Process Control - Project (WiSe 2020/21)

Control of a Multivariable Process

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Newell and Lee Evaporator

Process description:

A forced circulation evaporation process is an industrial process used to evaporate solvent from a feed-stream for concentration of inversely soluble materials, crystallizing duties, and in the concentration of thermally degradable materials which result in the deposition of solids. Figure 1 shows a diagram of a typical evaporator.

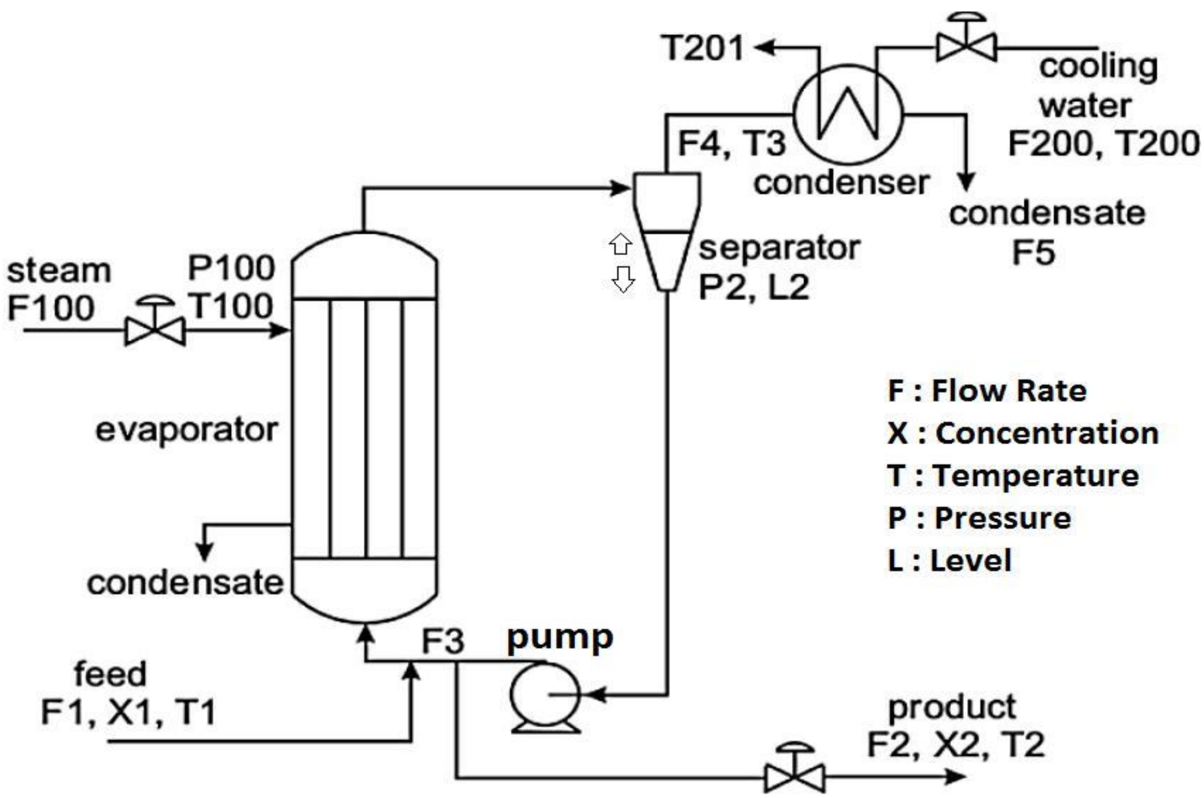

Figure 1: A typical evaporator schematics

A liquid ‘Feed’ with flow rate F1 comes in with Concentration X1 and Temperature T1 and is mixed with re-circulating liquor with flow rate F3. This mixture is pumped into the evaporator by itself, which is a heat exchanger, in which heat is exchanged with steam having a flow rate F100 at a temperature T100 and Pressure P100. Steam comes in at the top of the evaporator, and its condensate leaves at the bottom left. The working pressure within the evaporator is P2. The re-circulating liquor boils in the evaporator and a two-phase mixture of liquid and vapor flows to the Separator which creates the liquid level L2, where the liquid and vapor are separated from each other. The liquid, now more concentrated than when it entered the evaporator, is pumped round again using pump, and some of it is drawn off as ‘Product’ with flow rate F2, concentration X2 and temperature T2. The vapor with flow rate F4 and Temperature T3 flows to a Condenser, which is another heat exchanger, this time heat being exchanged with cooling water with flow rate F200 and temperature T200. 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. The condensate with flow rate F5 (which may itself be a useful product in some cases) leaves the process, see the top right of Figure 1.

Control design aspects:

Control Objective:

- The main variable which needs to be controlled is the ‘Product Composition’, which we will call *X*2. Keeping variations in the composition as small as possible maximizes the profitability of the evaporator, because it minimizes production of out-of-spec product (which cannot be sold, or has to be sold at a low price), while minimizing production costs, since it is possible to aim for a composition only a little better than the minimum acceptable one. However, it is also necessary to operate the evaporator safely, and without damaging the installed equipment. This requires the pressure in the evaporator (*P*2), and the level of liquid in the separator (*L*2), to be controlled.

- Economic Considerations: The cooling water that becomes steam with temperature T201 because of the heat exchange in condenser can be used in evaporator.

Input Variables:

Manipulated variable

- The mass flow rate of the product being drawn off from the re-circulating liquor (*F*2).
- The pressure of the steam entering the evaporator (*P*100).
- The mass flow rate of the cooling water entering the condenser (*F*200).

Disturbance variable

- The Feed flow rate (*F*1)
- The circulating flow rate (*F*3)
- The Feed composition (*X*1)
- The Feed temperature (*T*1)
- The cooling water inlet temperature (*T*200)

Output variables:

- The level of the liquid in the separator tank L2.
- Concentration of the liquid obtained as the product X2.
- The operating pressure P2 in the evaporator.

Unmeasured

- Condensate flow rate (F5).
- Temperature of Cooling water after heat exchange (T201)
- Temperature of Product (T2)

Constraints:

Hard Constrains

- Minimum and maximum liquid level in the separator (L2). If the separator overflows the condenser will be damaged; if it runs dry the pump will be damaged
- Minimum and maximum flow rates allowed

Soft Constrains

- Minimum and maximum pressure P2 in the Evaporator to maintain the product quality.

Operating Characteristics:

- As the feed is continuously supplied to the system and the product is also continuously drawn off, the process is a continuous process.
- There are multiple inputs and outputs so the system is a MIMO control system.

Control Structure:

- As there are multiple inputs, outputs and disturbance variables in the system we have to use a feed forward and feedback control.

Fundamental mathematical model:

The Separator Level (L2) is determined by equation

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

Where ρ is the liquid density and A is the cross-sectional area of the separator. It was assumed initially that ρA = 20 kg/m,

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

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

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

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

$$T3 = 0.507(P2) + 55$$

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

Where F4 is the vapor flow rate, F5 is the condensate flow rate, T2 and T3 are the product and the vapor temperatures, respectively, Q100 is the heater duty, and the coefficients have the following values:
M = 20 kg, C = 4 kg/kPa, Cp = 0.07 kW/°K(kg/min), λ= 38.5 kW/(kg/min).

Note that the signal 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 note that, although X2 and P2 are not needed as inputs to other parts of the process, they are crucial outputs of the whole process, 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):

$$T100 = 0.1538(P100) + 90$$

$$Q100 = 0.16(F1 + F2)(T100 - T2)$$

$$F100 = \frac{Q100}{\lambda_s}$$

Where T100 is the steam temperature, F100 is the steam flow rate, and λS is a coefficient with value λS= 36.6 kW/(kg/min).

Note that Q100 is needed as an output to the evaporator.

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

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

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

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

Where Q200 is the condenser duty, T201 is the cooling water outlet temperature, and UA2 is a coefficient with value UA2 = 6.84 kW/ħK. The other coefficients have the same values as above.

Note that F5 is needed as an output to the Evaporator.

Degree of Freedom Analysis:

Number of unknown variables: NV = 20

Number of independent equations (NE) = 12.

$$DOF = NV - NE = 20 - 12 = 8$$

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 $F1$, $X1$, $T1$, $F3$, *and T200* which are disturbance variables and $F2$, $P100$, $F200$ which are manipulated variables.

References:

- Newell, R.B, and Lee, P.L, *Applied Process Control, A Case Study*, New York: Prentice-Hall, 1989.
- Dorf, R.C, *Modern Control Systems, 6th edition*, Reading MA: Addison-Wesley, 1992.