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A computer model for starve-fed single-screw extrusion of polymer blends

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Abstract
A new computer model has been developed to simulate a starve-fed single-screw extrusion process of polymer blends. This is a composite model, which is based on combining melt conveying models with new fusion models for polymer blends. The model is able to predict pressure and temperature profiles, filling of the screw and rate of polyblend fusion. Computer calculations were executed for extrusion of high-density polyethylene and polystyrene blend at various technological conditions, and fill factor, pressure, temperature, and fusion profiles were calculated. The results of simulation studies were verified by experiment.

KEYWORDS
extrusion, modeling, polymer blends

1 | INTRODUCTION

Polymer extrusion process may be performed with two feeding modes. Classical flood feeding is usually used for single-screw extrusion, while starve feeding is mainly used for twin-screw extrusion. As starve feeding usually improves mixing and melting capacities of the extruder, this way of feeding has been applied for single-screw extruders.[1–3]

Flood fed single-screw extrusion is generally well understood, and the literature is very rich here. Tadmor et al.[4–6] first developed a mathematical model of fusion of polymers in single-screw extruders, and later a composite model of the process that includes polymer solid conveying, polymer fusion and polymer melt conveying.[7–10]

Starve fed extrusion process is much less known. Experimental studies on mixing and fusion capabilities of starve fed extruders were performed, only.[1,2,11–14] These studies have been discussed by Wilczyński et al.[15] General review on modeling of polymer extrusion has been presented elsewhere.[16–19]

Wilczyński et al.[15,20,21] first developed a mathematical model of fusion of polymers in starve fed single-screw extruders, and subsequently a composite model of the process, first for conventional screws, and later for non-conventional screws.[22,23] These models were confined to extrusion of thermoplastics.

Nowadays, extrusion is relatively rarely used for processing of pure thermoplastics as much more complex polymeric systems (e.g., polymer composites, polymer blends) are widely used in industry. Modeling of extrusion of these materials is much more complicated than modeling of extrusion of pure thermoplastics.

Blending and compounding of polymers are mainly performed by co-rotating twin-screw extrusion. Many studies have been carried out on fusion and morphology evolution of polymer blends in this process.[24–30] Blending is strongly affected by fusion of blend components, and this is complicated when the viscosity and melting temperatures of components are substantially different.[27]

Studies on evolution of polymer blend morphology in single-screw extruders were much less extensive. Gosh et al.[31,32] first observed that lamellar structures are produced from fusing pellets before breaking up by capillary forces. A few models have been developed for morphology evolution in flood fed single-screw extruders.[33–35]

In this article, modeling of starve-fed single-screw extrusion of polymer blends is discussed. So far, this problem has not been presented in the literature.

The composite model, which is proposed here, results from our recent experimental studies on fusion of polymer blends in starve fed single-screw extruders.[36] It results from these studies that mechanisms of fusion of polymer blends in the flood fed extruder and starve fed extruder are fundamentally different. CSM (contiguous solid melting) mechanism of Tadmor was clearly visible in the flood fed extruder. The molten polymer blend accumulated at the screw active flight, and the solid bed was gradually reduced by the effect of heat conduction and viscous dissipation.

A different fusion mechanism was seen in the starve fed extruder, which is depicted in Figure 1. Two phases of fusion were distinguished, in the partially filled area of the screw and in the fully filled area. In the first area, the polymer blend pellets accumulated at the screw active flight and fused by conduction. The polymer blend component of lower viscosity fused first and surrounded the pellets of the second component of higher viscosity slowing its fusion. If the polymer blend was not completely molten until the screw was fully filled up, the unmolten particles of one or two components were suspended in the previously molten polymer blend, and fusion progressed through heat dissipation. Number and size of unmolten particles continuously reduced until the polymer blend was completely molten.

According to these studies, a new mechanism of fusion of polymer blends in starve fed single-screw extruders has been proposed.[36] Four different areas of extrusion process have been distinguished: solid conveying (SOLIDS) in the partially filled area and fusion by conduction (MELTING_I) in this area, as well as dispersive fusion of one or two components of polymer blend (MELTING_II) in the fully filled area and melt flow (MELT) in this area.

Our goal in this article was to develop a composite model of the starve-fed single-screw extrusion of polymer blends to predict position and extent of filling, pressure and temperature profiles, and location of fusion.

2 | MODEL

Polymer extrusion process may be treated as a serial connection of the screw channel elements where the flow rate is the same and the other thermo-mechanical parameters that define the process are constant. This way of modeling is called lumped parameter modeling.

The modeling basis is an assumption that the parameters that define the process at the onset of each element are equal to the parameters at the end of the previous element, that is,

$$\pi_{i\_\mathrm{in}}(z) = \pi_{i-1\_\mathrm{out}}(z) \tag{1}$$

where π is the parameter that defines the process, π_{i_in} is the parameter at the onset of i—element, π_{i-1_out} is the

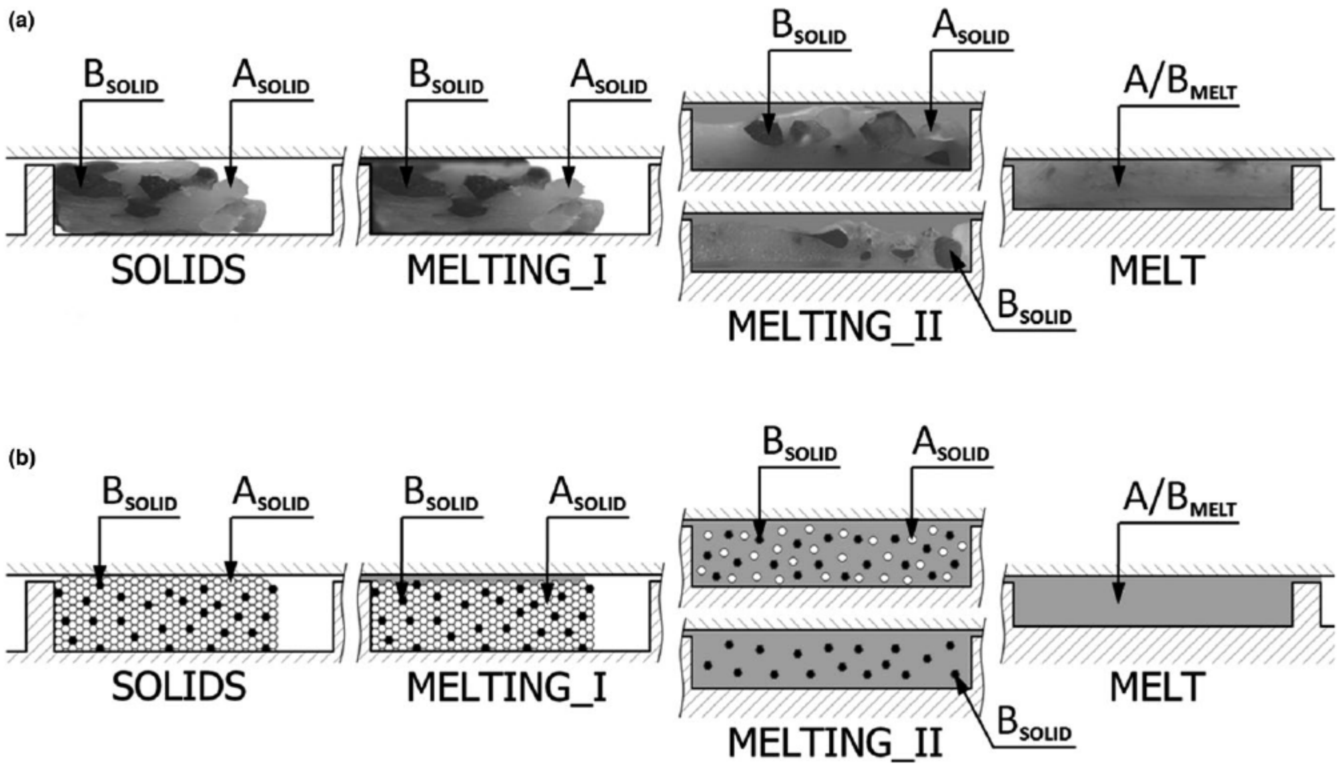

FIGURE 1 Fusion of polymer blends in case of starve-fed single-screw extrusion: (a) visualization of fusion process, (b) schematic model of fusion: A—major component of polyblend—HDPE, B—minor component of polyblend—PS, A/B—polyblend—HDPE/PS, MELTING_I—fusion occurring as a result of heat conduction, MELTING_II—fusion occurring as a result of energy dissipation[36]

parameter at the end of $(i-1)$—element, and z is the element position in the direction of the channel length.

Modeling of extrusion process of polymer blends requires the use of different algorithm of computations than modeling of extrusion of classical pure thermoplastics, and a new computation scheme is necessary.

There are two flow areas in the extrusion process with starving, area which is partially filled with material and area which is completely filled with material. In these two areas, there are two different mechanisms of material fusion and two different mathematical models for fusion are proposed.

In the unfilled area of the screw, the polymer blend is assumed to be a uniform material with some equivalent material properties, for example,

$$\pi_{mat} = \pi_{mat\_major}\Phi_{major} + \pi_{mat\_minor}\Phi_{minor} \tag{2}$$

where π_{mat} is the material parameter of the polymer blend, π_{mat_major} is the material parameter of the major component, π_{mat_minor} is the material parameter of the minor component, Φ_{major} is the volume fraction of the major component, and Φ_{minor} is the volume fraction of the minor component.

It was also assumed here that the pressure and heat of friction are not generated in this area. Thus, an energy balance may be written as

$$h_b X_b (T_b - T) = G c_{s\_blend} \frac{dT}{dz} + h_s X_s (T - T_s) \tag{3}$$

where G is the polyblend flow rate; c_{s_blend} is the specific heat of the polyblend; T is the average temperature; z is the coordinate along the length of the screw channel; h_s, h_b are the heat transfer coefficients on the surfaces of the screw and barrel; X_s, X_b are the dimensions of the solid material in contact with the screw and barrel; T_s, T_b are the temperatures of the screw and barrel.

The bulk temperature of the polyblend grows in accordance with Equation (3), and polyblend fuses after reaching the melting temperature. The energy rate that is necessary for fusion may be written as

$$q_{fusion} = G c_{s\_blend}(T_{m\_blend} - T_0) + G\lambda_{\_blend} \tag{4}$$

where q_{fusion} is the energy rate, T_{m_blend} is the polyblend melting temperature, T_0 is the initial temperature, and $\lambda_{\_blend}$ is the polyblend heat of fusion.

When the screw fully fills up with material, the polyblend fuses by energy dissipation, and the dispersed fusion model is proposed. An approach of Vergnes et al.[37] applied for co-rotating twin-screw extrusion of pure thermoplastics seems to be useful in modeling of starve-fed single-screw extrusion of polymer blends. Considering the thermo-mechanical flow field in the starve fed single-screw extruder, the polyblend flow has been analyzed as a flow of the solid/liquid mixture of two different materials, solid minor component, and liquid major component, with some equivalent material properties.

An energy balance has been made on the surface of the particle of minor component to model the fusion of minor component of polyblend. The particles of minor component have been assumed spherical of diameter D_{minor}, and fusion of the external layer of an elementary thickness $\Delta(D_{minor}/2)$ has been considered.

An energy balance on that layer may be written as

$$q_{fusion} = i\frac{\Delta V_{granule}}{\Delta t}\rho_{s\_minor}[c_{s\_minor}(T_{m\_minor} - T_0) + \lambda_{minor}] \tag{5}$$

where $q_{fusion} = \Phi_{s\_minor}\, q_{diss}$ is the power dissipated within an elementary volume used for fusion of the solid particle, q_{diss} is the total power dissipated within an elementary volume used for fusion of the solid particle and heating of the molten material, i is the number of solid particles, $\Delta V_{granule} = \pi D^2_{minor}(\Delta D_{minor}/2)$ is the volume of the layer of thickness $(\Delta D_{minor}/2)$ that is being fused in time Δt, D_{minor} is the particle diameter, and Δt is the time of fusion equal to the residence time within an elementary volume.

Number of solid particles may be calculated from their volume fraction in the flow as

$$i = \Phi_{s\_minor}\frac{WH\Delta z}{V_{granule}} \tag{6}$$

where $V_{granule} = (1/6)\pi D^3_{minor}$ is the volume of the solid particle of initial diameter D_{minor}, and Φ_{s_minor} is the minor solid particle volume fraction.

Based upon Equation (5), melting rate may be expressed by

$$\frac{\Delta D_{minor}}{\Delta t} = \frac{2q_{fusion}}{i\pi D_{minor}{}^2\rho_{s\_minor}[c_{s\_minor}(T_{m\_minor} - T_0) + \lambda_{minor}]} \tag{7}$$

And finally

$$\frac{\Delta D_{minor}}{\Delta t} = \frac{D_{minor} q_{diss}}{3WH\Delta z\rho_{s\_minor}[c_{s\_minor}(T_{m\_minor} - T_0) + \lambda_{minor}]} \tag{8}$$

where D_{minor} is the diameter of the minor component particle, ΔD_{minor} is the change of the particle diameter resulting from fusion in the time Δt, Δt is the time of fusion equal to the residence time of the particle in the computation element, q_{diss} is the energy dissipated in the unit time in the element; W (width of the screw channel), H (height of the screw channel), and Δz are dimensions of the computation element, ρ_{s_minor} is the solid density of the minor component, c_{s_minor} is the solid specific heat of the minor component, T_{m_minor} is the melting temperature of the minor component, T_0 is the initial temperature, and λ_{minor} is the heat of fusion of the minor component.

When the diameter of the particle of minor component reduces to zero, that is, $D_{\text{minor}} = 0$, or when the temperature of the minor component reaches the melting temperature, that is, $T = T_{\text{m\_minor}}$, the minor component is molten.

A temperature growth of the minor component in time Δt was calculated after[38] considering the unsteady heat transfer from the surface of the particle of diameter D_{minor} of temperature $T_{\text{m\_minor}}$ into the particle solid of temperature T_{solid}

$$\Delta T_{\text{solid}} = \frac{6(T_{\text{m\_}minor} - T_{\text{solid}})}{D_{\text{minor}}}\left[\left(\frac{\alpha\Delta t}{\pi}\right)^{1/2} - \frac{\alpha\Delta t}{D_{\text{minor}}} + 2(\alpha\Delta t)^{1/2}\sum_{i=1}^{\infty}\left[1 - \text{erf}\frac{iD_{\text{minor}}}{2(\alpha\Delta t)^{1/2}}\right]\right] \quad (9)$$

where ΔT_{solid} is the temperature growth of the solid particle of minor component in the residence time Δt, $T_{\text{m\_minor}}$ is the melting temperature of the minor component, T_{solid} is the temperature of the solid particle of minor component, D_{minor} is the diameter of the particle of minor component, Δt is the residence time, α is the thermal diffusivity of the minor component, and erf (x) is an error function.

3 | CALCULATIONS

Modeling of starve fed extrusion process requires a different algorithm of calculations compared to modeling of flood fed extrusion. In starve fed extrusion, the basis of calculations is that the flow rate is known, and it is equal to the feeder output.

For flood fed extrusion, the flow rate is not known. Modeling starts from the hopper for some initially assumed flow rate (e.g., equal to the drag flow) and continues toward the die. The process parameters are calculated along the screw and the die, and the pressure at the end of the die is compared to the atmospheric pressure. Calculations are iteratively repeated for modified flow rates until both pressures are equal. This is a forward scheme of calculations.

For starve fed extrusion of polyblends, we propose a new forward/backward algorithm of calculations, which is presented in Figure 2. Modeling starts from the hopper and polyblend fusion is modeled using appropriate fusion models, conductive model, or dispersed model (forward). When fusion is completed, the calculations are transferred toward the die (forward). Assuming some initially die melt temperature, the pressure drop in the die is calculated (forward), which is equal to the pressure at the end of the screw. Then, the screw pumping characteristics is applied to calculate the pressure gradient back along the screw (backward). Starving develops when pressure drops to zero, and filling of the screw may be evaluated. The process parameters are calculated (backward) until the end of fusion is reached. Melt temperature is compared to the melting temperature, and calculations are iteratively repeated for modified die melt temperature until both temperatures are equal. At each iteration, the fusion calculations are also repeated (forward), and the end of fusion as well fusion profile change, too.

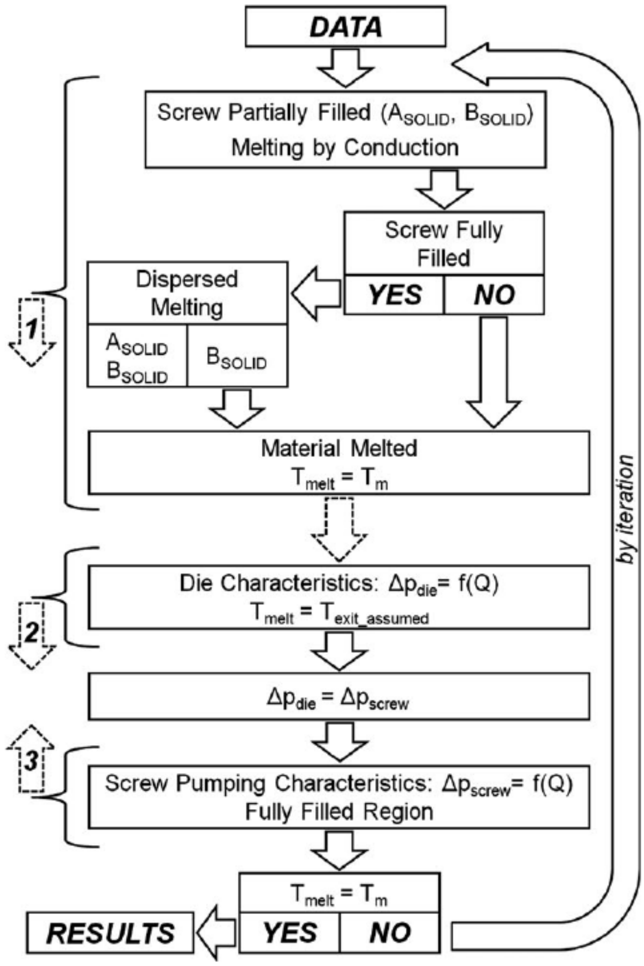

FIGURE 2 Algorithm of computer calculations: A—major component of polyblend, B—minor component of polyblend, T_{melt}—temperature of molten polyblend, T_{m}—melting temperature of polyblend, $T_{\text{exit\_assumed}}$—temperature of molten polyblend at the extruder exit (assumed at the first iteration of calculations), Δp_{die}—pressure drop in the extrusion die, Δp_{screw}—pressure growth in the screw, Q—volume flow rate, **1**—computations of the polyblend fusion profile, **2**—computations of the pressure/temperature profiles in the die, **3**—computations of the pressure/temperature profiles along the screw

Screw pumping characteristics for polyblend melt flow $\Delta p_{\text{screw}} = f(Q)$, the die flow characteristics $\Delta p_{\text{die}} = f(Q)$, and the power dissipated in the calculation element q_{diss} are calculated using the adequate Klein model for polyblends according to the schemes recently developed for extrusion of thermoplastics.[21]

Screw pumping characteristics are represented in terms of the dimensionless groups

$$Q^* = f(\Delta p^*) \quad (10)$$

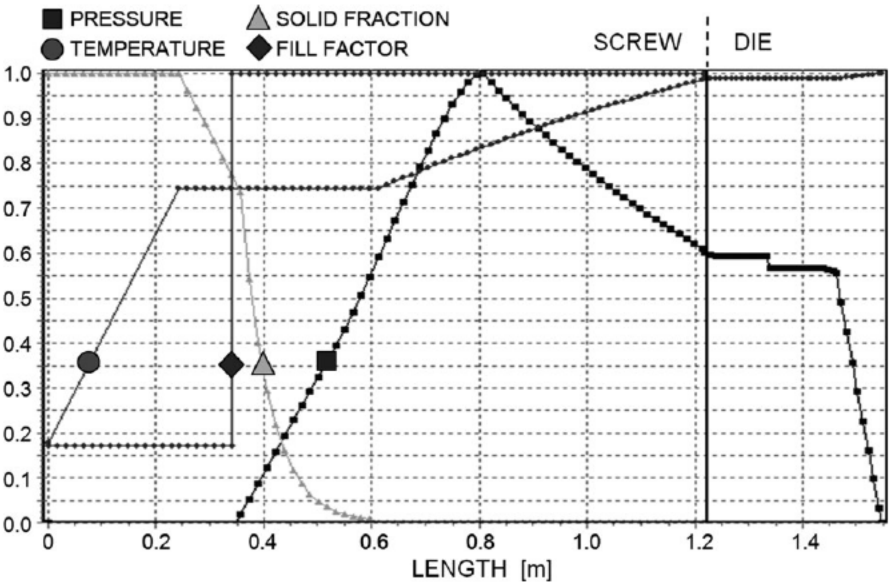

FIGURE 3 General simulation characteristics of the starve-fed single-screw extrusion of polymer blends (an example)

where Q^* is the dimensionless flow rate, Δp^* is the dimensionless pressure gradient, and

$$Q^* = \frac{2Q}{WHV_{\mathrm{bz}}} \tag{11}$$

$$\Delta p^* = \frac{H^{n+1}}{6mV_{\mathrm{bz}}{}^{n}}\frac{\Delta p}{L} \tag{12}$$

where Q is the flow rate, W is the screw channel width, H is the screw channel height, V_{bz} is the down channel velocity ($V_{\mathrm{bz}} = \pi D_{\mathrm{b}} N \cos\varphi$), D_{b} is the barrel diameter, N is the screw speed, φ is the helix angle, Δp is the pressure change over an element length L, and m is the consistency, n is the power law index.

For simulations, the given parameters are the material data, geometrical parameters of the screw and the die, as well as operating conditions (screw speed, barrel temperature profile, and the metered flow rate—for starve fed extrusion; for flood fed extrusion the flow rate is not known, and it is the result of simulations). The simulation results are process parameters, for example, melt temperature, pressure, filling of the screw, power consumption, and melting profile.

An example of simulation of starve fed extrusion of polyblends is shown in Figure 3. Here, both mechanisms of fusion are seen. In the first phase of fusion, in the partially filled area of the screw, the bulk polyblend temperature grows gradually (TEMPERATURE profile), and when the melting temperature is achieved, the polyblend fuses according to the first mechanism of fusion (SOLID FRACTION profile). When the screw fully fills up (FILL FACTOR profile), the second mechanism of fusion appears, and the pressure develops (PRESSURE profile).

The simulation results are depicted in the form of dimensionless process characteristics which includes pressure p, temperature T, solid fraction SF, and fill factor FF. Solid fraction SF = 1 means that all the polyblend is the solid, SF = 0 indicates that all the polyblends are molten, and 0 < SF < 1 indicates partial fusion. Fill factor FF = 1 means that the channel is completely filled up, FF = 0 indicates that the channel is empty, and 0 < FF < 1 means partial filling of the screw. It is important to note that in the fully filled area of the screw, polyblend may be completely molten or partially molten.

4 | EXTRUSION SIMULATION

The extrusion model that was discussed in the previous parts of the article has been used to simulate the starve fed extrusion process of the selected polymer blend using geometry data of the single-screw extruder (screw diameter $D = 45$ mm, length/diameter ratio $L/D = 27$) equipped with three-sectional screw of a compression ratio CR = 2.7. An extrusion of the high-density polyethylene and polystyrene blend of composition 85/15% has been studied. The polyethylene (INEOS, Rigidex HD5218EA) is characterized by density $\rho = 0.952$ g/cm^3, melt flow index MFR = 18 g/10 min (190°C, 2.16 kg), melting temperature $T_{\mathrm{m}} = 130$°C. The polystyrene (Styrolution PS 158N) is characterized by density $\rho = 1.04$ g/cm^3, melt flow index MFR = 3 g/10 min (200°C, 5 kg), glass transition temperature $T_{\mathrm{g}} = 109$°C. Using the temperature dependence of the storage modulus of amorphous polymers, it was assumed that the polystyrene should fuse at about 167°C.[27]

The Klein model has been used to characterize the polyblend viscosity

$$\ln \eta_{\mathrm{\_blend}} = a_0 + a_1 \ln\dot{\gamma} + a_{11}\ln^2\dot{\gamma} + a_{12}T\ln\dot{\gamma} + a_2T + a_{22}T^2 \tag{13}$$

TABLE 1 Material properties

Density–bulk	595 kg/m^3
Density—solid	966.37 kg/m^3
Density—melt	755.42 kg/m^3
Polymer-barrel friction factor	0.415
Polymer-screw friction factor	0.265
Heat of fusion	224817.5 J/kg
Heat transfer coefficient	500 W m^{-2}deg^{-1}
Solid specific heat	2199.3 J kg^{-1}deg^{-1}
Melt specific heat	2846.25 J kg^{-1} deg^{-1}
Thermal conductivity	0.25275 W m^{-1} deg^{-1}

where $\eta_{\_blend}$ is the polyblend viscosity, $\dot{\gamma}$ is the shear rate, T is the temperature, and $a_0 = 14.757698559$, $a_1 = -0.771831007, a_{11} = -0.01678397, a_{12} = 0.002352108, a_2 = -0.042502266$, $a_{22} = 0.000038986$.

The viscosity ratio of the polymer blend components (major component and minor component) was equal to $\lambda_{HDPE/PS} = 0.26$ in the processing range of shear rate and temperature and increased when shear rate increased. The other polyblend material data are listed in Table 1.

The starve fed conditions and flood fed conditions have been simulated, and an effect of the flow rate on the pressure and temperature profile, fusion capacity of the machine, and screw filling have been studied and depicted in Figure 4. It is seen that the pressure is much higher in flood fed case than in starve fed case. When flow rate grows, the pressure profile rises (Figure 4a), and the fully filled area grows (Figure 4d). The pressure falls to zero in the partially filled area (Figure 4a and d) where the fill factor is less than 1, FF < 1. Both mechanisms of fusion are seen (Figure 4c) for the metered feed rate $G_{SF} = 16$ kg/hr, and $G_{SF} = 17$ kg/hr. Fusion in starve fed extrusion is faster than fusion in flood fed extrusion.

5 | EMPIRICAL VERIFICATION OF THE MODEL

Experimental research of a single-screw extrusion of the high-density polyethylene and polystyrene blend was carried out,[36] and the presented computer model of the process was verified using the experimental results.

The polymer blend was fed into the hopper at the flood/starve fed conditions at starvation of 15% and 12.5% of the

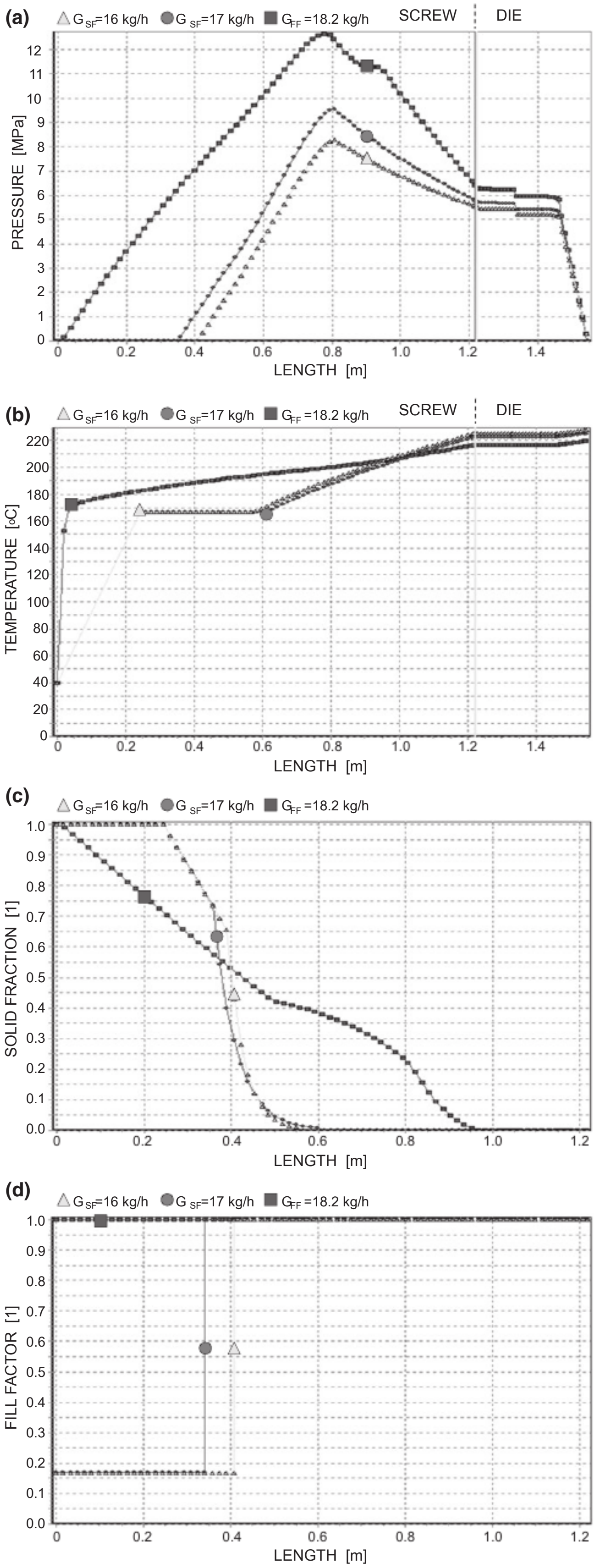

FIGURE 4 Results of simulation of extrusion process of the high-density polyethylene and polystyrene blend at the screw rotational speed $N = 50$ rpm, and at the metered feed rates $G_{SF} = 16$ kg/hr, $G_{SF} = 17$ kg/hr, and at the flood feed rate $G_{FF} = 18.2$ kg/hr: (a) pressure profiles, (b) temperature profiles, (c) solid fraction profiles, (d) fill factor profiles

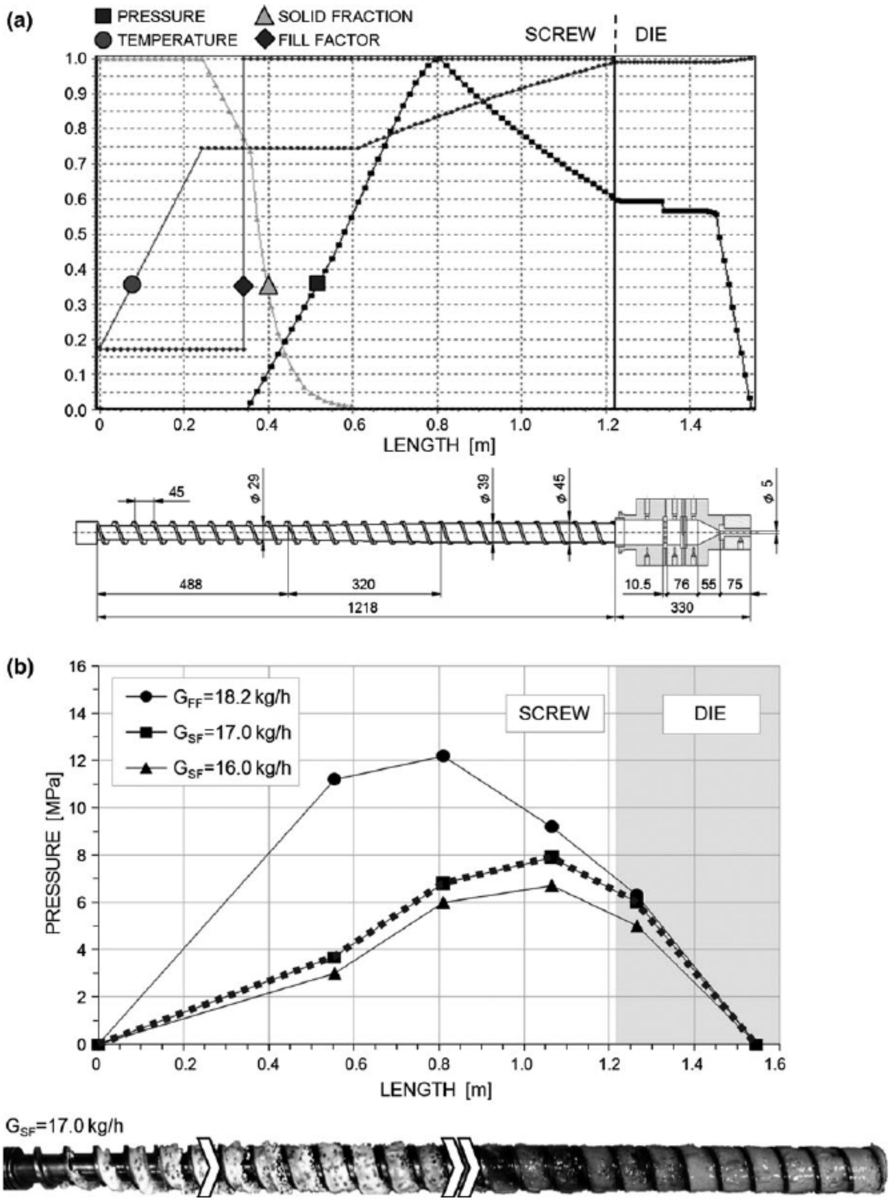

FIGURE 5 Experimental verification of extrusion of the high-density polyethylene and polystyrene blend at the screw rotational speed $N = 50$ rpm, and at the metered feed rate $G_{SF} = 16$ kg/hr (single arrow indicates the onset of the fully filled area, double arrow indicates the end of fusion): (a) results of simulation, (b) results of experimentation

flood fed flow rate. The screw rotation speed was fixed at $N = 20$ rpm and $N = 50$ rpm. The barrel temperature was equal to $T_b = 160/180/200$°C and the die temperature $T_{die} = 180$°C.

A "screw pulling-out technique" was applied to observe a polymer blend transport and flow alongside the screw. Fusion position and the starved/filled area of the screw were searched. The inclusions of minor component of the polymer blend were stained to distinguish the solids from the melt. The screws were photographed.

An influence of the feed rate (a growth from $G_{SF} = 16$ kg/hr, GSF = 17 kg/hr to $G_{FF} = 18.2$ kg/hr in flood fed case) at a constant screw rotation speed $N = 50$ rpm on the pressure and polymer blend distribution in the screw is depicted in Figures 5–7.

It is clear that filling of the screw grows with a growth of the flow rate at a settled screw rotation speed. When the flow rate is higher, the higher pressure must be developed to push more polymer blend through the die, which results in the longer filled area of the screw.

The filling of the screw was verified by comparing the lengths of the fully filled areas. The onset of the fully filled area is indicated by a single arrow. This position means the fill factor FF = 1 at the simulation chart. In general, the filling of the screw is well simulated, although it is underestimated by approx. 10%.

Observation and discussion on fusion of HDPE/PS polymer blend indicate that in the partially filled area, a mixture of polyethylene and polystyrene pellets accumulates at the screw active flight. Polyethylene as a polymer of lower viscosity ($\lambda_{HDPE/PS} = 0.26$) fuses first, surrounds the polystyrene pellets, and slows their fusion. When the screw fully fills up, the particles of unmolten polystyrene are dispersed in a molten polyethylene. Number and size of unmolten particles continuously reduce until the polymer blend is molten.

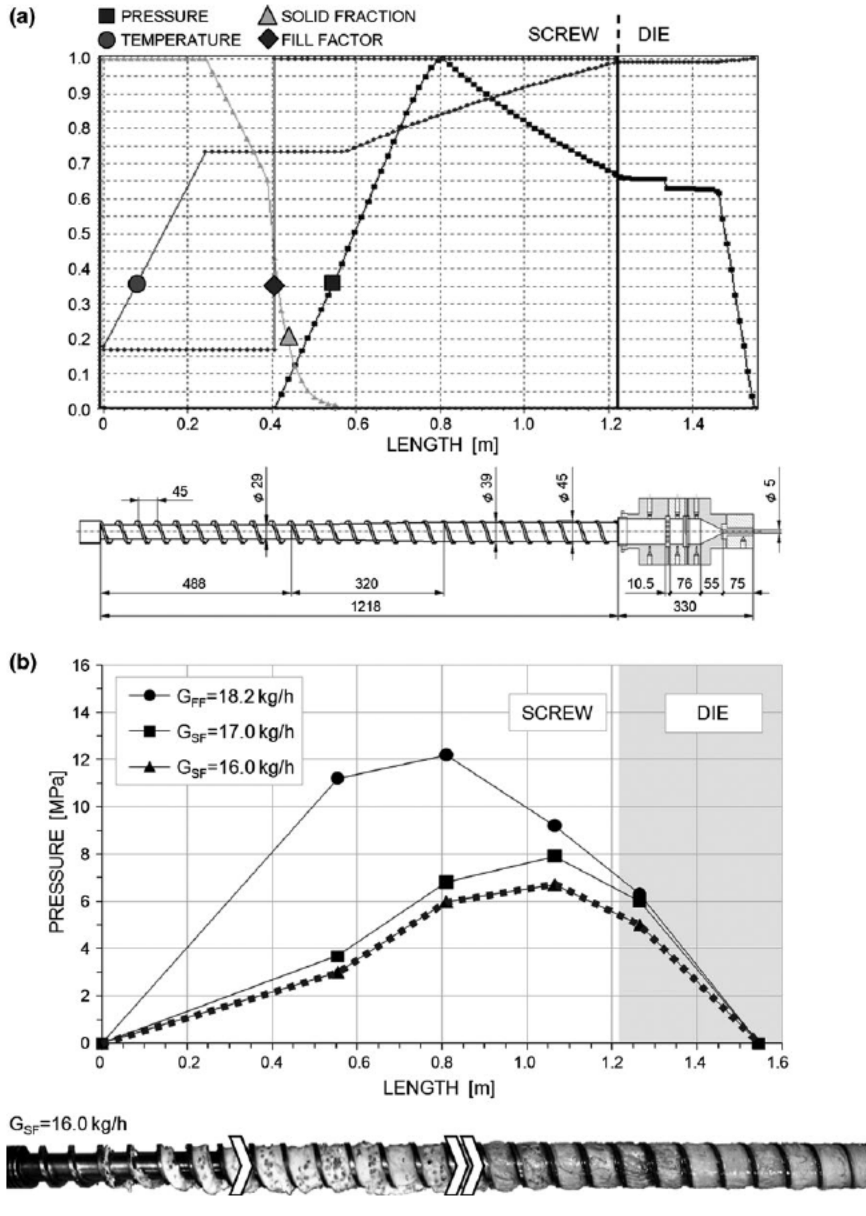

FIGURE 6 Experimental verification of extrusion of the high-density polyethylene and polystyrene blend at the screw rotational speed $N = 50$ rpm, and at the metered feed rate $G_{SF} = 17$ kg/hr (single arrow indicates the onset of the fully filled area, double arrow indicates the end of fusion): (a) results of simulation, (b) results of experimentation

Fusion rate may be evaluated using the parameter SF defined by a fraction of the solid in a total volume of the polymer blend. Fusion models were tested and verified by comparing the simulated and experimental fusion lengths. In case of feed rates $G_{SF} = 16$ kg/hr (Figure 5) and $G_{SF} = 17$ kg/hr (Figure 6), both mechanisms of fusion occur. In the first fusion phase, the material heats up until the melting temperature is achieved, and the solid fraction is equal to SF = 1. When melting temperature is achieved, the fusion starts, and the solid fraction drops, that is, SF < 1. When the screw fills up, the second fusion phase occurs, and when the polymer blend fuses completely, the solid fraction drops to SF = 0. The end of fusion is located a bit farther at higher feed rate. Fusion predictions are underestimated by approx. 10%. Fusion is fast.

Experimental pressure data and simulated pressure profiles are depicted in Figure 7. Pressure exists in the fully filled area only and grows with a growth of the feed rate and drops to zero in the starved area. The pressure is well predicted in flood fed case, and it is overestimated in starve fed case. It results from an experiment (Figure 7) that small reduction of feed rate causes lowering the pressure profile, and maximum pressure significantly drops. Consequently, the process energy consumption will drop, too.

6 | CONCLUSIONS

A new model has been presented, which simulates a single-screw extrusion of polymer blends at starved fed conditions, and includes metering, fusion, and solid conveying. Computer calculations were executed for extrusion of high-density polyethylene and polystyrene blend at various technological conditions, and fill factor, pressure, temperature, and fusion profiles were calculated and verified by experiment.

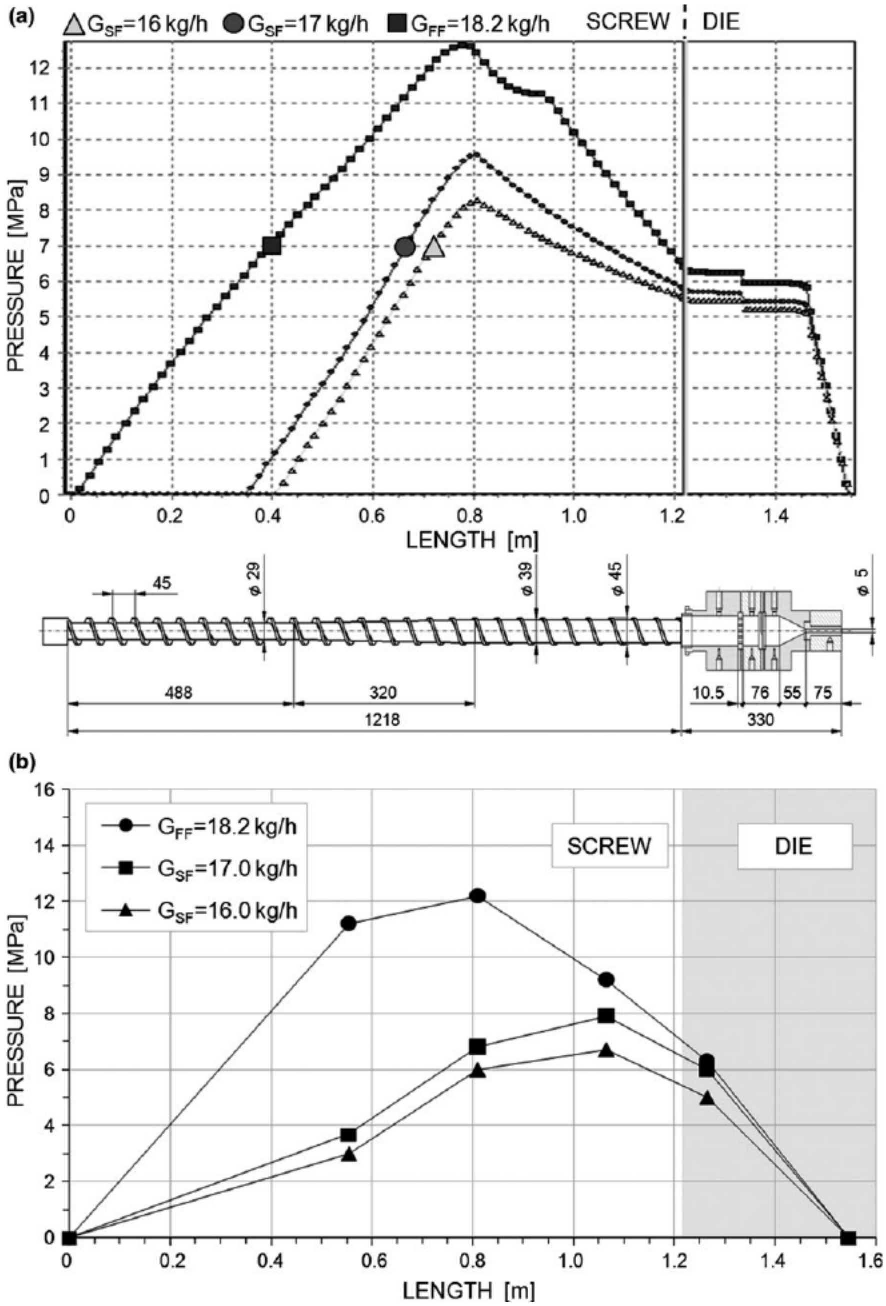

FIGURE 7 Experimental verification of pressure profile computations for extrusion of the high-density polyethylene and polystyrene blend at the screw rotational speed $N = 50$ rpm, and at the metered feed rates $G_{SF} = 16$ kg/hr, $G_{SF} = 17$ kg/hr and at flood feed rate $G_{FF} = 18.2$ kg/hr: (a) results of simulation, (b) results of experimentation

Based on the simulation and experimental study, it can be stated that fusion of polymer blends in starve fed case significantly differs from fusion in flood fed case, and it is generally faster. In starve fed case, melting length is shorter; however, it grows when feed rate grows. The screw is only full in its final part and starved beyond it. The fully filled screw length is dependent on the feed rate and grows with a growth of feed rate. The pressure exists in the fully filled area only and grows when feed rate grows. The pressure gradient in the screw can be positive or negative. It is dependent on the operating conditions and on geometry of the die. In general, high resistance of the die produces positive gradient, and low resistance of the die produces negative gradient.

In this article, dispersed melting of one solids (minor component) has been considered. However, a different case is possible when two solids (minor and major component) are dispersed. Then, the issue requires multi-phase flow modeling. And this would be the future work directions along this line. Moreover, modeling of starve-fed single-screw extrusion process of other advanced polymeric materials, like composites (e.g., wood plastic composites, WPC), would be also of high importance.

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