A Heuristic Method for Modeling the Initial Pressure Drop in Melt Filtration Using Woven Screens in Polymer Recycling

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This paper addresses the use of heuristic optimization algorithms to generate generally valid analytic equations for estimating the initial pressure drop of square and Dutch woven screens in polymer recycling. We present a mathematical description of the isothermal initial pressure drop of non-Newtonian polymer melt flows through woven screens without the need for numerical methods. We first performed numerical CFD simulations to create a set of 9,000 physically independent modeling set-ups as a basis for heuristic modeling. Then, we applied symbolic regression based on genetic programming to develop pecScreen models, achieving coefficients of determination $R^2 > 0.9995$. For verification of our models, we performed experiments using both virgin and slightly contaminated in-house and post-industrial recycling materials. The experimentally determined data are in good agreement with the approximation results, which yielded a coefficient of determination $R^2$ of 0.926. Our modeling approach, the accuracy of which we have proven, allows fast and stable computational modeling of the initial pressure drop of polymer melt flows through woven screens. POLYM. ENG. SCI., 00:000–000, 2019. © 2019 The Authors. Polymer Engineering & Science published by Wiley Periodicals, Inc. on behalf of Society of Plastics Engineers.

INTRODUCTION

With the role and importance of plastics in our economy continuously growing in the past 50 years, the annual demand for plastics in Europe has steadily increased, reaching 49 million tons in 2016. Hence, also the potential for the recycling of plastic waste in the EU has increased, as around 25.8 million tons of plastic waste are generated every year. These and goals (e.g., to recycle 75% of the packaging waste by 2030) proposed by the European Strategy for Plastics in a Circular Economy are intended to protect the environment and to make plastics recycling profitable for business [1–3].

The quality of end products made out of regranulates strongly depends on (i) their physical properties and (ii) their color, clarity, surface roughness, and imperfections due to contaminations. Depending on the application, the allowed levels of defects differ, but if the extent of contamination exceeds the specified threshold, the product must be downgraded. A key objective in plastics recycling is therefore to minimize contaminations, which can be achieved by melt filtration [4].

The material can be contaminated by a large variety of substances, including paper, metals, wood, foreign plastics, glass, dust particles, and also unmelted or degraded polymer formations. Screen changers, such as slide-plate screen changers, piston screen changers and rotary disc filters, differ in the processes and types and amounts of contaminations they are suitable for, their throughput rates and extruder sizes as well as run length [5, 6]. Furthermore, various types of metallic filter medium exist, for instance, woven screens, sintered metal powder, super plates and random fibers, which differ in terms of permeability and their ability to hold contaminants and capture gels (see Table 1) [6, 7].

Woven screens of different designs and sizes, such as square or Dutch weave, are mostly widely used. The screen pack normally consists of screens with various degrees of fineness; a coarse screen is placed against the breaker plate for supporting the finer screens [5, 7]. The size of particles that can be removed from the polymer melt is determined by both wire diameter and mesh number of the woven screen [4], and can be calculated as:

$$MW = \frac{25.4}{MN}d_W,$$

where $MW$ is the mesh opening or mesh width of the screen in mm, $MN$ is the number of wires per inch, and $d_W$ is the wire diameter in mm. Depending on screen type and mesh size, particles ranging from 500 µm to approximately 5 µm in size can be removed [5]. Subsequent to the removal of undesirable particles from the polymer melt, screen packs increase the shear working imparted to the melt in order to improve homogeneity [8].

For selection of a suitable filtration system: (i) the screening performance depending on type and amount of contamination and (ii) the initial pressure drop of the system must be determined. The total pressure drop of the filtration system is composed of the pressure drop of the screen changer system as a function of flow geometry and the pressure drop of the filtration medium. Since woven screens are the most commonly used extruder screens in industry, this paper presents a novel generally valid analytic equation for estimating the initial pressure drop of square woven and Dutch weave screens that is based on numerical as well as heuristic modeling.

STATE OF THE ART

Based on various theories, several models for calculating the initial pressure drop of fresh woven screens are available. Carley and Smith [8] presented a method for calculating the pressure drop in a polymer melt based on the assumption that the flow behavior is adequately represented by the power law due to the narrow range of shear usually encountered in a screen pack.
The major finding of their work was that the pressure drop in a single screen is a function of the melt flow rate and thus of the Reynolds number Re and a friction factor $f$:

$$ f = \frac{16}{Re}. \quad (2) $$

According to Carley and Smith [8], the initial pressure drop $\Delta p_{\text{Screen}}$ can be determined based on the screen resistance factor $F_S$:

$$ \Delta p_{\text{screen}} = F_S \cdot \eta \cdot \dot{\gamma}^{1-n} \left( \frac{4 \cdot \dot{m}}{D_s^2 \cdot \pi \cdot \rho} \right)^n, \quad (3) $$

where $\eta$ is the viscosity, $\dot{\gamma}$ is the shear rate, $\dot{m}$ is the mass flow rate, $D_s$ is the screen diameter, $\rho$ is the melt density, and $n$ is the power-law exponent. The screen resistance factor $F_S$ according to Carley and Smith [8] can be calculated by:

$$ F_S = 2^{n+3} \left( \frac{3 + \frac{1}{n}}{(900 \cdot \pi)^n} \frac{d_w}{MN \cdot MW^{3n+1}} \right), \quad (4) $$

which was later modified by Todd [4, 9] for power-law fluids:

$$ F_S = 2^{n+3} \left( \frac{3 + \frac{1}{n}}{(900 \cdot \pi)^n} \frac{d_w}{MN \cdot MW^{3n+1}} \right), \quad (5) $$

where $n$ is the power law exponent, $d_w$ is the wire diameter, $MN$ is the mesh number, and $MW$ is the mesh opening or mesh width.

Another way of calculating the initial pressure drop of the screen pack is based on Darcy’s Law, where the screen is assumed to be a porous medium. According to Brackett-Rozinsky et al. [10] and Edle and Gooding [11], the pressure drop $\Delta p_{\text{screen}}$ of a polymer melt flow through porous media can be determined as:

$$ \Delta p_{\text{screen}} = \frac{v \cdot \eta \cdot \delta}{k}, \quad (6) $$

where $k$ is the relative permeability, $v$ is the velocity, $\eta$ is the fluid viscosity, and $\delta$ is the thickness of the filter medium. The relative permeability parameter $k$ is modeled using a Blake-Kozeny relationship according to Bird et al. [12] and depends on the average pore size $d_p$ and the current filter porosity $\varepsilon$:

$$ k = \frac{d_p^2 \cdot \varepsilon^3}{150 \cdot (1-\varepsilon)^2}. \quad (7) $$

Based on knowledge of the pressure drop calculation of polymer melts in pipes, the flow in a metallic wire mesh can be understood as a flow in a group of parallel tubes. Müller and Piesche [13] presented a model for calculating the initial pressure drop of non-Newtonian melts based on similarity laws using the dimensionless Euler $Eu$ and Reynolds $Re$ numbers:

$$ \Delta p_{\text{screen}} = Eu \cdot \rho \cdot v_0^2, \quad (8) $$

where $\rho$ is the melt density and $v_0$ is the undisturbed velocity of the melt. The dimensionless Euler number $Eu$ for square woven screens.

<table>
<thead>
<tr>
<th>Wire mesh</th>
<th>Square woven</th>
<th>Dutch twill</th>
<th>Sintered metal powder</th>
<th>Random metal fiber</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gel capture</td>
<td>Poor</td>
<td>Fair</td>
<td>Good</td>
<td>Very good</td>
</tr>
<tr>
<td>Contaminant capacity</td>
<td>Fair</td>
<td>Good</td>
<td>Fair</td>
<td>Very good</td>
</tr>
<tr>
<td>Permeability</td>
<td>Very good</td>
<td>Poor</td>
<td>Fair</td>
<td>Good</td>
</tr>
<tr>
<td>Price</td>
<td>Low</td>
<td>Fair</td>
<td>High</td>
<td>High</td>
</tr>
</tbody>
</table>

FIG. 1. Flowchart of numerical and heuristic modeling for determining the pecScreen models.

![3D geometries of (a) square and (b) Dutch weave wire screens; elementary cells are shown in blue. Elementary cells for (c) square and (d) Dutch weave screens. [Color figure can be viewed at wileyonlinelibrary.com]]
is a function of wire diameter $d_w$, screen thickness $\delta$, specific screen surface $\phi$, mesh size $MW$, porosity $\varepsilon$, and Reynolds number $Re$:

$$Eu = \frac{14 \cdot \delta \cdot \phi}{\varepsilon^{1/2} \cdot d_w \cdot (1 + \frac{MW}{d_w}) \cdot Re}.$$  

Here, we present new models for calculating the initial pressure drop of square woven and Dutch weave screens that are based on numerical and heuristic modeling.

**MODELING**

The aim of this work was to generate generally valid analytic equations for estimating the initial pressure drop of isothermal and stationary flows of non-Newtonian polymer melt flows in woven screens. These so-called pecScreen models are based on numerically determined data used for heuristic optimization algorithms employing genetic programming [14–16].

**Numerical Modeling**

For numerical simulation as a basis for genetic programming, we first defined the 3D geometry of various woven screen types and fineness. Both for square woven and Dutch weave screens, we defined repeating elementary cells in order to allow fast computational solving of the modeling process (see Fig. 2).

After generating the geometry, we extracted the flow domain and defined characteristic boundary conditions for each elementary cell (see Fig. 3). The flow of the polymer melt was assumed to be isothermal and stationary. As the elementary cell was repeated to fill the entire screen, a periodic boundary condition on the sides was set. In addition to wall adhesion of the melt at the wire surfaces, a pressure outlet at the bottom of the volume was defined. To calculate numerical solutions for each of the 9,000 design points, we parameterized the simulation set-up in terms of material properties and processing conditions. To this end, we varied the specific mass flow rate $m_{\text{spec}}$ and the specific volume flow rate $V_{\text{spec}}$, which is

![FIG. 3. Boundary conditions of the flow-domain for the numerical CFD simulation. [Color figure can be viewed at wileyonlinelibrary.com]](image)

**TABLE 2. Parameter ranges of screen geometry and specific throughput and material properties used for numerical modeling of the screen geometry.**

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Abbreviation</th>
<th>Unit</th>
<th>Min.</th>
<th>Max.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fineness</td>
<td>$F$</td>
<td>$\mu m$</td>
<td>25</td>
<td>1,140</td>
</tr>
<tr>
<td>Mesh width</td>
<td>$MW$</td>
<td>mm</td>
<td>0.07</td>
<td>1.14</td>
</tr>
<tr>
<td>Consistency index</td>
<td>$K(T)$</td>
<td>Pa.s$^{-n}$</td>
<td>390</td>
<td>20,500</td>
</tr>
<tr>
<td>Flow exponent</td>
<td>$n$</td>
<td></td>
<td>0.30</td>
<td>0.90</td>
</tr>
<tr>
<td>Specific throughput</td>
<td>$m_{\text{spec}}$</td>
<td>kg/h/cm$^2$</td>
<td>0.10</td>
<td>4.40</td>
</tr>
</tbody>
</table>

Figure 1 shows the complete modeling sequence including numerical modeling and genetic programming. We started with building the 3D geometry of the woven screens and defining the boundary conditions for the numerical simulation in order to create 9,000 datasets of the throughput-pressure gradient relationship ($m \cdot \Delta p$). After simplification and pruning of the models, we performed various error analyses for evaluation and validation.

![FIG. 4. Throughput-pressure drop relationships of (a) an 80 mesh (200 $\mu$m) square woven screen and (b) a 50/250 mesh (60 $\mu$m) Dutch weave screen for LDPE, PP, PET, and HDPE at three melt temperatures: T$_1$ solid lines, T$_2$ dotted lines, and T$_3$ dashed lines (200°C, 220°C, and 240°C for LDPE, PP, and HDPE and 270°C, 290°C, and 310°C for PET). [Color figure can be viewed at wileyonlinelibrary.com]](image)
the total throughput $m_{\text{total}}$ over the cross-sectional area of the total filtration surface $A_{\text{screen}}$:

$$\dot{m}_{\text{spec}} = \frac{m_{\text{total}}}{A_{\text{screen}}}, \quad (10)$$

$$\dot{V}_{\text{spec}} = \frac{\dot{m}_{\text{spec}}}{\rho_{\text{melt}}}, \quad (11)$$

Therefore, the volume flow rate of the elementary cell $\dot{V}_{\text{cell}}$ can be determined by:

$$\dot{V}_{\text{cell}} = \dot{V}_{\text{spec}} \cdot A_{\text{cell}}, \quad (12)$$

The shear thinning nature of the polymer melt was described by a power-law model with consistency index $K$ and flow exponent $n$ at the desired melt temperature:

$$\eta(\dot{\gamma}, T) = K(T) \cdot \dot{\gamma}^{n-1}. \quad (13)$$

Table 2 summarizes the parameters ranges for the geometry of the screens, the material properties described by consistency $K(T)$ and flow exponent $n$, and the range of the specific mass flow rate.

Figure 4 illustrates the results of the numerical calculations of the throughput-pressure gradient relationship by use of examples of an 80 mesh (200 μm) square woven screen and a 50/250 mesh (60 μm) Dutch weave screen.

**Heuristic Optimization**

The results shown in the previous section represent numerical solutions for the 9,000 design points, describing the throughput-pressure gradient relationship.

**TABLE 3. Mathematical building blocks provided to the heuristic optimization algorithm.**

<table>
<thead>
<tr>
<th>Mathematical building blocks</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>State variables</td>
<td>✓</td>
</tr>
<tr>
<td>Constants</td>
<td>✓</td>
</tr>
<tr>
<td>Operators</td>
<td>+, -, /</td>
</tr>
<tr>
<td>Functions</td>
<td>Cosine, Sine, Square</td>
</tr>
</tbody>
</table>

where $A_{\text{cell}}$ is the surface of the elementary cell.

FIG. 5. Symbolic regression model in mathematical notation and in the form of a parse tree.

FIG. 6. Experimental set-up (a) including extruder, screen changer system, die unit and measuring points of melt temperature ($T_{\text{IN}}, T_{\text{OUT}}$) and melt pressure ($p_{\text{IN}}, p_{\text{OUT}}$); (b) piston filter and adaptive screen pack; and (c) radial temperature measurement with positions $T_{R1}$ to $T_{R4}$. [Color figure can be viewed at wileyonlinelibrary.com]
pressure gradient relationship of polymer melt flows through woven screens. However, to avoid numerical calculations, we sought a generally valid approximate analytic relationship that predicts the numerical results without the need for CFD simulations. We derived a mathematical relationship between the characteristic input quantities ($V_{cell}$, $K(T)$, $n$, $MW$, $d_k$, $d_s$) and the target variable $\Delta p_{pecScreen}$:

$$
\Delta p_{pecScreen} = f\left[V_{cell}, K(T), n, MW, d_k, d_s\right].
$$

We applied heuristic optimization, using several metaheuristic optimization algorithms, to the data set. To derive an equation that predicts the numerically determined relationship between throughput and pressure gradient, we employed symbolic regression based on genetic programming using the open-source software package HeuristicLab [17]. By minimizing the mean squared deviations between estimated mathematical solution and the simulation result, we developed the pecScreen models.

Symbolic regression is a nonparametric regression and function discovery approach by induction of mathematical expression on data for modeling and analyzing data [18]. In contrast to other modern methods for determining an algebraic relationship between a target variable and a set of independent input quantities, symbolic regression has the ability to identify nonlinear white-box models without the need for specifying their structure [19]. Whereas other regression methods assume a specific model structure and vary only its complexity and optimize its parameters, symbolic regression seeks to evaluate an optimal approximation without a priori assumptions. No starting point for regression needs to be defined, as the method attempts to derive the approximation from the data itself. Simultaneous optimization of the model structure and its parameters is a key feature of this technique [20].

If no limits are imposed on the set of mathematical building blocks in the solving process (by specifying, e.g., state variables, constants, operators, and analytical functions), the search space in symbolic regression is theoretically infinite [20–22]. Therefore, these expressions must be restricted to reduce computational time. A parse tree as shown in Fig. 5 represents the structure of the model that relates the target variable to the set of independent input variables.

Tree-based genetic programming is commonly used to solve symbolic regression problems by considering a huge variety of mathematical expressions in various combinations [19, 21]. Genetic programming is a widely applicable metaheuristic for automated synthesis of mathematical formulae in syntax-tree representation [23]. Genetic programming searches for solution candidates by iteratively applying the evolutionary operators selection, crossover and mutation with the aim to continuously optimize the solution quality based on fitness [21].

This technique is considered particularly suited to the given task for the following reasons: First, the hypothesis space, and thus the set of models considered, is significantly greater than that of conventional data-based modeling techniques, such as polynomial regression. Second, symbolic regression is able to identify interpretable models in terms of mathematical expressions which

### TABLE 4. Filtration parameters of the square woven (SW) and Dutch weave (DW) metal screens used.

<table>
<thead>
<tr>
<th>Screen Type</th>
<th>Type</th>
<th>Fineness</th>
<th>Porosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>14 mesh SW</td>
<td>1,140 μm</td>
<td>73%</td>
<td></td>
</tr>
<tr>
<td>80 mesh SW</td>
<td>200 μm</td>
<td>68%</td>
<td></td>
</tr>
<tr>
<td>150 mesh SW</td>
<td>100 μm</td>
<td>67%</td>
<td></td>
</tr>
<tr>
<td>24/110 mesh DW</td>
<td>150 μm</td>
<td>63%</td>
<td></td>
</tr>
<tr>
<td>50/250 mesh DW</td>
<td>60 μm</td>
<td>65%</td>
<td></td>
</tr>
<tr>
<td>200/600 mesh DW</td>
<td>25 μm</td>
<td>55%</td>
<td></td>
</tr>
</tbody>
</table>

### TABLE 5. Results of the error analysis of the pecScreen models for square woven and Dutch weave screens.

<table>
<thead>
<tr>
<th>pecScreen models</th>
<th>$R^2$</th>
<th>MAE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Square woven screens</td>
<td>$\Delta p_{square}$</td>
<td>0.9995</td>
</tr>
<tr>
<td>Dutch weave screens</td>
<td>$\Delta p_{dutch}$</td>
<td>0.9996</td>
</tr>
</tbody>
</table>

FIG. 7. Comparison of numerical simulation results and approximation for (a) an 80 mesh (200 μm) square woven screen and (b) a 50/250 mesh (60 μm) Dutch weave screen; dots and lines indicate the numerical simulation and approximation results, respectively. [Color figure can be viewed at wileyonlinelibrary.com]
can easily be manipulated, validated and transformed into expert systems [20].

Table 3 shows the mathematical building blocks for the heuristic optimization algorithm. The accuracy of the models thus developed was optimized by minimizing the mean squared deviations between estimated mathematical solution and simulation result.

EXPERIMENTAL

The experiments for validating our analytical screen models involved a variety of screen changer systems and sizes, testing various types of woven screens. At EREMA (Engineering and Recycling Maschinen und Anlagen Ges.m.b.H) recycling plants, we performed experiments using various slightly contaminated in-house as well as post-industrial recycling materials, varying the mass flow rates within a range of 60–600 kg/h. Additionally, we conducted experiments at an SW 2/82 DF direct-flow double-piston screen changer system, testing different virgin materials, such as PP, HDPE, LDPE, PET, and PA.

In order to precisely analyze the throughput-pressure gradient relationship of every single screen, we performed adaptive tests. In the first step, we determined the initial pressure drop of the filtration system without any woven screen. We then adaptively added screens to the filtration system, ultimately building the complete screen pack, analyzing the filtration behavior of each screen layer (see Fig. 6).

For verification of the models, we measured the melt pressures ($P_{IN}$, $P_{OUT}$) and melt temperatures ($T_{IN}$, $T_{OUT}$) right before and after the selected screen changer system. Figure 6 schematically shows the experimental set-up. We also measured the radial temperature distribution in order to analyze melt-temperature homogeneity in relation to filtration fineness. To this end, we used adjustable melt-temperature sensors, as shown in Fig. 6.

The filtration fineness was varied within a range from 1,140 down to 25 μm for both square woven and Dutch weave screens (see Table 4). By varying the filtration system and size, mass flow rates, filtration type and fineness, more than 380 data points were generated and then used for validating the models.

RESULTS

Heuristic Modeling

Approximating the numerical results of 9,000 design points, we identified a mathematical relationship between the target variable $\Delta P_{Screen}$ and the set of independent input parameters.

For square woven screens, the following equation was formulated:

$$\Delta P_{square} = c_1 + \frac{c_2}{n} + c_3 \cdot d_K \cdot \left( f_1 + \frac{MW \cdot f_2}{V_{cell} \cdot (c_8 + d_K) \cdot f_3} \right) + \frac{f_4}{f_5 + K \cdot (f_6 + f_7)}$$

(15)

where $f_1$ to $f_7$ are sub-functions containing 26 constants (see Appendix).
The global accuracy of our model, based on all design points, was evaluated by means of an error analysis that yielded a mean absolute error MAE of 0.115 bar and a coefficient of determination $R^2$ of 0.9995, as summarized in Table 5.

A similar model was developed for Dutch weave screens:

$$
\Delta p_{\text{dutch}} = c_1 + f_1 \cdot d_4 + c_{10} \cdot \cos[c_{11} \cdot d_4] \\
\cdot \left( f_5 + f_6 \cdot f_7 \right) \cdot \left( c_{22} \cdot K + (f_6 \cdot f_7) \left( K \cdot n \cdot V_{cell} \right) \right)^{-1} + f_8 + f_9 ,
$$

where $f_1$ to $f_9$ are, again, sub-functions (see Appendix). In this case, the mean absolute error was 0.294 bar and the coefficient of determination $R^2$ was 0.9996.

A comparison between numerical simulation results and approximated solutions obtained from Eqs. 15 and 16 using the exact values of the constants determined for the selected screens is plotted in Fig. 7. A scatter plot showing the numerically obtained and the approximated pressure drop values is given in Fig. 8. To demonstrate the high accuracy of our modeling approach, Fig. 8 shows all design points.

These figures highlight the high accuracy of our models for estimating the initial pressure drop of woven screens, as the numerically determined data are in good agreement with the approximated values from the models.

**Experimental Verification**

In addition to the error analysis, we verified our pecScreen models experimentally and compared them to other state-of-the-art models.
As shown in Fig. 6, we measured and analyzed the radial temperature distribution both at the inlet and at the outlet of the melt filtration system in order to analyze the melt homogeneity in relation to filtration fineness. Figure 9 shows the radial temperature distribution at the in- and outlets for an HDPE polymer melt. For a clear representation of the temperature profile, we mirrored the measured values $T_1$, $T_2$, and $T_3$ at the symmetry axis (indicated by a dashed line in the diagram). As $T_1$ represents the melt temperature at the barrel wall, the average bulk temperature was evaluated only between $T_2$, $T_3$, and $T_4$.

Since we observed slight differences in the bulk temperature between in-and outlet, the flow situation was determined using the dimensionless Cameron number [24]. For calculating the pressure drop, a constant bulk melt-temperature was assumed as the dimensionless Cameron number with values ≥ 1 indicating isothermal flow conditions.

Figure 10 shows scatter plots comparing the experimentally determined and approximated pressure drop values for different models. The figures show the experimentally determined pressure drop versus the pressure drop according to the desired model. It can be seen that the results of our generally valid analytic equations match the experimentally determined data accurately.

Table 6 summarizes the results of the experimental verification for three different types of models in the form of the mean relative error MRE and the coefficient of determination $R^2$. The pecScreen models are in very good agreement with the experimentally determined data, as a coefficient of determination of 0.926 was achieved compared to 0.665 for the other models.

### Table 6. Results of the experimental verification of the models. Coefficient of determination $R^2$ and mean relative error MRE.

<table>
<thead>
<tr>
<th>Model</th>
<th>$R^2$</th>
<th>MRE</th>
</tr>
</thead>
<tbody>
<tr>
<td>pecScreen</td>
<td>0.926</td>
<td>14.8%</td>
</tr>
<tr>
<td>Similarity law model</td>
<td>0.665</td>
<td>28.6%</td>
</tr>
<tr>
<td>Resistance factor model</td>
<td>0.661</td>
<td>29.6%</td>
</tr>
</tbody>
</table>

**CONCLUSION**

We developed algebraic relationships for calculating the initial pressure drop of polymer melt flows in woven screens under isothermal conditions. The results of our approximate equations match accurately the solutions of an extensive parametric study in which 9,000 set-ups were solved numerically. We employed a heuristic optimization algorithm that uses symbolic regression based on genetic programming to approximate the numerical results. An error analysis demonstrated the high accuracy of our pecScreen models, giving respectively a mean absolute error and a coefficient of determination $R^2$ of 0.115 bar and 0.9995 for square woven, and 0.294 bar and 0.9996 for Dutch weave screens.

Experimental verification of the models using various virgin and slightly contaminated in-house recycling materials also confirmed the high accuracy of our models. We investigated the throughput-pressure drop relationship within a wide range of mass flow rates from 60 to 600 kg/h using a variety of screens with a fineness from 1,140 to 25 μm. Our models predict the experimentally determined data very well, yielding a coefficient of determination $R^2$ and a mean relative error of 0.926% and 14.8%, thus outperforming other models in terms of accuracy. Our models can be easily implemented in practice and remove the need for time-consuming and computationally expensive numerical procedures such as the finite-element method (FEM) and the finite-volume method (FVM). Hence, our pecScreen models enable fast and stable computational modeling of the initial pressure drop of woven screens.

**ACKNOWLEDGMENTS**

This work was supported by Erema Engineering Recycling Maschinen und Anlagen Ges.m.b.H. and funded by the Austrian Research Promotion Agency (FFG; project number: 867202).

**REFERENCES**

APPENDIX

Sub-functions for $\Delta p_{\text{square}}$ Eq. 15:

\begin{align}
    f_1 &= c_4 + K \cdot (c_5 + c_6 \cdot MW) + \frac{c_7 \cdot K}{MW}, \\
    f_2 &= dK^2 \cdot (c_{10} + c_{11} \cdot K) + MW \cdot (c_{12} + c_{13} \cdot dK), \\
    f_3 &= (c_9 + K) \cdot (dK \cdot K + c_{14} \cdot n),
\end{align}

\begin{align}
    f_4 &= c_{15} \cdot K \cdot n^3 \cdot (c_{16} \cdot dK + c_{17} \cdot n), \\
    f_5 &= \left( c_{18} + \frac{c_{19}}{c_{20} \cdot dK + dK \cdot K} \right) \cdot n + \frac{c_{21} \cdot dK^2 \cdot MW}{V_{cell}}, \\
    f_6 &= \frac{c_{22}}{c_{23} + K} + dK \cdot n \cdot (c_{23} + c_{24} \cdot n), \\
    f_7 &= V_{cell} \cdot \left( c_{25} + c_{26} \cdot \frac{V_{cell}}{MW^2} \right).
\end{align}

Sub-functions for $\Delta p_{\text{dutch}}$ Eq. 16:

\begin{align}
    f_1 &= c_2 \cdot n \cdot (c_3 \cdot MW + c_4 \cdot n), \\
    f_2 &= c_5 \cdot K + (c_6 \cdot d_s + c_7 \cdot n)^2 \cdot (c_8 \cdot K + c_9 \cdot n), \\
    f_3 &= c_{12} + c_{13} \cdot d_s^2, \\
    f_4 &= c_{17} \cdot MW + (c_{18} \cdot MW + c_{19} \cdot n)^2, \\
    f_5 &= c_{14} \cdot (c_{15} + c_{16} \cdot K) \cdot n^2 \cdot (c_{20} + c_{21} \cdot n), \\
    f_6 &= c_{23} \cdot (c_{24} \cdot d_k + c_{25} \cdot d_n) \cdot MW^2, \\
    f_7 &= 1 + c_{26} \cdot MW + (c_{27} \cdot MW + c_{28} \cdot n)^2, \\
    f_8 &= c_{29} \cdot K \cdot n^3 \cdot (c_{30} + c_{31} \cdot d_n + n) \cdot (c_{32} + K + c_{33} \cdot n) \cdot V_{cell} \cdot \\
        &\frac{K^2 \cdot n \cdot V_{cell} + MW^2 \cdot (d_k \cdot (c_{34} + c_{35} \cdot n)) \cdot \cos[c_{36} \cdot MW]}{K^2 \cdot n \cdot V_{cell} + MW^2 \cdot (d_k \cdot (c_{34} + c_{35} \cdot n)) \cdot \cos[c_{36} \cdot MW]}, \\
    f_9 &= \frac{c_{37} \cdot \left( \frac{c_{38} \cdot K}{MW} \right) \cdot (c_{39} + c_{40} \cdot d_k + c_{41} \cdot MW) \cdot V_{cell} \cdot \csc[c_{45} \cdot d_s]}{c_{42} + c_{43} \cdot d_k + c_{44} \cdot n}.
\end{align}