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Document Version
Submitted manuscript

Link to publication record in Manchester Research Explorer

Citation for published version (APA):
Abeykoon, C., McAfee, M., Li, K., Kelly, A. L., & Brown, E. C. (2010). Monitoring the effect of operating conditions on melt temperature homogeneity in single-screw extrusion. In *host publication* (pp. 1799-1806)

Published in:
host publication

MONITORING THE EFFECT OF OPERATING CONDITIONS ON MELT TEMPERATURE HOMOGENEITY IN SINGLE-SCREW EXTRUSION

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Abstract

Delivery of a melt which is homogenous in composition and temperature is paramount for achieving high quality extruded products. However, melting stability can be difficult to determine via typical melt pressure and thermocouple instrumentation. This can result in inefficient operation through non-optimized operating conditions or extruder screw geometry. In this work, melt temperature homogeneity in a single screw extruder is investigated experimentally using a thermocouple mesh technique. The effect of barrel temperature settings and screw speed on die melt temperature homogeneity is investigated. Inferential methods of determining melting stability in-process are investigated with the aim of developing modeling and control techniques to improve process quality and efficiency.

Introduction

Melt temperature measurement provides potential information about the melting conditions inside the extruder barrel, i.e. melt flow homogeneity and poor or excessive heating. Ideally, there should be a homogeneous melt temperature profile that is, a uniform melt temperature across the melt flow. Fluctuations in melt temperature can affect melt degradation, product quality, and process efficiency (i.e., time and energy to melt the polymer and then cool the product). The bulk melt temperature and the temperature profile are strongly influenced by screw speed, screw geometry, barrel set temperatures, and material type [1-5]. For a given machine and material, optimization of process settings is paramount to achieve a high quality melt output. However, it is difficult to predict which conditions will result in optimal melt quality. Generally, producers will run at conservative rates to avoid introducing excessive temperature fluctuations, but this results in inefficient processing with sub-optimal throughput.

Conventionally, barrel wall mounted thermocouples are used to measure the melt temperature [6,7]. These measurements are dominated by the barrel metal temperature and are not capable of measuring the temperature profile across the melt. Similarly, due to slow response time these transducers are not capable of detecting rapid variations in the melt temperature [8]. However, such measurements are useful to obtain rough measures of the melt temperature.

More recently, a number of alternative temperature measurement methods have been used to monitor the melt temperature profile including a thermocouple (TC) mesh technique [1-5], fluorescent techniques [9,10], infrared (IR) sensors [8,11], and ultrasonic velocity measurements [12]. In these studies, workers attempted to measure the melt temperature profiles across the extrusion die, across screw channels, or the radial temperature profile in between screw root and barrel wall. Of these techniques, none provide all the required attributes for use in production; the TC mesh is not robust under production conditions and like the fluorescence technique is invasive; ultrasonic velocity measurements require careful calibration and provide only a bulk measurement while IR sensors can provide temperature information only at a specific point and with limited penetration into the melt.

In this study, a thermocouple mesh technique is used to observe melt temperature profile with different extruder barrel set temperatures and screw speeds. The effect of barrel set temperatures and screw speed on the melt temperature homogeneity in the die is explored. Also, the ability to detect melt temperature fluctuations through melt pressure and screw torque signals is explored.

Equipment

All measurements were carried out on a 63.5mm diameter single screw extruder (Davis Standard BC-60). A tapered compression screw with 3:1 compression ratio (Feed-4D, Compression-10D, Metering-10D) was used to process materials. The extruder was fitted with an adaptor prior to a short cylindrical die with a 12mm bore. The barrel has four separate temperature zones equipped with Davis Standard ‘Dual Therm’ controllers.

Melt temperature profiles at the die were measured using a thermocouple mesh (TC) placed inbetween the adapter and die as shown in Figure 1. The melt temperature was measured at five points across the melt flow (distances from the die centre line: 0mm, 3mm, 5mm, 8.5mm, and 15mm) by placing the TC mesh junctions along the die diameter as shown in Figure 2.

The extruder drive is a horizontal type SEDC (separately excited direct current) motor which has ratings: 460Vdc, 50.0 hp (30.5kW), at the speed 1600rpm. The motor and screw are connected through a fixed gearbox with a ratio of 13.6:1, hence gearbox efficiency is relatively constant at all speeds (~96%). Motor speed was controlled by a speed controller (MENTOR II) based on speed feedback obtained through a DC tachometer generator.

The extruder was instrumented with two high voltage probes to collect armature and field voltage data (Testoon GE8115) and two current probes were used to measure armature and field current (Fluke PR430 and PR1001). The melt pressure was recorded by a Dynisco TPT463E pressure transducer close to the screw tip. A LabVIEW software program was developed to communicate between the experimental instruments and a PC. All signals were acquired at 10kHz using a 16-bit DAQ card (National Instruments PCMCIA 6036E) through a SC-2345 connector box. Amplification was applied to the armature current, field current, and melt pressure signals. A high sampling speed was necessary as the electrical signals contain high frequencies associated with rectification of the a.c. supply.

Materials & Experimental conditions

Experimental trials were carried out on a recycled extrusion grade black HDPE, (RH), (MFI –0.16g/10min and density 0.967g/cm^3) provided by Cherry Pipes Ltd. The MFI value is presented according to the ISO 1133 standard (190°C, 2.16kg). Extruder temperature settings were fixed as described in Table. 1 and three experimental trials were carried out and named as A, B, & C.

Table. 1: Extruder barrel temperature settings

Test	Temperature settings/°C						
	Barrel Zones				Clamp Ring	Adapter	Die
	1	2	3	4			
A	130	155	170	180	180	180	180
B	140	170	185	200	200	200	200
C	150	185	200	220	220	220	220

The screw speed was adjusted from 10rpm to 90rpm in step sizes of 40rpm in tests A & C and in steps of 20rpm in test B with the extruder running for about nine minutes at each speed. Mass throughput at each speed was measured by collecting and weighing the output over two minutes.

Results & Discussion

Extruder throughput at different barrel set temperatures and screw speeds are shown in Figure 3. Extruder output rates did not change significantly with barrel temperature changes at a particular screw speed.

The measured temperature traces at each TC mesh position following each step change in speed in Tests A, B and C are illustrated in Figure 4. At low screw speeds, the step increase in screw speed results in an increase in melt temperature at all melt points due to enhanced viscous heat generation. Figure 4-b (Test B at 10rpm) is an exception to this, where there appeared to be conveying instabilities leading to melting fluctuations. At higher speeds, and depending on the barrel temperatures, the centre of the melt continues to see an increase in temperature following the screw speed increase but the melt close to the wall actually becomes colder, e.g., Figure 4-f & g. It can be seen that with lower barrel temperature settings (i.e. Test A) all areas of melt flow experience an increase in temperature. According to the widely accepted contiguous melting theory [13], the majority of melting takes place in a melt film between the solid polymer bed and the barrel wall due to conduction and viscous heat generation. As barrel set temperatures are increased heat generated from viscous and frictional mechanisms may be reduced due to the decrease in material viscosity in the melt film. Therefore, while some material is intensively heated at the barrel wall, the overall melting rate reduces. This becomes a bigger problem at high screw speeds due to a shorter residence time and hence less time for heat conduction through the material.

The minimum, maximum, and average values of the measured melt temperature at each mesh junction under quasi-steady conditions (i.e., in the 8th minute of processing) were calculated and plotted against the radial position of the die as shown in Figure 5. The previous studies of Kelly et al., [2,4] have shown that temperature profiles are symmetrical across the mesh centre line. Therefore, melt temperature profiles were calculated only for one half of the die and mirrored over the centerline to plot a symmetrical melt temperature profile. Die wall set temperatures at each test are shown in the ±19mm radial position. There is a slight difference between measured and actual melt temperature values based on mesh wire diameter due to shear heating effect [5] and only measured melt temperature values were considered in this study. Thermocouple mesh wires with very small diameter were used to minimize the effect of shear heating on measured melt temperature value.

The flatness of the melt temperature profile (i.e., the temperature homogeneity across the melt flow) reduces as screw speed increases and the magnitude of temperature variations at each junction also increases. Changes to the barrel temperatures also show a slight effect on flatness of the average melt temperature profile and to the magnitudes of temperature fluctuations. The difference between the maximum melt temperature and the die wall temperature reduced with increasing barrel and die temperature settings. For example, these differences at 50rpm are 36.0°C, 34.5°C, and 32.1°C for tests A, B, & C respectively. A similar trend can be observed at 90rpm.

The ratio of maximum and minimum melt flow temperature (T_{max}/T_{min}) at each mesh point under different test conditions are shown in Figure 6. In most cases, fluctuations increase in magnitude from the die centerline to close to the die wall. The highest melt temperature fluctuations across the melt flow can be observed at the T_{15} (±15mm) radial die position. Figure 6 clearly shows the effect of process settings on thermal homogeneity in terms of temporal fluctuations. The degree of temperature variations depends strongly on screw speed but barrel temperature settings also clearly play a significant role – particularly at high screw speed.

Although the spatial variations in temperature across the die could be improved by introducing a filter or screen pack for better mixing of the melt, fluctuations in temperature with time are a greater concern. A power spectral density (PSD) analysis was implemented on T_{15} mesh point melt temperature signals to identify typical frequencies of temperature fluctuations. The Welch method was used with a Hamming window equal to the data length. Temperature data at the T_{15} mesh point was selected as the highest magnitude of temperature fluctuations occurred at this position. PSDs of the T_{15} melt temperature signal at 10, 50, and 90rpm in Tests A, B, & C are shown in Figure 7. The magnitude and spread of the frequency distribution increases with screw speed, and typical fluctuation periods are in the range 5-50 seconds inbetween 10-90rpm. Such low frequency variations in temperature are difficult to compensate for and will result in poor product quality.

Melt pressure and motor electrical data were collected in parallel with melt temperature measurements as described above. The estimation of screw torque from armature and field current is described in previous work [14]. It is expected that fluctuations in the melt temperature would lead to fluctuations in both pressure and torque and analysis of these signals may provide a useful indicator of melting stability. Fluctuations in both signals increased with the onset of melting fluctuations with increasing screw speed but differences between the different barrel temperature settings were more difficult to detect. To try to identify differences in fluctuations in different frequency bands an orthonormal discrete wavelet transform (DWT) analysis was implemented on the melt pressure and estimated torque signals based on Daubechies (db) method [15]. In general, DWT performs signal analysis by decomposing the signal into different frequency bands, such that the variation within each frequency band against time can be observed. For this study, a db20 method was used with 19 levels to analyze five minutes of quasi-steady data (i.e., data from 3.5 minutes after screw speed change when transients died out). Frequency bands of reconstructed orthogonal signals of ten lowest frequency levels were closely examined (4.9-9.8Hz; 2.45-4.9Hz; 1.2-2.4Hz; 0.6-1.2Hz; 0.3-0.6Hz; 0.15-0.3Hz; 0.075-0.15Hz; 0.0375-0.075Hz; 0.01875-0.0375Hz; and 0.009375-0.01875Hz). Higher frequencies were ignored as these were unlikely to be related to melting.

Frequency bands up to and including screw frequency for melt pressure signals are shown in Figure 8 at 50rpm and 90rpm for each test. The measured pressure signals which are shown in top of each plot are a filtered signal by using a 5th order Butterworth filter with 10Hz cutoff frequency. From Figure 6 it is clear that the magnitude of temperature fluctuations at 50rpm in Test A is much better than in Tests B & C. The wavelet analysis of the corresponding pressure signals (Figures 8 – a, b, & c) shows that the pressure fluctuations in the low frequency bands were much lower for Test A than in Test B and C, with B exhibiting the largest magnitude of fluctuations. At 90rpm, no temperature data was available for Test A, but fluctuations were greater in Test B than C. However, no clear differences in the magnitudes of pressure fluctuations could be observed in the different frequency bands of the corresponding pressure signals in this case (Figure 8 – d, e, & f). Wavelet analysis of the screw torque signals did not show any significant correlation with the melt temperature fluctuations and is not presented here.

Conclusions & Future Work

Analysis of experimental results show that melt temperature homogeneity across the melt flow is highly dependent upon selection of screw speed and barrel set temperatures for a given material and screw geometry. An attempt was made to identify correlations between melt temperature fluctuations and melt pressure and screw torque fluctuations. From the analysis so far, it appears that the ability to differentiate between changes in melting efficiency with different barrel temperatures from these signal is limited. Therefore it is suggested that a more sensitive temperature measurement approach is required in order to detect the changes in temperature fluctuation with different barrel temperature settings. In this work, it was shown that the highest temperature fluctuations existed within 4mm from the die wall. Therefore, measurement of the melt temperature in this region with an IR temperature sensor is feasible.

Future work will concentrate on modeling the relationship between the process settings and the resulting melt temperature homogeneity, taking account of material properties and machine design. These models can be used in conjunction with an IR temperature sensor to develop a controller to tune screw speed and temperature settings on-line to maximize throughput rate while maintain temperature fluctuations within an acceptable range.

Acknowledgements

This work was supported by Engineering and Physical Sciences Research Council (EPSRC) under grant number EP/F021070/1. The authors would like to thank John Kissick, Graham Garrett, Stephen Armstrong, Dr. Xueqin Liu, and Dr. Bronagh Millar of Queens University Belfast and Ken Howell, Steve Brook, and Dr. Tim Gough from the University of Bradford, for their assistance. Also, the support provided by 'Cherry Pipes Ltd' in providing materials is greatly acknowledged.

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Key Words: Temperature Fluctuation, Thermocouple Mesh, Process Optimization and Control.

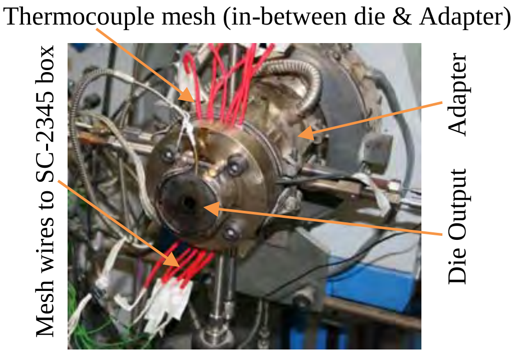


Fig. 1: Extruder die, adapter, & TC mesh

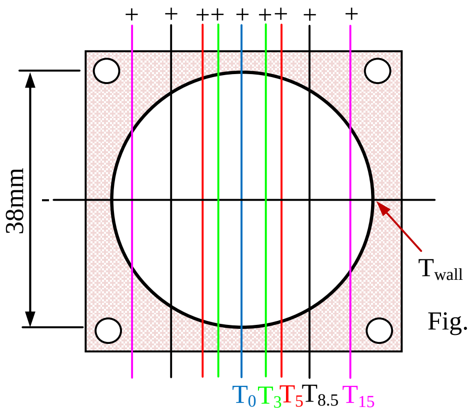


Fig. 2: TC mesh arrangement

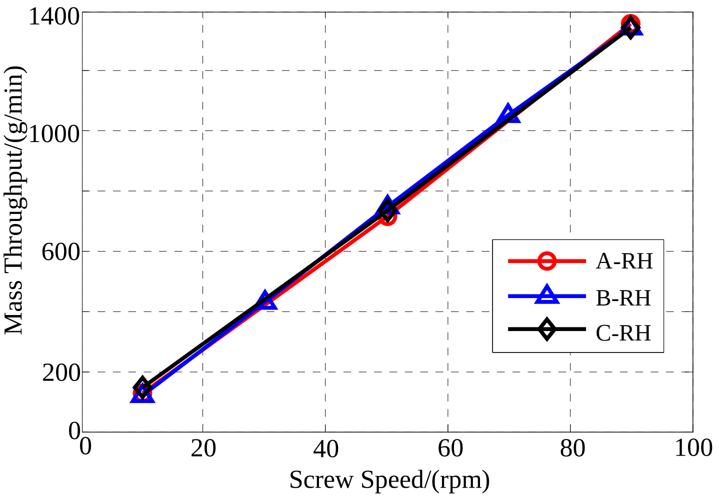


Fig. 3: Mass flow rates at each screw speed with different barrel set temperatures

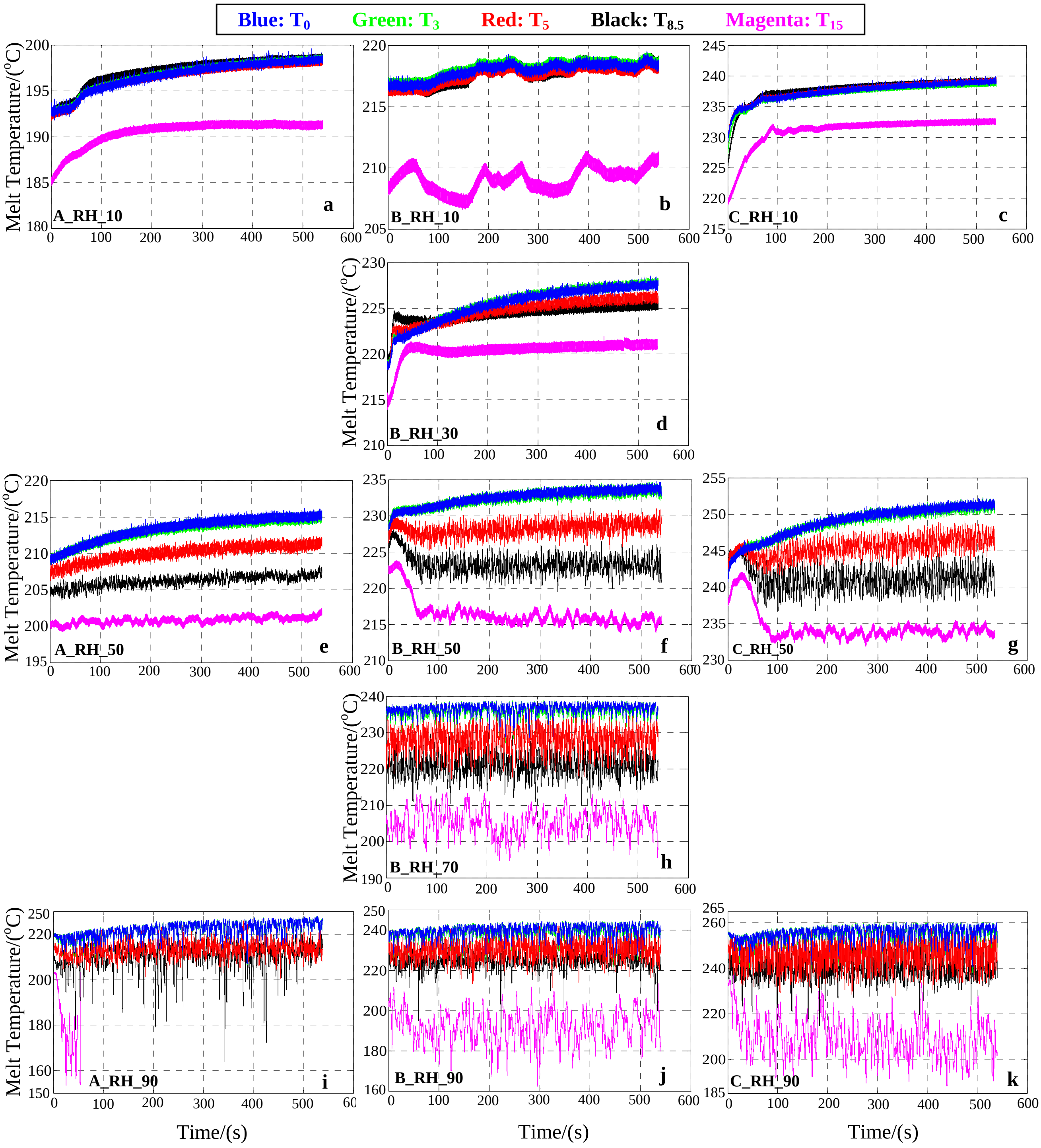


Fig. 4: Measured melt temperature traces at each mesh point at different operating conditions over nine minutes

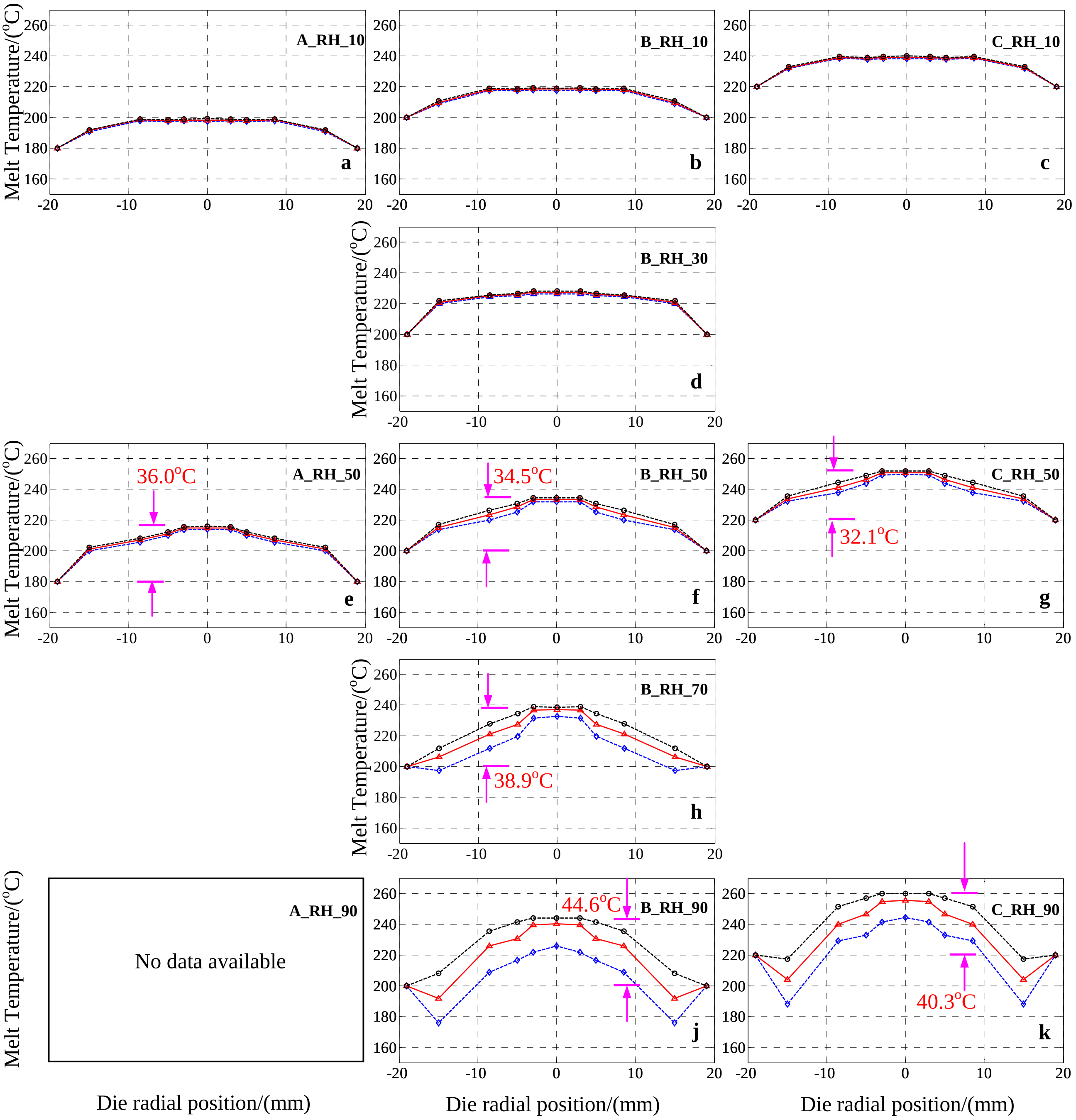


Fig. 5: Die temperature profiles with magnitudes of fluctuations at the 8th minute

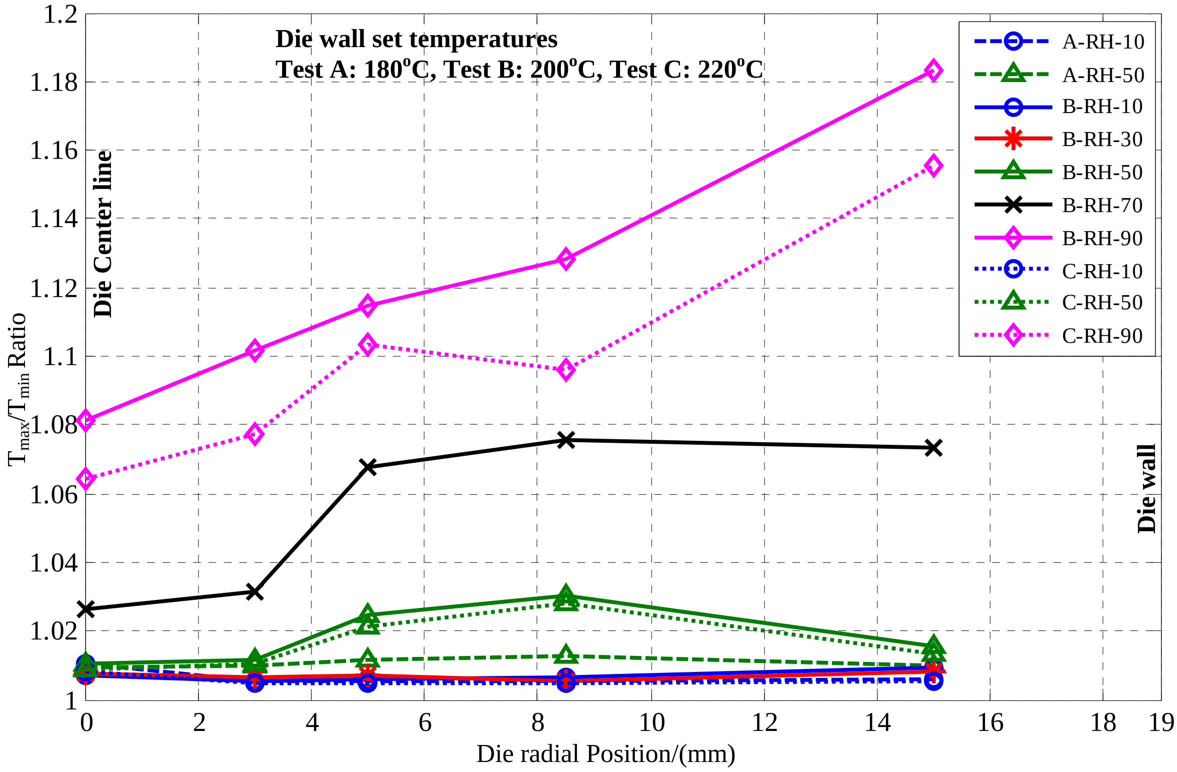


Fig. 6: T_{max}/T_{min} Ratio vs. die radial position at different screw speeds and set temperatures at the 8th minute

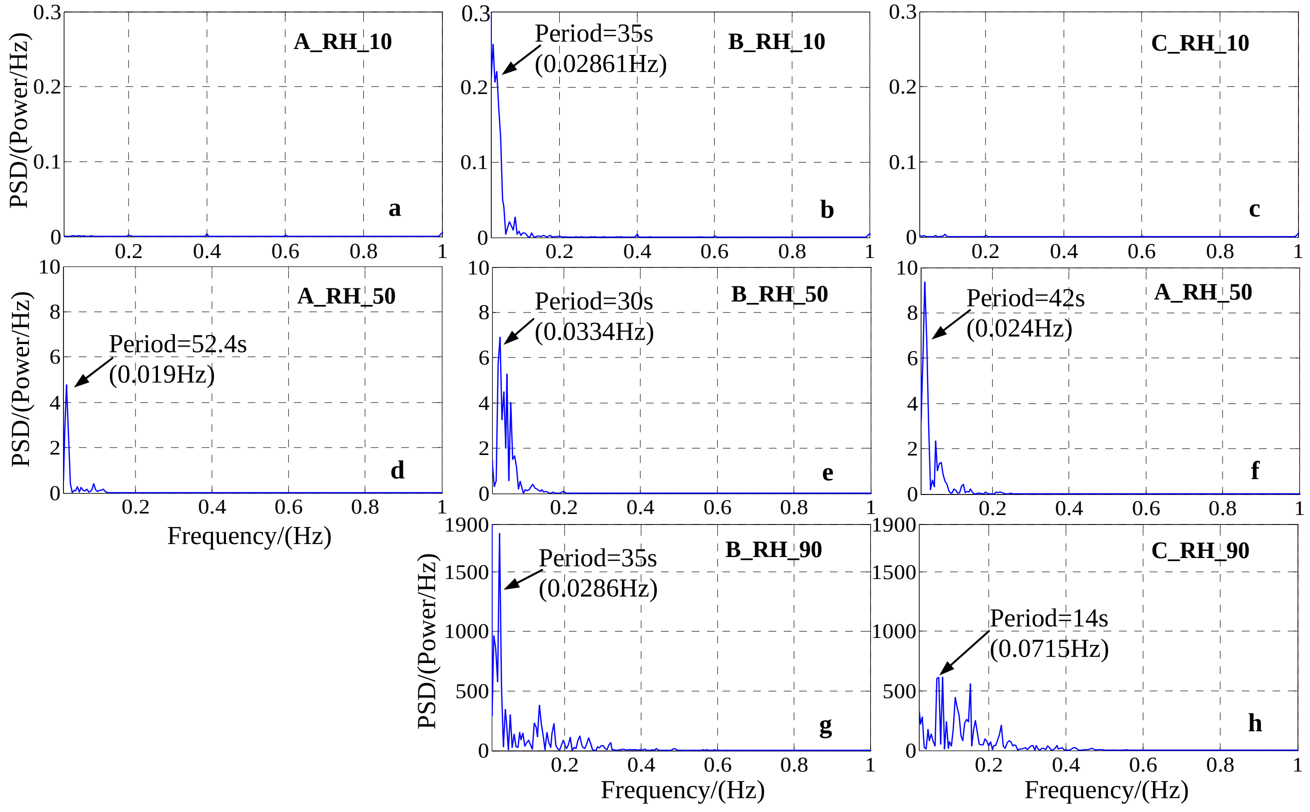
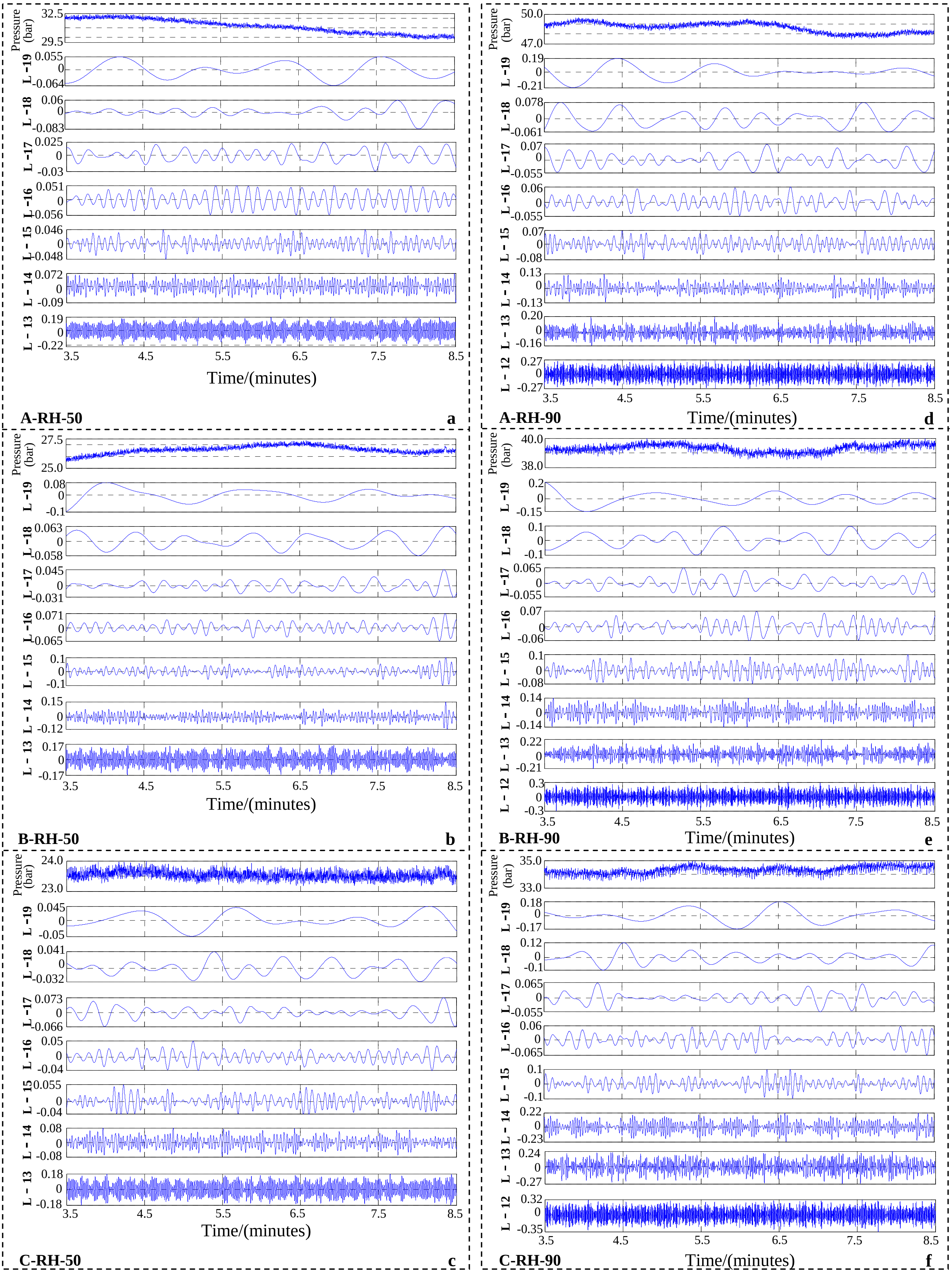


Fig. 7: Power Spectral Density spectra of T_{15} melt temperature signals at 10, 50, & 90rpm at tests A, B, & C for 5.5-8.5minutes



Levels:- **L-12**:1.2-2.4Hz, **L-13**:0.6-1.2Hz, **L-14**:0.3-0.6Hz, **L-15**:0.15-0.3Hz, **L-16**:0.075-0.15Hz, **L-17**:0.0375-0.075Hz, **L-18**:0.01875-0.0375Hz, **L-19**:0.009375-0.01875Hz.

Fig. 8: Wavelet analyze of melt pressure signals by db20 at 50 and 90 rpm