Technical Paper

Continuous Gravimetric Extrusion Control

Integrated, on-line loss-in-weight blending offers extrusion processors significant performance and cost saving advantages over traditional techniques

Gravimetric extrusion control has been around since the mid 80's. The sophistication, accuracy, and level of integration have improved greatly since the first systems were introduced due to the increasingly widespread use of computers and network technologies.

The goal of gravimetric extrusion control is to govern the extruder speed so that its output has a predictable and repeatable mass flow. This is desirable for three primary reasons. First, without gravimetric extrusion control the product may not be viable to produce in an economic fashion. The second reason is to maintain or improve product quality. And lastly, even though the initial investment may be considerable, gravimetric extrusion control can offer significant cost savings.

This technology is most often used in conjunction with single screw flood-fed extruders. Single screw machines are much more complex than they appear at first glance. Even with a well designed screw, the extruder is not a positive volumetric displacement device. If it were, rate checks would not be required for initial commissioning and each new material formulation. The output of the extruder is not a linear function and cannot be accurately determined by just monitoring the speed of screw rotation, motor amps, and die pressure. Throughput is a function of many variables including screw speed, screen pack blockage, die back pressure, polymer viscosity, melt temperature, material bulk density, conveying efficiency, screw fouling, screw/barrel wear, and material variation. Even with virgin material, clogging of the screen pack alone can reduce extruder throughput 10% or more within a week.

By actually measuring material throughput, gravimetric extrusion control can compensate for material and process variations and provide more consistent end product quality. The most common applications include profile extrusion, cast sheet, blown film, cable coating, laminating, precision tubing, and pipe extrusion. Gravimetric extrusion control is a virtual necessity for multi-layer coextrusion systems.

Discontinuous Gravimetric Extrusion Control Systems

The least sophisticated extrusion control systems use a pre-weighed batch of material (usually 3 to 5 kg) and a material proximity switch in the throat of a small surge hopper mounted on the inlet of the extruder. When the proximity switch becomes uncovered the pre-weighed material is dropped into the surge hopper through a refill valve. The time between switch closures and the previous batch weight are used to calculate the extruder throughput.

This approach lends itself well to a single ingredient system or use with a weigh-batch blender. Significant time between batches may be required to allow the weigh-batch blender to feed multiple ingredients and attempt to mix them in its weighed hopper. From a performance standpoint, in addition to material homogeneity issues and repeatability of the proximity switch, extruder throughput can only be calculated and corrected once each cycle. Even then, the correction can be made only after the measured batch is entirely consumed. At low extruder speeds the time between corrections could be quite long.

Another issue that potentially affects end product consistency is the necessarily large variation of material headload at the extruder inlet. Like any auger, material headload has a significant impact on extruder conveying efficiency. In addition, a system of this type requires significant headroom above the extruder to accommodate the surge hopper, refill valve, weighed hopper, possibly a mechanical mixer, feeders, and refill equipment.

The majority of the current systems installed use a weigh-hopper and the 'loss-in-weight' principal to measure and control extruder throughput. In this type of system a small surge hopper supported from one or more load cells is used as a weigh-hopper. The weigh-hopper supplies material to the extruder inlet but must be physically isolated from the extruder and equipment above it so that it can weigh the material it holds. It can only approximate the weight because the hopper must be open at the bottom to supply the extruder. A column of material extends up into the hopper that is actually supported by the extruder rather than by the walls of the hopper. As above, the system works by periodically refilling the weigh-hopper. Once the weigh-hopper is filled to some nominal weight, the control system shuts off the in-feed and monitors the weight lost from the weigh-hopper verses time. The extruder throughput is then calculated directly based on the loss of weight per unit time. Depending upon load cell resolution, plant vibration, extruder rate, and other factors control update times can vary considerably.

Loss-in-weight blending system with vacuum receivers mounted above a weigh-hopper on a single screw extruder, the third extruder on five-layer coextrusion sheet line ruder., the third extruder in a five-layer coextrusion sheet line.

Typically such systems need a weight loss of 0.5 to 1kg in order to estimate the extruder mass flow rate and make adjustments to screw speed. Of course, while the weigh-hopper is being refilled no rate calculation can be made.

Again, the feed system is usually discontinuous. There are several different feed system options. A weigh-batch blender can be used to supply the weigh-hopper through a discharge valve on its mixing chamber. Volumetric or gravimetric feeders can be cycled on and off to fill the weigh-hopper directly, or they could be used to fill an intermediate surge hopper with a discharge valve. Weigh-batch blenders have algorithms that attempt to maintain the desired ratio of ingredients in each batch. However, simply cycling multiple volumetric or gravimetric feeders on and off does a very poor job of delivering well proportioned ratios, and this method should be avoided for critical applications. Depending upon the implementation details, this type of system can also require significant headroom.

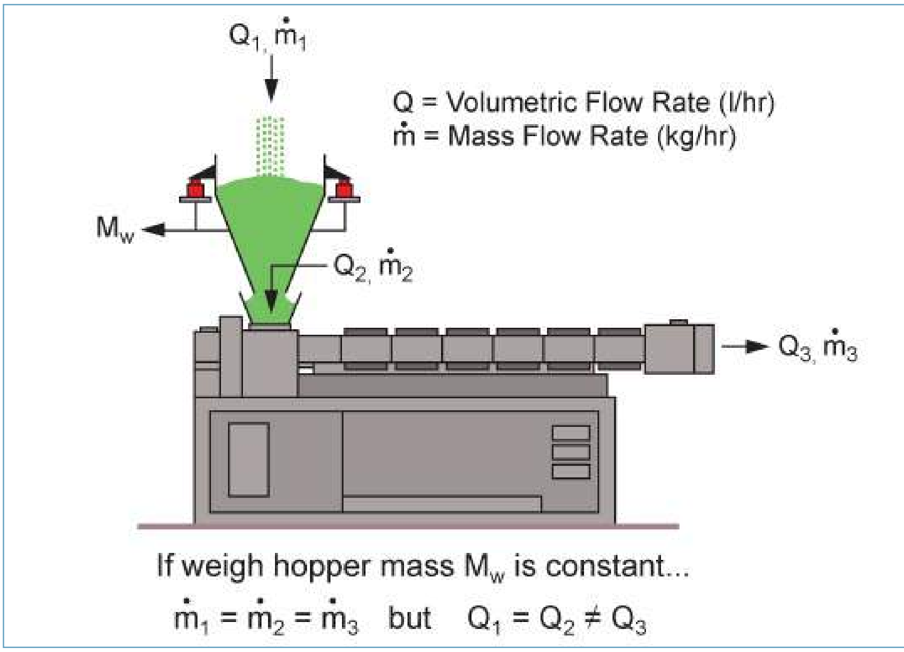

Figure 1 - Mass balance

Continuous Gravimetric Extrusion Control Systems

The systems described thus far don't take advantage of all the technology available through integration. A gravimetric feeder, especially a loss-in-weight feeder, can provide unparalleled accuracy and tremendous amounts of real-time information.

To attain the highest level of accuracy from the feed system a gravimetric loss-in-weight blender should feed all of the ingredients continuously at their correct ratio. Constantly starting and stopping multiple feeders creates small errors in the blend ratio due to timing errors and the difference in feeder dynamics between high rate and low rate feeders. Running all ingredients continuously ensures a good gravimetric blend ratio and avoids the problem of a segregated mix. In addition, if you can run a loss-in-weight feeder continuously it can determine the actual material mass flow in real-time with a high degree of precision.

To achieve the best short-term volumetric repeatability from a single screw extruder two things are required: steady screw speed and a constant material head on the extruder inlet. Modern variable frequency drives do an excellent job of controlling extruder screw speed, so that should no longer be an issue. As previously stated, significant deviations in material headload affect the conveying efficiency of the extruder screw. Despite this fact the gravimetric extrusion control techniques to date all rely on a headload change to calculate extruder mass flow. Is this really necessary?

If the level of material in a surge hopper on the extruder inlet is constant over some period of time then the volume of material entering the surge hopper must be equal to the volume exiting the surge hopper. A volumetric flow balance has been achieved. The goal is to achieve a mass flow balance since the extrudate has a much lower volume than the typical palletized bulk material entering the extruder. If the information from the continuous loss-in-weight feed system is utilized, then the mass flow into the surge hopper is known and a mass flow balance can be achieved.

As shown in Figure 1, under steady state, if the inlet level is constant, then the mass per unit time entering the extruder is the same as exiting the extruder. This can also work seamlessly for materials that must be introduced to the extruder through a side feeder. One or more materials can be gravimetrically fed to a starve-fed side feeder in the correct proportion to the balance of materials whenever the extruder is running. The loss-in-weight feed system now provides a dual role: it acts as both a gravimetric feeder control *and* a real-time gravimetric flow sensor.

Using this method, an extruder throughput deviation can be detected independent of extruder speed if the material level above the extruder inlet can be measured with sufficient speed and precision.

As usual there are several choices available to measure the level. The most frequently used technology for sensing of bulk materials used in plastics processing is capacitance. These sensors are primarily used for on/off applications, but in this case the level must be measured over a considerable range with good resolution. Capacitive ring sensors have been used but they are problematic and require recalibration for material changes and drift. Other possibilities include ultrasonic, microwave, or even laser, but these tend to be costly and can be confused by the incoming streams of material from the feed system.

It turns out that the best way to measure the material level is by weight. Although an open bottom weigh-hopper cannot measure absolute weight, relative weight is good enough to maintain a constant material head. The weigh-hopper does not care that material is entering and exiting, that the material surface is not flat on top due to its angle of repose, that its dielectric constant changes with formulation and humidity, or that the material has an electrostatic charge. There are still many challenges for a weigh-hopper used in this way, however. The weighing system must deal with constant vibration and large temperature variations but still have fast response, exhibit high resolution, good repeatability, low hysteresis, low drift and low creep.

As shown in Figure 2 it is the integrated control of the loss-in-weight feed system with a precision weigh hopper that provides the most accurate gravimetric extrusion control. Under this approach extruder headload is held constant, feeding is continuous and accurate, material ratios are always correct, material segregation is unlikely, and extruder mass flow can be continuously measured and controlled.

In the integrated system the extruder's mass flow is calculated as:

Mass Flow =
Sum of Feeder Mass Flows +
(Weigh-Hopper Weight Change ÷ Time)

If the weigh-hopper weight is constant (no weight change) then the extruder mass flow is equal to the total feed system mass flow. If the feed system needs to be stopped for a quick adjustment or repair,

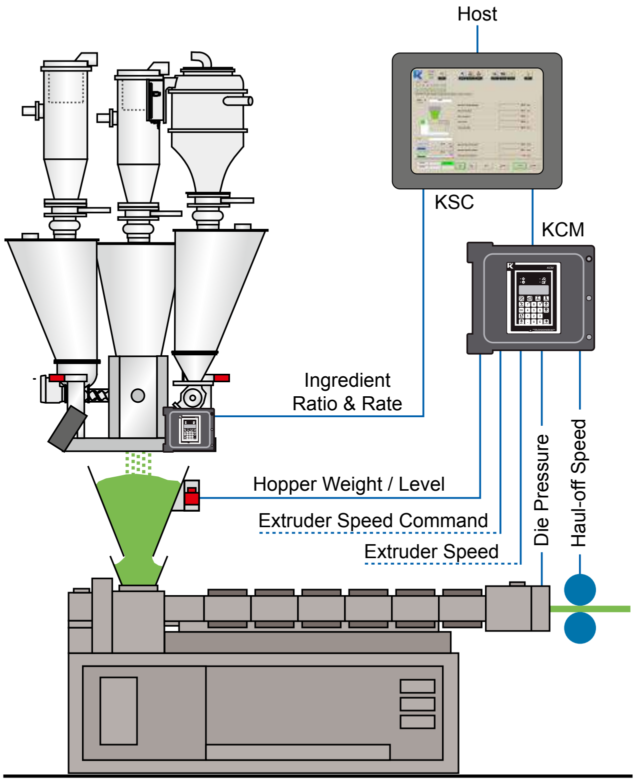

Figure 2 - Integrated gravimetric extrusion control with loss-in-weight feed system and precision weigh-hopper maintains constant headload at extruder inlet

the mass flow calculation simple reverts to that of a loss-in-weight weigh-hopper. The operator need only be concerned with the mass flow set point of the extruder and the percent ratio of the various materials being fed. The control system has an internal set point for the level in the weigh-hopper and to satisfy this set point the controller will adjust both the feeder set points and the speed of the extruder. This system provides additional benefits in that it can detect problems sooner while there is still significant material in the weigh-hopper, allowing the operator to react before the product goes out of specification. Thanks to computer and networking technology, data can also be more easily exchanged between multiple systems for both alarm and control purposes. Since most extruder suppliers also control their systems with a computer or PLC, information like extruder screw speed, die pressure, haul-off system speed, and even gauge data can easily be made available to the gravimetric extrusion control system.

Operating Modes

Once extruder mass flow can be continuously and accurately measured, there are several control modes that can be implemented. Obviously the simplest gravimetric extrusion control mode is mass-per-time (kg/hr), which is nothing more than controlled mass flow. This can give a simple profile or sheet extrusion a high level of consistency when combined with a constant speed take-off system. Dimensional checks can be made on-line or off-line and the operator can make changes by adjusting the extruder mass flow or the take-off speed. Once the process is stable, long production runs are possible since the extruder will now output a constant mass flow rate until maximum pressure or speed limits are exceeded.

A highly engineered co-extruded sheet may have six or more layers. Each of the layers is the output of a single extruder. The feed streams are usually combined in a single die to form the multi-layer sheet. Often the overall sheet thickness is continuously measured on-line using a beta gauge. Unfortunately, the beta gauge can only measure overall thickness. Traditionally, to determine the thickness of the individual layers pieces of the sheet need to be taken from the run and analyzed off-line. As shown in Figure 3, using gravimetric extrusion control the individual layer thicknesses can be measured and controlled with good precision. Since each layer is usually made up of multiple ingredients, it is not as simple as looking at the relative mass flow of each extruder, a blend density is also required.

With initial calibration, the loss-in-weight feeder can dynamically estimate each material's bulk density, which is usually a good estimate of relative specific gravity. To calculate the thickness contribution of each layer, the percentage of each ingredient in the layer is multiplied by its bulk density and then summed together to determine the relative density of the layer. The relative density of all layers is then summed and the thickness contribution of each layer is the ratio of layer's relative density to the sum. If a beta gauge measurement is available, each layer's thickness contribution can be expressed in the same units as the gauged thickness. Using the recipe capability of the gravimetric extrusion control system, each layer's formulation and thickness can be adjusted while still maintaining the overall thickness of the sheet.

Additional capabilities are possible when the take-off speed is also measured by the gravimetric extrusion control system. This provides the ability to control the weight-per-length (kg/m) of the extruded product, which now becomes the units for the system set point. This technique is often used with precision small-bore tubing where only the outside diameter can be directly measured on-line.

Several system arrangements are possible with a weight-per-length system. The gravimetric extrusion control system can be set up to automatically adjust either the extruder mass flow or the haul-off system speed as the primary control variable to maintain the weight-per-length set point. The operator can adjust the secondary variable and the controlled variable will follow. This is particularly convenient for applications where frequent line speed changes are required to change finished product spools or rolls. The operator can slow down the haul-off system, change the spool, then ramp the haul-off speed back to the operating rate while the extruder and feed system follows along maintaining the weight-per-length set point. If this ramping maneuver needs to be done rapidly the extrusion control system should be able to characterize and store the extruder throughput as a function of speed so as to improve control accuracy.

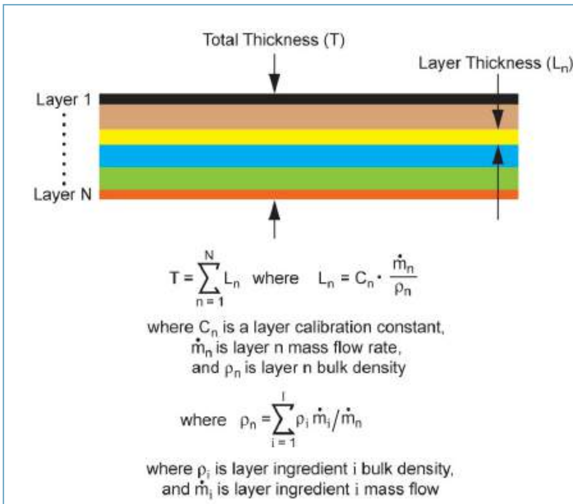

Figure 3 - Layer thickness control in multi-layer co-extrusion

Five layer co-extrusion sheet line running purge material. Shows four of five loss-in-weigh blending systems with vacuum receivers. Each sits above a continuous weigh-hopper.

Return On Investment

Gravimetric extrusion control provides many cost savings benefits. It can reduce start-up and product changeover times, improve product quality, reduce scrap, operate with less operator intervention, and reduce the need for frequent off-line quality assurance testing. In addition, an integrated system can provide information on long-term feed system and extruder performance for maintenance purposes and, of course, provide data for inventory control. These are all indirect savings, but direct savings can be even more significant.

There are two areas where raw materials savings can be found. The first is by operating the system closer to the minimum gauge specification for the end product. Because of the short- and long-term accuracy of the gravimetric extrusion control system, extruder output variations are significantly reduced. With speed-based control, it is not uncommon to run the extrusion system 5% above the minimum thickness specification to avoid producing non-conforming product. With a gravimetric system it is easily possible to reduce this by half or more. For example, if a sheet line running at 500 kg/hr operated 6,000 hours per year, it would require 3,000,000 kg of resin per year. The gravimetric system could allow the process to reduce throughput so that it could be run at only 2% above the minimum thickness. As a result there would be a material savings of 90,000 kg annually. Assuming an average resin cost of 1 Euro per kilogram, the direct material savings would be 90,000 Euro per year.

The second area of direct cost savings is through recipe optimization. Just as the improved accuracy of gravimetric extrusion control can provide material savings, so can the high accuracy of the loss-in-weight feeding system. By adopting a new, tolerance-based model of recipe formulation the processor can employ high-accuracy feeding to strategically exploit permitted variations in recipe proportions. Minimizing the use of expensive ingredients and maximizing the less costly ingredients can achieve a maximum savings without violating product specifications. Analytical tools are available to perform the calculations, but a good understanding of the process requirements and equipment capabilities is necessary.

Conclusion

Gravimetric extrusion control is a proven and powerful way to improve many extrusion applications. It enables the processor to directly close the control loop around end product attributes where dimensional requirements or consistent mass per length are critical. In all applications, it can make extruder output predictable, repeatable, and stable over a wide range and number of system variables.

The potential for both direct and indirect cost savings is significant, and will easily outweigh the initial investment over a modest timeframe. In addition, it can be shown that investment in higher precision and integration will result in greater savings and improved quality.

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