Process Control - Project Task 1
Control of a Multivariable Process

Submitted by
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Newell and Lee Evaporator

Process Description and Flow Diagram:

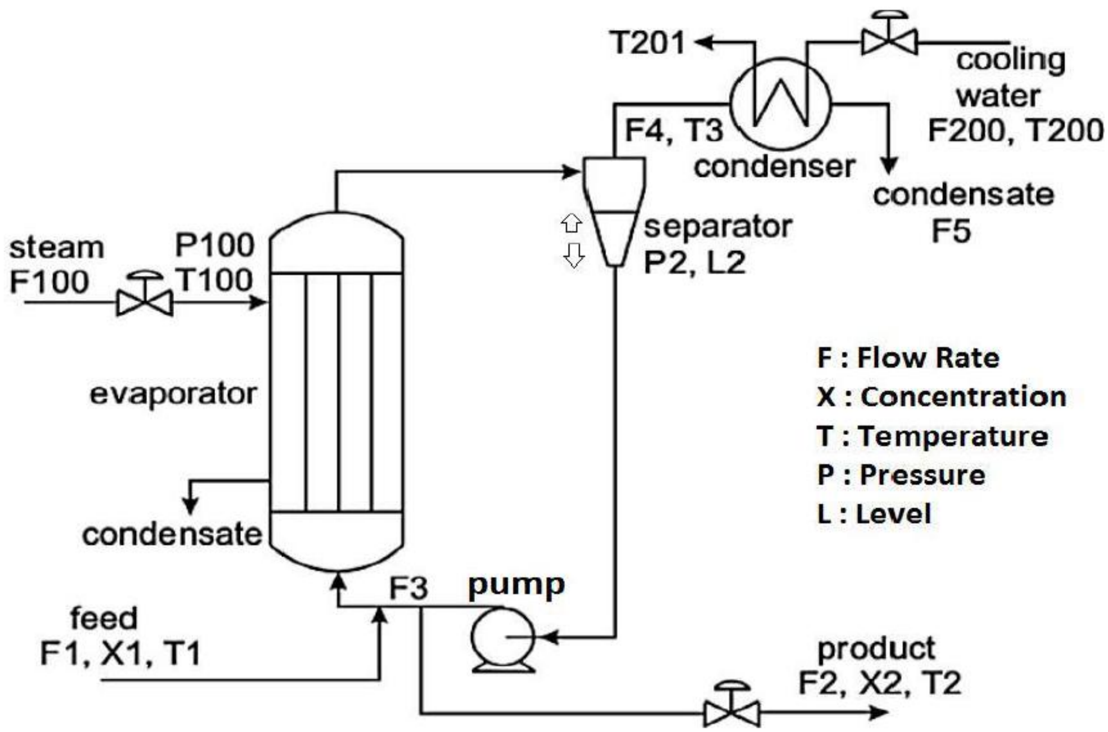

Figure 1: A typical evaporator schematics

Evaporation is the process of heating a liquid to its boiling point to remove water as vapor. An evaporator plant is an industrial process for evaporating solvents from a feed (e.g., in paper making or sugar production).

A liquid “Feed” (F1, X1,T1) is carried in and combined with the recirculating liquor. It’s (F3) pumped into the evaporator, which is a heat exchanger that uses steam to exchange heat. The steam (F100, T100, & P100) enters to the evaporator at the top and the condensate exits at the bottom left (ignored here, but could be used to improve efficiency) . In the evaporator, the recirculating liquor boils, forming a two-phase combination of liquid and vapor are segregated (in the separator: P2 & L2). The liquid is now more concentrated than when it entered the evaporator, is pump round again and some of it is pulled out as output "Product" (F2, X2, & T2). The vapor is transferred to a condenser, which is another heat exchanger and now heat being exchanged with cooling water (F200, & T200). In the top right of Figure 1, the condensate (F5), which can be a valuable product in some situations, leaves the operation. After heat exchange the temperature of this cooling water becomes T201 with is usually very high and can be used as steam in evaporator to increase efficiency.

Design aspects of a process control system:

Control Objective:

Keeping variations in the product composition as small as possible in the presence of disturbances. To operate the evaporator safely and without damaging the installed equipment, it requires the pressure in the evaporator (*P2*) and the level of liquid in the separator (*L2*) to be controlled. If the separator overflows the condenser will be damaged. If it runs dry, the pump will be damaged.

Input Variables:

Manipulated Variables:

In order to control the evaporator, we assume we can adjust three variables

1. The mass flow rate of product being drawn off from the recirculating liquid (F2)
2. The pressure of steam entering the evaporator (P100)
3. The mass flow rate of the cooling water entering the condenser (F200)

Disturbance variables:

I. The feed flow rate (F1)

II. The circulating flow rate (F3)

III. The feed composition (X1)

IV. The feed temperature (T1)

V. The cooling water inlet temperature (T200)

Output Variables:

Measured

- ❖ The main variable which needs to be controlled is the 'Product Composition', which we will call X2
- ❖ The level of the liquid in the separator tank L2
- ❖ The operating pressure in the evaporator P2

Unmeasured

- ❖ Condensate flow rate (F5)
- ❖ Temperature of cooling water during leaving the condenser heat exchange (T201)
- ❖ Temperature of output product (T2)

Constraints:

Hard constraints: constraints that can not be violated

- ❖ As a rule of thumb, Minimum (10% of the maximum limit) and maximum (double of a nominal value) flow rates are allowed

Soft Constraints: constraints that may be violated up to certain degree

- ❖ Minimum and maximum pressure P2 in the evaporator to maintain output product quality
- ❖ Liquid level of L2 in the separator. If it overflows the condenser may be damaged; if it runs dry the pump may be damaged

Operating Characteristics:

As the input feed F1, and hence F3 is continuous, therefore the output product is also continuously drawn off. The process is continuous.

Since there are Multiple inputs and outputs, hence the system is MIMO control system

Control Structure:

Because of the multiple inputs, outputs, and disturbances variables in the system, we have to consider both feed-forward and feedback control.

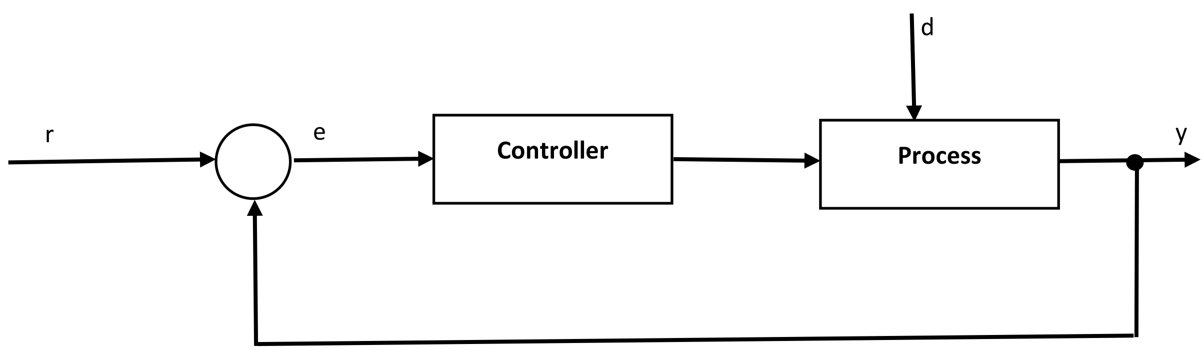

Figure 2: A typical feedback control look with disturbance

Here,

y → process output, controlled variable
r → reference signal, set-point
e → error signal, control error
Computed by the comparator (or summing point): $e = r - y$
d → disturbance signal

Fundamental Mathematical Model:

The separator level (L2) is determined by equation

$$\rho A \frac{dL}{dt} = \mathrm{F1} - \mathrm{F2} - \mathrm{F4}$$

Where ‘ρ' is the liquid density and ‘A’ is the cross sectional area of the separator. It was assumed initially that $\rho A = 20\ \mathrm{kg/m}$,

The evaporator itself is modeled by five equations (Newell, 1989):

$$\mathrm{M}\frac{dX2}{dt} = \mathrm{F1(X1)} - \mathrm{F2(X2)}$$

$$\mathrm{C}\frac{dP2}{dt} = \mathrm{F4} - \mathrm{F5}$$

$$\mathrm{T2} = 0.5616(\mathrm{P2}) + 0.3126(\mathrm{X2}) + 48.43$$

$$\mathrm{T3} = 0.507(\mathrm{P2}) + 55$$

$$\mathrm{F4} = \frac{\mathrm{Q100} - \mathrm{F1} * \mathrm{C_p}(\mathrm{T2} - \mathrm{T1})}{\lambda}$$

Here,

F4= vapor flow rate

F5= condensate flow rate

T2= Output product temperature

T3= Vapor temperature entering to condenser

Also the values for coefficients have been selected as:

M=20 kg, C= 4 kg/kPa, Cp= 0.07 kW/°K(kg/min), λ=38.5 kW/(kg/min)

Note: T2 will be needed as an output to the Steam Jacket model, T3 will be needed as an output to the Condenser, and F4 will be needed as an output to the Separator. Also X2 and P2 are not needed as inputs to other parts of the process, they are crucial outputs of the whole proce3ss, and will be among the most important variables being controlled. So, it is crucial to bring them out as outputs of the evaporator.

The Heater Steam Jacket is described by equations (Newell, 1989):

$$\mathrm{T100} = 0.1538(\mathrm{P100}) + 90$$

$$\mathrm{Q100} = 0.16(\mathrm{F1} + \mathrm{F2})(\mathrm{T100} - \mathrm{T2})$$

$$\mathrm{F100} = \frac{\mathrm{Q100}}{\lambda_{\mathrm{S}}}$$

Where,

T100= Steam temperature

F100= Steam flow rate

λ_s = Coefficient with the value of 36.6 kW/(kg/min)

Note: Q100 is needed as a n output to the evaporator.

The Condenser is described by equations (Newell, 1989):

$$\mathrm{Q200} = \frac{\mathrm{UA2(T3 - T200)}}{1 + (\mathrm{UA2})/(2\mathrm{C_p} \times \mathrm{F200})}$$

$$\mathrm{T201} = \mathrm{T200} + \frac{\mathrm{Q200}}{\mathrm{F200} \times \mathrm{C_p}}$$

$$\mathrm{F5} = \frac{\mathrm{Q200}}{\lambda}$$

Where,

Q200 = Condenser duty

T201 = Cooling water outlet temperature

UA2 = Coefficient with value 6.84 kW/°k

The other coefficients have the same value as above.

Note: F5 is needed as an output to the evaporator

<u>Degree of Freedom analysis (DOF):</u>

Number of unknown variables: NV = 20

Number of independent equations: NE = 12

Hence,

$$\mathrm{DOF = NV - NE} = 20 - 12 = 8$$

The degree of freedom of the system is 8, hence we have to define 8 variables to make DOF=0 and get the solution.

These variables are:

Disturbance variables = F1, X1, T1, F3, and T200 &

Manipulated variables = F2, P100, and F200

References:

- https://www.researchgate.net/publication/258029979_Nonlinear_Model_Predictive_Control_of_an_Evaporator_System_Using_Fuzzy-Neural_Model
- https://www.sciencedirect.com/science/article/pii/S1474667016420811

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