Scaling Up- Or Down

Published on May 1, 2017

Paul Martin

This pilot plant had 700 pieces of equipment, with extensive use of creative scale-specific solutions.

A good pilot-plant design must balance the need for physical and equipment similarity to the commercial process with the other goals of the pilot-plant program. Careful and creative design is necessary to ensure that the equipment will continue to work reliably for the duration of a campaign while maintaining sufficient process similarity to give reliable pilot-scale experimental data and observations.

I had a memorable lesson in grade 13 physics- one which would be strangely prophetic of what I would do for the rest of my career. Our physics teacher, Richard Haiser, started the lesson in his deliciously Hungarian-spiced baritone:

“Consider the Lilliputians…”

Photograph of a mural of Gulliver with the Lilliputians on a toy shop in Bremen, painter unknown, photo by Javier Carro c/o Wikipedia

I don’t know what inspired this lesson, because it seems somewhat beyond the normal high school physics curriculum of the day- but it was obviously effective for me, as it got me thinking about scale, which is the stuff and trade of the pilot plant business. He did this by comparing a few factors associated with the scale of the Lilliputians’ and Brobdingnags in Swift’s Gulliver’s Travels, to show how the physics of scale affect the living things around us.

He had us consider the Lilliputian- a person 1/12th the scale of a regular human. The Lilliputian’s volume, and hence mass, scaled with the cube of the scale dimension, whereas its surface area scaled with the square of the scale dimension. The Lilliputian’s ratio of mass (i.e. the number of cells available for heat generation) to surface area (i.e. the area through which he would lose heat to the surroundings) was 1/12th that of a regular human- and hence his food intake would need to be 12 times as high, in relative terms. It is therefore no surprise that mice and small birds have to eat a large fraction of their body mass in food each day to stay alive.

Scene from Gulliver's Travels, painting by Richard Redgrave, permanent collection, Victoria and Albert Museum, UK

He then had us consider the Brobdingnags, who were 12 times as large in all dimensions as a regular human. Here, the problem was that the volume and hence mass was 12^3 as high, and yet the strength of the bones varied as their cross-sectional area, which would only increase by 12^2. The Brobdingnag would be in serious trouble unless his physical form changed as he was scaled up… This of course puts some interesting limits on the size and shape of land animals, and goes some distance towards explaining why we find the largest animals in the sea.

The pilot plant designer's key problem is exactly what Mr. Haiser was trying to get across to us with his lesson: that some factors change with scale, and others don't. Within a process, there may be intermixing of factors that scale with those that will not. For example, residence time and solid feed particle size are generally kept constant with scale, but the volume and linear dimensions of reactor vessels, the area of settlers and heat exchangers, and the sizes of piping/tubing and throttling valve orifices vary with scale, and to different powers of the scale factor. When the variables and the constants collide, severe processing problems such as plugging, inadequate gas contact time, or excessive heat loss, can result.

Sometimes a particular scale cannot be achieved for a pilot plant at all. There will be cases where at a certain minimum scale, geometric scale down of the commercial unit operation or equipment becomes fundamentally infeasible and alternative approaches must be used for the pilot unit. Often these approaches involve switching some unit operations, such as solids feeding and slurry letdown from continuous to semi-batch, but sometimes it's more complicated than that. Zeton has about 700 projects worth of specialist knowledge related to how such problems may be successfully solved, as we encounter them on nearly every project to some degree.

Chemical engineers have a powerful tool to help with scale-up: dimensional analysis, and its result, the "dimensionless number". We have a host of dimensionless numbers which we work with every day: Reynolds, Prandtl, Nusselt, etc., but there are many more- the Peclet, Bodenstein, Froude and various Damkohler numbers etc. The rule here for scale-up is pretty simple: pick one and keep it constant with increasing scale. But which one? Still not so easy!

A very illustrative problem is the plug flow reactor (PFR). To get something approximating "plug flow", one needs fully developed turbulence, with a Reynold's number of at least 10,000. But anyone who has tried to size a PFR rapidly concludes that there is a minimum scale below which a PFR becomes impractical due to pressure drop- and even if you were to manage, you'd do well to dig out your copy of Levenspiel's Omnibook and do the calculations related to axial dispersion. Plug flow is an idealization, and axial dispersion may give you a residence time distribution very different than what that idealization might suggest. Conversely, in a large pipe, a Re of 10,000 may be achieved at surprisingly low velocities, rendering a PFR practical at scales where it might be dismissed out of hand.

An example of a pilot-scale PFR for a confidential client and process

Add a little viscosity and the PFR concept seems, at first glance, to go straight out the window. But we at Zeton have done many PFRs for polymer applications and other applications for viscous liquid processing. How are they done? Static mixers. Static mixers don't fully approximate plug flow, but they do a decent job, and most importantly they constantly move material from the heated or cooled shell to the interior.

Mechanical mixing also changes with scale, getting worse as scale increases. A key design issue is how to impair the usually spectacular mixing achievable in a pilot unit, so that it meaningfully approximates what you will get in your commercial unit. Mixing consultants and the specialists as some of the mixer manufacturers can help with this. There's more to it than merely varying the mixer RPM during your experimental work!

Heat loss and heat gain are the most obvious problem for pilot scale equipment. The heat loss situation for pilot units is often extreme. Depending on the nature of the process and the materials being processed, electric heat trace, cold tracing or even vacuum insulation may be required. In some cases, the stream may just be allowed to heat or cool to ambient and then needs to be "tempered" before entering the next unit operation. In others, the effectiveness of heat tracing determines almost entirely how long your campaign will last before you get a blockage and are shut down.

The process of selecting the scale multiplication factor between pilot and demonstration, or between either of these steps and the commercial plant, is too complex a topic to cover in a LinkedIn article. Zeton has a lot of skilled people who can help you make the right decision.