A NEW MEASURING DEVICE FOR MEASURING THE INTERNAL AND EXTERNAL COEFFICIENT OF FRICTION OF COMPRRESSED POLYMER BULK GOODS

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SUMMARY
The friction measuring device presented here serves to determine the external and internal coefficient of friction of bulk plastic materials. It is a shearing cell with a continuous powder replacement, which works on the principles of a vertically arranged solid conveyance extruder. Of particular importance is the new pressure measuring technique, which allows the measurement of radial pressures on the cylinder wall from a few millibars up to several 100 bars. By interchanging the cylinder bushes the internal as well as the external coefficient of friction can be measured. It is also possible to use so-called grooved bushes. Though the pressure conditions in this shearing cell with a continuous powder replacement are not constant, an evaluation technique was developed which permits the determination of the coefficient of friction as a function of pressure, velocity and temperature. The shearing cell with a continuous powder replacement can also be rebuilt to a closed shearing cell.

Keywords: Coefficient of Friction, Solids Conveying, Pressure Build Up, Single Screw Extrusion, Plastics Processing

1 INTRODUCTION
About 60 % of all plastics are processed with screw extruders. The starting point for plastics processing is a bulk compound of either powder, grit (small particles) or granulate which is compressed, melted and homogenised in the single screw extruder and then formed in the die. The individual functional zones can be seen in Fig. 1. The conveyance of the bulk material in the feed zone is of utmost importance since it is partially responsible for the steady flow of the material in the following extruder zones respectively in the die.

![Fig. 1: Schematic section through an extruder with the functional zones: hopper (I), solid material conveyance zone (II), delay zone (III), melting zone (IV), metering zone (V)](image)

To calculate the relevant parameters such as pressure and temperature along the screw for a defined melt throughput, simulation programmes are commonly used. The transport process is described by the equation of motion. Along with the calculation model, the material properties must be known. Most important are the internal and external coefficients of friction, the pressure anisotropy and the density as a function of pressure and temperature.

In order to draw in the bulk material into the extruder and to reach the processing pressure as quickly as possible the cylinder walls have tapered axial or spiral grooves. A relative movement is created between the material in the screw channel and in the grooves. Especially the shearing force at the grooved barrel rises between the solid material and the cylinder wall thus accelerating the feed and pressure build-up. During this conveyance, the bulk material is subject to both internal shearing in the area of the grooves and an external sliding at the smooth metal surfaces. Because the internal coefficient of friction is considerably larger than the external one, it is possible to assume a solid plug flow in the screw channel.

In contrast to fluids, pressure in bulk plastics does not propagate in all directions equally, a pressure anisotropy develops. To describe this pressure anisotropy, the coefficient of pressure anisotropy $k$ is used. This factor $k$ describes the relation of the pressures perpendicular to the direction of the external forces in a bulk material bed.

$$k = \frac{P_x}{P_z} \quad \text{bzw.} \quad k = \frac{P_x}{P_z}$$

(1)

The factor $k$ indicates a clear dependence of the pressure in the bulk material, the temperature of the bulk material, and the shape and hardness of the granules [1], [2]. The external and internal coefficient of friction show the same dependence. Besides, the coefficients are often dependent on the sliding velocity.

In the literature one finds various devices to measure external coefficients of friction. Goldacker [3] worked with an apparatus, which pressed the bulk material against a heatable rotating metal disk. To measure the internal coefficient of friction the bulk material was sheared in an annular gap, which was split horizontally in the middle. The bulk material was compressed using a coaxial annular piston. The surfaces at the front side of the annular gap had saw-toothed grooves so that the material was sheared in discrete layers in the area of the horizontal gap.

In Spalding’s device [4, 5] and in the tribometer of the Department of Plastics Processing of the University of
Leoben (fig. 2), [6], the plastic sample is pressed onto a rotating, heatable steel roll.

![Image of Rotortribometer](image)

**Fig. 2: Rotortribometer**

The friction device according to Hennes [7] (fig. 3) compresses the bulk material in the annular gap on both front sides by a coaxial annular piston. The outer cylinder moves intermittently while the compressed material inside remains still.

![Image of Friction device according to Hennes](image)

**Fig. 3: Friction device according to Hennes [7]**

The problem with these friction devices mentioned here is that with most of them only relatively low pressures or shearing forces can be used. At higher pressures there is the danger that the samples will melt too soon because of the friction heat so that no steady state conditions for the temperature can be realized. Comparison of the friction mechanism with real conditions in practice is thus only possible to a limited extent.

Measurements of internal coefficients of friction are hardly available. The problem of thermal changes is even more drastic. Under real processing conditions the external and internal coefficients of friction should be measurable for pressures up to at least 200 bar. For this reason it was decided to develop a shearing cell through which virgin material could be continuously transported to ensure a very close reproduction of the conveyance process in an extruder.

2 DESIGN AND FUNCTION OF THE NEW MEASURING DEVICE

2.1 Shearing cell with a continuous powder replacement

The most important features of the new measuring device are shown in Figure 4: the vertical arrangement of a solid conveying extruder, in which the screw (D = 70 mm ∅) extends perpendicularly into the hopper. Flow resistance is created by a coaxial annular piston which is positioned at the end of the 3 D long extruder. Interchangeable cylinder bushes are inserted in the temperature controlled extruder barrel. Of particular importance are the 5 radial pressure measuring probes which are based on the principle of a load cell.

![Image of Continuous flow-through shearing cell for bulk materials](image)

**Fig. 4: Continuous flow-through shearing cell for bulk materials**

The radial measuring tappets are guided in ball roller bushes. The particular advantage to this pressure measurement technique is that radial pressures from a few millibars up to several hundred bars can be measured. The load cells can be interchanged very quickly for any measurement requirements. Thanks to the ball roller bushes the measuring tappets move easily without jamming. The large, square measuring areas are adapted to the contour of the cylinder wall.

Both the cylinder barrel and the screw can be separately heat controlled. The surface temperature of the cylinder bushes is determined by heat flow sensors. The inner surfaces of the interchangeable cylinder bushes can be designed with various groove geometries. A smooth bush can be inserted for the measurement of the external coefficient of friction, and for the measurement of the internal coefficient of friction, polished axial saw-toothed grooves of various sizes can be used. The size
of the saw-toothed grooves depends on the size of the particles. The saw-toothed grooves are worked in uniformly for measuring the internal coefficient of friction. At their front ends the grooves have an open cross section so that they can be flushed.

2.2 Closed annular gap shearing cell

The shearing cell with a continuous powder replacement can also be rebuilt to become a closed annular ring shearing cell, as seen in Fig. 5. The screw is interchanged with a smooth shaft or one with grooves on its surface. The cylinder bushes of the continuous flow-through shearing cell can be used here as well. The annular gap is filled with a material sample which then is compacted by two coaxial annular pistons on both front ends.

![Fig. 5: Closed annular gap shearing cell](image)

3 EVALUATION TECHNIQUE

3.1 Shearing cell with a continuous powder replacement

The evaluation technique is based on measuring the torque, the back pressure and the radial pressure distribution. The radial pressure depends on the back pressure. In connection with the torque measured, the following evaluation can be made which allows us to determine the coefficient of friction dependent on pressure and velocity as well as on the temperature.

The differential torque \( dM \) is the product of the differential friction force \( dF_z \) on the cylinder wall and the half cylinder diameter \( D \):

\[
    dM = dF_z \cdot \frac{D}{2} \tag{2}
\]

The friction force on the cylinder is obtained from the shear stress \( \tau \) and the surface element \( dA \):

\[
    dF_z = \tau \cdot dA \tag{3}
\]

The shear stress can be derived from the coefficient of friction \( \mu \) and the average radial pressure \( p_r \) around the circumference:

\[
    \tau = \mu \cdot p_r \tag{4}
\]

The differential surface element is obtained from the channel width \( b \) and the differential unwound channel length \( dz \):

\[
    dA = b \cdot dz \tag{5}
\]

With these equations the differential torque writes:

\[
    dM = \mu \cdot p_r \cdot b \cdot \frac{D}{2} \cdot dz \tag{6}
\]

Integrating along the channel length \( L \), one obtains the torque:

\[
    M = C \cdot \int_0^L \mu \cdot p_r \cdot dz \tag{7}
\]

with

\[
    C = b \cdot \frac{D}{2} \tag{8}
\]

The measured torque \( M_{\text{ges}} \) must be reduced by the idle running torque \( M_L \):

\[
    M = M_{\text{ges}} - M_L \tag{9}
\]

The equation for the torque (7) is now converted in such a way that the integration can be carried out along the radial pressure profile.

\[
    \ln(p_r) \quad \text{z}
\]

Experiments show that the pressure development can be approximated by an exponential function of the form (Fig. 6)

\[
    p_r = p_{r,0} \cdot e^{\alpha \cdot z} \tag{10}
\]

For the differentiation of \( p_r \) at \( z \), one obtains

\[
    \frac{dp_r}{dz} = p_{r,0} \cdot \alpha \cdot e^{\alpha \cdot z} = \alpha \cdot p_r \tag{11}
\]

After the substitution of \( z \) by \( p_r \) one obtains for the torque

\[
    M = \frac{C}{\alpha} \cdot \int_{p_{r,0}}^{p_r(L)} \mu dp_r \tag{12}
\]

This equation is now partially differentiated at the radial pressure on the position \( z = L \):

\[
    \frac{dM}{dp_r(L)} = \frac{C}{\alpha} \cdot \left( \frac{1}{\alpha} \right) \cdot \int_{p_{r,0}}^{p_r(L)} \mu dp_r + \frac{C}{\alpha} \cdot \mu(p_r(L)) \tag{13}
\]
With the equation
\[ p_1(L) = p_{r,0} \cdot e^{\alpha L} \]  
follows for the differential equation of \( \alpha \)
\[ \frac{d\alpha}{dp_1(L)} = \frac{1}{L \cdot p_1(L)} \]  
One arrives at the differentiation of the reciprocal value of \( \alpha \)
\[ \frac{d}{dp_1(L)} \left( \frac{1}{\alpha} \right) = \frac{-1}{\alpha^2 \cdot \frac{1}{L \cdot p_1(L)}} \]  
Equation (12) can be converted to
\[ \int \mu dp_1 = \frac{\alpha}{C} \cdot M \]  
Equation (16) and (17) are inserted in equation (13). The following equation results:
\[ \frac{dM}{dp_1(L)} = \frac{1}{\alpha} \left( -\frac{M}{L \cdot p_1(L)} + C \cdot \mu(p_1(L)) \right) \]  
Now the coefficient of friction can be explicitly expressed with equation (19):
\[ \mu(p_1(L)) = \frac{1}{C} \left( \alpha \cdot \frac{dM}{dp_1(L)} + \frac{M}{L \cdot p_1(L)} \right) \]  
\[ \text{Fig. 7: The torque } M \text{ and the exponent } \alpha \text{ over } p_1(L) \text{ to determine the coefficient of friction} \]

Finally, the resulting values for the torque \( M \) over the pressure \( p_1(L) \) from several measurements have to be plotted into one graph (fig. 7). For each value of \( p_r(L) \), the torque \( M' \) and the gradient of the torque can be determined. When inserted in equation (19), with the corresponding \( \alpha' \), one obtains the value for the coefficient of friction at the pressure \( p = p_{rt}(L) \).

In addition an evaluation is carried out using the method of smallest error quadrates.

### 3.2 Closed Shearing Cell

The evaluation technique is based on the measurement of the torque, the piston pressure and the radial pressure. The torque \( M \) is calculated from the shearing force \( F_R \) and the diameter of the shaft \( D_r \).

\[ M = F_R \cdot \frac{D_r}{2} \]  
The internal coefficient of friction \( \mu_i \) is obtained with equation (21):
\[ \mu_i = \frac{2 \cdot M}{D_r^2 \cdot \pi \cdot L \cdot p_r} \]  

### 4 CONCLUSIONS

Constant temperature conditions cannot be realized at high pressures using a closed shearing cell. This is especially the case in measuring the internal coefficient of friction. The shearing cell with a continuous powder replacement allows the determination of relevant material data describing the material flow in the feed zone of an extruder. The evaluation technique permits both the determination of the external and the internal coefficient of friction as a function of pressure, velocity and temperature.

### 5 ACKNOWLEDGEMENT

The developed and built measuring apparatus was financed by the Austrian FWF. The authors would like to thank the FWF cordially for financing the project P14360-TEC.

### 6 REFERENCES