozzle with a slit die at the end. A drawback of the method is the small pressure drop between the two pressure transducers. For actual in-line moulding they often only employ a single pressure sensor to minimise the melt reservoir inside the nozzle.

![Figure 3. Schematic of rheometer nozzle.](image-url)
Sykutera et al. (2018a) describe the estimation of the apparent viscosity in the mould cavity of a simple two-cavity mould producing tensile bars. A pressure sensor is located close to the gate of the cavity, and a temperature sensor is located at a distance \( s \) from the pressure sensor. Measurement of pressure and temperature begins when the injection moulding machine sends an injection start signal. Equation (5) is utilised to calculate the apparent viscosity. \( \Delta p \) is the pressure increase from the melt passing the pressure sensor until it reaches the temperature sensor. The flow rate is calculated by the average cross-sectional area, divided by the time it took the melt to travel between the pressure and temperature sensor. In Sykutera et al. (2018b), the apparent shear rate and apparent viscosity are compared to results obtained in a rheometer and plastometer. The data obtained from the three different methods show a similar tendency during tests with polypropylene (PP). The results show that the apparent viscosity drops linearly in a log-log graph as a function of the apparent shear rate. The linear relationship is expected and is in agreement with equation (1). There is some difference between the three methods, the maximum difference is at an apparent shear rate of 500 s\(^{-1} \) where the difference in apparent viscosity is approximately 100 Pa\( \cdot \)s. The reason could be the difference in boundary conditions for the different measuring methods, e.g. the rheometer is temperature controlled whereas the mould is cooled through a tempering unit that ensures the melt cools down and freezes as soon as the polymer hits the mould wall.

Ross et al. (1990) describe the use of an instrumented nozzle with 3 pressure sensors, to avoid having to correct for end-effects. The experiments are run in polybutylene terephthalate (PBT) material and compare the results measured on the injection moulding machine with the results obtained on a laboratory rheometer. They describe that the pressure effect is usually not accounted for, but the effects can be significant at high pressure that occur in an injection moulding machine meaning it can be relevant to calculate the viscosity at a reference pressure. The experiments show a good correlation between in-line measured viscosities and laboratory measured viscosity, and they also found it is a possible way to detect the amount of moisture in the material.

Sherbelis and Speight (2001) described the usage of a nozzle with two pressure sensors to detect viscosity changes in the material. The paper further describes the idea of utilising the melt temperature to manipulate the viscosity because the temperature has a smaller effect on, e.g., \( pVT \) than velocity/pressure-induced manipulation of the viscosity.

The approach described above needs two pressure sensors to obtain the apparent viscosity. Asadizanjani et al. (2012); Fan et al. (2016); Gao and Kazmer (2012); Gao et al. (2014); Gordon et al. (2015); and Pacher et al. (2014) all present the development of a multivariate sensor that can measure both pressure and temperature, and thereby calculate the velocity and viscosity through a single sensor. The sensor measures pressure through a piezoelectric stack and temperature with an IR sensor. The sampling time of the IR sensor is in the range of 0.01 \( \mu \)s, making it possible to measure the velocity of the melt as the ramping rate of temperature as it passes over the sapphire window of the sensor. The velocity is estimated by Eq. (6).

\[
\nu = \frac{\pi r}{2 T_0} \left( \frac{dT}{dt} \right)_{\text{max}}
\]
Where \( v \) is the melt velocity, \( r \) is the radius of the sapphire window, \( T_0 \) is the reference temperature of a thermocouple and \( \left( \frac{d^2 T}{dt} \right)_{\text{max}} \) is the maximum temperature gradient with respect to time. The velocity measurement has proven to be good at estimating velocity at speeds up to approximately 500 mm/s when compared with the melt time of arrival between two sensors.

To enable the measurement of pressure drop with a single sensor, equation (5) is adapted to calculate the apparent viscosity by utilising the pressure gradient of the single pressure sensor instead of the pressure difference between two sensors. The shape of the channel is changed from round to square meaning the apparent viscosity is calculated by Eq. (7).

\[
\eta_a = \frac{H^2}{12v^2} \frac{dp}{dt}
\]  

\( \eta_a \) being the apparent viscosity, \( H \) being the height of the channel, \( v \) being the velocity of the flow and \( \frac{dp}{dt} \) being the pressure gradient. The difficulty in using this method is the numerical differentiation of both temperature and velocity with respect to time that is necessary. The measured viscosity results are in good agreement with simulated data for a range of velocities, where melt velocity is proportional to shear rate. The sensor is further developed to be wireless in a radio frequency (RF) shielded environment sending the signal out of e.g. the mould. This enables easier mounting of the sensor without having to adapt all mould plates between the sensor location and the outside of the mould. The sensor has not been commercialized yet.

### 2.2. Methods and Results to Measure the Viscosity Index

The literature describing the utilisation of apparent viscosity measurement is limited, and a possible explanation for this is the larger melt reservoir when using two sensors (Coates et al., 1994). Another approach is to estimate the viscosity based on an index. The principle of a viscosity index is to identify viscosity changes relative to a baseline. It is useful as it can be calculated from e.g. machine parameters minimising the amount of sensors (Bakharev et al., 2002; Speight et al., 1997, 1995).

Speight (1993) describes the viscosity index that utilises the specific pressure integral at a certain part of the moulding cycle. By comparing hydraulic-measured injection pressure with nozzle-measured injection pressure, it is found that there is a linear correlation of approximately one between the two measurements, in the velocity controlled part of the injection phase. Therefore, it is suggested that the hydraulic injection pressure might be as sensitive as the nozzle pressure when measuring the viscosity index. Brincat et al. (2004) proposes two ways to define the starting and finishing point for the pressure integral related to either the injection time or stroke of the screw. The integral can be of hydraulic pressure, nozzle melt pressure, or cavity pressure. Yi-Sheng Chen et al. (2021) state the general equation for the pressure integral (PI) as in Eq. (8).

\[
PI = \int_a^b p(t) \, dt
\]  

Where \( p(t) \) is the hydraulic, nozzle, or cavity pressure as a function of time and \( a \) and \( b \) are the starting and finishing points of the integral. In the original paper by Yi-Sheng
Chen et al. (2021), the integral is stated with boundary conditions related to a specific time, this is generalised in this review due to the considerations from Brincat et al. (2004).

It is important when the boundaries for the integral are determined to consider the signal noise to achieve the best possible calculation of the viscosity index. The best signal-to-noise ratio is achieved in the velocity controlled part of injection, at 60–80% of the injection time according to Kelly et al. (2000). Speight et al. (1994) found a similar result, without specifying generalised percentages. The reason for choosing this part of the injection time is as stated above due to the high signal-to-noise ratio. The reason for this period having low variance could be due to the velocity control of the screw, yielding greater uncertainty when accelerating and decelerating (Speight et al., 1999).

The viscosity index has proven to be successful in determining viscosity variations in moulding trials. Speight et al. (1994) report on moulding experiment utilising multiple different materials e.g. crylonitrile butadiene styrene (ABS) and polyoxymethylene (POM), and successfully distinguish between different batches within each material. Furthermore, a correlation between the pressure integral and product’s weight and height are shown. Coates et al. (1994) proved it is possible to distinguish between different bags of the same polymer, in this case ABS and high-density polyethylene (HDPE). Coates et al. (1999) conducted moulding trials on polyamides studying the moisture content of the hygroscopic material. Through the design of experiments, it is found that the velocity of the screw and melt temperature have the highest influence on the mean viscosity index, while moisture content affected the variability of the viscosity index the most. Kelly et al. (2000) conducted moulding experiments on 6 polyamides, a polyacetel and a flexible polyvinyl chloride. The experiments showed that the viscosity index measured in a low noise region of the primary injection phase is sensitive to the variation of the process. The experiments also showed that there was no direct correlation between viscosity index and product weight for the shapes and materials tested, which is a contradiction to the results obtained in Speight et al. (1994). Brincat et al. (2004) investigated the sensitivity of the viscosity index to regrind in an acrylonitrile butadiene styrene – polycarbonate (ABS-PC) blend with 10% glass fiber. The viscosity index detected the change in viscosity when a material change was made from virgin to reground material. It was further proven that a change in temperature could change the viscosity back to the same level as when virgin material was used. Yi-Sheng Chen et al. (2021) experimentally showed a correlation between viscosity index and part weight for an unknown material as it is not reported in the paper, and further utilized the viscosity index for switchover control. Speight et al. (1999) suggest to use temperature integral instead of pressure integral for materials with low flow behavior index, as through moulding trials it has shown to be more sensitive to changes in rheology.

A general difficulty utilising the viscosity index as stated in Eq. (8) is that it requires the process to be velocity controlled with a constant injection velocity. The viscosity index can mainly be used to compare with a reference cycle and thereby not contain information about the true viscosity. Alternative indexes will be presented in the following.

Jian-Yu Chen et al. (2019) proposes a different version of the viscosity index compared to Eq. (8), by multiplying the integral with a mould-specific constant $C$, stated in Eq. (9).

$$PI = C \int_{t_1}^{t_2} p(t) \, dt$$ (9)
Where $p(t)$ can be system pressure, nozzle pressure, or cavity pressure. The limit is determined to be similar to the viscosity index described previously. The paper doesn’t reveal why the constant $C$ is included and how it is determined as it is a simple scaling. The scaling does not change the correlation effect and thereby seems unnecessary.

Chen et al. (2019) further provide an index based on the energy utilized for the injection and holding phase given in Eq. (10).

$$EI = A_{\text{screw}} \int_{x_{\text{int}}}^{x_{\text{end}}} p(x) \, dx$$

(10)

Where $EI$ is a energy index, $A_{\text{screw}}$ is the area of the screw, $x_{\text{int}}$ is the starting point of injection, $x_{\text{end}}$ is the endpoint of injection and holding phase and $p(x)$ is either the hydraulic pressure, nozzle pressure, or cavity pressure. The Energy index and viscosity index have a similar correlation to product weight.

Gornik (2008) utilises a similar index called monitoring of feedstock quality (MFQ). Instead of integrating the pressure, it integrates the effect. The MFQ is calculated as Eq. (11).

$$MFQ = \frac{\int T \omega dt}{V_{\text{met}}}$$

(11)

$MFQ$ being the viscosity index, $T$ being the torque, $\omega$ being the screw angular velocity and $V_{\text{met}}$ is the total metering volume. However, the paper does not present the results or sensitivity to viscosity changes.

Heinzler and Wortberg (2014) utilize a similar approach by investigating the influence of moisture on the viscosity of PBT. Offline tests show that the viscosity decreases as the moisture content increases. Online machine data is available at a rate of 500 Hz, and instead of using injection velocity the screw rotational torque is used, due to the fact that the injection velocity is part of the moulding cycle. The screw is feedback velocity controlled meaning it is possible to compare the torque for each cycle to track changes. Disregarding the acceleration and deceleration of the screw, experiments show a change in the mean torque of 2.41% for a material moisture change from 0.02% to 0.03%.

Finally, Theunissen et al. (2017) describes the definition of a viscosity index based on two pressure sensors installed in the mould cavity. The index is defined as Eq. (12).

$$K_{pl} = \frac{p_1 - p_2}{V}$$

(12)

$K_{pl}$ being the viscosity index, $p_1$ being the pressure value close to the gate, $p_2$ being the pressure sensor at end of the fill and $\dot{V}$ being the volume flow. The pressure measurement is taken when the second sensor measures a pressure of 5 bar. The flow rate when filling the cavity changes and the index is therefore only possible to calculate a single time per cycle. The virgin and reground PBT is first characterised in a laboratory rheometer to show that there is a viscosity change of approximately 600 Pa·s. Moulding trials show that the index proves to be sensitive to the addition of reground PBT.
3. In-line Melt Temperature Measurement Methodologies

The melt temperature is an important parameter in injection moulding affecting e.g. viscosity, pvT diagrams, appearance, and residual stresses (Bendada et al., 2004; Dininger, 1994; Obendrauf et al., 1993; Reiter et al., 2014; Rose et al., 1990). Temperature measurement can be conducted directly with temperature sensors, the types of sensors are mainly thermocouples, IR, and ultrasonic sensors (Ageyeva et al., 2019). However, the measurement of melt temperature in-line is nontrivial (Bendada et al., 2004; Reiter et al., 2014). It is possible to measure melt temperature in multiple positions on the injection moulding machine, e.g. in the nozzle, inlet, and cavity. For practical reasons, the sensors need to be flush mounted to ensure a minimum of visual defects and flow alterations (Kamal et al., 1986). The temperature of the melt in the barrel is not constant, as it depends both on the position in the length and depth of the barrel (Amano & Utsugi, 1989). This review focuses on determining an average value of melt temperature in the barrel, as methods utilised in the cavity generally are shape specific (Panchal & Kazmer, 2010; Reiter et al., 2014; Varela et al., 1996). The most widespread method to measure melt temperature is off-line and is done by purging material into an isolated cup and measuring temperature by moving a probe around in the material to find the hottest spot. The probe is preheated to 30 degrees above the expected temperature (Ashwin Kumar et al., 2017). The review focuses on three different sensor types to measure the melt temperature, namely an IR sensor, a thermocouple, and an ultrasonic sensor.

3.1. Melt Temperature Measurement: IR Sensor

The IR sensor works by guiding infrared (IR) radiation from a distance inside the melt through a sapphire window and fibre optics to the detector, the detector converts the infrared radiation to a temperature. The temperature measured from the IR sensor is the average melt temperature from a distance down in the melt to the surface. The first-order response time of an IR sensor is relatively fast and less than 10 ms. To use the IR sensor, the emissivity of the material must be known (Dininger, 1994; Dontula & Campbell, 1995; Hopmann et al., 2017; Key et al., 1998; Obendrauf et al., 1993; Rawabdeh & Petersen, 1999; Speight et al., 1999).

Obendrauf et al. (1993) described a method to determine the emissivity, by melting material in a square-shaped cavity, with space for IR sensors and a reference thermocouple. By measuring the temperature of the molten plastic with the thermocouple it is possible to calibrate the IR sensors to the same value by adjusting the emissivity value. Straka et al. (2015) described a similar procedure, also with a thermocouple to make the reference temperature, but instead of molten material, a thin sample is moulded and placed on an insulated heated plate. The thermocouple is again acting as a reference and the emissivity is found from an IR camera.

Sheth (2001) compares the response of an IR sensor with that of a handheld pyrometer at the beginning and end of a moulding trial. The two methods show only a very small difference within a couple degrees.

Key et al. (1998) compared the temperature measurement of an IR sensor with the result of a thermocouple inserted into the melt and a flush-mounted thermocouple in an extrusion machine. The results show good agreement between the thermocouple inserted into the melt and the IR sensor, whereas the flush-mounted thermocouple differs due to heat conduction from the steel.
Speight et al. (1997) investigated the effect of heater bands on the IR sensor and thermocouple response, and it was seen that the thermocouple was again influenced by the mounting material temperature, whereas the IR sensor was not.

Speight et al. (1999) have further concluded that the IR sensor is unaffected by pressure, except through compression heating. It is further independent of the temperature of the surrounding media. The measurement of temperature with an IR sensor has the drawback of calibration; however, no single direct measurement method with a better precision is described in literature. The drawback of the sensor is the price and the size meaning it is often impractical to mount in the nozzle of the injection moulding machine (Kamal et al., 1986; Kazmer et al., 2005; Key et al., 1998).

3.2. Melt Temperature Measurement: Thermocouple

A thermocouple is a cheap and reliable temperature sensor, however, the temperature a flush-mounted thermocouple measures is not the true melt temperature. Instead, it measures an interface temperature between mould steel and melt. This is due to heat conduction from the steel it is mounted in. The response time of a thermocouple is relatively slow in comparison with the IR sensor and is in the range of minimum 0.2 seconds (Dininger, 1994; Kazmer et al., 2005; Straka et al., 2015; Rawabdeh & Petersen, 1999; Speight et al., 1997, 1999).

Patterson et al. (1985) installed the thermocouple in the screw-tip, to make it less affected by the heater band. The installation required is comprehensive due to the rotating nature of the screw. This requires slip rings to transfer data from the rotating screw to the stationary part. Furthermore, a hole drilled through the screw to guide the cables, removes some of the strength from the screw. The paper does not compare with alternative temperature measurement techniques, meaning the precision is unknown.

Johnston et al. (2006, 2015) describes the use of a flush-mounted thermocouple to measure the interface temperature and from that estimate the melt temperature. The estimation algorithm is based on heat conduction from the mould-melt interface through the mould to the cooling lines. The governing equation is the equation for transient conduction in a semi-infinite solid given in Eq. (13).

$$\frac{\partial^2 T}{\partial z^2} = \frac{1}{\alpha} \frac{\partial T}{\partial t}$$  \hspace{1cm} (13)

Where $T$ is the temperature, $\alpha$ is the thermal diffusivity, $z$ is the distance from the mould surface and $t$ is the time. The boundary conditions can be stated as Eq. (14)

$$T(z, 0) = T_{\text{mould, ini}}$$

$$T(\infty, t) = T_{\text{mould, ini}}$$  \hspace{1cm} (14)

Where $T_{\text{mould, ini}}$ is the initial mould temperature. The assumption is that the mould starts at the mould temperature at the wall and the mould temperature far away from the cavity does not change as a function of time. Based on the solution to equation (13), the boundary conditions in equation (14), an assumption that the temperature in the melt is uniform and the total energy conducted into the mould equals the removed energy it is possible to estimate the melt temperature.
The main difference between the two papers is the experimental method and the verification method of the estimated melt temperature. Johnston et al. (2006) designed the experiment so the cooling time is 200 s, to ensure the heat gradient in the element is zero. They furthermore compare the results only to numerical simulations. The comparison shows that the estimated temperature is generally larger than the temperature calculated in the simulation. Too large a temperature is estimated independent of change in barrel temperature, coolant temperature, and injection velocity.

Johnston et al. (2015) compared the result with an IR sensor, this time the mould is run with a traditional cooling time meaning the element is warmer than the mould when ejected. The results show a similar tendency when compared to the IR sensor when barrel temperature, coolant temperature, injection velocity and cooling time are varied. However, the estimation predicted a lower temperature, which is due to the heat removed when the element is ejected out of the mould. Furthermore, the precision of the thermocouple is of great importance due to the integration, meaning any error will be amplified.

### 3.3. Melt Temperature Measurement: Ultrasonic Sensor

Ultrasonic measurement of temperature is an indirect measurement method that requires a model specific to the material that the measurement should be conducted on (Kariminejad et al., 2021; Kauffer, 2011). The principle works by sending an ultrasonic pulse through the plastic material. The temperature is estimated from the time of flight of the pulse and it is therefore an average temperature (Brown et al., 1999; Hopmann et al., 2017; Straka et al., 2015; Praher et al., 2019; Rawabdeh & Petersen, 1999; Yi-Lin et al., 2017). The measurement method is considered non-invasive, even though a pulse is sent through the material, due to the mechanical input power in the material from the sensor being approximately $10^{-10}$W (Piché et al., 1999). The ultrasonic sensing can be performed either with two sensors, one in transmission mode and one in measurement mode, or by one sensor in reflection mode (Lionetto & Maffezzoli, 2008). An illustration of the measurement with an ultrasonic sensor can be seen in Figure 4.

Praher et al. (2014); Praher et al. (2013, 2014); Straka et al. (2017); and Klaus Straka et al. (2015) all describe a similar method of how to estimate the melt temperature from the ultrasonic sensor. The longitudinal ultrasonic velocity of the ultrasonic pulse can be calculated if the distance of the traveled melt is known together with the time of flight, as given in Eq. (15).

$$c_L = \frac{d}{t}$$  \hspace{1cm} (15)

Where $c_L$ is the longitudinal ultrasonic velocity, $d$ is the distance the ultrasonic pulse has travelled in the polymer melt and $t$ is the time of flight. By knowing this parameter it is possible to estimate the temperature as the sound velocity is dependent on the temperature and pressure.

Gon et al. (2004) showed that the longitudinal ultrasonic velocity is related to the adiabatic bulk modulus and the melt density by Eq. (16).
Where $c_L$ is the longitudinal ultrasonic velocity, $\rho$ is the melt density of the polymer and $\kappa$ is the adiabatic compressibility. The adiabatic compressibility is given in Eq. (17).

$$
\kappa = -\frac{1}{\nu} \left[ \left( \frac{\partial \nu}{\partial p} \right)_T + \frac{T}{c_p} \left( \frac{\partial \nu}{\partial T} \right)_p \right]^2
$$

Combining equation (16), (17) and (20) it is possible to estimate the average melt temperature if the pressure is measured in the same position.

Thomas et al. (1994) utilises a different approach to relate the ultrasonic velocity to temperature but reaches the same conclusion and the methodology is therefore not brought into the review. The study furthermore focuses on predicting ultrasonic velocity from temperature. It is found that it differs 10% for the studied polymer at room temperature and pressure compared to experimental values. This is attributed to the difference in pvT properties between the material utilised in the study and the material utilised to construct the pvT diagram.

Praher et al. (2014); Praher et al. (2013) have designed a fan-shaped array of ultrasonic transducers to estimate the 2D distribution of melt temperature over the diameter of the ante-chamber in front of the nozzle. The ring consists of a single transmitter and five ultrasound receivers. Simulation shows that it is possible to measure a temperature distribution that is in alignment with previous literature measured off-line (Amano & Utsugi, 1989). The simulated result shows the melt is hottest at the centre and coldest near the wall. They further investigate the error created by a wrong pressure measurement and a wrong measured time of flight for the ultrasonic pulse. They conclude that an erroneous pressure measurement will shift the whole temperature distribution up or
down. This should not be an issue due to the precision of the pressure sensors utilised in the industry.

Straka et al. (2015) successfully utilized the method to estimate temperature in the screw chamber and positions along the barrel of the injection moulding machine as the machine prepares the next volume of melt for injection. The study does not compare the results to other methods or simulations.

Straka et al. (2017) compared an ultrasonic temperature measurement in the antechamber with an IR camera mounted in front of the nozzle in-line, on an injection moulding machine, for different machine settings. Generally, the melt temperature is not constant, due to the different residence times in different locations in the antechamber. The material closest to the nozzle is identified as the hottest, whereas the material closest to the screw tip is the coldest. The experiments show a good agreement between the two measurement methods. The temperature distribution further shows good agreement with a previous study (Amano & Utsugi, 1989).

Zhao et al. (2021) compared the temperature measurement from an ultrasonic transducer, with an IR sensor and thermocouple. The method is similar to the one described above. The main difference is the assumption that the reference pressure and the actual measured pressure are taken at the same temperature. The error between the IR measurement and the proposed ultrasonic measurement is maximum 5.5% for the two materials tested which were LDPE and PVC.

The ultrasonic sensor utilized to measure temperature has, like the IR sensor, a drawback as calibration to the material used is necessary. The size of the ultrasonic sensor is small in comparison with the IR-Sensor. Furthermore, it measures the average melt temperature through the whole thickness. Lastly, an IR sensor is approximately 14 times more expensive than the ultrasonic sensor (Zhao et al., 2021).

4. In-line pvT Measurement Methodologies

The equation of state relates the states of e.g. pressure, temperature, and volume. A popular method within plastics is to use pvT diagrams where "p" is the pressure, "v" is the specific volume and "T" is the temperature. The empirical Tait equation of state has proven successful in describing the pvT relationship for a wide variety of polymers in the glassy and melt states (Speranza et al., 2011; Yi & Zoller, 1993). For amorphous materials, it is generally chosen to use the two-domain Tait model due to the transition at the glass transition temperature. The two domain Tait equation is given in Eq. (18)

$$v(T, p) = v_0(T) \left( 1 - C \ln \left( 1 + \frac{p}{B(T)} \right) \right) + v_1(T, p)$$

(18)

Where v is the specific volume, T the temperature, p the pressure, $v_0(T)$ is the specific pressure at zero gauge pressure, $B(T)$ represents the pressure sensitivity of the material and C is a universal constant set to 0.0894. The thermodynamic properties of polymers change at the transition between solid and melt state requiring two temperature domains of the pvT model. The two-domains are given in Eq. (19) and (20).

For $T < b_5 + b_6p$
\[ v_0(T) = b_{1s} + b_{2s}(T - b_5) \]
\[ B(T) = b_{3s}e^{-b_0(T-b_5)} \]
\[ v_1(T,p) = b_7e^{b_6(T-b_5)-b_6p} \]

(19)

For \( T \geq b_5 + b_6p \)

\[ v_0(T) = b_{1m} + b_{2m}(T - b_5) \]
\[ B(T) = b_{3m}e^{-b_{1m}(T-b_5)} \]
\[ v_1(T,p) = 0 \]

(20)

Where \( b_5 \) is the volumetric transition temperature at zero gauge pressure, \( b_6 \) is the linear increase in transition from one domain to the other with pressure and \( b_7, b_8, b_{1x} - b_{4x} \) where \( x = \{s, m\} \) are constants. The constants are experimentally determined. The manufacturers of simulation software have databases containing these values for a range of materials. The benefit of being able to estimate the pvT diagram in-line is that the specific values for the materials may not be known due to e.g. regrind, mixtures of materials or addition of masterbatch. A typical pvT diagram for an amorphous and a semi-crystalline material can be seen in figure 5 and 6. An amorphous material changes from solid to viscous state whenever the material temperature rises above the glass transition temperature \( T_g \). For a semi-crystalline material, two distinct temperatures exist, namely the glass transition temperature \( T_g \) and the melting temperature \( T_m \). The semi-crystalline materials are generally brittle below \( T_g \) due to the amorphous part of the structure being solid. The semi-crystalline material is ductile above \( T_g \) and well below \( T_m \). When the temperature rises above \( T_m \) the crystalline phase turns into an amorphous phase.

Figure 5. pvT diagram of the amorphous material acrylonitrile butadiene styrene (ABS).
Laboratory equipment has been developed to measure pvT properties off-line through e.g. the piston die technique and the confining fluid technique (Suárez et al., 2015; Wang, 2012b).

The estimation of the pvT diagram and parameters in-line will now be reviewed. As the melt is molten in the injection moulding machine, only parameters related to the molten state (Eq. (20)) can be estimated.

The patent by Nunn (1989) describes the use of the injection barrel as a pressure chamber when the nozzle is blocked. By pressurising the melt and measuring the screw movement it is possible to calculate the volume. Afterward the material is purged and weighed on a scale. Varying the pressure and the temperature makes it possible to plot them as a function of specific volume. Regression techniques can be used to estimate the constant parameters as a different equation of state is utilized given in Eq. (21).

\[
(p + \pi)(v - \beta) = RT
\]  

(21)

\(p\) being the melt pressure, \(\pi\) a material constant, \(v\) melt specific volume, \(\beta\) a material constant, \(R\) the universal gas constant and \(T\) the melt temperature. The precision of the method is limited according to Wang (2012a).

Chiu et al. (1995) described a similar procedure, utilising the one-domain Tait equation of state. The barrel is also used as a pressure chamber in this case. The one-domain Tait equation takes the form:

\[
v(p, T) = v(0, T) \left( 1 - C \ln \left( 1 + \frac{p}{B(T)} \right) \right)
\]  

(22)

\[
v(0, T) = v_0 e^{v_1 T}
\]  

(23)

\[
B(T) = B_0 e^{-B_1 T}
\]  

(24)

Where \(B_0\), \(B_1\), \(v_0\) and \(v_1\) is coefficients, \(C = 0.0894\). The model is reduced to only four coefficients compared to the model described in equation (18). The specific volume at
zero pressure is first measured by purging the material in the barrel. The specific volume at zero pressure can be calculated by weighing the purged shot by:

$$v(0, T) = \frac{X_cA_b}{M_s}$$

(25)

Where $X_c$ is the barrel displacement, $A_b$ is the cross-sectional area of the barrel and $M_s$ is the weight of the sample. From this, it is possible to calculate the full mass of material in front of the screw as there will be some excess material that will not be pushed out due to e.g. the nozzle design as:

$$M_T = \frac{V_T}{v(0, T)}$$

(26)

Where $V_T$ is the full volume in front of the screw and $M_T$ is the total mass of material in front of the screw. To gain data on the material under pressure, a similar approach to the one above is stated. The nozzle is sealed off and experiments by varying pressure on the screw and melt temperature are conducted. The relation between specific volume for the distinct data points is given by Eq. 27.

$$V(P, T) = \frac{V_T - X_cA_b}{M_T}$$

(27)

From this, it is possible to estimate the coefficients $B_0$, $B_1$, $v_0$ and $v_1$ from regression. The results presented in the paper show a good correlation with data obtained with standard lab equipment.

5. In-line Melt Density Measurement Methodologies

The relation between density and specific volume is that the specific volume is the reciprocal of the density. Determining the specific volume in-line will make the determination of pvT diagrams automatic, as described in section 4. Laboratory equipment exists to measure melt density off-line e.g. Density-Gradient-Column (Piché, 1984). This section will therefore focus on the described methods for measuring the material melt density in-line. Kariminejad et al. (2021); Xu et al. (2011) described the use of an ultrasonic sensor to measure melt density.

Kariminejad et al. (2021) described how this can be achieved due to ultrasonic impedance is related through Eq. (28).

$$Z = \rho c$$

(28)

Where $Z$ is the ultrasonic impedance, $\rho$ is the melt density and $c$ is the speed of the ultrasonic wave in the measured material. The speed $c$ can be calculated as in Eq. (15).

The ultrasonic impedance can be measured based on the difference in amplitude between a reference medium and the medium of interest according to Puttmer et al. (2000); Wang et al. (1997) by calculating the reflection coefficient $R$ given in Eq. (29).

$$R = -\frac{A_{\text{meas}}}{A_{\text{ref}}} k$$

(29)
\( A_{\text{meas}} \) being the amplitude of the unknown material, \( A_{\text{ref}} \) being the amplitude measurement of a known material and \( k \) being a calibration factor for the sensor. The impedance of the unknown material can then be calculated by Eq. (30).

\[
Z = \rho_{\text{ref}} V_{\text{ref}} \frac{1 + R}{1 - R}
\]  

(30)

Where \( \rho_{\text{ref}} \) is the density of a known material and \( V_{\text{ref}} \) is the velocity of the ultrasonic pulse in the known material. It can be calculated similar to equation (15). Combining equation (28) – (30) it is possible to calculate the density of the unknown material.

The method is described concerning injection moulding in Kariminejad et al. (2021); Praher et al. (2019) however, no results are presented by the author. No results have been found utilising the method in-line on an injection moulding machine. Instead, results found for extrusion are reported. Abu-Zahra (2004a); Abu-Zahra (2004b) compare results of melt density obtained in-line with solidified samples cut out and measured in the laboratory with a \( R^2 = 0.96 \) and a \( R^2 = 0.91 \) respectively. Kažys and Rekuvienė (2011) describe a similar procedure also for an extrusion process where the melt density measured in-line and in the laboratory has an \( R^2 = 0.96 \).

6. Current and Future Research Topics

Injection moulding is a complex process influenced by multiple parameters as described in the introduction. Any variation in these parameters results in variations in the produced elements. The process and material properties described in this paper, are still not widely utilised in the industry. In general, for technology to be attractive to implement in a production, the product needs to yield either savings, quality, or productivity benefit. It further requires a minimal set-up time and little to no specialist knowledge. The accomplishment of any of these statements is not evident from the papers reviewed. The results are mainly based on experiments, set up for the specific test, and not tested in general production. Future research within the area is needed to make the methodologies applicable. The robustness of the methodologies needs to be tested, a possibility is to perform a measurement system analysis. This will make it possible to compare the different methodologies, from key performance indicators such as precision and repeatability including the variance of these.

A common difficulty in all the described in-line methods is the repetitive nature of the moulding process. The aim of zero variation from the machine vendors, makes little to no variation in the data-points measured for each mould. This is common for viscosity, pvT and melt density. Research enabling different parts of the process to gain additional data-points, will make it possible to create e.g. regression models. Yet another approach to update the model parameters could be to implement stochastic observers, e.g. Kalman filters. The model enables the possibility to include the monitored parameters in closed-loop control to adjust e.g. machine settings. The adaption of full models instead of single working points will enrich the data, besides control purposes it may be used for e.g. material inspection and simulation, as described in the introduction.

A generic measurement method should ideally not need calibration dependent on grade, vendor etc., as the whole purpose of measuring the process and material properties in-line is that previous testing and knowledge about the material is less important. This is a difficulty when utilising e.g. melt temperature measurement due to the necessity of a precise pvT
diagram of the material. If this needs to be obtained beforehand the method is limited in its use. The possibility to combine the different measurement methods for the different properties could potentially make calibration obsolete or less intensive.

7. **Summary: In-line Process and Material Property Measurement**

The research within in-line estimation of process and material properties has been ongoing since the 1990s. The focus has mainly been on viscosity and melt temperature measurement, compared to inline pvT and melt density measurement. Taking the release date into consideration the focus has shifted from viscosity to the measurement of melt temperature. The measurement of both pvT and melt density has had very limited focus within injection moulding, however melt density measurement has been researched more heavily in extrusion. Each of the four identified properties will be summarised below.

7.1. **Summary: Viscosity Measurement**

The research within the field of in-line viscosity measurement is thorough and most papers further describe a correlation to e.g. part mass. Multiple different approaches exist to measure the viscosity in-line. The methods are categorised into two categories, namely apparent viscosity and a viscosity index.

The apparent viscosity aims at estimating the true viscosity relative to a shear rate. The advantage of utilising the apparent viscosity is that it is possible to compare it with e.g. laboratory measurements. The measurement is further process independent as it is related to some specific shear rate. A disadvantage is that the direct measurement of the melt pressure requires additional investment in sensors adding cost. The added sensor often also requires a large reservoir in front of the screw, which is undesired. The possibility exists to measure at several shear rates, and the measurement does not require a specific injection profile but rather knowledge about plastic flow.

The viscosity index compares against a baseline and can be based on multiple different parameters, but research is mainly focusing on the use of hydraulic pressure as it does not require the installation of additional sensors and thereby does not introduce additional cost and volume in front of the screw. The disadvantage is that the indexes are not necessarily comparable to one another. Moulds, machine, process and material all influence the baseline. The described process needs to be speed controlled in some part of the cycle, as the resulting pressure is used for the viscosity index. A pressure controlled process would therefore give the same viscosity index due to the controlled pressure.

Both approaches contain advantages and disadvantages and the desired method needs to be chosen case by case. If the objective is to use a cost-effective solution, where comparison between e.g. moulds is not necessary the viscosity index is the best solution. If the objective is to compare viscosity of the material between machines, moulds etc. or create e.g. simulations and digital twins, the apparent viscosity measurement is the best solution.

7.2. **Summary: Melt Temperature Measurement**

Measurement of melt temperature is complicated due to the temperature gradient through the material and the interaction between melt and mould interface. Non-flush
mounted sensors disturb the flow and are therefore undesired from a processing perspective. Three flush mounted methods of melt temperature measurement are reviewed, namely, the IR sensor, the thermocouple, and ultrasonic temperature measurement.

The IR sensor measures the true melt temperature over a distance into the melt, if it is calibrated adequately. The first-order response time of the IR sensor is in the range of 10 ms. The calibration is specific to the material and needs redoing whenever the material is changed. The dimensions and relatively high cost compared to both thermocouples and ultrasonic sensors make it infeasible to install in the nozzle of the injection moulding machine in most cases. The IR sensor is especially relevant as a baseline when a measurement system is tested.

A thermocouple is a low-cost sensor, with a first-order response time of approximately 0.2 s. The disadvantage is that it is in contact with the mounting material, and the temperature measured is an interface temperature. This temperature is then utilized in a heat conduction model, however both precision and accuracy are poor. The price point, size, and general popularity make them attractive and they are widely utilized meaning research within this field could be beneficial for later use in production environments.

Ultrasonic temperature measurement measures the average temperature through the whole depth of the melt, as the ultrasonic pulse is transmitted from the sensor and reflected in the interface between materials. The advantages are the size of the sensor, low cost, and the possibility to measure a true average temperature comparable with the manual pyrometer measurement.

All three melt temperature measurement methods require material knowledge and calibration. The very poor precision and accuracy of the thermocouple, makes them infeasible for melt temperature measurement, but they could potentially be used for stability analysis. The comparison between IR sensor and ultrasonic sensor is therefore a trade off between sourcing price and the calibration task. Another thing to consider is the physical dimensions of each sensor type, where limited size is a requirement, as ultrasonic sensors are smaller compared to IR Sensors.

7.3. Summary: pvT Measurement

No recent studies have been found on estimating pvT diagrams in-line on the moulding machine, even though pvT diagrams are used to measure melt temperature as described in section 3. It is further used for pvT optimisation control in several papers (Hopmann & Reßmann, 2014; Hopmann et al., 2015; Reiter et al., 2014; Sheth & Nunn, 1997). The difficulty exists in using the technique in running production due to the necessity of weighing the purged shot and varying both pressure and temperature. The methods described utilise only a one-domain Tait equation, as the in-line measurement is only on melted plastics. Due to the shortcomings of melt density measurement and the difficult to vary temperature, there needs to be future research within this topic in order to measure pvT diagrams in-line for use in a production environment.

7.4. Summary: Melt Density Measurement

Methods are described in the literature to determine melt density; however, none of the stated methods is utilised in-line in injection moulding. A study is presented with data from an extrusion process showing promising results. Before it is possible to assess the
method within injection moulding, it is necessary to run experiments verifying the theoretical results. It is noted that the melt density or specific volume will be pressure and temperature-dependent as described in section 4.

8. Conclusion

Injection moulding machines are generally repeating a static set of settings independent of the material feedstock. A cascaded control loop structure can be utilized to take variation from e.g. material into account. This review has focused on the research conducted to measure important process and material parameters in-line for use in process control, material control, and in simulations.

A large part of the research within in-line measurement has been focused on viscosity, where both special nozzles, sensors, and viscosity indexes have been developed to characterize the feedstock material.

Measurement of the process parameter melt temperature is of great importance, as it alters the states of the moulding process. The measurement is, however, non-trivial. The use of thermocouples is desired due to price and size, but the precision is very poor due to heat conduction from the material it is mounted in. Both IR sensors and ultrasonic sensors require calibration to the specific material measured, but will measure the actual melt temperature if calibrated. Research to enable in-line calibration will increase the market for such technology.

The equation of state describing the pvT behaviour of the plastic is defining the dimensions of the produced element depending on the states of e.g. pressure and cooling rate in the cavity. Attempts to measure this in-line have been proposed, but the process is not matured to a level where it is fully automatic. This limits its use in running production.

The measurement of melt density in-line is the area that had the least amount of research papers and no literature describing experiments on an injection moulding machine has been found to validate the theory. Instead, in-line measurement of an extrusion process is considered with promising results.

A general difficulty in obtaining the material parameters in-line is the need for calibration and the lack of variability in the repeatable process, meaning the working point will often be constant. Future research should therefore focus on; minimising the need for calibration, and utilize the different parts of the process to add variability into the gained data for regression modelling or implement stochastic observers. This will increase the use of the parameters in closed loop controlled systems, to enable control of desired states.

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Data availability

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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