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Batch Process Control Strategy

Examining How Manufacturers Are Using Modern Process Control To Maintain Batch To Batch Quality

Presenter

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Topics

- Why are Batch Processes Difficult?
- Applying Data analytics to batch end points to prevent bad batches to increase both plant capacity and yield for maximum plant profit
- Reviewing waits and sequential operations to reduce batch cycle times to increase batch capacity for maximum saleable product
- Computing batch profile slopes for control and prediction to enable more repeatable batches and better batch decisions
- Quantifying online batch metrics for measuring and improving batch costs and capacity to maximize profit
- Evaluating logic for decisions on optimization of yield versus capacity to determine optimum batch completion time
- Assessing batch process dynamics and controller tuning to improve loop performance and reduce batch variability
- Examining control strategies to maximize production rate and batch repeatability for maximum saleable product

Why are Batch Processes Difficult?

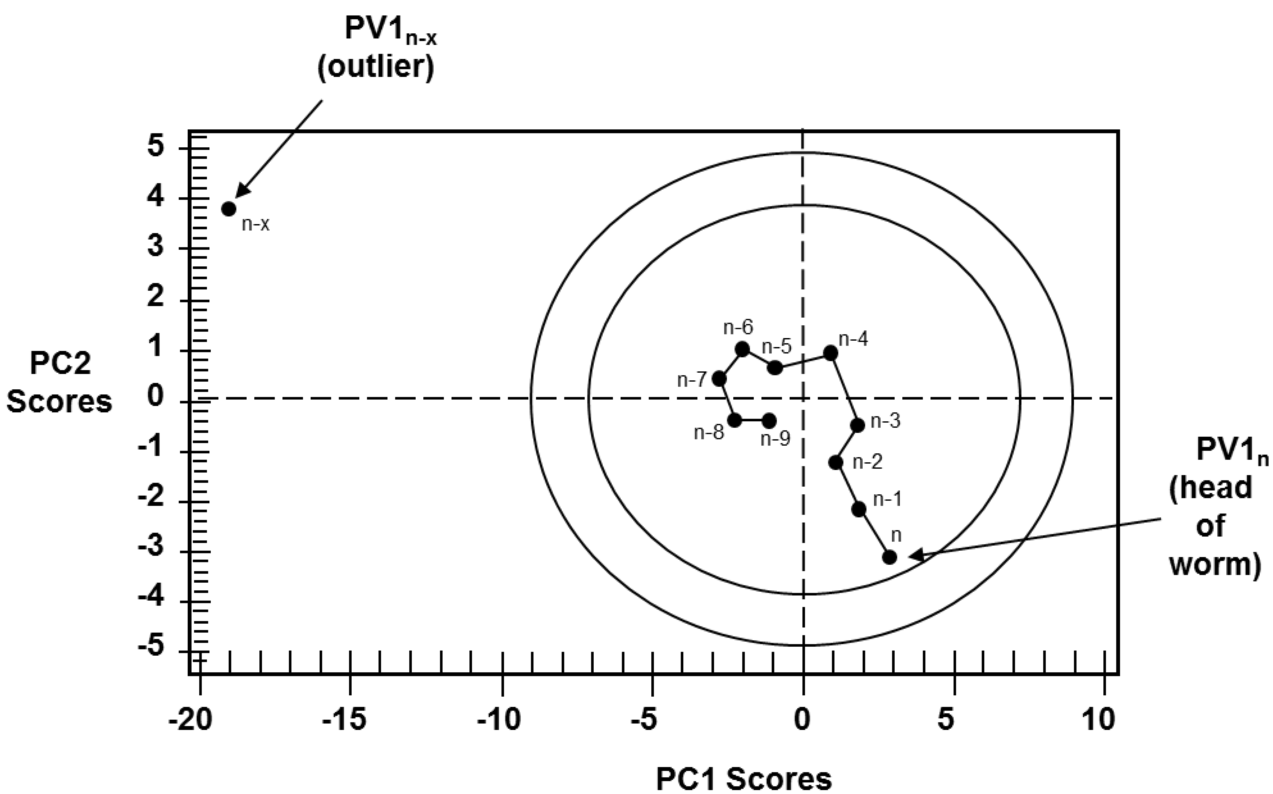
- Like a perpetual startup and shutdown
- Every phase is a process onto itself
- Wide spectrum of product grades and formulations
- Extensive sequencing and operator involvement
- Non Self-Regulating (non stationary with no conventional steady state)
- Extreme rangeability of manipulated flows for temperature & concentration control (e.g., crystallization & reaction rates go from zero to max)
- Nonlinear due to changing volume and concentrations
- Unidirectional response in some cases (response in only one direction)
- Setpoint overshoot is problematic (e.g., < 0.1 ^{o}C and 0.1 pH for bioreactors)
- Window of allowable PID gains (oscillations from too low or high PID gain)
- Contaminants, impurities, and inhibitors are trapped in batch
- At-line & Offline Analysis results often too late (e.g., after phase completed)
- Variability captured in batch endpoint (no inherent attenuation)
- Batch process yield, production, quality, and repeatability are interrelated
- Data exclusion frequently needed for batch analysis

Principal Component Analysis (PCA)

- Exclusion “Off” measurements and valves (inactive phases)
- Reduction of data compression
- Use of manipulated flows as inputs since PID transfers variability from process variable to manipulated variable
- Translation to rates of change (batch profile slopes)
- Enough but not too many batches (e.g., 30 < # < 50)
- Test set of batches kept off to side to validate model
- Model for each product grade and formulation
- Minimized number of Principal Components (e.g., # < 5)
- Use of Hotelling T^2 and Q SPE as complementary statistics
- Drill down to contributions when control limit is exceeded
- Exclusion of outliers
- Verification measurement integrity for major contributors
- Verification of process “cause and effect” for major contributors

Partial Least Squares (PLS)

Good News!
Partial Least Squares (PLS) end point predictions do not need dynamic Compensation require in continuous processes for synchronization and correction with Analysis results



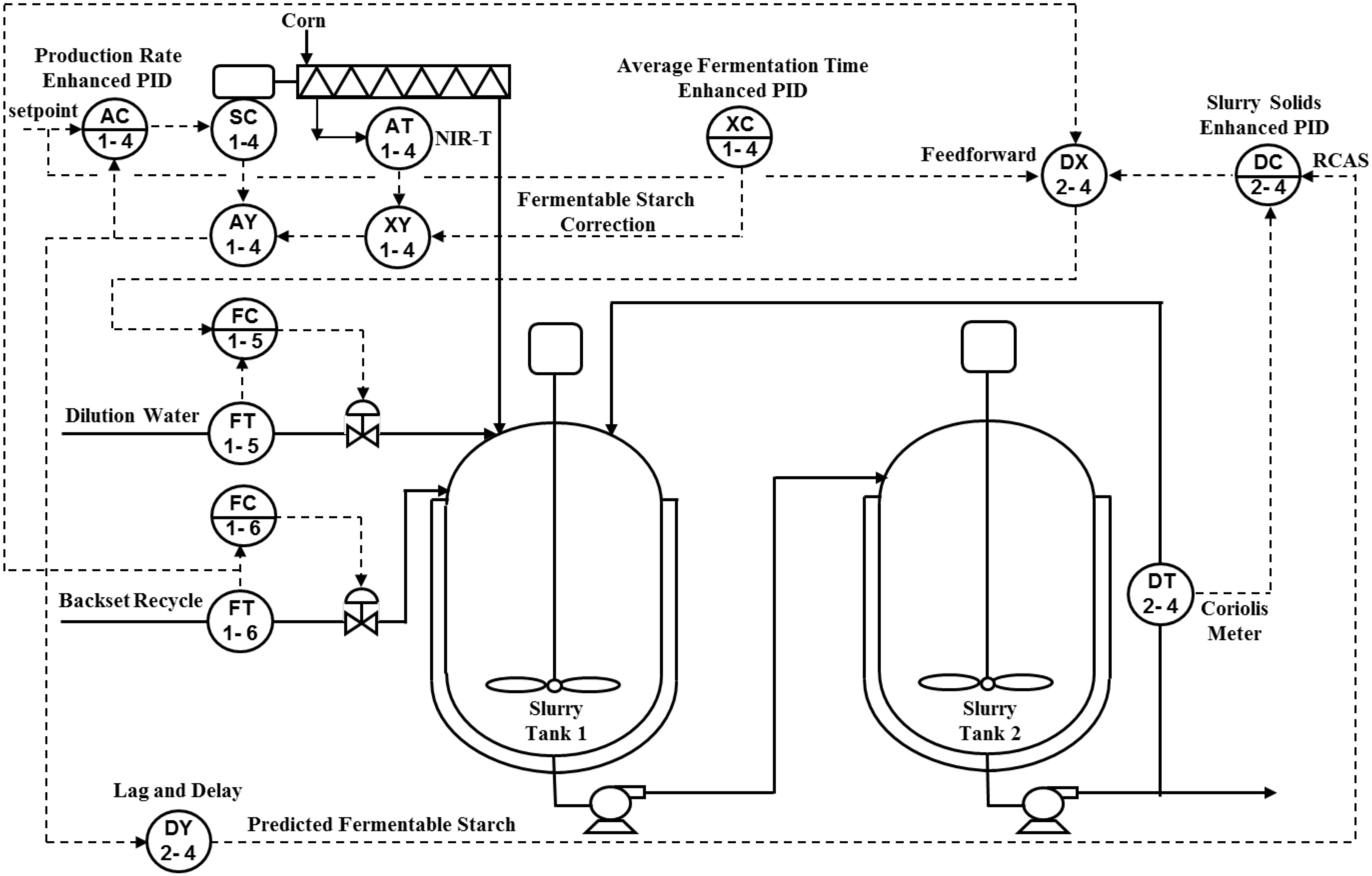
Worm plots show where future batches are headed

Elevation of Operator Role

- Elevating operator role from manual actions to supervision improves repeatability, quality, efficiency, and capacity.
  - Automation intelligence & repeatability enables continuous improvement
- Smart alarm logic to activate only a root cause alarm
- Minimization of wait & phase times & operator attention requests
  - Smart PID features and sequences eliminate manual actions
  - PCA used to automatically proceed if within control limits
  - PLS used to automatically proceed if predictions good
  - Phase hold times minimized by lab and first principle models and tests
  - Smart digital valve controller readback used to confirm positions
  - Middle signal selection of pH electrodes reduces noise, failures & errors
  - Smart transmitters improve accuracy and reliability and give diagnostics
  - Sensors used with least drift and best threshold sensitivity (e.g., RTDs)
  - Operations made simultaneous rather than sequential
  - Intelligent detection of end points

Optimization by Enhanced PID

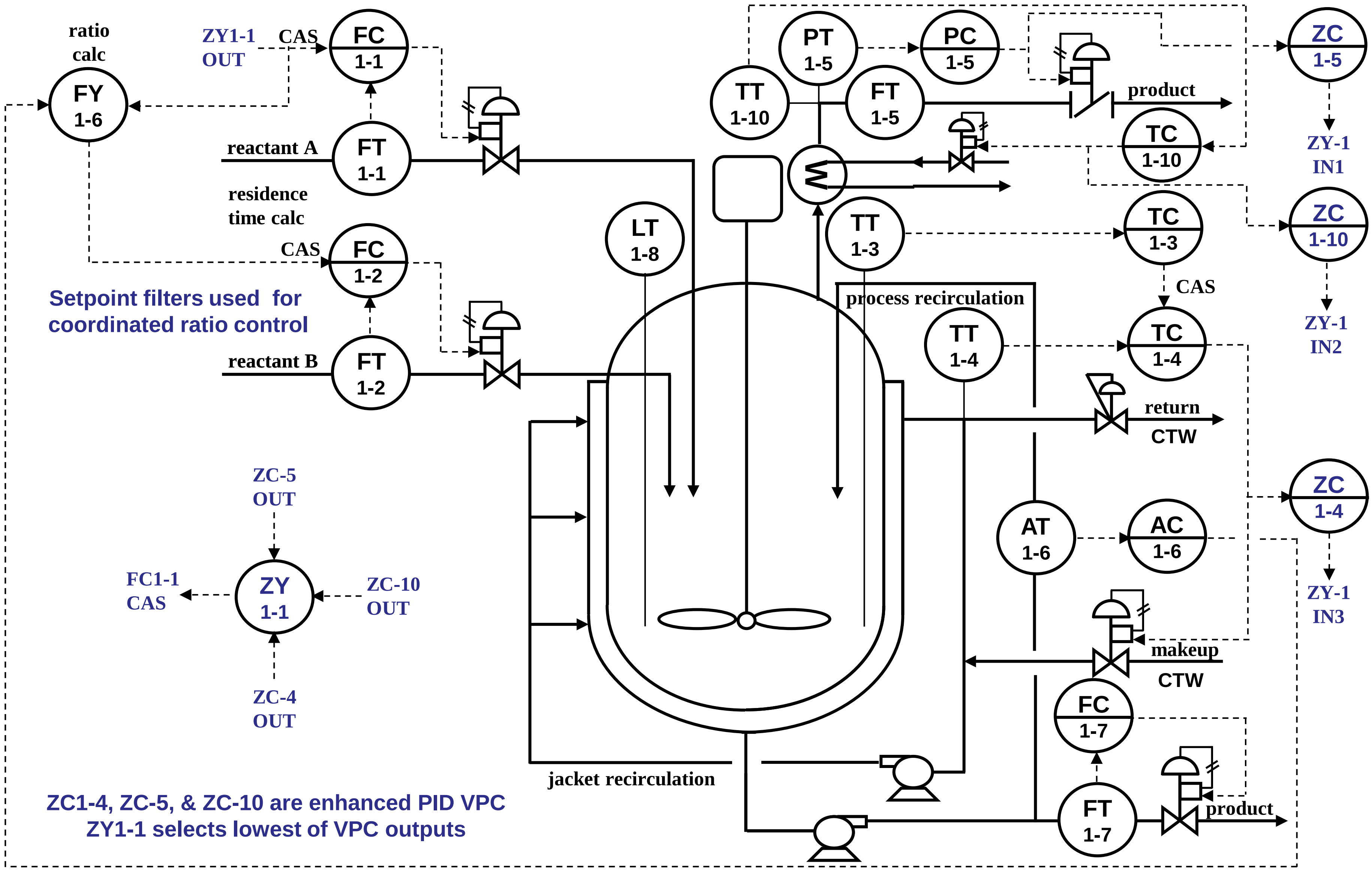
Enhanced PID on continuous unit operations upstream and for the profile slope of batch operations eliminates the need to retune for large and variable analysis times and can thus effectively use the results from at-line and even off-line analyzers as controlled variables.



Valve Position Control (VPC)

- Feed rate for fed-batch reactors maximized by VPC pushing the following valves to their maximum effective valve position:
  - Jacket coolant
  - Condenser coolant
  - Vent
- External reset feedback with slow down and fast up setpoint rate limits on reactor feed flow controller setpoint provide a directional move suppression enabling a gradual smooth optimization and fast correction for abnormal conditions
- Enhanced PID developed for wireless with a threshold sensitivity setting can ignore limit cycles in valve positions
- Coordinated ratio control of fed batch reactants by use of filtered setpoint enables minimizes upsets to stoichiometry

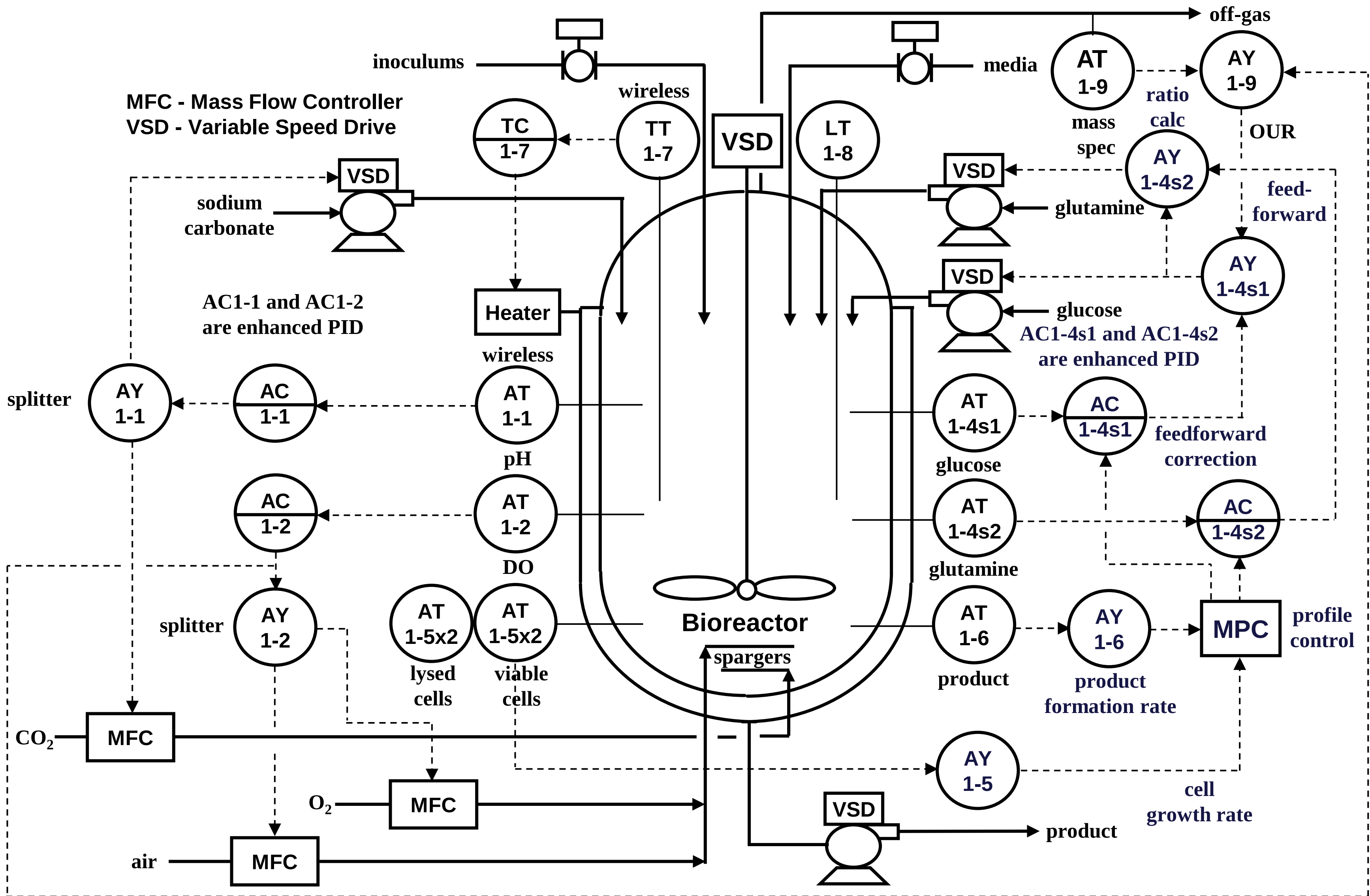
Optimization by Valve Position Control (VPC)



Batch Profile Slope Opportunities

- Essential methods to compute batch profile slope:
  - For continuous measurements (e.g., online analyzers), pass process variable (PV) or manipulated variable (MV) through a dead time block. Output of block (old value) is subtracted from input of block (new value) and divided by dead time. The resulting rate of change is multiplied by a time interval and added to new value to get future valve. Dead time and time interval are chosen large enough to provide good signal to noise ratio. The dead time block is key to continuous & fast updates.
  - For discontinuous measurements (e.g., at-line and offline analyzers) compute slope when measurement is updated (e.g., analysis result)
- The batch profile slope enables end point prediction by:
  - Sudden change in key PV (e.g., conductivity) or MV (e.g., vent flow)
  - Vectored approach of PV (e.g., concentration) or MV (e.g., cooling)
- The batch profile slope enables decision in trade off between reducing cycle time (increasing capacity) and increasing yield
- The batch profile slope enables model predictive control:
  - Slope converts a variable's unidirectional response to bidirectional

Optimization by Model Predictive Control (MPC)



Integrating Process Tuning Rules

reset time (sec) → $T_i = 2 * \lambda + \theta_o$

control objective arrest time (sec) → λ

maximum dead time (sec) → θ_o

controller gain (dimensionless) → $K_c = \dfrac{T_i}{K_i * (\lambda + \theta_o)^2}$

Integrating process gain (1/sec) → K_i

Setting reset time first and then controller gain per above tuning rules prevents violation of low gain limit. Arrest time greater than dead time prevents violation of high gain limit.

Slow rolling oscillations will develop if the following low PID gain limit is violated:

$$K_c > \frac{2}{K_i * T_i}$$

Derivative action is normally used in temperature control where rate time is set equal to the secondary time constant from process heat transfer surface or thermowell lags.

Best Practices - 1

- Coriolis meters on liquid feeds for precise concentration control and extremely accurate component totalization
- Analysis of raw materials for trace components (e.g., inhibiters) that could affect conversion time or product quality and take compensatory actions
- As many unit operations made simultaneous as possible such as filling, heating, and pressurization to reduce batch cycle time
- Automation of all manual actions by smart PID control and sequences
- Elimination of wait and hold times by proceeding without manual operator or lab data entry or approval by inferential measurements and data analytics
- Smart instruments with best repeatability, reliability, & least drift sensors
- Online metrics of batch efficiency and capacity
- Data analytics to monitor batch repeatability and predict endpoints
- Integrating process tuning rules with arrest time set relative to dead time for primary batch composition, pH, pressure, and temperature PID controllers
- Unidirectional (single ended) process responses where process variable can only go in one direction (e.g. heating with no cooling), a proportional plus derivative controller structure (no integral) or translation of process variable to be the slope of the desired profile are employed

Best Practices - 2

- Control of the batch profile slope where the slope can decrease as well as increase (bidirectional response) by the use the rate of change of the key batch process variable as the controlled variable eliminates overshoot.
- Rate of change computation of a process variable or manipulated variable of indicators and controllers, respectively to predict and detect the end of batch phases and make economic decisions (e.g., efficiency vs capacity)
- Inferential measurements of conversion such as cooling rate and total for chemical reactors and crystallizers, oxygen uptake rate and total for bioreactors, and carbon dioxide production rate and total for fermenters
- For rate of change computation & future value of a process or manipulated variable, dead time block used to improve signal to noise and immediacy
- Feeds optimized based on raw material and batch composition analysis
- Enhanced PID used for batch composition control with at-line or offline analyzers for stopping limit cycles from deadband & resolution limits and enable directional move suppression for split range point discontinuities
- Valve position control and override control to maximize fed-batch feed
- Model predictive control to optimize batch profiles
- High fidelity models & virtual plant to explore and develop opportunities

Related Resources

- "Life is a Batch", *Control*, May 2005
- "Unlocking the Secret Profiles of Batch Reactors", *Control*, July 2008
- ***"***Get the Most Out of Your Batch*", Control,* Sept 2012
- *Advances in Reactor Measurement and Control,* ISA, 2014
- *Good Tuning: A Pocket Guide – 4th Edition*, ISA, 2015
- "How to avoid common tuning mistakes", *InTech*, May/June 2015