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Dynamic Temperature and Pressure Measurement in Polymer Processing

The use of a fast responding infrared thermometer enables to measure the mass temperature across the screw channel and the resultant profile over the screw length during the plasticizing process. With a response time of 10 milliseconds this IR-Thermometer is more than 1000 times faster than conventional thermometers. Furthermore, the use of fiber-optical pressure sensors allows the measurement of the pressure profile in the feeding across the screw channel without being destroyed. Thus, the possibility is generated to measure the solid bed width in this section. Hence, the melting behaviour can be analysed.

Dynamische Temperatur- und Druckmessung in der Kunststoffverarbeitung

Die Verwendung eines schnell ansprechenden Infrarotthermometers ermöglicht die Messung von Temperaturprofilen quer zum Kanal und des Temperaturprofil über der Schneckenlänge im stationären Betrieb. Mit einer Ansprechzeit von 10 Millisekunden ist das Thermometer ungefähr 1000mal schneller als konventionelle Thermometer. Darüber hinaus erlaubt die Verwendung faseroptischer Drucksensoren die Messung von Druckprofilen quer zum Kanal im Bereich der Einzug- und Aufschmelzzone. Hier besteht nicht mehr die Gefahr der Zerstörung der Membran durch Granulatkörner, wie bei herkömmlichen DMS-Drucksensoren, da die Membran ungefähr 10 mal so dick ist. Somit wird die Möglichkeit gegeben, die Feststoffbettbreite in diesem Bereich zu ermitteln, wodurch das Aufschmelzverhalten analysiert werden kann.

Dynamic Temperature and Pressure Measurement in Polymer Processing

K. Anger, H. Potente, V. Schöppner, E. Enns, E. Giese

1 INTRODUCTION

To achieve a constant product quality during the extrusion and injection moulding process, it is of utmost importance to keep a certain mass temperature inside the screw channel and over the screw length. Local temperature peaks have to be avoided as they can lead to thermal degradation of the material. To design a plasticizing unit for a particular application, the theoretical modelling of temperature profiles over the screw length is important. The real temperature profiles are required for validating these theoretical models.

Until now the measurement of temperature profiles inside the screw channel has been very complicated due to of the slow-going response time of thermometers. The application of a fast responding infrared thermometer makes it possible to measure the temperature of these profiles during the plasticizing process. With its response time of 10 milliseconds this IR-Thermometer is more than 1000 times faster than conventional thermometers. Therefore, it can be classified as a dynamic temperature measurement. Analyses of first measurement results show that the temperature profiles inside the channel and at the channel bar could be measured. The thermometer and first practical results are presented in this paper.

2 THEORETICAL MODEL OF CONTIGUOUS MELTING

The melting behaviour is one of the central tasks of a plasticizing extruder that is why screws are classified according to their capacity of melting solid material [1]. It affects the throughput of the extruder and the quality of the melt. Thus, the knowledge of the melting profile is essential for designing specialized screws. For the evaluation and calculation of the melting behaviour, the radial temperature profile inside the screw channel has to be evaluated. From the radial temperature profile, the temperature profile over the screw length can be calculated. Without these profiles, the knowledge about the rates of the solid and melting fraction is unknown. The temperature profile across the screw channel can also be used to show the melting behaviour of the material. With the help of this temperature profile the location of the solid bed and the melt pool can be observed accurately. Due to in the area of the solid bed the temperature is lower than within the melt pool area.

The Tadmor model was the first theoretical analysis of the melting process [1]. Subsequent visual qualitative analyses of the melting process have led to the known melting models of Lindt, Klenk and Maddock. To a large extent, the Maddock model become accepted for melts that do not slip at the wall [2], shown in Figure 1.

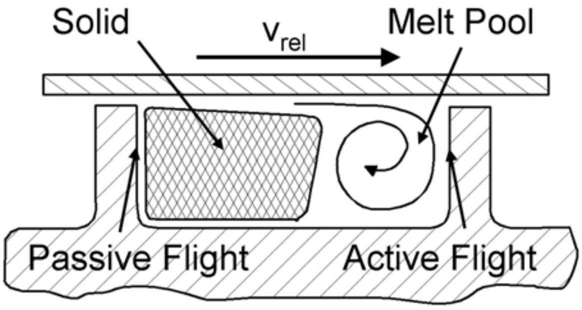

Figure 1: Melting model based on Maddock

Because of using wall adhering material, the Maddock Model is used for all further considerations. While processing wall adhering plastics according to the Maddock model, the generated melt film is transported into the melt pool. This is because of the motion of the screw. For materials that adhere at the wall, the solid bed is in front of the passive flight and the melt pool develops in front of the active flight. The solid bed and the generated, increasing melt pool are transported into conveying direction. The melt film along the axis of the barrel is generated through thermal conduction from the heated cylinder into the resin. The relative speed between the screw and the cylinder is called v_{rel}.

3 SOME PREVIOUS EXPERIMENTAL INVESTIGATIONS

In the past it was already possible to measure the pressure profile across the channel. Some investigations about the measurements of pressure profiles across the screw channel were made by [3], [4], [5], [6] and [12]. It was shown that the peak of the pressure profile is in front of the active flight and decreases over the flight. Then the minimum pressure is at the passive flight. Inside the screw channel the pressure level increases continuously from the passive to the active flight. These characteristics are shown in Figure 2.

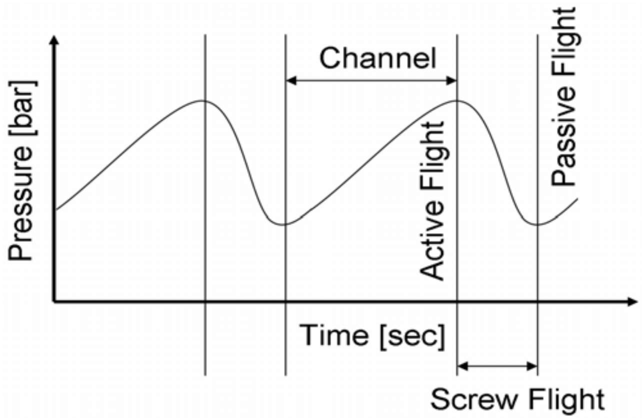

Figure 2: Melting model based on Maddock

Now, with the use of the described infrared thermometer it is also possible to measure the corresponding temperature profile across the screw channel. In the past some inquiries were already made with infrared temperature measurement [8] and [9].

4 SPECIFICATION OF THE INRARED THERMOMETER

Even the best standard melt thermometers (thermocouples or platinum resistor thermometers) have response times of 10 to 30 seconds. Thus, they will not be able to detect thermal inhomogeneities across the screw channel within the melt while plasticizing the resin inside the extruder. The temperature readout from these thermometers is just the average of the local temperature of the melt giving no information about the local dynamic temperature effects. For this kind of investigations FOS Messtechnik GmbH in cooperation with the Institut für Kunststofftechnik at the University of Paderborn has developed a special IR-melt-thermometer with an axial shiftable measuring tip. The front end of the thermometer can be seen in Figure 3.

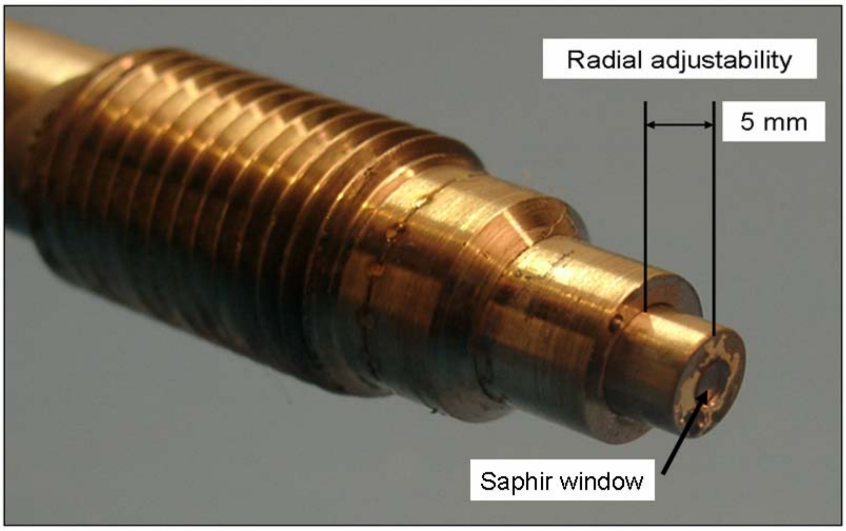

Figure 3: The front end of the infrared thermometer with radial adjustment of the sensor to measure also a radial temperature profile in the channel

It is a standard size melt-thermometer with ½ inch-20 thread, 45° cone sealing and a front diameter of Ø7.80 mm. In the centre of the measuring tip a small sapphire window can be seen. The infrared radiation of the melt passes this window and is transmitted to an infrared detector with a response time of about 10 milliseconds. Furthermore, there is no inertia of the thermometer because of heat conduction like for conventional thermometers. These are the reasons why this IR temperature measurement is about 1000 times faster than best conventional thermometers.

The polymer melt emits a broad band of electromagnetic radiation when being heated up. The higher the temperature the higher is the emitted infrared radiation power from the melt. The IR detector is sensitive to the power of the radiation passing the sapphire window, generating an electrical voltage signal proportional to the incoming radiation power. The sapphire of the measuring tip is very suitable for this application. It is extremely wear resistant and transmits electromagnetic radiation from visible light to the middle range of IR-radiation up to 6.5 µm wavelength. The IR thermometer can be calibrated by means of a black radiator with an emissivity of about E=0.9 on a test stand. The primary thermovoltage signal of the IR-detector is amplified, linearized and calibrated to 25mV/°C. The measuring range of the thermometer is 50°C to 400°C. The temperature radiation detected by the sensor is coming from a small cylindrical volume of polymer in front of the sapphire window with a diameter about Ø 1.5 mm and a height of 0.1 mm up to 1.0 mm depending on the material. In most cases the penetration depth of the IR-Thermometer is about 0.2 mm for polymers and it can be exactly determined by laboratory investigations using a sample of the plastics polymer being in use. Additionally, this infrared thermometer is equipped with two small tips at the front end of the probe, which are shown in Figure 4. These are small thermocouple thermometers with fast response time of about 10 seconds, which are used to give absolute temperature readings from the melt and for calibration purposes of the IR-thermometer. Furthermore, the IR-measuring tip can be shifted precisely up to 5 mm radial into the melt. This allows temperature gradient measurements in radial direction [10] and [11]. It is possible to measure the temperature profile from the barrel wall up to 5 mm down to the ground of the screw channel. This thermometer combines a variable physical penetration depth with a fast responding IR temperature measuring technique. Figure 4 shows all the measuring points being integrated into this device, whereas the output of these signals is an amplified output-signal for experimental process investigations:

- IR (1): Sapphire window for the IR-radiation input,
- Sensor-Body (2): thermocouple being used for internal compensation purposes,
- TIP(3): Thermocouple to detect the front end (surface) temperature of the tip,
- Front (4): Thermocouple to detect the internal surface temperature at the interface of the barrel and the melt and
- Sealing (5): Thermocouple to detect the temperature of the barrel in the sealing area.

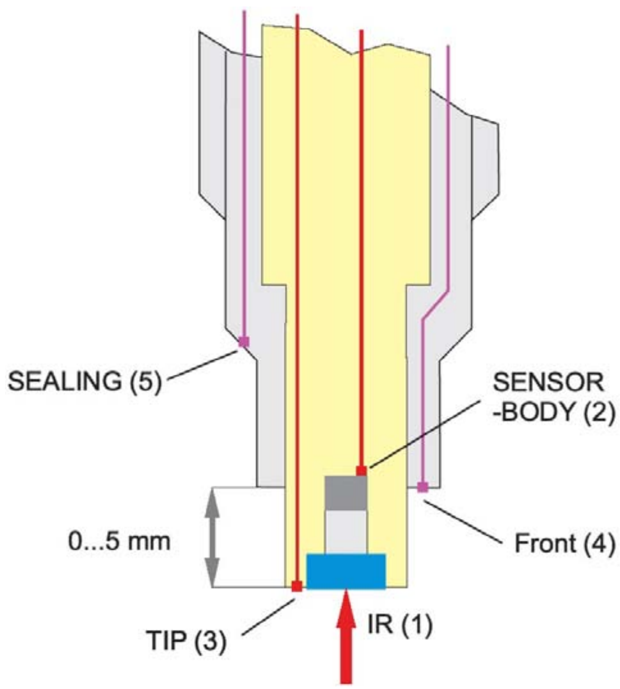

Figure 4: Measuring points being integrated in the infrared thermometer

5 SPECIFICATION OF THE FIBER OPTICAL PRESSURE SENSORS

In difference to the normally used piezo-resistive DMS-pressure sensors, the principle of the pressure sensors produced by *FOS Messtechnik GmbH* are based on a fiber-optical sensor. The measuring principle of the optical pressure sensor is shown in Figure 5. The Figure shows a section through the sensor head and its basic design.

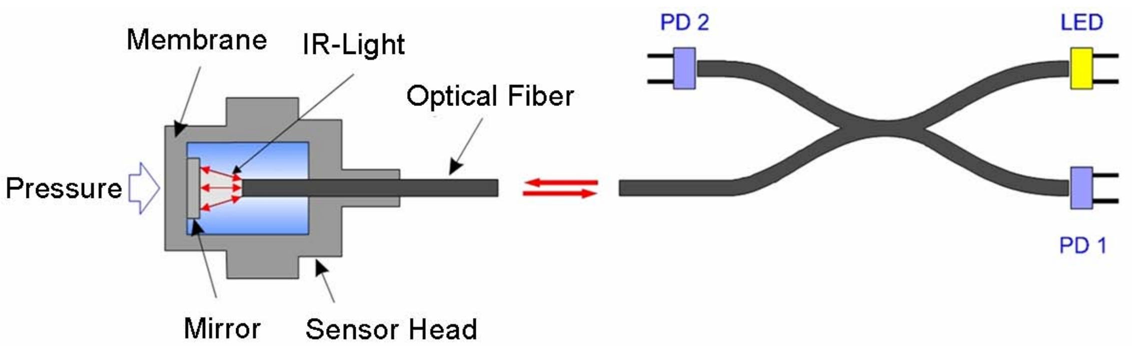

Figure 5: Measuring points being integrated in this fiber optical pressure sensor

The light of an infrared LED is coupled into an optical fiber and the power of the coupled light is exactly measured. The light reaches the detector PD2 across the X-branching point as well as to the sensor head. The detector PD2 and an electronic control circuit are responsible, that in any circumstances the illumination of the LED is kept constant.

In the sensor head it illuminates a mirror which is a platinum reflector and is based on the back of the membrane. The pressure acting on the membrane varies the distance between the mirror and the surface of the glass fibre by several micrometers under full pressure action. Depending on the mirror position, more or less light is reflected back into the same fiber and guided back to an amplifier. Thus, less illumination is reflected, when distance to the PD1 is long and much illumination is reflected, when the distance to the PD1 is small.

The measurement amplifier consists of an optoelectronic detection device. Here, the light intensity coming from the sensor head is compared with the one transmitted. This quotient is a measure of the pressure at the sensor head. The light is conveyed across the X-branching point to the detector PD1. There, the light signal is converted into an electric current.

Consequently, the measuring system is a non-contact working and high-definition faser-optical measuring system. The pressure sensor could be used until 1000°C and the membrane is nearly indestructible. The design of the sensor features an extremely stable membrane/mirror construction. As compared to the liquid-filled systems, the membrane can be ten times as thick, which has a positive effect on the wear resistance, shear-off strength and service life of the sensor. Furthermore, the response time is very fast and it can be used for high dynamic processes. The basic material of the membrane can be designed very thick and is very wear-resistant, even with abrasive materials.

6 MATERIAL PARAMETER

For the experimental measurements a Polypropylene Homopolymer HC600TF, developed by Borealis Polyolefine GmbH was used. It is designed for In-Line and Off-Line thermoforming, for housewares and thin wall packaging, margarine tubes and to generate copolymers. Its Melt flow rate (230 °C/2.16 kg) is 2.8 g/10min and its density is 905 kg/m^3. The melting temperature range is between 162 and 166 °C. Advantages are good process ability and melt stability.

7 REPORT OF THE EXPERIMENTAL RESULTS

A 45 mm diameter extruder with a 32 length-to-diameter ratio (L/D) was used to collect extrusion process data. This extruder had seven pressure sensors along the axis of the barrel to measure pressures along the screw. Furthermore, it had seven temperature sensors along the axis of the barrel, whereof six were thermocouples and one was an infrared thermometer. The points of measurements along the axis of the barrel are shown in Figure 6.

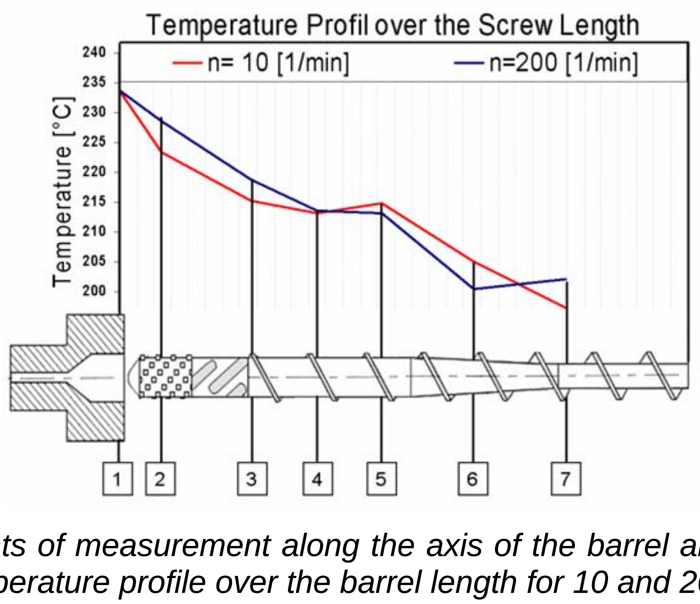

Figure 6: Points of measurement along the axis of the barrel and the adjusted temperature profile over the barrel length for 10 and 200 rpm

The extruder was equipped with six barrel temperature control zones. The measurement technique was connected to Dasylab, 16-bit data acquisition system, which allows pressure and temperature data to be collected at rates up to 100 KHz.

This report describes results from some sets of experiments conducted on a conventional screw with a shearing and mixing zone. The screw used was single-flighted and had a channel depth in the feeding section of 8.6 mm for 8.8 L/D, a transition length of 8 L/D, and a meter depth of 4.06 mm for 8.9 L/D. The adjusted temperature profiles over the barrel length for the different rotation speeds are also shown in Figure 6. The applied rotation speeds were 10, 15 and 200 rpm to measure identifiable profiles. The feeding temperature of the resin was between 20 and 25 °C. The pressure at the screw tip was for 10 rpm approximately 26 bar, for 15 rpm 32 bar and for 200 rpm 60 bar.

All further considerations concerning the melting behaviour of this material are based on the Maddock model. This is because the considered experiments to investigate the temperature profile across the screw channel were conducted with a melt that does not slip at the wall.

The pressure and temperature profiles were measured at four different points along the axis of the barrel, whereas the infrared thermometer has to be displaced to the actual measuring point. The points are shown in Figure 6 and are indicated as number three, four, six and seven. The infrared thermometer and the pressure sensor were displaced about 90° or $\pi/2$ within the radius of the barrel, shown in Figure 7.

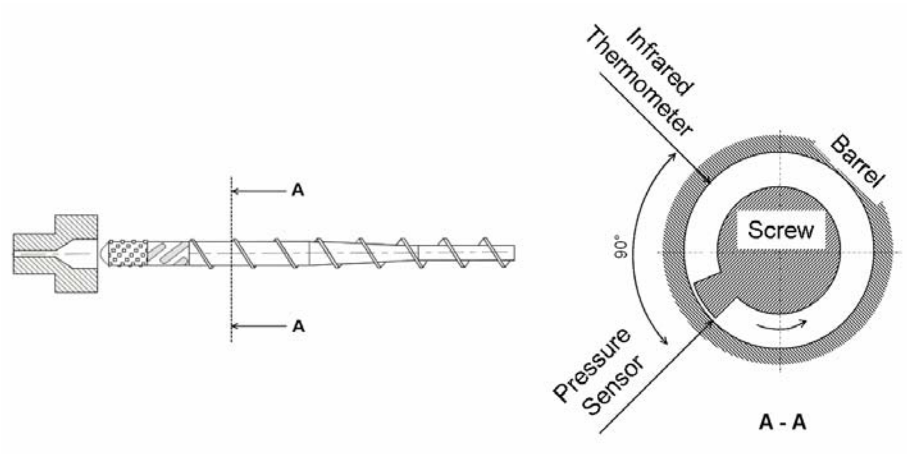

Figure 7: Positioning of the infrared thermometer and the pressure sensor

First the temperature was measured at a decided position and 90° later the pressure was detected at the same position along the screw. Therefore, the measured profiles are temporarily shifted. Not till then they could be compared and declarations could be made about their positioning across the screw channel. Hence, the obtained results are displayed for one radial position inside the cylinder. Against the rotation speed the characteristics of the temperature and pressure profiles are repeated continuously every 360° or 2π. As a result the periodical variations of the pressure and the temperature profile are measured and discussed below. The measured temperatures are interface temperatures at the barrel wall. For the evaluation of the measured values the correlation using the Fast Fourier Analyses was applied [7]. Furthermore, the measured profiles were averaged.

8 RESULTS AND DISCUSSION

For the operated rotation speeds about 10, 15 and 200 rpm, one can identify the differences in temperature and pressure profiles between the area of the screw where there is a solid bed and the area which is completely filled with melt. The pressure profile changes its slope, when the solid bed is running under the pressure sensor. In the metering section, where is no residual solid bed, the slope of the pressure profile is nearly constant. Furthermore, a bigger width of the solid bed for higher rotation speeds can be observed due to the changing slope of the pressure profile, as can be seen in *Figure 8*.

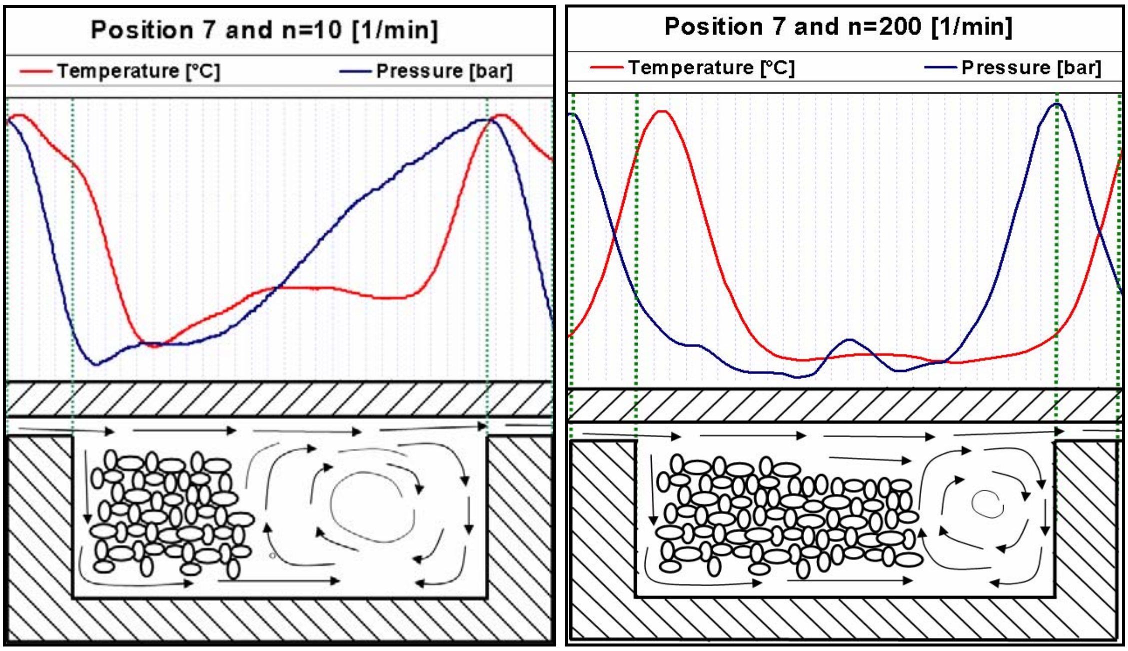

Figure 8: Solid bed width for 10 [rpm] (left) and for 200 [rpm] (right)

left: Temperature and pressure profile across the screw channel for n = 10 [rpm] at position 7

right: Temperature and pressure profile across the screw channel for n = 200 [rpm] at position 7

For high rotation speeds the pressure gradient at position 7 is also caused by the same effects than for low rotation speeds. That means the pressure profile is rising from the passive flight to a maximum at the active flight. Furthermore, the solid bed can be located clearly because of the changing slope of the pressure gradient. One can see that the solid bed width is more widen for high rotation speeds than for low rotation speeds at position 7. This is because of the residence time of the plastic inside the screw channel. In summary, the melting process of the solid bed is definitely spatiotemporal more slowly for high rotation speeds (Figure 8 / right) than for small rotation speeds (Figure 8 / left).

The temperature profile is different for high rotation speeds than for low rotation speeds. For 10 and 15 rpm the temperature profile of the melt film at the barrel also shows a minimum of the gradient at the area of the solid bed in the feeding section. This is because the melt film at the barrel is cooled in the area of solid by the heat conduction gradient from melt to solid bed and the melting polymer with a definitely lower temperature. Thus, the melt film at the barrel achieves its lowest temperature at this place.

The highest temperatures for small rotation speeds are around the active flight. The heating between the solid bed area and the active flight results from the hot melt pool. The profile decreases over the flight due to heat conduction of the cool screw flight in the feeding section. The screw flight and the cylinder are cooler than the incoming melt film. This results from the dominance of the heat conduction for low rotation speeds.

For 200 rpm the melt film is heated up over the screw flight because of the high rotation speed and the resultant high shearing rates. Thus, the temperature profile is rising over the screw flight. Differences in temperature between the maximum and the minimum are more visual for high rotation speeds. For high rotation speeds the temperature increase is about 9°C and for low rotation speeds it is about 5°C. In Figure 9 and Figure 10 the temperature and pressure profiles for 10 and 200 rpm for a definite period are shown.

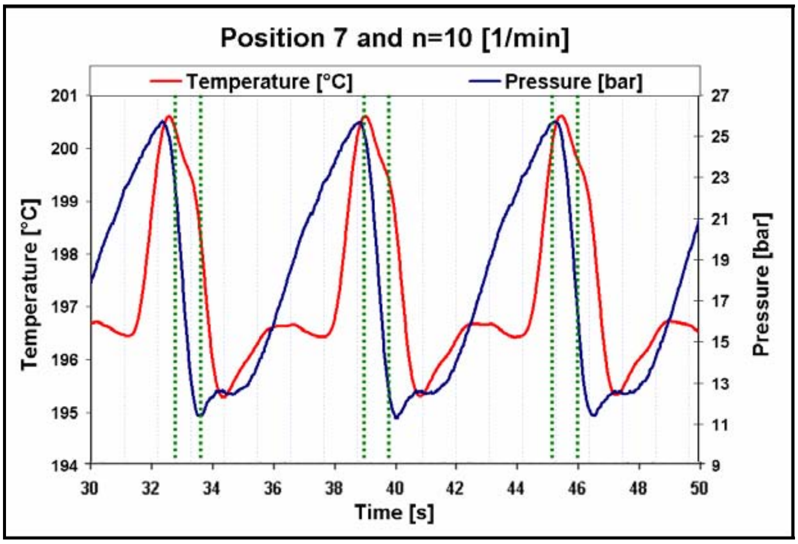

Figure 9: Temperature and pressure profile across the screw channel for n = 10 [rpm] at position 7

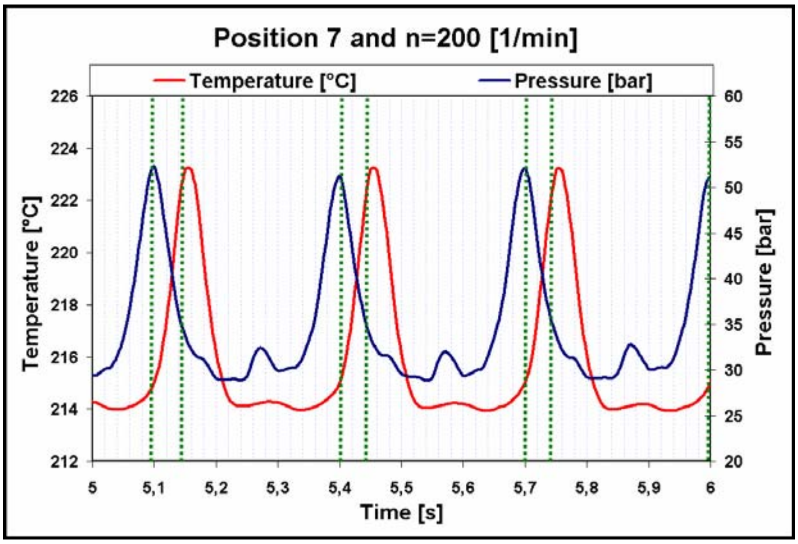

Figure 10: Temperature and pressure profile across the screw channel for n = 10 [rpm] at position 7

In Figure 11 the pressure and temperature profiles in the melt conveying section are shown.

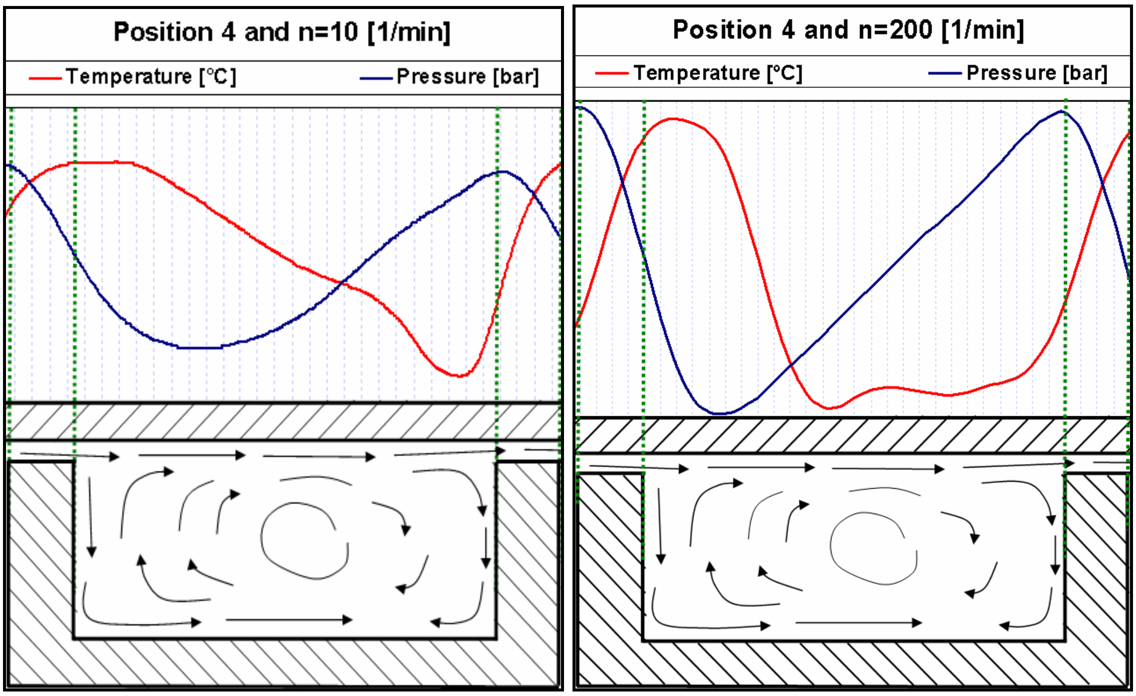

Figure 11: Process profiles width for 10 [rpm] (left) and for 200 [rpm] (right)

left: *Temperature and pressure profile across the screw channel for n = 10 [rpm] at position 4*

right: *Temperature and pressure profile across the screw channel for n = 200 [rpm] at position 4*

Of course, in the melt conveying section of the screw, where the channel is completely filled with melt, is nearly the same pressure profile characteristic for 10 and 15 rpm and for 200 rpm. In contrast to the feeding section in this section, the pressure profile has no visible changing slope justified by solid. The pressure profile is rising from a minimum slightly behind the active flight to the maximum at the active flight.

The rising pressure value inside the screw channel from the passive to the active flight is not as developed for 200 rpm than for lower rotation speeds. It is more difficult to measure clear gradients. But the fundamental behaviour of the pressure gradient is the same for high and low rotation speed. That means, the pressure profile is rising from a minimum at the passive flight to a maximum at the active flight.

Additionally, the temperature profile gradient is also nearly the same. The maximum of the temperature profile for all investigated speeds is slightly later than the maximum of the pressure profile. Thus, the maximum temperature is nearly exactly at the passive flight. Therefore, the lowest temperature is inside the screw channel. There is a precipitous increase of the temperature profile over the screw flight to a maximum near the front of the passive flight. This warming of the melt film is generated mainly by heat conduction for small rotation speeds, caused by temperature gradients between the melt film and the barrel as well as the screw flight. The warming of the melt film for 200 rpm is mostly caused by shearing effects. For high rotation speeds the temperature and pressure processes are more dynamic and faster due to the high flow speed of the melt and the fast motion of the screw. The shearing effects are always more effective than heat conduction for high rotation speeds. Therefore, the temperature differences between the maximum and the minimum are more visual for high rotation speeds. For high rotation speeds the temperature increase is about 10°C and for low rotation speeds it is about 5°C.

Then the hot melt film is mixed with the colder melt pool inside the screw channel, where it cools down to channel temperature level. Consequently, one can say that the minimum of the temperature profile characteristics is nearly identical to the average melt temperature inside the screw channel.

In Figure 12 and Figure 13 the temperature and pressure profiles for 10 and 200 rpm for a definite period are shown.

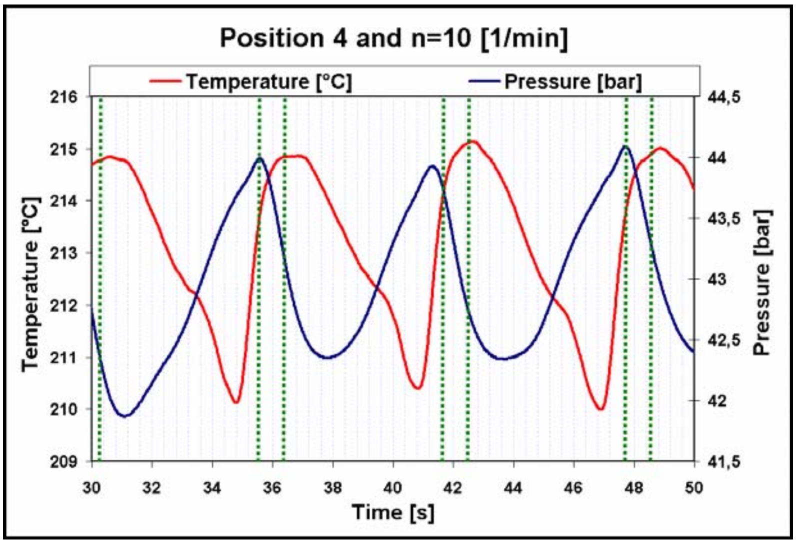

Figure 12: Temperature and pressure profile across the screw channel for n = 10 [rpm] at position 4

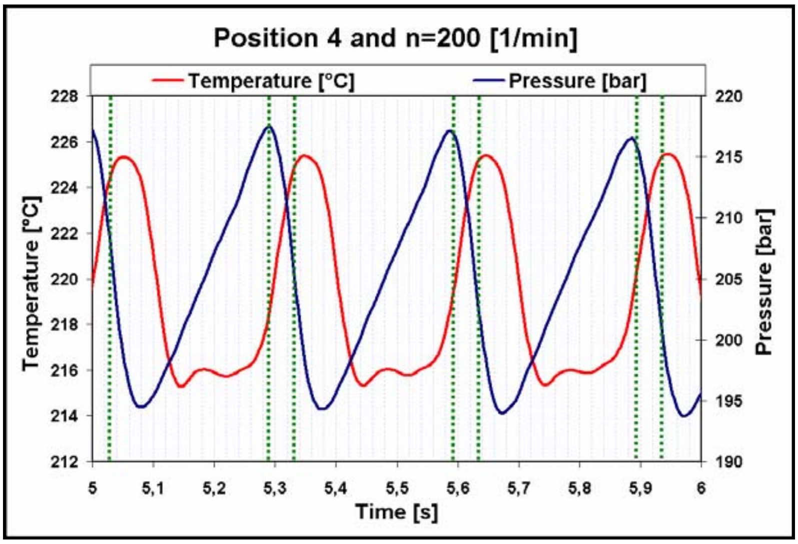

Figure 13: Temperature and pressure profile across the screw channel for n = 10 [rpm] at position 7

9 CONCLUSIONS

The use of an infrared thermometer is very helpful to measure the temperature profile across the screw channel. With thermocouples or related methods it is impossible to measure these profiles. It is very helpful to know the temperature gradient to classify the melting behaviour. Also maximal temperatures could be located and possibly eliminated. Furthermore, this infrared thermometer will be used to measure radial temperature profiles in the screw channel to support the modelling of temperature profiles along the axis of the screw.

In addition, the measurement of the pressure profile across the screw channel and over the screw length in the feeding section is possible with the fibre optical pressure sensors. Thus, the solid bed width and the resultant melting behaviour can be located. Hence, the dynamic temperature and pressure measurement is very helpful to analyse and describe the melting behaviour and temperature phenomena inside the screw channel and over the screw length.

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