Biological and Chemical Reactor Control Opportunities

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ABSTRACT

Biological and chemical process performance is largely determined by reactor performance. The stage for product quality and process efficiency and capacity is set by reaction yield and selectivity. The burden and difficulty for downstream separation and purification processes is minimized by better reactor control. In this tutorial the factors affecting reactor performance are described with examples. For chemical reactors, the general effect on reaction rate of temperature and the concentration of reactant and recycle is described. For biological reactions the effect of pH, temperature, dissolved oxygen, byproduct, substrate, and inhibitor concentration on cell growth rate and product formation rate is discussed. Basic control strategies are discussed for chemical reactions based on liquid and gas phases and for biological reactions based on cell type. Considerations for polymerization reactions are briefly outlined. The relative advantages of cooling and heating control system designs are summarized. Simple translations of variables or additions to the basic control strategies are offered for optimizing production rate. Fed-batch profile opportunities are outlined for chemical and biological reactors for faster and more repeatable batches. The dynamics of reactor response are categorized into three general types. The effect of application dynamics such as process response, controller tuning, noise, and automation system response on the ability of reactor control systems to reach setpoint quickly and reject disturbances is explored. An enhanced PID algorithm developed for wireless measurement and control is explained and the algorithm's ability to eliminate oscillations from backlash-stiction, large update or sample times, split range discontinuities, and valve position control interactions is discussed. The use of dynamic reset limiting and directional velocity limits for preventing oscillations and safety instrumentation system activation is noted.

INTRODUCTION

Reactor yield is the mass of product produced divided by the mass of reactants added. Conversion is the mass of reactants converted divided by the mass of reactants added. If there are no waste products or byproducts, conversion becomes a good indicator of yield. An increase in yield can be used to

increase production rate for same reactant feed rate or can used to decrease raw material costs for the same production rate. For batch reactors, an increase in yield can be taken as shorter cycle time for the same reactant charges or as smaller reactant charges for the same cycle time. Yield also determines product quality. A higher yield reduces downgraded products, recycle, and waste. Reactor type, reaction rate, and time available for reaction affect yield. Process conditions such as temperature and concentrations affect reaction rate. Process conditions such as inventory, feed rate, and agitation affect mixing and residence time, which determines uniformity and time for reaction. ***Process control is essential for controlling process conditions and hence reaction rate and time for maximum yield.*** The automation system strategy, dynamics, tuning, and PID algorithm are all critical for success.

OVERVIEW

REACTOR TYPE

Reactors involving liquid reactants can be categorized as continuous stirred tank reactors (CSTR), batch, fed-batch (semi-batch or semi continuous), and plug flow. In continuous reactors, there is a continuous discharge of product flow. A level controller is used in the CSTR to maintain a level that provides enough reaction time for a given production rate. In batch and fed-batch reactors, the discharge valve is closed until the batch is ready to transfer. A gas product or byproduct may be continuously generated during the batch and condensed and accumulated in an overhead system but a liquid and/or solids phase reaction without a continuous liquid and/or solids discharge flow is the distinguishing characteristic of batch and fed-batch. The implications as to dynamics, yield, and inventory control are significant.

Reactors have 3 types of dynamic responses when the PID is put in manual and a step change is made in the PID output. For purposes of identification and characterization of the response, there are no process disturbances or effects from other loops so that the open loop response observed is totally the result of the change in the PID output. ***If the response lines out at a new value (steady state), the process is termed "self-regulating." If the response continues to ramp and doesn't settle out to a new value, the process is termed "integrating." If the response accelerates with a continually increasing rate of change, the process is termed "runway." An initial response of any of these processes in the opposite direction of the eventual response is termed an "inverse response."*** Temperature control by manipulation of cold feed can exhibit an inverse response particularly for slow reactions. The dynamic parameters and implications of these responses are discussed in the performance and tuning sections.

The residence time for a CSTR is the volume divided by the total flow of feeds. For a batch reactor, the residence time is the cycle time. In a CSTR some of the reactants appear in the discharge within one turn over time, which in general is less than 1/20 of the residence time. The amount of time spent in the

reactor varies resulting in a residence time distribution and a loss in yield in the CSTR. Several CSTR reactors in series or a reactant recovery and recycle system can be used to improve the yield of the production unit. For a batch reactor, the residence time distribution is tight except for the some variation from reactions taking place during the charge of reactants or as the batch is being emptied. For a given size reactor, the production rate is higher for a CSTR than a batch or fed-batch reactor A CSTR after startup is continually producing whereas a batch or fed-batch takes time to charge reactants, bring the contents to the proper temperature and pressure, wait for the reaction to complete, and then empty the reactor. In some cases the reactor may need to wait on shared resources such as feed weigh tanks or on operator actions or lab results.

There is generally no level control except perhaps in terms of a high level override or high level shutdown of feeds in batch and fed-batch reactors. ***In batch reactors, the reactants are fed sequentially and shutoff when charge tank weight measurements or flow totals indicate the total amount charged is complete.*** On-off isolation valves are used to start and stop feeds. Flow controllers and control valves are sometimes used to prevent vapor system overload and provide a repeatable feed cycle time. ***In fed-batch operation, the reactants are fed simultaneously at a rate determined by a control system.*** As a minimum there are flow controllers for each reactant. ***Many of the same control systems used for continuous reactors are applicable to fed-batch, except there typically is no level and residence time control.*** The literature does not lead one to understand that the pressure, temperature, and composition controllers used in continuous reactors to manipulate reactant flow setpoints can be used for fed-batch. The use of these cascade control systems in fed-batch may even be more important because of the opportunity of these systems to provide batch profile control.

A plug flow reactor has no back mixing (axial mixing). Plug flow reactors are inline systems often as pipes or tube(s). In static mixers baffles are used to provide radial mixing. In extruders, a screw pushes a viscous liquid and solids to the exit. Since there is no back mixing the reaction mass exits at a time equal to the transportation delay. A plug flow reactor is similar to a fed-batch reactor in that there is generally no level control and the residence time distribution is tight. If you consider a subsection of the reaction mass moving from the entrance to the exit, there is no discharge from this volume until the subsection approaches the exit.

Polymerization processes often use batch and plug flow reactors operating with high viscosities. For highly viscous products the residence distribution is not as tight. Product can accumulate on the vessel walls in batch reactors. The velocity near the pipe wall in plug flow reactors is slower from frictional drag causing the product near the wall to arrive later. The increase in time available for reaction increases the viscosity of the fluid near the wall aggravating the problem.

There is a profile of temperature, physical properties, and composition with respect to length for a plug flow reactor whereas a fed-batch vessel has a profile with respect to batch time. Both plug flow and fed-batch reactors have opportunities for profile control and optimization. ***Since composition generally goes in one direction only with length and time, the slope is controlled at points in time***

and length for composition profile control. For extruders, the decrease of temperature and the increase of viscosity with length can be optimized.

Gas phase reactors are generally always continuous. Many use fluidized catalyst beds. There is little to no back mixing except from turbulence. Consequently, the residence time distribution is tight and the dynamic response to changes in reactant feed is a transportation delay similar to the plug flow liquid reactor except the reaction times are faster and the residence time shorter from a much higher velocity. Relatively fast temperature control is possible for highly exothermic gas reactors by the manipulation of reactant feed rate. ***The process deadtime from transportation delay of reactants is small compared to the lags from catalyst heat capacity and thermowell design.***

Continuous processes cost less in terms of investment and utilities for a given capacity but generally require greater process research, development, and design. ***Mature high capacity products (e.g. oil, gas, and petrochemicals) tend to use continuous reactors whereas new high value processes (e.g. specialty chemical and biological) primarily use batch and fed-batch reactors.*** As volumes increase and the profit margins decrease (product becomes a commodity), there is increased emphasis on developing a continuous process to provide a higher capacity and lower operating cost.

The fastest and simplest implementation is batch with quantities charged sequentially mimicking lab experiments much like ingredients in a recipe. As knowledge is gained batch reactors can move to become fed-batch reactors and eventually continuous reactors if there is enough demand and reaction chemistry permits a variable residence time. Sometimes fed-batch is called semi-batch or semi-continuous**.** However, there is an important distinction between fed-batch and continuous reactors in that in fed-batch as in batch reactors there is no liquid product discharge flow until the end of the batch. The lack of a liquid discharge flow causes the level to rise with reactant addition. The increase in level from the start to the finish of the batch has significant implications as to the dynamic response of temperature and composition requiring tuning methods and settings not commonly discussed in the control literature. For example, a temperature controller gain of 50 is possible for fed-batch reactors.

Candidates for continuous reactors are products with a low profit margin, high volume requirement, fast reaction, minimal adverse reactions, preventable buildup of inhibitors and inactive components, and extensive R&D history leading to a deep fundamental knowledge of kinetics. Oil, gas, chemical intermediates, petrochemicals, and commodity chemicals use continuous reactors. Extensive integration of unit operations for energy recovery and recycle of materials offers complex opportunities for optimization.

Candidates for batch reactors are products with a high profit margin, low volume requirement, slow reaction, significant side effects, and minimal knowledge of kinetics. Specialty chemicals and especially biopharmaceuticals are produced by batch reactors. For new biopharmaceuticals with the patent expiration clock ticking and extraordinarily high prices (e.g. > $1000 per gram), the time to

market supersede any consideration of process efficiency. These processes have extremely slow kinetics requiring days to weeks for the cells to produce product. Also, the buildup of dead and mutated cells, toxins, inhibitors, viruses, and bacteria must be prevented by emptying, cleaning, and sterilizing the equipment after each batch. Some mature biopharmaceuticals are produced by "perfusion" processes operating in the continuous mode for months at a time with extensive recycle. Periodically, these processes are shutdown for decontamination.

A CSTR has a slow self-regulating response. A batch and fed-batch reactor has a slow integrating response. A plug flow and gas phase reactor has a fast self-regulating response. These reactors can develop a runaway response when the increase in reaction heat release with temperature exceeds the cooling capability. The use of an analyzer with a sample, cycle, and/or multiplex time almost guarantees deadtime dominance (total loop deadtime larger than open loop time constant) for composition control of continuous, plug flow, and gas reactors. A subsequent section on performance will show that that the deadtime or self-regulating time constant must be much smaller than the runaway positive feedback time constant for stability.

Table 1 Reactor Type Dynamics and Control
(* - additional control besides temperature and pressure control)

Reactor Type	Dynamic Response	Residence Time Distribution	Reaction Rate	Additional Control *
CSTR	Near-Regulating Runaway	Wide	Moderate	Level Composition
Batch	Integrating Runaway	Very Tight	Slow	None
Fed-Batch	Integrating Runaway	Very Tight	Slow	Time Profile
Plug Flow	Self-Regulating Runaway	Tight	Fast	Length Profile
Gas	Self-Regulating Runaway	Tight	Very Fast	Composition

REACTION RATE

The yield and consequently the product quality and capacity depend upon reaction rate. ***Reaction rate depends upon temperature and composition.*** The reaction rate can increase dramatically with temperature. High temperatures can trigger side reactions to undesirable byproducts, degrade product, and in the case of biological reactions cause cell death. Since temperature is readily measured, a considerable increase in reaction rate is often possible by knowledge of the optimum temperature setpoint, accurate temperature sensors, and tight temperature control.

Reaction rate depends upon the concentration of reactants, initiators, promoters, inhibiters, byproducts, waste products, and primary products. In chemical reactions the reactants are chemical compounds. For catalytic reactions, the reaction rate also depends upon the concentration and condition of the catalyst. In polymerization reactions, the reactants are monomers, joined chemical compounds, and the product is a chain of these monomers. In biological reactions, the reactants are oxygen and food sources such as glucose and glutamine called substrates. Waste products such as acetate, ammonia, carbon dioxide, glutamate, lactate and phosphate inhibit cell growth or product formation. Some of these waste products affect cell pH and osmotic pressure, both critical for the health of the cell. Biological products are either held in the cell or secreted. The oldest products, such as alcohol for beverages and fuel, are simple chemical compounds secreted by yeast. New pharmaceutical products are complex proteins found in the body that require the mammalian cell, an incredibly sophisticated reactor, for formation.

To prevent an excess or deficiency of reactants, the reactant concentration must be in the ratio set by the stoichiometric equation, the fundamental basis for the reaction. Reactant feed flow setpoints are often ratioed to help maintain the right concentration ratio in the reactor. However, errors in flow measurements, stick-slip and backlash in valves, differences in flow loop responses, non-ideal mixing, cause concentrations in the reactor to vary from the ideal ratio.

Chemical reactions can use chromatographs for reactant and product concentrations but the significant resource requirement often distracts small companies and small products from making the investment in the capital and expertise for the design, installation, and maintenance of the analyzer and the sample system. ***High capacity products such as petrochemicals and intermediates greatly depend upon the added value of chromatographs because even a fractional percent increase in production rate is millions of dollars.*** Often there are parallel trains of reactors that can share a chromatograph. ***For polymerization reactions gel chromatographs are used to determine molecular weight distribution for yield prediction and control.*** Viscosity meters can provide in some cases inferential measurements of average molecular weight. Polymer quality also depends upon non-molecular characteristics, such as impact resistance, tensile strength, color, and optical clarity that require special lab tests.

Biological reactions utilize a wide variety of composition measurements including potentiometric and amperiometric electrodes for substrates and waste products, and dielectric spectroscopy and digital imagery for viable cell concentration, and near infrared (NIR) spectroscopy for chemical compounds. The analysis of complex proteins presently requires special tests that can take days.

Inventory control by the use of simple pressure or level control can be used to help prevent an excess accumulation of a reactant. A pressure control manipulating a gas reactant feed rate for a liquid product and a level controller manipulating a liquid reactant for a gas product will automatically add reactant at the rate the reactant is consumed and shutoff the feed when the reaction stops. This relationship holds true for batch, fed-batch, or continuous reactors. A purge from the opposite phase of the product is necessary to prevent the accumulation of inerts or non-reactants that reduces the volume of reactants. For a gas product, a liquid purge and for a liquid product, a gas purge is needed.

REACTION TIME

Neutralization acid-base reactions are essentially instantaneous and occur as fast as mixing allows. Most other reactions have a measureable reaction rate. ***The amount of time reactants stay in contact is called residence time in continuous operations and is simply the reactant phase volume divided by the total volumetric reactant phase flow rate.*** If the volume does not change with reaction rate, the residence time changes. If significant solids buildup on the wall in polymer reactions or inert accumulation occurs, the volume of reactants and consequently the residence time is reduced.

For fed-batch and batch operations, a batch cycle time is used instead of the residence time for the liquid phase. If the time is too short, the reaction is not complete. If the time is too long, side reactions producing waste products may develop and reverse reactions may occur. There is an optimum residence time or batch cycle time.

In batch operations, the batch cycle time is often longer than necessary for completion of the reaction. The primary reasons for this practice is the lack of online composition measurements, a conservative approach, the lack of product degradation, insufficient research, and the simplicity of a fixed batch cycle time. Consequently batch reactions are candidates more for capacity than yield improvement. Batch cycle time improvements are often easy to implement and offer an order of magnitude greater increase in capacity typical improvements in continuous processes (e.g. capacity improvements of 20% for batch versus 2% for continuous).

In continuous operations, some reactants end up in the exit flow because a non-zero reactant concentration is necessary for the reactant to proceed and a well mixed volume means some of the reactant is in the discharge flow. For continuous reactions requiring precise residence time control, a plug flow reactor is used that by definition has no axial or back mixing. The lack of back mixing

means that the time the reactant takes to go from the entrance to exit of the reactor is constant. Eliminating the variation in residence time for reactants provides a more repeatable reaction result. However, for concentration control, the process response is pure deadtime that is a transportation delay with no time constant. A process time constant acts as a filter to attenuate oscillations from reactant pressure fluctuations or valve stick-slip and noise from non ideal mixing. If a pipe is used there is little radial mixing. If a static mixer (baffled section of pipe) is used there is considerably more radial mixing. High viscosity reduces radial mixing. The cross sectional variation in reactant concentration increases as radial mixing decreases. If the plug flow reactor is operated with no heat transfer, there is also very little temperature variation in the cross section except for high viscosity fluids due to less radial mixing and heating along the wall from shear. If temperature control is used to vary the heat transfer, there is a temperature gradient from the wall to center of the pipe or static mixer. There is an axial temperature and concentration along the length of the reactor as the reactants react in the path from the entrance to exit. The temperature profile may be controlled by manipulation of heat transfer fluid to zones of the reactor. An extruder is essentially a plug flow reactor with a moving radial agitator (screw) where the polymer is processed as it moves from entrance to exit. Extruder zones are temperature controlled. The speed of the screw is a greater source of energy input and has a greater impact on product quality than zone temperatures. There is an optimum specific energy consumption (SEC) (kJ/kg or BTU/lb) for a given residence time. Since the extruder volume is fixed, the residence time is proportional to feed rate. There are generally efficiency ellipses in a plot of SEC versus feed rate with the greatest efficiency at the center.

CONTROL SYSTEM

The predominant controller for reactors is the PID. ***For highly exothermic reactors, the exceptional disturbance rejection of the PID with maximized gain and rate time settings is the proven way to prevent a runaway.*** In highly exothermic reactors, an increase in temperature can cause an exponential increase in reaction rate and heat release and subsequently temperature. In some polymerization reactions, the heat release can exceed coolant system capabilities resulting in a point of no return. To prevent the temperature from accelerating, the PID must take aggressive action based on the direction and rate of change of temperature provided by proportional and derivative action in the PID. Thus, an increase in temperature below setpoint will preemptively provide additional cooling Integral action would be working to decrease cooling or in split range applications to increase heating leading to overshoot of the setpoint. Integral action is decreased for reactors by increasing the reset time.

The dynamics of the process and automation system set the ultimate limit to loop performance. ***The process dynamics for vessels offer incredibly tight concentration, level, pH, pressure, and temperature control.*** The process dynamics of plug flow reactors not conducive to tight control. Regardless of the type of reactor, the automation system dynamics are the overriding factor for the ultimate limit to loop performance. The practical limit to loop performance is set by PID controller tuning. The practical limit approaches the ultimate limit as the controller tuning becomes more aggressive. Tuning method, process nonlinearity, measurement delay and lag, valve sensitivity, and

noise largely determine how aggressive the tuning can be. In general gain action should be maximized and reset action minimized. Also, the approach to an optimum must be slow to avoid upsetting operating conditions and the recovery from disturbances driving the reactor into activation of an SIS or relief device must be fast. Enhancements to the PID algorithm eliminate cycling from sensitivity limits and noise and provide a cautious approach to optimums and a fast getaway from undesirable conditions for rapid disturbances.

CHEMICAL REACTOR CONTROL

Inherent reactor performance depends as with most unit operations upon process design. ***The volume must provide sufficient residence time at the highest future production rate and enough cooling for the worst case condition of high production rate and high temperature excursions. The mixing must provide intimate contact of reactants and a uniform distribution of temperatures and concentrations.*** The methods of agitation and reactant addition must provide minimal deadtime from turnover times and transport delays. The jacket and coil heat transfer systems should minimize nonlinearities and discontinuities created by split ranged valves used for heating and cooling.

SINGLE PHASE CHEMICAL REACTORS

For reactions that are all in one phase (gas, liquid, or solid), inventory control (pressure or level control) cannot not automatically adjust a reactant flow for changes in conversion to prevent an excess or deficiency of reactant. For well mixed reactors the largest sources of improper reactant concentration are errors in reactant flow measurement and changes in reactant composition. Coriolis meters can be used to provide the greatest mass flow measurement precision and rangeability with density correction for any changes in reactant feed concentration. If the reactant and solvent densities are similar and product density is quite different, a Coriolis meter in a recirculation line could provide a measurement of product concentration. Online composition measurements by means of sensors in a line are preferential to at-line analyzers with sample systems to eliminate sample and analyzer cycle times. If online or at-line analyzers are not feasible, lab analysis results with the time the sample was taken noted must be communicated as quickly as possible to the control system. The composition measurements should be used to provide a correction of the ratio of reactants. Coriolis meters are most accurate on liquid streams but can used on gas streams of sufficiently high density due to pressure or molecular weight.

For liquid reactants and liquid product, a level loop controls the inventory and time available for reaction by manipulating the discharge product flow (Figure 1a). ***If the desired reactor residence time multiplied divided by the total reactant flow is scaled and used as the setpoint of the level controller, the level loop helps maintain a constant residence time for continuous reactors.*** Batch reactors don't

have a level loop and the concept of a residence time is replaced with a batch time for available time for reaction. The rising level of a batch increases the non-self regulation of the open loop temperature and composition response necessitating the use of higher controller gains to provide sufficient closed loop regulation. Integral action is also more likely to produce overshoot of setpoint.

Temperature loops control the energy balance and the reaction rate*. *The cascade temperature control system offers the greatest linearity and responsiveness to coolant pressure and temperature upsets (Figure 1a). The reactor temperature PID manipulates the setpoint of a jacket inlet temperature control that in turn manipulates makeup coolant flow ensuring a constant jacket coolant flow. An enhanced PID is used for jacket inlet temperature loop to prevent limit cycling from valve stick-slip. The relative merits of various temperature system designs are discussed in the subsection on cooling and heating systems. For fed-batch reactors, there is no level control and hence no residence time control but otherwise the same control scheme is applicable.

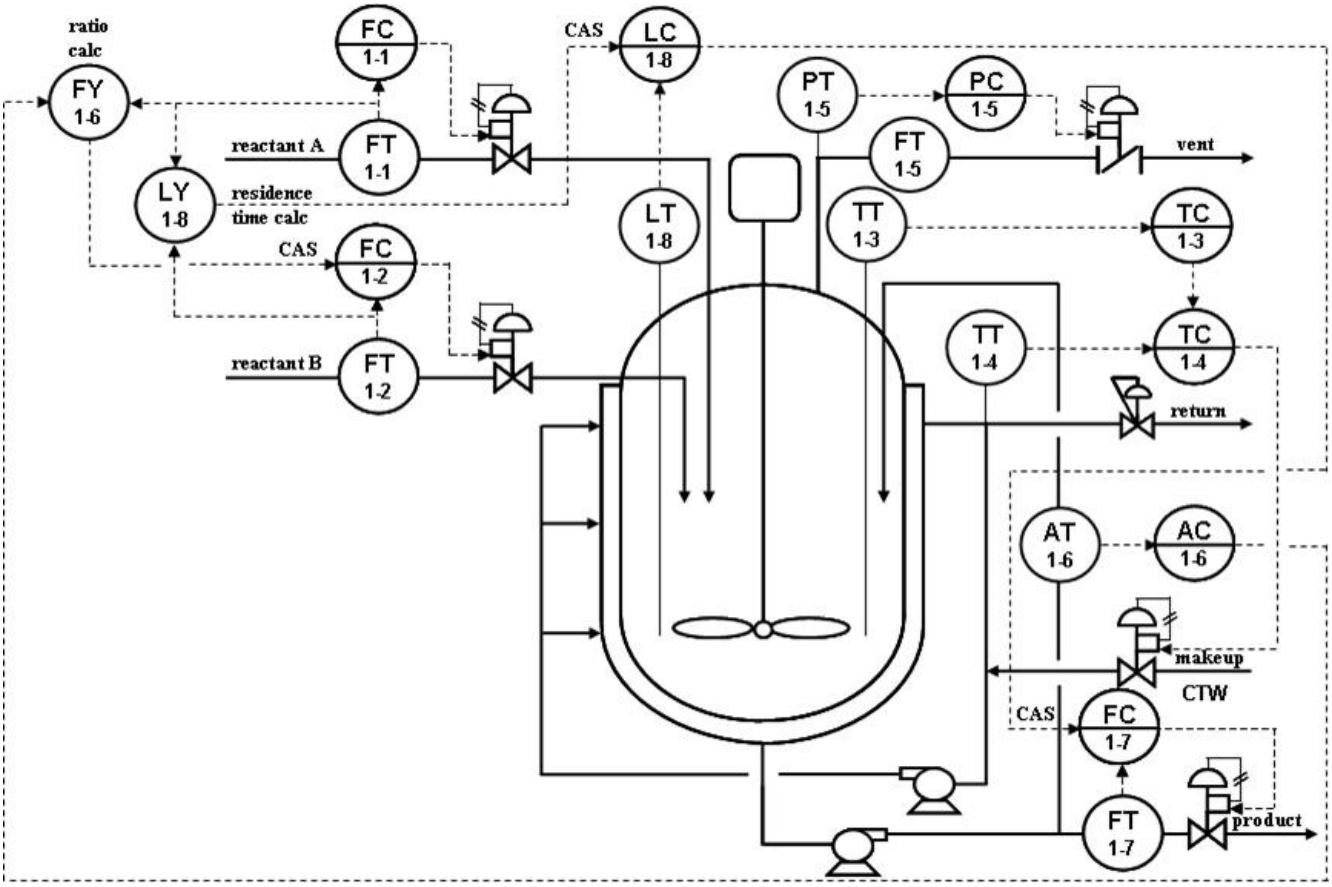

Figure 1a. For a liquid reactor, level control sets reaction time via residence time, temperature control sets reaction rate via energy, and composition control enforces the stoichiometric ratio
(Strategy is also applicable for fed-batch reactors without reactor level and residence time control)

Poor flow distribution and the lack of radial and axial (back) mixing in the fluidized catalyst bed create noise and hot spots. Multiple temperature sensors are used in each thermowell to compute an average temperature. The highest of the average temperatures is selected for PID control.

An at-line analyzer with a sequenced sample system can provide composition control for several reactors to correct the ratio of reactants (Figure 1a). An enhanced PID is used in the composition loop to prevent excessive reset action and cycling from the large sample and analyzer cycle time.

The simplest control scheme for maximizing production rate would be simply setting the coolant valve completely open and having the temperature controller bringing as much feed as the maximized coolant system can handle. ***The manipulation of reactant feed by a temperature controller for maximization of production rate causes inverse response for feeds colder than the reaction temperature and introduces a large lag that is the composition time constant of the vessel volume***.

In a first order plus deadtime approximation for the temperature response, all times constants smaller than largest time constant are converted to equivalent deadtime. The largest time constant should be the primary process time constant, the thermal process time constant for temperature control. The direct manipulation of feed rate for temperature control coupled with a slow reaction rate can cause a composition response time constant larger than the thermal time constant. An incredibly coated temperature sensor could cause a measurement time constant larger than the thermal time constant. The slow composition response causes slow correction and the slow sensor causes slow recognition. In either case, control severely deteriorates and the thermal time constant becomes effectively deadtime.

For fast gas reactions, the residence time and consequently the composition time constant are small enough for this scheme to be effectively used, particularly when reactions are highly exothermic with a large heat generation that overwhelms any cooling effect of feeds.

Production rate can be maximized by the use of a valve position controller (VPC) monitoring coolant valve position (Figure 1b). The VPC setpoint is the maximum desirable valve position, and the VPC process variable is the jacket temperature controller output. The use of actual valve position is unnecessary if the coolant valve has a digital positioner. The maximum throttle position setpoint keeps the coolant valve near a point on the installed characteristic that has sufficient slope (valve gain) to correct for disturbances. The output of the VPC trims the setpoint of the “leader” reactant flow controller. An enhanced PID with dynamic reset limiting for the VPC eliminates limit cycles, reduces interaction between the VPC and the jacket temperature controller, and enables smoother optimization with faster correction for large disturbances. The VPC analog output block velocity limit would be faster for correcting an increase in valve position to prevent running out of valve for high heat releases. The velocity limit would be slower for the opposite direction to provide a more gradual optimization. Dynamic reset limiting in the PID automatically prevent PID reset action from going faster than

velocity limits allow or the feed flow can respond. ***To see the increase in production rate in fed-batch operation, either the batch cycle time must be allowed to decrease or the batch mass to increase.***

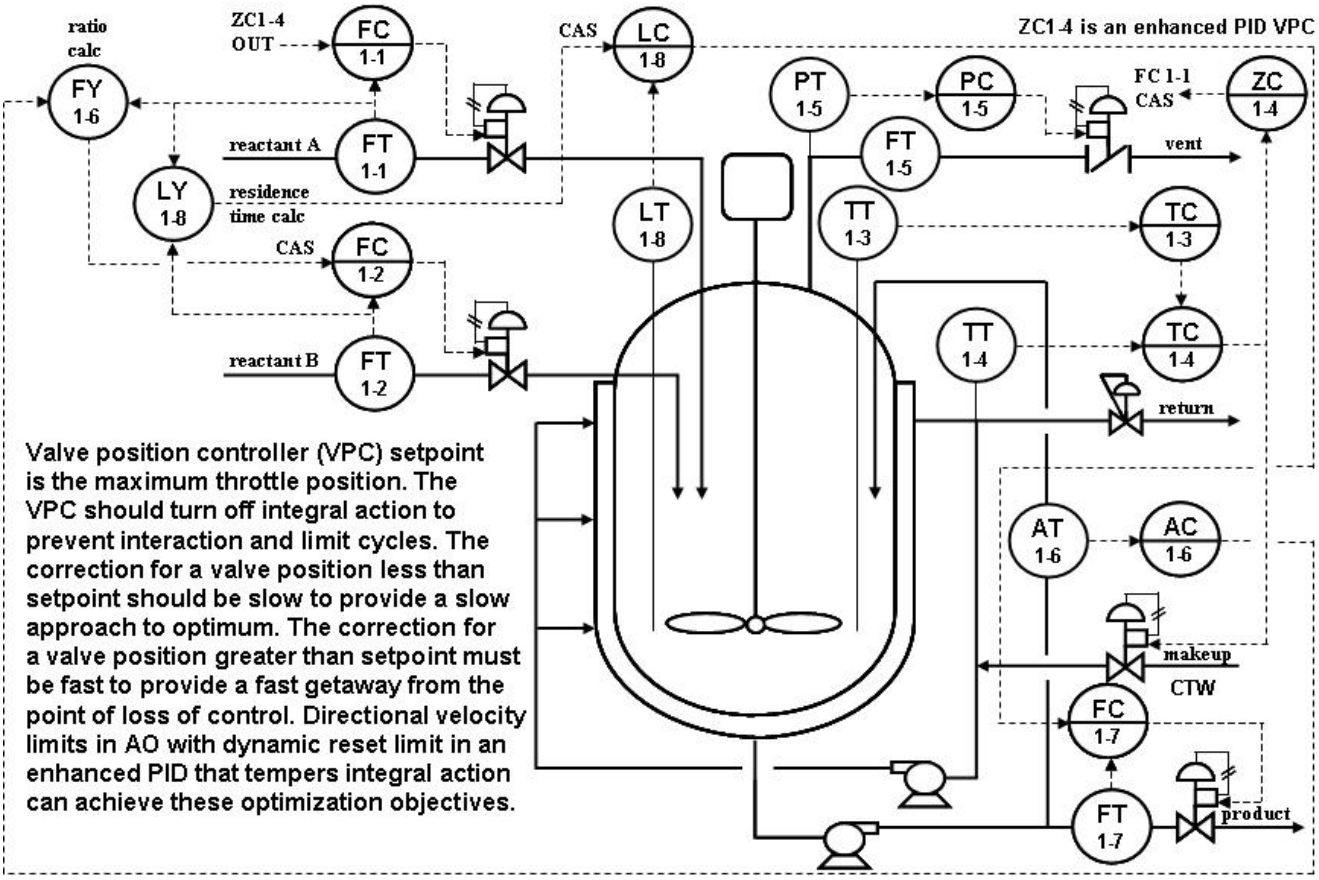

Figure 1b. For a liquid reactor, the production rate can be maximized by a VPC (ZC1-4) that increases reactant feed till the jacket temperature valve reaches maximum position
(Strategy is also applicable for fed-batch reactors without reactor level and residence time control)

For high temperatures and heat releases, boiler feed water (BFW) is used to generate steam (Figure 2a). The boiling of water provides an isothermal (constant temperature) sink important for the stabilization of exothermic reactors. The jacket pressure and level controller maintain inventory of the vapor and liquid phases. An increase in heat release causes an increase in steam generation. The pressure controller lets out the additional steam keeping the jacket pressure and jacket temperature constant. Thus, an increase in heat release for a constant reactor temperature do not cause an increase in jacket temperature as it would do with liquid coolant systems. For high heat releases, the coolant temperature approaches the reactor temperature reducing the temperature difference across the heat transfer surface that is the driving force for heat transfer. The generation of steam keeps the temperature difference constant if the reactor temperature has not changed. If the temperature of the reactor changes the temperature controller changes the setpoint of the pressure controller, which changes the steam temperature. An increase in reactor temperature decreases the steam pressure

setpoint. The pressure control in turn opens the outlet steam valve resulting in a decrease in pressure in the jacket and temperature per the steam tables. The reactor control loops are the same for coolant systems depending upon the reaction phases. For fed-batch reactors, there is no reactor level control and hence no residence time control but otherwise the same control scheme is applicable.

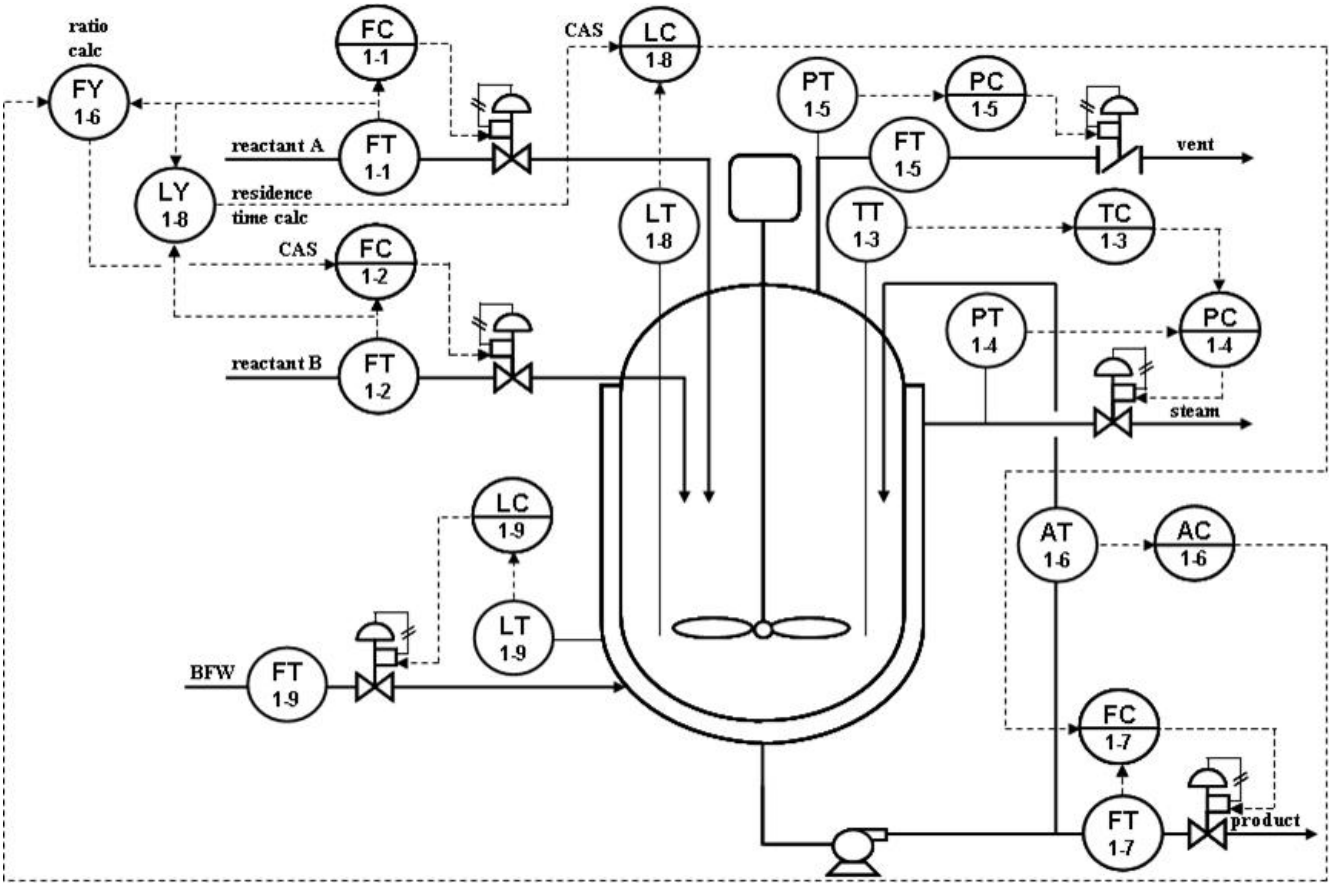

Figure 2a. For a high temperature liquid reactor, coolant in Figure 1a is replaced with the boiling of water to provide a constant temperature heat sink that helps stabilize highly exothermic reactions (Strategy is also applicable for fed-batch reactors without reactor level and residence time control)

Production rate can be maximized by the use of a valve position controller (VPC) monitoring BFW and steam valve positions (Figure 2b). The VPC setpoint is the maximum desirable valve position, and the VPC process variable is the highest of the level and pressure controller outputs. Differences in the nonlinearity of the coolant and vent valve can be eliminated by signal characterization so the valve curve slope (gain) and setpoint are about same for either valve. The output of the VPC trims the setpoint of the "leader" reactant flow controller. An adaptive PID for the VPC could switch tuning settings based on which valve is being controlled. An enhanced PID with dynamic reset limiting for the VPC eliminates limit cycles, reduces interaction between the VPC and the level and pressure controllers, and enables smoother optimization with faster correction for large disturbances.

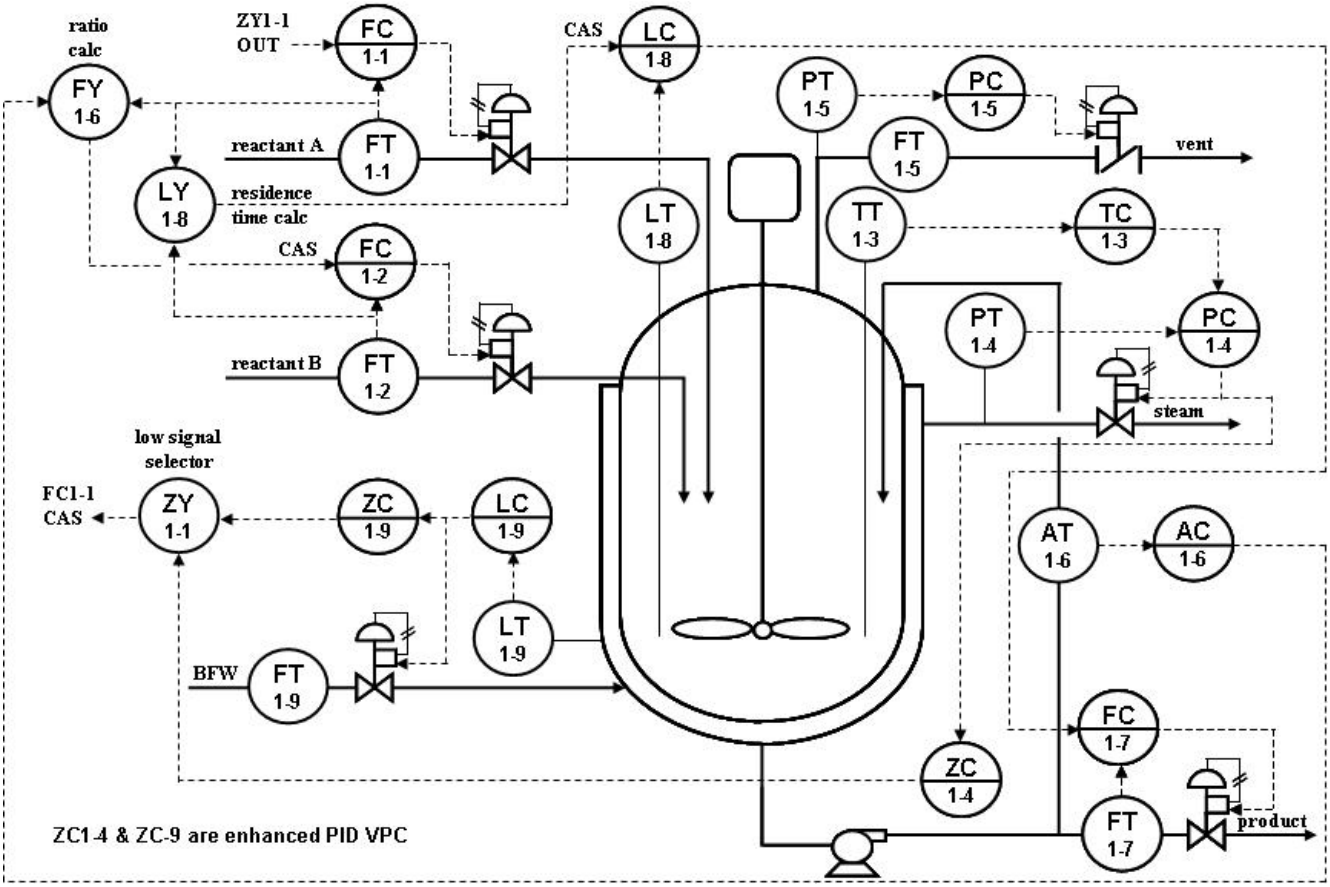

Figure 2b. For a high temperature liquid reactor, the production rate can be maximized by a VPC that increases reactant feed till the BFW or steam valve reach maximum position
(Strategy is also applicable for fed-batch reactors without reactor level and residence time control)

The simultaneous feeding of reactants is termed fed-batch control or semi-continuous control. The reactant ratio is not corrected by composition control as seen in large chemical intermediate reactors, because traditional batch operation of sequenced flows is based on endpoint control achieved by accurate charges and a batch cycle time long enough to insure complete reaction. See the Fed-Batch Profile Control section for a discussion of the opportunities for more repeatable batch composition and temperature profiles and a faster batch cycle time.

For gas reactants and a gas product, a pressure loop controls the material balance and time available for reaction by manipulating the discharge product flow (Figure 3). A fluidized catalyst bed is used to promote reaction rate. ***If a temperature loop manipulates the leader gas reactant flow, the production rate is automatically maximized by the temperature and pressure controllers for a given cooling rate established by BFW flow***. Valve position control is not needed unless a control strategy is added to

manipulate the BFW. Direct manipulation of feed rate by the temperature control is possible in gas reactors because the additional time lag for composition response is negligible due to the small residence time and the inverse response is negligible due to the fast reaction and high heat release.

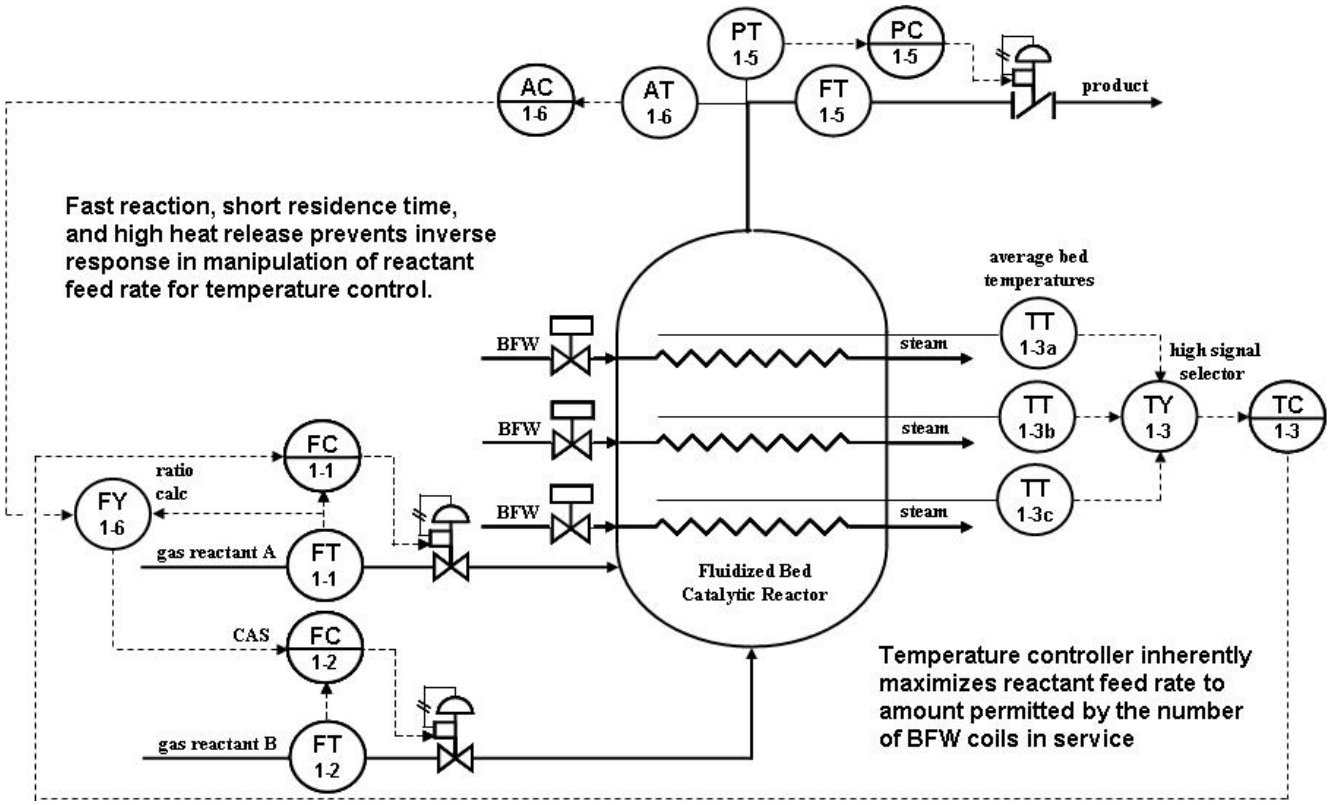

Figure 3. An enhanced PID of an at-line analyzer sets the gas reactant flow ratio, a pressure controller sets reaction time, and a temperature control system maximizes reaction rate by setting gas feed rate.

The plug flow of reactants through the reactor provides tight residence time control. Changes in discharge composition are mainly due to errors in the flow measurement, hot spots triggering side reactions, or insufficient radial mixing. Often an excess of one reactant is used to insure complete conversion of other reactants. ***An at-line analyzer on the gas product can be used to correct the gas reactant ratio to improve yield by reducing excess reactant***. The leader reactant flow multiplied by a ratio factor is the feedforward signal for the composition controller. A feedforward summer is used even though a feedforward multiplier can compensate for the inverse relationship between process gain and flow because of scaling and analyzer reliability issues and the predominant error seen is a bias rather than a span error in the flow measurements. The composition loop trims the feedforward signal. An enhanced PID with a threshold sensitivity setting helps deal with the analyzer sample and cycle time and the noise from poor mixing.

A gas reactor with a fluidized catalyst bed may develop hot spots from localized high reactant concentrations due to a non uniform flow distribution and no back mixing. Numerous separate coils are used so operations can switch in coolant coils to deal with hot spots and changes in production rate. However, the switching causes a disturbance to the temperature controller as fast as the BFW valves can move. Numerous thermowells each with multiple sensors traverse the reactor. The average temperature is computed for each traverse with the highest average selected as the control temperature. Only 3 thermowells and BFW coils are shown in Figure 3 due to pictorial space limitations. ***A feedforward signal with a gain and velocity limit set to match the BFW valve installed characteristic slope and stroking time can provide preemptive correction for the disruption of coil switching.***

MIXED PHASE CHEMICAL REACTORS

If the reactants are in different phases and the product is a single phase, inventory control can be used for continuous endpoint control. The product must be a gas, liquid, or solids with no recycle or co-products in other phases. Endpoint control prevents the accumulation of excess reactant in the opposite phase as the product by inventory control of the reactant phase. For a liquid product, excess gas reactant is inherently prevented by pressure control. For a gas product, excess liquid reactant is inherently prevented by level control.

For a liquid product a pressure controller provides continuous endpoint control by increasing gas feed for a decrease in pressure from a deficiency of gas reactant and decreasing gas feed for an increase in pressure from an excess of gas reactant (Figure 4). Normally the gas phase reaction is fast enough for the gas reactant to be totally consumed in the reaction so that the only inerts are left in the overhead vapor space. An overhead purge flow prevents the accumulation of inerts. A level controller maintains the liquid material balance by manipulating the liquid product discharge flow. The residence time control by the level loop shown for single phase liquid reaction (Figure 1a) could help maintain the residence time in the gas phase besides the liquid phase by keeping the bubble rise time constant by changing the bubble path length for a change in bubble velocity. For batch reactors there is no level control and hence no residence time control but otherwise the same control scheme is applicable.

For a gas product a level controller provides continuous endpoint control by increasing liquid feed for a decrease in level for a deficiency of liquid reactant and decreasing liquid feed for an increase in level from an excess of liquid reactant. A purge flow from the bottom prevents the accumulation of inerts in the liquid phase. A gas pressure controller maintains the gas material balance by manipulating the gas product discharge flow. For residence time control, the liquid controller setpoint computed as the liquid reactant flow multiplied by the desired residence would need a lag inserted because the level controller manipulating the liquid reactant flow forms a positive feedback loop. For fed-batch reactors this strategy is not applicable because there is no level control or purge.

Production rate can be maximized in both cases by the use of a valve position controller (VPC) monitoring coolant valve position. The VPC setpoint is the maximum desirable valve position, and the VPC process variable is the temperature controller output. The output of the VPC trims the setpoint of the liquid and gas reactant flow controller for liquid and gas products, respectively. An enhanced PID with dynamic reset limiting for the VPC eliminates limit cycles, reduces interaction between the VPC and temperature controller, and enables smoother optimization with faster correction for disturbances.

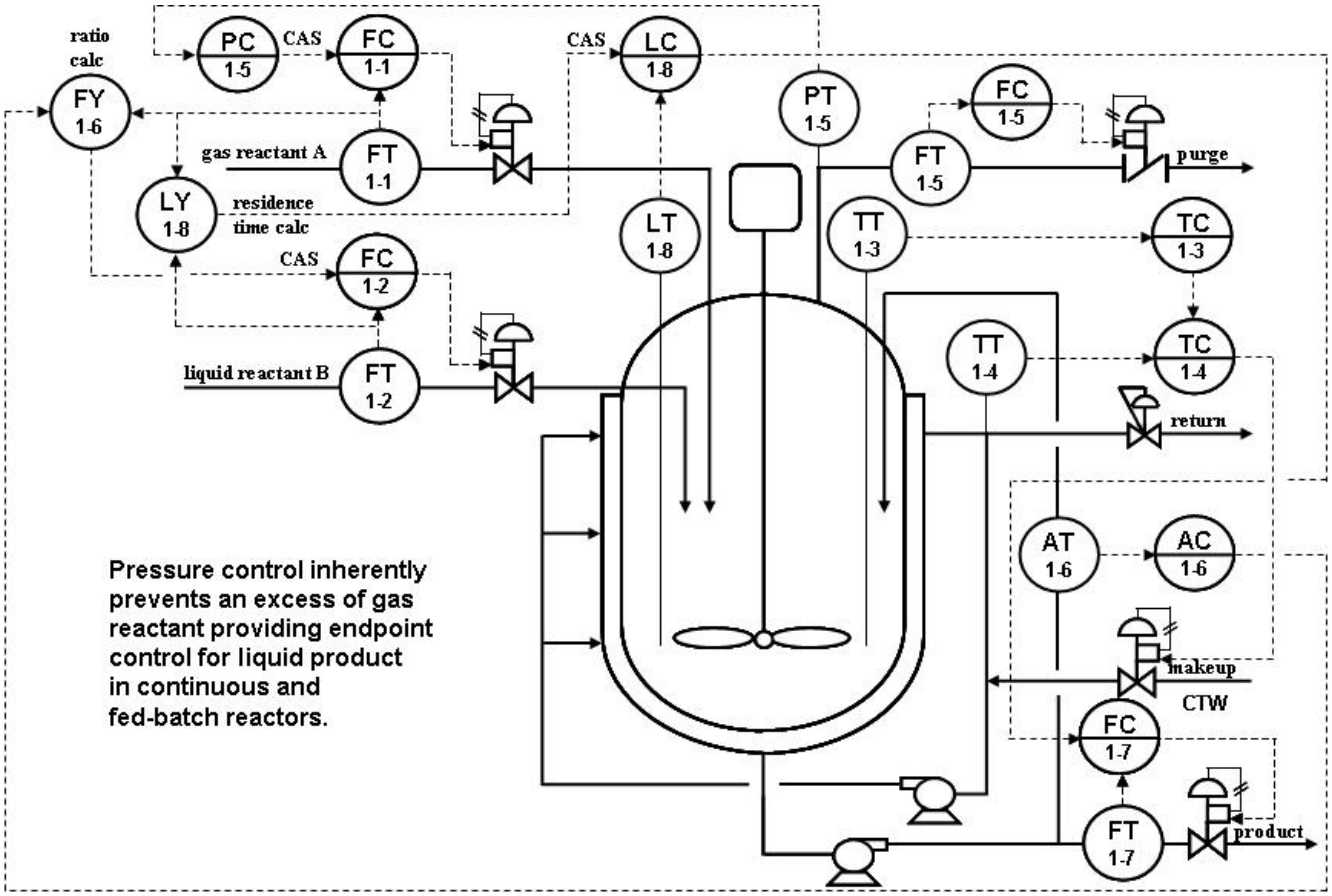

Figure 4. For a liquid and gas reactants, and a gas product, pressure control maintains continuous composition endpoint control and level control maintains the liquid inventory
(Strategy is also applicable for fed-batch reactors without reactor level and residence time control)

If there are products in different phases, continuous endpoint control requires an online or at-line analyzer because the level and pressure controllers have to regulate the liquid and gas, respectively, for inventory control. Analyzers can provide composition control by manipulating the ratio of reactants or manipulating a 2 phase product flow.

INFERENTIAL CHEMICAL MEASUREMENTS

Conductivity, density, NIR, and viscosity measurements can in some reactors provide an online inferential measurement of product concentration. If the product has a higher conductivity than the reactants or solvent, conductivity can be used if the conductivity is known to be on one side or other of the peak in the conductivity curve. Plots of conductivity versus concentration have at peak. A few ionic species such as sulfuric have 2 peaks. For product conductivity that traverses across the peak, concentration control cannot start until the conductivity is well to the right of the peak. If the product density significantly differs from reactant and solvent density, the density measurement of a Coriolis meter can be used as an inferential measurement of product concentration. If a distinct near infrared (NIR) spectrum is indicative of product concentration, a NIR statistical model can be built from a diverse array of samples to predict product concentration. If the viscosity of the reaction mass increases significantly as the product concentration increases, viscosity may be used as an inferential measurement of product concentration. The conductivity probe, Coriolis meter, and viscometer located in the recirculation line provide a continuous measurement. The NIR probe in a sample automatically withdrawn from the recirculation line can provide an average analysis of a dozen samples in less than a minute. Noise in the inferential measurements can be effectively ignored by the use of a deadband (threshold sensitivity) setting in the enhanced PID. The PID output trims reactant ratio.

A computation of heat removal rate in a cooling system can provide an inferential measurement of reaction rate for exothermic reactors. The heat removal rate uses temperature sensors on the inlet and outlet of the jacket. The inlet temperature measurement is sent through a deadtime block with a deadtime setting equal to the transportation delay so the inlet temperature can be synchronized with the outlet temperature. ***Resistance temperature detectors (RTDs) provide a more accurate inferential measurement.*** The heat removal rate is the outlet temperature minus the synchronized inlet temperature multiplied by the jacket flow and the heat capacity of water at the operating temperature. If the jacket circulation flow is not constant, the heat removal computation and the transportation delay must be updated based on a jacket flow measurement. For a constant coil or jacket flow and cooling or chilled water temperature, the difference between the reactor and coil or jacket outlet temperature (approach temperature), can be used as a simpler computation. ***The integration of the heat removal rate over the course of the batch or for the residence time of a continuous reactor can provide an inferential measurement of conversion.***

Wireless temperature transmitters and annubar mass flow meters can be used to establish the variability in coil and jacket flow and utility temperature besides inexpensively prototyping inferential measurements. **Wireless measurements can demonstrate and quantify the benefits of online metrics and diagnostics**.

CHEMICAL FED-BATCH PROFILE CONTROL

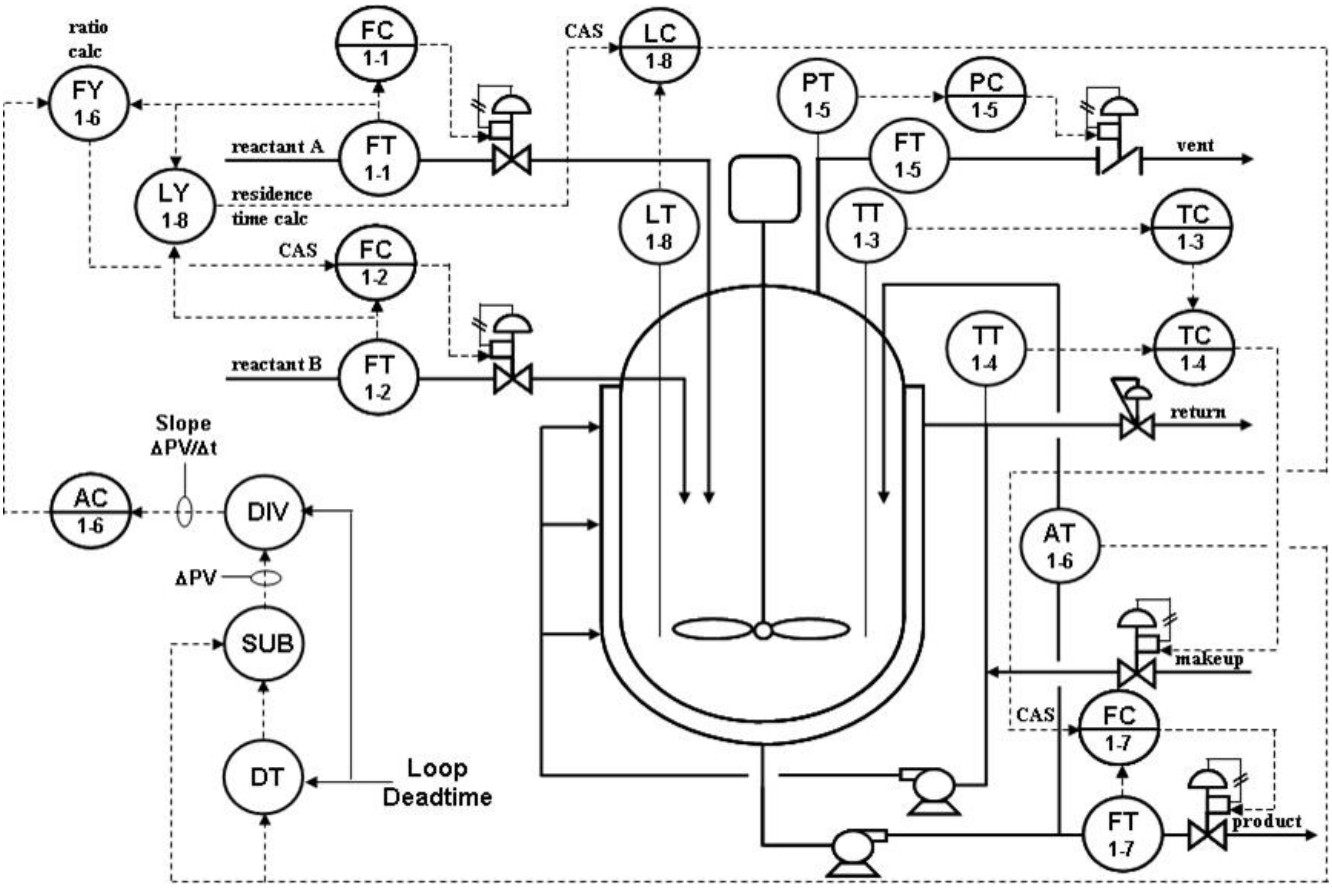

Figure 5. The translation of the PID process variable (PV) from concentration to rate of change of concentration (ΔPV/Δt) provides slope control of the batch profile.

Chemical batches have an optimum profile of product concentration. If an at-line or online analyzer can provide a product concentration measurement, the profile can be measured and controlled. Since the product concentration should only increase as the batch proceeds, the simple use of concentration as the process variable of a PID controller with a profile setpoint is not feasible because the PID assumes it can make negative as well as positive corrections in the process variable in order to match setpoint. ***If the rate of change of the concentration is computed as the process variable, the slope of the concentration profile can be controlled and increased or decreased.*** The rate of change calculation must be done by passing the analyzer measurement through a deadtime block to create an old analysis value. The rate of change is the new value minus the old value divided by the block's deadtime parameter value (Figure 5). The deadtime should be chosen large enough so that the true change in concentration is significantly larger than analysis noise. For chemical reactors, the deadtime is in the range of 5 to 10 minutes. At the beginning of the batch, the deadtime block is turned off so

that the entire series of internal deadtime block values becomes the current analysis. When the deadtime block is turned on a new rate of change is available within a few seconds after each analyzer update. Methods to compute rate of change based on waiting a time interval to provide the new value introduce a process deadtime equal to the update interval. For the method that uses the deadtime block, the additional process deadtime is just half of the deadtime block execution time and is negligible compared to the reactor and analyzer response time. In terms of concentration control the tuning settings for the rate of concentration control can be viewed as differentiated. The proportional mode for rate of change control is effectively a rate mode for concentration control. The integral mode for rate of change control is effectively a proportional mode for concentration control. There is no integral mode for concentration control, consistent with the inability to provide a close match to a concentration setpoint by decreasing the product concentration. The fed-batch product profile slope control can manipulate reactant temperature or fed-batch reactant ratio. For example at the end of batch it may be desirable to change the concentration of a limiting reactant or the reaction rate through temperature. Profile PID output limits must be set to match the permissible range of temperature or reactant ratio.

Temperature rate of change has been used for reactor temperature profile control to increase the reaction rate as the batch progresses. Since too rapid of an increase in reaction rate could trigger a runaway polymerization of a hazardous reactant, a smooth and gradual increase in temperature was essential. Rate of change temperature control was successful in accomplishing this optimization.

BIOLOGICAL REACTOR CONTROL

Cells can be viewed as sophisticated reactors that can be genetically programmed. Yeast cells were first used centuries ago to ferment grapes to wine. Today yeast cells are used to produce large variety alcohols besides wine and beer. Fungal cells were developed to produce antibiotics. Bacterial cells were genetically engineered to digest waste and to provide more complex pharmaceuticals such as antibodies. Finally, mammalian cells were genetically engineered to provide proteins of incredible molecular complexity and folding for the expanding spectrum of biopharmaceuticals that duplicate the beneficial response of key factors within the human body. There is no chemical route possible for most of the complex proteins sought as new products today. Mostly mature generic pharmaceuticals are produced by chemical reactions and these are done for high volume increasing contracted out to toll producers. Most of the product research and development in the pharmaceutical industry is focusing on the use of bioreactors.

YEAST BIOREACTORS (FERMENTERS)

Bioreactors that use yeast are called fermenters and the liquid is referred to as broth. ***Yeast fermenters to produce ethanol and alcoholic beverages traditionally only have temperature control.*** The

subscribed permissible pH range is quite large (e.g. 4 to 6 pH). These fermenters typically don't have pH control. A gradual decrease in pH during ethanol fermentation is normal due to acetic acid and lactic acid formation. A greater than normal drop in pH is indicative of a bacterial contamination so pH may be monitored. The main opportunity for maximizing production is taking advantage of a decrease in the time to reach the desired alcohol batch concentration endpoint. ***The inhibition effect of alcohol concentrations above the endpoint dramatically slows down and suspends further conversion to alcohol.*** Consequently, longer batch times do not translate into greater ethanol concentrations.

Production rate can be increased by reducing the batch time to when the endpoint is reached. An online near infrared analyzer or at-line chromatograph can provide a measurement of ethanol. Most batch cycle times are much longer than the average time to an endpoint because of the variability in time to the endpoint. ***If batch cycle times are fixed, a consistent early endpoint can be used to reduce corn feed rate to improve ethanol yield typically expressed as gallons per bushel.*** Corn is the largest cost for ethanol production. ***An improvement in yield taken as a decrease in corn feed rate significantly decreases cost and decreases the carbon footprint, which increases revenue.***

The front end of the ethanol plant consists of slurry, liquefaction, cooling, and saccharification-fermentation (SSF) areas. The front end is continuous with batch operation of the fermentors in the SSF area. The basic control system for the front end of an ethanol plant controls the temperature and pH of the fermenter feed. The fermenter may have temperature control as well. The pH in the fermenter will fall over the course of the batch from acetic acid and lactic acid formation. While there is an optimal pH for yeast growth and product formation, the effect of the change in fermentation batch cycle time is not thought to significant enough to warrant pH control in the fermenter. The control system developed for optimization of ethanol yield in the front end uses three enhanced PID controllers, an at-line corn feed analyzer, and an at-line multiplexed ethanol analyzer for the fermentors. The PID controllers optimize the corn feed rate and solids in the slurry tanks based on predicted fermentable starch and actual SSF batch time to reach the ethanol end point.

In beer, wine, and other alcoholic beverage production, the mixture of fermentable sugars and other ingredients developed by brew masters from taste tests is critical. The masters are not particularly interested in more sophisticated process control. Agitation may not be used. Special fermenter wall material (e.g. oak) is used to help establish flavor. For small specialty beverages, the mixture may just sit in a barrel in a cool room. For large scale production fermenters wall designs (e.g. stainless steel dimpled jackets) are used for more efficient and repeatable operation. For the big producers, offline lab analysis is used for monitoring beverage consistency. Production can be increased by knowledge of when the fermentation is complete. Carbon dioxide production rate (CPR) are can be used as inferential measurement of alcohol production rate. Load cells and a loss in weight calculation has been used for wine fermentors to provide an online CPR.

New processes are being developed to use genetically engineered yeast to produce large volume chemical intermediates, such as adipic acid that have been traditionally produced by petrochemical processes. The process control requirements may be more extensive for these new products.

FUNGAL BIOREACTORS

Fungal bioreactors have been extensively employed to produce a wide spectrum of antibiotics and some chemical intermediates such as citric acid. ***These bioreactors have air flow control, agitation control, dissolved oxygen (DO) control, pH control, and pressure control besides temperature control.*** Dissolved oxygen control may be split ranged to manipulate agitation rate and air flow. The split range may be extended to include vessel pressure if higher pressures do not cause undesirable higher dissolved carbon dioxide concentrations. The pH may be split ranged between an acid reagent (e.g. sulfuric) and a base reagent (e.g. ammonia). Glucose addition rate is fixed or scheduled to provide a more constant concentration. Many of the opportunities for increasing production rate by modeling and advanced control discussed for mammalian bioreactors are applicable to fungal bioreactors.

BACTERIAL BIOREACTORS

Bacterial bioreactors are used to produce more complex molecules such as the human epidermal growth factor (hEGF). Bacterial bioreactors have the same type of controls as the fungal reactors. The split range for dissolved oxygen (DO) control may be extended to include the addition of oxygen at high growth rates. The rangeability requirement for oxygen demand is addressed by low agitation and low air flow in the pre-exponential growth phase when oxygen demand is low. At this point, the DO control may be noisy due to intermittent bubbles from lower sparge rates and less mixing. Many of the opportunities for increasing production rate by modeling and advanced control discussed for mammalian bioreactors are applicable to bacterial bioreactors. Oxygen uptake rate (OUR) can be used as an inferential measurement of growth rate.

MAMMALIAN BIOREACTORS

Mammalian reactors have the most stringent control requirements particularly for pH and temperature. The liquid termed media consists of water, nutrients, and a substrate of sugar (glucose) and amino acid (glutamine). Agitation is kept a low rate because mammalian cells have no cell walls and are easily damaged by impeller shear. ***Mammalian bioreactors have all of the process control for bacterial bioreactors but with more complex DO and pH loops*** (Figure 6a). Sparger design is critical to provide dispersion of gases and mixing and reduce interaction between the DO and pH controllers.

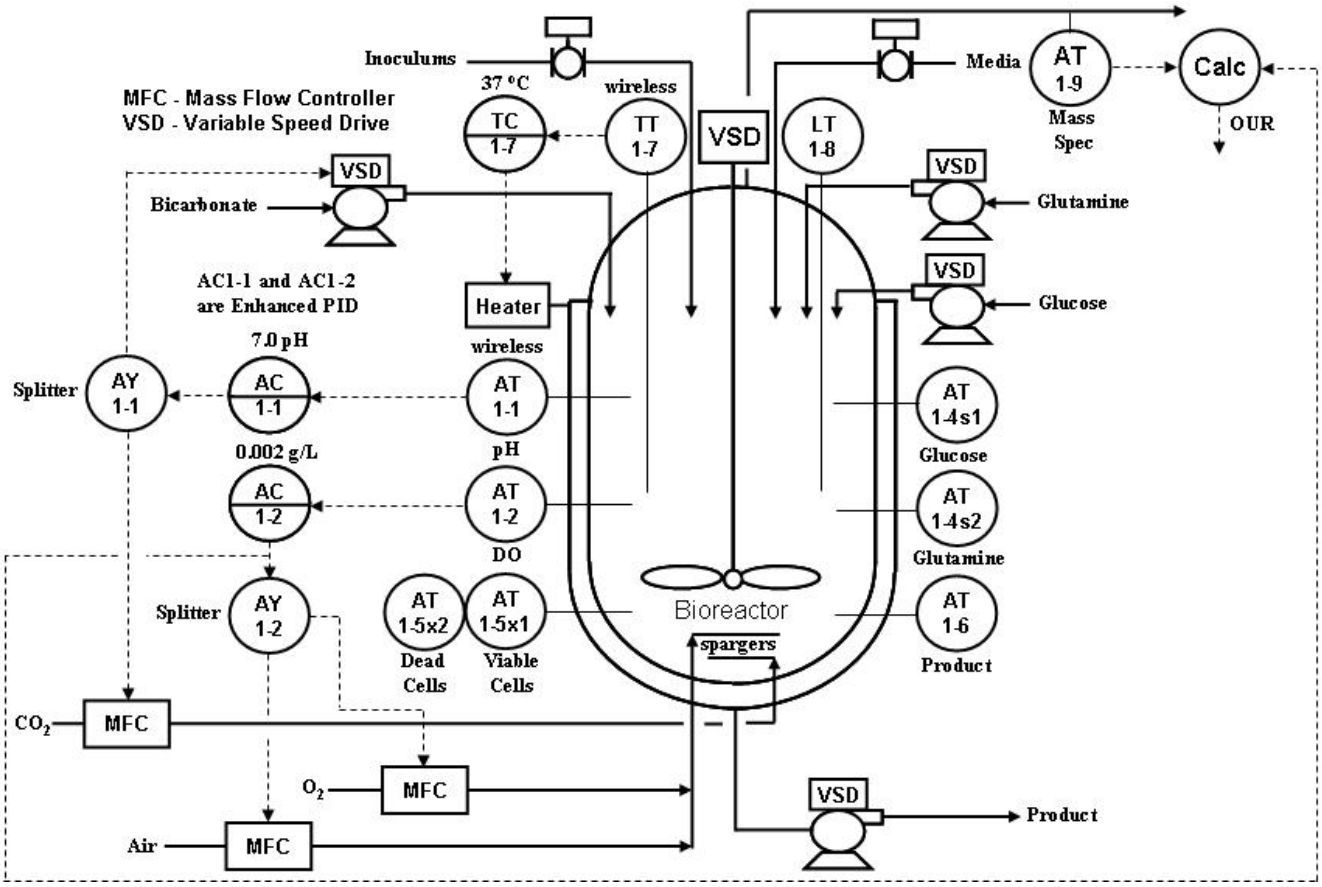

Figure 6a. Mammalian bioreactors have all of the process control of bacterial reactors but with more complex DO and pH loops with decoupling and smarter split ranged control.

The DO controller output is split ranged to manipulate air and oxygen sparge and air overlay (vapor space addition). The pH controller output is split ranged between carbon dioxide addition (carbonic acid) and sodium bicarbonate (base). These are weak acids and bases providing a great moderating (buffering) effect on the titration curve slope enabling much tighter pH control. Weak acids and bases and the use of a tiny aperture for the reference electrode junction reduce the liquid junction potential providing a more accurate pH measurement. With proper tuning, pH control within 0.01 pH is possible. The focus is then on interaction with the DO control, high carbon dioxide concentrations, and excessive accumulation of sodium bicarbonate concentrations.

Interaction between DO and pH control can be greatly reduced by sparger design. Remaining interaction can be dealt with by an enhanced PID for DO and pH control with a deadband (threshold sensitivity) and decoupling feedforward signal that is the opposing controller's gas addition rate.

High concentrations of carbon dioxide can be avoided by preventing overreaction of the pH controller to setpoint changes by the use of a velocity limit on the setpoint. High carbon dioxide concentrations will dissipate with time.

Mammalian batches take 10 or more days. The incredibly slow kinetics translates to extremely slow changes in reagent, oxygen, and cooling demand. Exceptionally slow load disturbances and slow integrating process gains result in negligible errors from disturbances. ***The concern for well designed pH, dissolved, and temperature loops is in terms of setpoint response and optimization rather than disturbance rejection.*** The recognized opportunity is getting to a setpoint quickly with no overshoot for a temperature and pH shift to move from enhancing cell growth to promoting product formation.

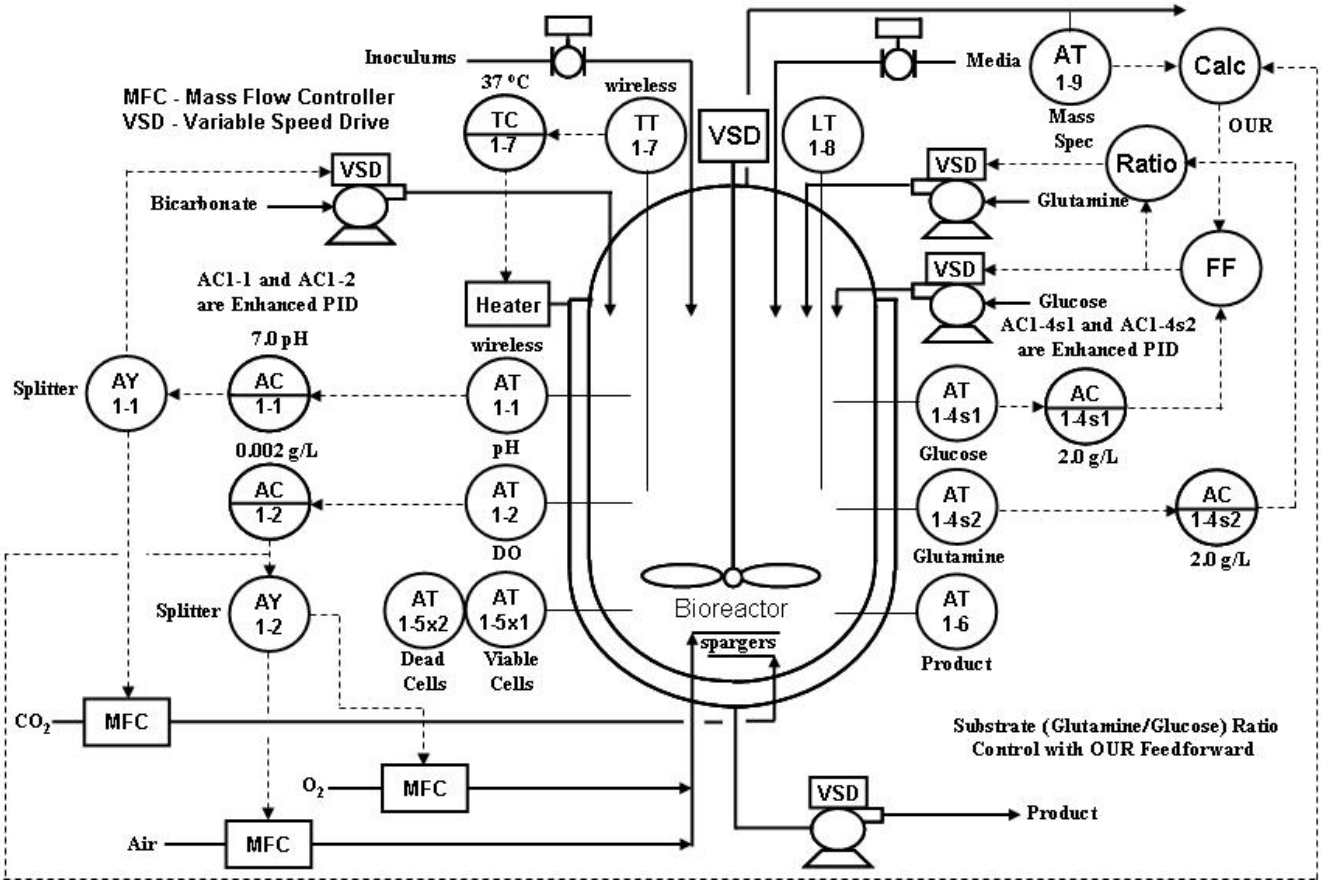

Figure 6b. Online and at-line analyzers enable substrate concentration control with glutamine feed ratioed to glucose. A feedforward based on OUR anticipates changes in glucose utilization rate.

Excessive accumulation of sodium bicarbonate causes a high sodium concentrations that leads to high osmotic pressure that can contribute to cell membrane rupture and cell death. Unlike carbon dioxide that can escape in the vent gas, sodium bicarbonate is trapped in the media. Excessive crossing back and forth of the split range point for pH control over the course of the batch can lead to high osmotic pressure. A split range gap or deadband complicates tuning and does not stop the eventual

excursion from the integrating process response. An enhanced PID with a deadband (threshold trigger) to ignore short term changes and a directional velocity limit with the dynamic reset limit to slow down a movement into the direction of adding sodium carbonate can reduce unnecessary split range excursions without requiring special tuning. New at-line analyzers can measure osmolality (osmotic pressure) by freeze point depression.

New online and at-line analyzers to measure glucose and glutamine open the opportunity for improved concentration control of this sugar and amino acid. Presently, glucose and glutamine addition is scheduled in anticipation of utilization rates. A move from sequenced batch charges to fed-batch closed loop control can compensate for disturbances and consistently maintain a concentration (Figure 6b). The glutamine feed setpoint can be ratioed to the glucose feed setpoint. A feedforward signal for glucose addition rate based on oxygen uptake rate (OUR) can provide preemptive correction for the acceleration of substrate utilization in the exponential growth phase. The sampling rate for at-line analyzers doesn't need to be more frequent than 4 hours because the changes in mammalian cell metabolism are slow. An enhanced PID can provide tight control for relatively large sample times and suppress reaction to noise and feedforward timing errors by a deadband (threshold sensitivity) setting.

INFERENTIAL BIOLOGICAL MEASUREMENTS

The negative rate of change of weight measured by load cells has been used by the University of California – Sacramento to compute carbon dioxide production rate (CPR) as an indicator of yeast growth rate and production rate for wine.

The oxygen uptake rate (OUR) has been used an indication of fungal and bacterial growth rate. The sparge oxygen concentration minus the concentration of oxygen in the off-gas measured precisely by mass spectrometers multiplied by the total gas flow provides the OUR. For a high consistent oxygen transfer rate and a constant sparge oxygen concentration, the DO controller output is considered by a major biopharmaceutical company to be a sufficient indicator of OUR.

CPR and OUR are used for diagnostics and prediction of batch endpoint. The use of data analytics to detect and diagnose abnormal batches through principal component analysis (PCA) and to predict product quantity and quality through projection to latent structures (PLS) benefit from inputs such as CPR and OUR that have embedded process knowledge. OUR can also be used as a feedforward signal for glucose and glutamine control loops.

A virtual plant running real time in synch with the actual plant can provide inferential measurements of key component concentrations. Valve position controllers can adapt virtual plant model parameters for utilization rates by matching virtual to actual loop outputs. At-line or offline lab

controllers can adapt parameters for formation rates by matching actual to predicted concentrations. An enhanced PID can deal with discontinuous measurements, noise, and interactions for adaptation.

BIOLOGICAL FED-BATCH PROFILE CONTROL

If the rate of change is computed for viable cell and product concentration by passing these concentrations through a deadtime block, growth rate and product formation rate can be indicated and controlled (Figure 6c). The concentrations can be measurements from online or at-line analyzers or inferential measurements from OUR or a virtual plant running in synch with the actual plant. The profile for both rates tends to start slowly, accelerate, and decline. Profile control can provide a more consistent and faster rate at the most appropriate time. The glucose setpoint or the glutamine to glucose ratio may be directly manipulated by growth rate or product formation rate controllers whose setpoint is a function of batch phase. Product formation rate control may start later in the batch at which point growth rate control may be suspended to given less priority through tuning. An enhanced PID is used for these controllers to deal with discontinuous measurements, noise, and interactions.

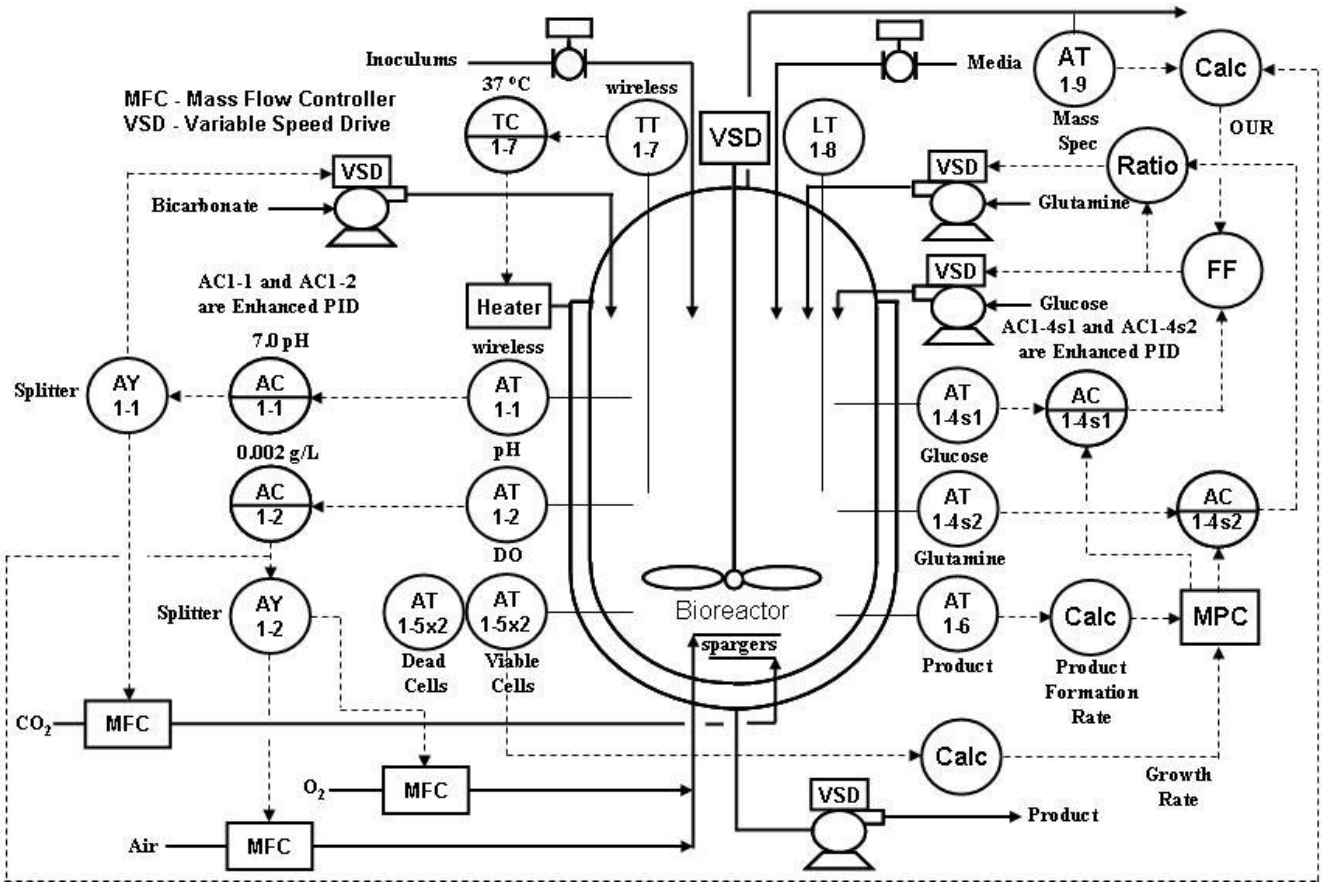

Figure 6c. Growth rate and product formation rate from the rate of change of actual or inferential measurements can provide fed-batch profile control by the manipulation of glucose and glutamine

ENHANCED PID

The enhanced PID executes as fast as the traditional PID. A change in setpoint, feedforward signal, and remote output translates immediately (within PID execution time interval) to a change in PID output. However, integral action does not make a change in the output until there is an update. When an update occurs, the elapsed time between the updates is used in an exponential calculation that mimics the action of the filter block in the positive feedback implementation of integral action. If derivative action is used, the elapsed time rather than the PID execution time interval is used to calculate the rate of change of the process variable***. The integral and derivative calculations are executed only once when triggered by a change in setpoint or measurement***. A threshold sensitivity setting is used to prevent an update from PV noise when the PID output is moving.

The enhanced PID with a threshold sensitivity setting will stop a limit cycling from valve stiction or backlash and suppress oscillations from split range discontinuities, interactions, feedforward timing errors, and large analyzer sample and cycle times. Most of the benefit originates from the suspension of integral action until a valid change in the PV occurs.

A traditional PID will have to be detuned to prevent instability for a large increase in the time between updates associated with an analyzer sample time and cycle time. The enhanced PID will continue to be stable for even the longest update time interval. ***For an analyzer update time interval larger than the process response time, the enhanced PID controller reset time can be set based on the process deadtime and gain can be set equal to the inverse of the open loop gain to provide a complete correction for a setpoint change or analyzer update.***

The positive feedback implementation of integral action enables a dynamic reset limit that can prevent the PID output from changing faster than a final control element can respond as indicated by an external reset signal. ***The dynamic reset limit is important for preventing a burst of oscillations for a large disturbance or setpoint change that causes the primary PID output to change faster than a secondary PID loop in a cascade control system or a final control element.*** The external reset signal is the PV of the secondary PID in cascade control. When the feature is used for slow final control elements, the analog output PV is used since valve position readback or variable frequency drive speed feedback may not be available each execution of the PID.

The dynamic reset limit can be used with directional velocity limits in the analog output to provide faster recovery from unsafe directions. The velocity limit for cooling would be faster than the velocity limit for heating in an exothermic reactor. The tuning would not be affected.

The enhanced PID and dynamic reset limit can make valve position control (VPC) easier to tune and more effective. The elimination of oscillations from backlash, stiction, and interaction and the

faster reaction to significant changes from the use of the proportional mode reduces variability. The use of directional velocity limits with dynamic reset can provide a slow approach to the optimum and fast recovery from undesirable operating conditions without retuning.

CONCLUSION

Biological and chemical process performance is largely determined by reactor performance. The stage for product quality and process efficiency and capacity is set by reaction yield and selectivity. An increase in yield can be used to increase production rate for same feed rate or used to decrease raw material costs for the same production rate. For batch reactors, an increase in yield can be taken as shorter cycle time for the same charges or as smaller charges for the same cycle time. A higher yield reduces downgraded products, recycle, and waste. Reactor type, reaction rate, and time available for reaction affect yield. Temperature, concentration, and sometimes pressure affect reaction rate. Inventory and feed rate determines the amount of time reactants are in reactor (residence time), which determines time available for reaction. Process control of temperature, concentration, pressure, inventory, and feed rate is essential to achieve reaction rate and time for maximum yield. Endpoint control inherently prevents the accumulation of excess reactants. Valve position control increases reactant feed rate to limits of utility systems. Valve position control increases rangeability of utility systems. Simple PID control strategies can optimize production rate and yield by controlling reaction rate, reaction time, selectivity, and availability. An enhanced PID can make the optimization smoother and easier to tune. Many of the strategies are applicable to fed-batch reactors by the simple omission of the level control used in continuous reactors.

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