

Choosing your approach

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A process technologist or plant manager, tasked to improve productivity via process spectroscopy, might be forgiven for being overwhelmed by the apparent choice of methodologies, techniques and technologies currently available. However, if a systematic approach is followed the choices soon narrow down and, with a little luck, one or two solutions begin to present themselves as the most likely to succeed.

A methodology that I have found quite successful in the past has been to follow the sequence: Application; Output; Sampling; Technique; Technology; Modelling (see Figure 1). However, this sequence must always be considered with reference to *the process sample*. The process sample, at the process sampling point, is the single most important consideration and must be considered at each stage; this is not as trivial as it may seem. For example, the application may be to control the additive concentrations of polyethylene pellets, but the near infrared (NIR) probe used to do this may be inserted into the extruder and so will be seeing a hot, high-pressure melt. Even this is not totally straightforward, as the conditions experienced by the probe if it were to be inserted inside the extruder barrel would be much more extreme than those encountered at the formation tool on the extruder nozzle.

Application: what is the question?

Another not-quite-so obvious choice is the application. One needs to consider if the application is going to achieve the desired result. The normal requirement or objective for a process spectroscopic installation is *the cost-effective increase in throughput of high-quality product*. This statement is worth a little amplification: "Cost-effective" normally means payback within one financial year. That payback calculation also needs to take into account the cost-of-ownership as well as the capital cost and installation expenses. Longer payback times can result in the benefit being lost in the general variability of process/market conditions and can lead to an obfuscation of the benefit of the process

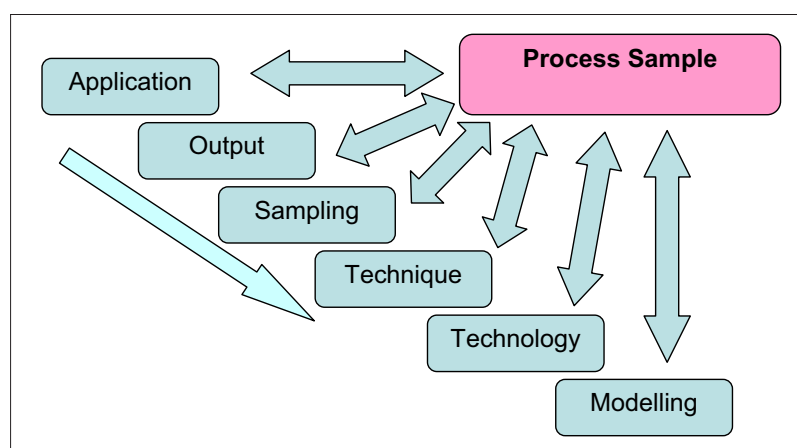


Figure 1.

monitoring itself. "High quality" means "in specification" with the added advantages of reducing giveaway and expensive over-processing of product.

The objective is best achieved by "de-bottlenecking", which implies that the process bottleneck (or rate determining step) of the process is identified and this addressed with the appropriate spectroscopic monitoring. In multi-step processes, the synthesis of the product can be a relatively fast process, the bottleneck occurring in the drying of the solid product. Monitoring of fluid bed driers by, say, reflectance NIR, allows the shortening of the drying cycle, and hence increases the existing plant capacity. Once the useful application has been identified a rational choice of process monitoring can then be made.

Output: what is the answer for?

The most common request for output is that it gives a number: the concentration of the product in the reaction matrix, the purity of the active, the amount of residual solvent in a drying process or quantity of unreacted material left in a vessel. These quantitative measures might well be accessible via process spectroscopy, but will require that the process is sufficiently well modelled to give a robust prediction. The model(s) will have to accommodate both variation within the process (inter batch) and between processes (inter

product) so that quality critical decisions can be confidently made on the basis of the data delivered to the operator or control system. The construction of such robust models can be both time consuming as well as expensive. There is often an alternative. GO/NOGO outputs can often achieve all that is required. For example, when reaction monitoring, it is normally sufficient to know that the reaction mixture is no longer changing and has therefore reached its endpoint, without a full quantitative model predicting exact concentrations. Such a qualitative model is much easier to construct as it can rely on relative data statistics, e.g. the rolling average of a UV absorbance, or the minimisation of the standard deviation of a wavelength region in the NIR spectrum or even the attainment of a multi-dimensional box (hypercube) in a plot of principal component scores calculated from Raman process data. There is a huge difference between a laboratory analysis and a process analysis even of the same parameter. In the laboratory situation it is usually possible to construct calibration samples that allow the spectroscopic response to the constituent of interest to be well characterised. In the case of the process sample, calibration samples are much less easy to obtain and data might need to be collected over a period of years in order to sufficiently model the process variability (e.g. in the case of a seasonal

product such as grain, which might be analysed for protein and moisture content). The use of a qualitative model can dramatically cut the cost and implementation time, whilst still delivering useful process information.

Sampling: the process/world interface

In most “real world” examples the sampling position is not a free choice. In nearly all cases there are a very limited number of places where the process sample can be accessed at reasonable cost. Few plants are built with the spare nozzles in the reactor and or extra transfer pipe sight glasses that would facilitate retro-fitting of a process analyser. Still fewer plants are built with the concept of in-line spectroscopic measurement as an integral part of the process. Most plants are built relying only on the output of simple, univariate sensors such as thermocouples and pressure transducers. Whilst these sensors can convey valuable information they do not yield the deeper, molecular information that is often required for highly-tuned, modern production. The cost of adding an extra nozzle to a reactor to allow the insertion of a Raman probe may well not be excessive; however, the cost of re-validating a pressure vessel is usually many times greater and can easily make the entire application unviable. Access to reactors is normally constrained to existing ports, baffles or sampling points (and sometimes at the expense of one of the simple sensors). Consequently the choice of sampling is constrained by the available access. If ports are already present, then fibre optic probes might be appropriate (e.g. NIR or UV/vis). If only a sight glass is present, some form of non-contact analysis is required (e.g. reflectance NIR, Raman or laser frequency modulation spectroscopy). If no optical access is possible the sample may have to be accessed via a fast loop to a flow cell or probe. The chemical nature of the sample will dictate whether a contact (UV, mid-IR) or remote sensing technique (e.g. Raman) is required and will constrain the materials of construction. Highly chemically resistant materials do not always have the required optical characteristics to be spectroscopic interfaces.

If only the sample headspace is accessible or the sample itself is gaseous, then low sample concentration is going to be an issue. Therefore high-sensitivity techniques need to be employed and the use of multipass cells may need to be considered, e.g. use of a 22-pass white cell for incinerator gas analysis.

Technique: the type of data to be utilised

It is only at this point, after having considered the requirements and constraints that have been highlighted by the first three considerations that one is in a position to consider the appropriateness of some of the different techniques available. It is certainly not true that all spectroscopic techniques can be sensibly incorporated into process analysis. In my opinion there are three classes of process spectroscopic techniques:

- those generally suitable for process analysis, e.g. UV/vis, NIR, Raman; those suitable for certain niche processes, e.g. mid-IR, head space mass spectrometry;
- those which are more challenging to incorporate directly into a process, e.g. NMR.

It is normally much easier to build an at-line system (i.e. a system that involves some form of extractive sampling) than to implement truly on-line, in-process analysis. In the case of at-line analysis great care must be taken that the sample at the analysis point is still representative of the bulk of the material remaining in the reactor. The extraction of a sample will always change it in some way, whether by altering the pressure, temperature or sheer forces. This means that an extracted sample is normally different from the bulk material and inferences then have to be drawn about the bulk material from the data in the extracted sample. Certain processes, e.g. crystallisation and polymerisation are particularly problematic with respect to extractive analysis as product can crystallise/polymerise in the extraction loop/flow cell.

Much could be written on the strengths and weaknesses of various spectroscopic techniques. Table 1 shows a personal view of such strengths and weaknesses for some of the most

commonly available process technologies.

Technology: the way in which the data is obtained

Often there are a number of different technologies available to obtain the same class of spectroscopic data. For instance, NIR spectra can be obtained by filter-, dispersive-, acoustic optical tuneable filter- (AOTF) and interferometer-based analysers. It is not possible to cover all the combinations of technologies for the different techniques available in this piece. However, there are a few general points to be made.

1) Different technologies have different strengths and weaknesses, e.g. filter instruments, for NIR say, are often cheap and simple. However, the data obtained is permanently limited to the filters selected. A full spectrum analyser allows the use of full multivariate analysis as well as the opportunity for future expansion of the analyser applications. An FT-based analyser will allow high resolution and high repeatability. An AOTF-based system will offer extremely rapid scan times.

2) Not all technologies are equally applicable to process conditions. As a rule of thumb, a process analyser should still be capable of delivering good quality data whilst being turned upside down and shaken. A minimum number of moving parts is desirable, as is a long period between routine maintenance events.

3) Technologies capable of remote sensing [e.g. interfaced with light guides (mid-IR), non-contact optics (e.g. Raman) or fibre optics (e.g. UV/vis or NIR)] are extremely desirable for process analysis. Remote sensing can remove the need for expensive, intrinsically safe systems and complex purged cabinets as the electrically powered

Table 1. Strengths and weaknesses of some commonly-available process technologies.

Technique	Mid-IR	NIR	Raman	UV	Visible
High sensitivity applications	✓	✗	✗	✓	✓
Relative capital cost of analyser	2	2	3	1	1
Analysis of organic in aqueous	✗	✗	✓	✓	✓
Analysis of aqueous in organic	✓	✓	✗	✗	✓
Suitability for remote sampling	(✓)	✓	✓	(✓)	✓
Good sample averaging	✗	✓	✗	✓	✓
Solid/slurry samples	✗	✓	✓	✗	✓
High chemical resolution	✓	✗	✓	✗	✗
General applicability of technique	✓	✗	✗	✗	✗
General applicability of technology	(✗)	✓	✓	✓	✓

parts of the analyser can be situated remotely in "safe" areas.

In a laboratory, the differences between technologies can often be blurred as different sampling regimes, data collection times and accessories can be used to overcome particular technology-based issues. In the process, the sampling conditions are much more constrained and are defined by the process sample itself.

Modelling: converting data into information

How process spectroscopic data is treated and then presented can be key to a successful process application. The presentation of a spectrum on a screen in the control room is not sufficient and the calculation of a quantitative result or some quality parameter, which can be assigned warning and alarm levels, is necessary to make that data useful. Simple univariate type models are easily understood, validated and maintained. Multivariate models often offer a wealth of additional information, outlier detection and statistical significance testing, but are generally more complex to construct and more sensitive to process changes or interferences.

Summary

A systematic approach can be used to select an appropriate process spectroscopic solution. Of course, there are exceptions to any rule. A large minority of process spectroscopy applications are safety related (e.g. monitoring the formation of toxic or explosive by-products). Whilst safety applications are by their nature different, and may have different constraints which affect the approach taken, they are still process-related and hence the application; output; technique; technology; modelling methodology can still provide a useful route map to a successful application.

What is important is that each potential process spectroscopic application is considered on its merits without preconceptions. One should approach a process with an open mind and let the sample and process define the approach to be followed rather than starting from the premise that one wants to put a particular spectrometer on-line.

Further reading

M.J. Pelletier, *Analytical Applications of Raman Spectroscopy*. Blackwell Science (1999).

I.R. Lewis and H.G.M. Edwards (Eds), *Handbook of Raman Spectroscopy: From the Research Laboratory to the Process Line*. Marcel Dekker, New York (2001).

J.M. Chalmers, *Spectroscopy in Process Analysis*. CRC Press (2000).