Control of continuous distillation columns

DINAMICA E CONTROLLO DEI PROCESSI CHIMICI
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Corso di Laurea Magistrale in Ingegneria di Processo e dei Materiali

MolBNL MOLECULAR BIOLOGY AND NANOTECHNOLOGY LABORATORY
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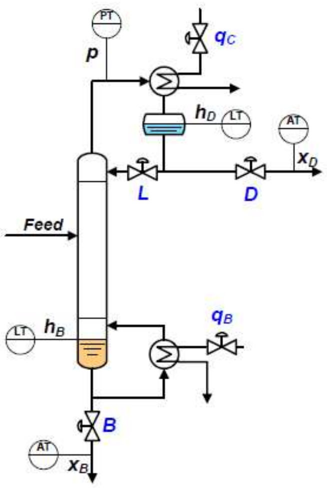
OBJECTIVE OF CONTINUOUS DISTILLATION

- Given a feed stream F, split it into two products, D and B
  - Of assigned composition (one species in each product) → **quality** specifications
  - With maximum throughput → **quantity** specifications
  - With minimum energy expenditure → **energy** specifications
- At steady state, the composition of each product depends on how the components distribute **inside** the column
  - For each interanl distribution, a different set of product composition exists (see McCabe-Thiele diagrams)
- To obtain both products on spec, the control system must ensure that the internal distribution **of the components is the correct one**
  - At steady state



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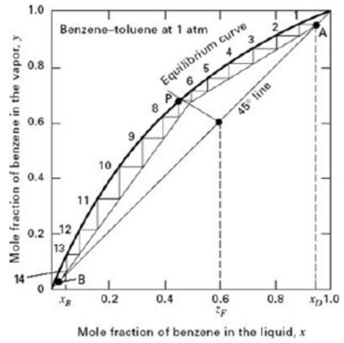
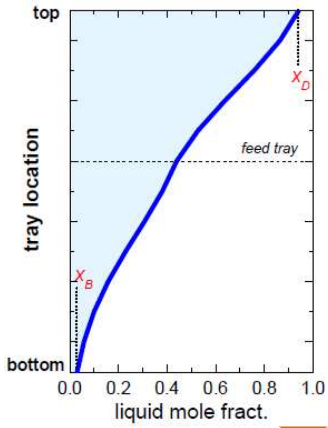
THE INTERNAL DISTRIBUTION OF COMPONENTS

- Assume that the following is given: column (N_{rect}; N_{strip}), feed (F; z_F; q) and operating pressure
- If the product composition x_D and x_B are assigned, then:
  - The internal flows (L; V') are univocally determined
  - The composition on each tray is univocally determined





The more **horizonal** the x profile on a tray, the larger the fractionation achieved on that tray

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DEGREES OF FREEDOM AND INDEPENDENT VARIABLES

How many variables are available to ensure that the steady state achieved is the desired one?

- Given the feed conditions and the operating pressure, an existing column has 2 degrees of freedom (at steady state)
  - Setting **2 independent variables** is a necessary and sufficient condition to completely **define the column steady state**
- The two independent variables can be chosen among:
  - Flow (L) or ratio (L/D) of liquid reflux
  - Flow (V') or ratio (V'/B) of vapor boilup

  } Operating variables

  - Mole fraction of a component in one of the products ($x_{D,i}$, $x_{B,i}$)
  - Product split (D/F or B/F or D/B)
  - Temperature in one column section (as long as «reasonable»)

  } Performance specifications

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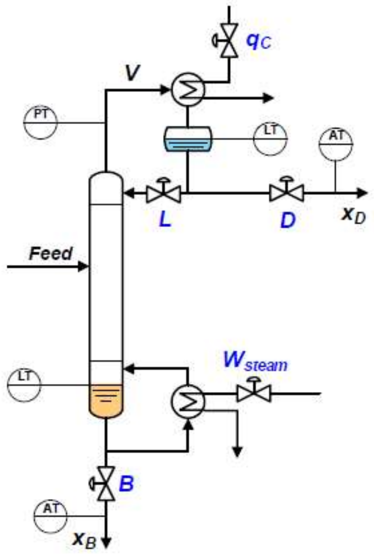
MATERIAL BALANCES AROUND THE COLUMN

- At steady state, the following must hold true: $\begin{cases} F = D + B \\ F z_F = D x_D + B x_B \end{cases}$
- If the specifications x_D and x_B for both products are assigned, then the product flows (D and B) remain assigned as well, **regardless the column available** (i.e., regardless its number of trays)

$$\frac{D}{F} = \frac{z_F - x_B}{x_D - x_B} \quad \text{and} \quad \frac{B}{F} = \frac{x_D - z_F}{x_D - x_B} \quad \Rightarrow \quad \frac{D}{B} = \frac{z_F - x_B}{x_D - z_F}$$

- If two controllers are used to mantain the two desired compositions, in the long run **they must «somehow» act on D/B split**
  - At steady state, the product split must be the one dictated by the overall material balances
  - For a given feed, whatever the control scheme, the required split is the same…
  - …as well as the energy expenditure (which must be large enough)



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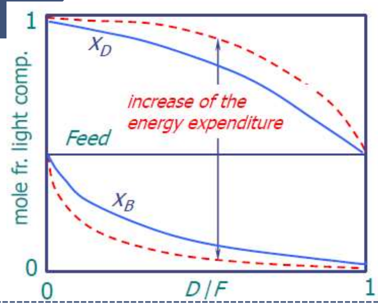
MATERIAL BALANCES AND ENERGY EXPENDITURE

- Given a column and assigned the energy expenditure, by reducing the flow of a product, the purity of that product is increased
  - At steady state, the flow of the other products increases, making its purity decrease

$$\frac{D}{F} = \frac{z_F - x_B}{x_D - x_B} \quad ; \quad \frac{B}{F} = \frac{x_D - z_F}{x_D - x_B}$$

- The energy expenditure determines the achievable degree of separation
  - Note that the effect of a change in the interal traffic propagates onto the product compositions with slow dynamics
- The material balance (D/B ratio) determines how the separation is distributed between the two products
  - Note that the effect of a change in the total material balance propagates onto the product composition with fast dynamics



Remarks
- Given the feed, it is not possible to simultaneously assign **both product flows** arbitrarily (D+B=F)
- If the flow of a **single product** is assigned, by increasing the energy expenditure (internal traffic) the separation increases

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INVENTORY CONTROL

- The control system must first ensure that the column **operates at steady state** (stability of operation)
  - Accumulation of vapor or liquid must be avoided ⟶ inventory control

- Therefore, the **basic controls** are:
  - Control of **pressure** (avoiding vapor accumulation)
  - Control of **levels** (avoiding liquid accumulation)

- Notice.
  - In the control schemes that follow, the transmitters are not indicated for ease of drawing

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INVENTORY CONTROL: PRESSURE CONTROL

- Why stabilizing the pressure?
  - Safety
  - Ensuring that the internal temperature provide a univocal indication of composition (at least for binary separations)

- Pressure is also an **indicator of the overall material balance closure** in the vapor phase
  - A pressure variation indicates a vapor-phase imbalance
    - A vapor flow is introduced into the column (through the reboiler), but this flow is different from the one withdrawn from the column (through the condenser)

- To control the pressure:
  - One may either act on the **vapor generation** (q_B, i.e., the energy spent to achieve the separation)
    - Very rare: one instead wishes to «push» the column load to the maximum
    - Exception: superfractionators (e.g., propylene/propane splitters)
  - One may act on the **vapor condensation** (q_C, i.e., condenser partialization)

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CONDENSER PARTIALIZATION

$$q_C = U \times S \times \Delta T_m$$

- Partializing the **mean temperature difference** ΔT_m
  - Changing the cooling water (or air) flow to the condenser
- Partializing the **heat exchanger area** S
  - Partially flooding the condenser with the condensed vapor
- Partializing the **overall heat exchange coefficient** U
  - «invading» the condenser with noncondensable gases
- Not always is the logic identified sharply
- In all these cases, the PC **indirectly** acts on the «internal» material balance (in the vapor phase)
  - Through the exchange of heat
- In some cases (e.g., vapor-phase distillate product), a **direct** action on the **overall** material balance (in the vapor phase) is carried out

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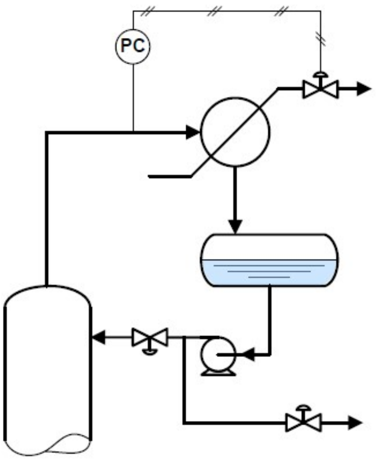
PARTIALIZATION OF ΔT_m

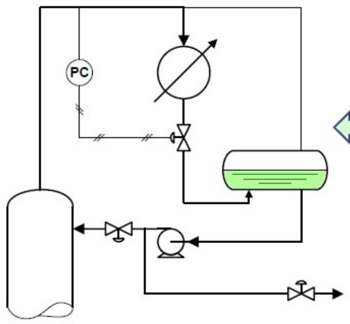


PROS
- Very simple: varying the H2O flow is equivalent to varying the mean temperature difference ΔT_m

CONS
- With large H2O flows, changing the water flow provides only a minor variation of the heat exchange
- With small H2O flows, the water outlet temperature may increase a lot
- Heat exchanger scaling is faster (if water is not demineralized)

REMARKS
- Setting a minimum H2O flow may be convenient
- The control valve is mounted downstream if the exchanger water side is to be mantained under pressure (e.g., for leakage reasons)

PARTIALIZATION OF S



PROS
- Simple; small control valve
- A pressure increase is compensated for quickly by discharging a larger condensate flow

CONS
- Increasing the condenser level (for pressure decrease) takes longer → nonlinear response
- The condenser must be mounted above the reflux drum

REMARKS
- The equalization line makes the pressure in the condenser and in the drum equal → the condenser remains flooded and the discharge of liquid is driven by gravity
- This scheme is used when a large reflux drum is required

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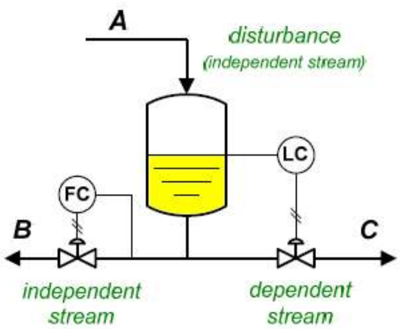
INVENTORY CONTROL: LEVEL CONTROL

- Why stabilizing the level?
  - It is required to ensure the conservation of the total (liquid) mass inside the colum
- The possible accumulation points are:
  - The reflux drum
  - The bottom sump
- In both cases, level control is obtained by partitioning a liquid stream
  - To fulfill the steady-state overall material balance (Accumulation = 0), only **two out of three flows** of the partition can be assigned **arbitrarily**
    - The arbitrary flows are disturbances and/or those determined by an FC
  - The LC determines the third flow by difference (C=A-B), **at steady state**



Recommendation

Avoid obtaining by difference (hence, avoid manipulating through an LC) **a «small» flow if a «large» flow is available** for manipulation

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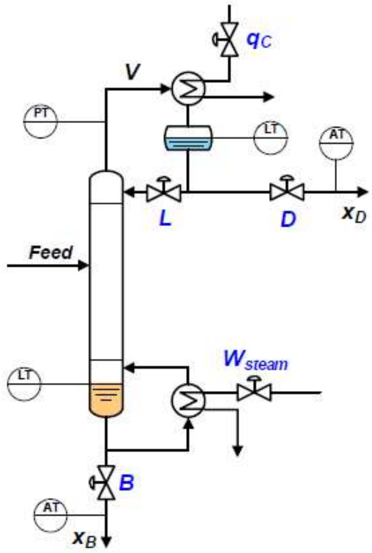
THE FLOWS AVAILABLE FOR CONTROL

- **Once the system pressure has been set under control, 4 valves remain available** (for a given feed)
  - 4 possible manipulates flows
- Of these, 2 are used for inventory control in the liquid phase (level controllers)
  - Top: since the overhead vapor V cannot be manipulated (it is a disturbance), one flow between L and D **must** be manipulated by a LC
  - Bottom: since the internal liquid flow L' cannot be manipulated (it is a disturbance), one flow between B and W_{steam} **must** be manipulated by a LC
- The other **2 flows can be manipulated arbitrarily** at steady state (by two controllers)
  - This amounts to saturating the 2 degrees of freedom ad steady state
  - Often, one flow is used to affect the material balance, the other one to affect the energy balance



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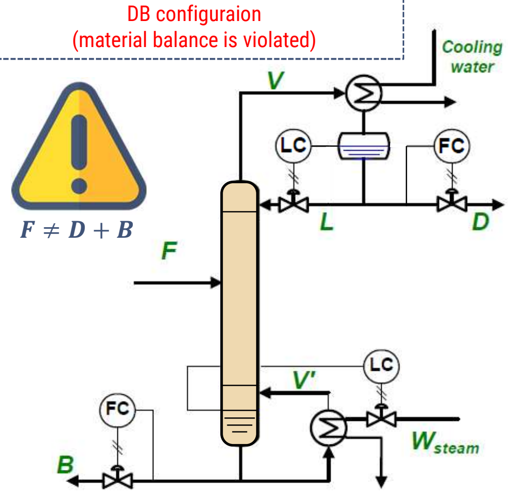
BASIC CONFIGURATIONS
(with inventory control, but without composition control)



- All the configurations seen so far assign the product **compositions** only indirectly
  - The 2 degrees of freedom are saturated by assigning the set-points of the 2 FCs
  - The product compositions (i.e., the internal composition/temperature profiles) are a **consequence** of the assigned set-points
- Instead of assigning **flow** set-points, it would be more convenient to directly assign the product **composition** set-points
  - Then, the **flows** would become **a consequence** of the selected composition set-points
- However, often an **online** measurement of composition is not available
  - It is available instead, the 2 FCs may be simply replaced by 2 Acs
  - Or the FCs may be slaved to 2 master ACs

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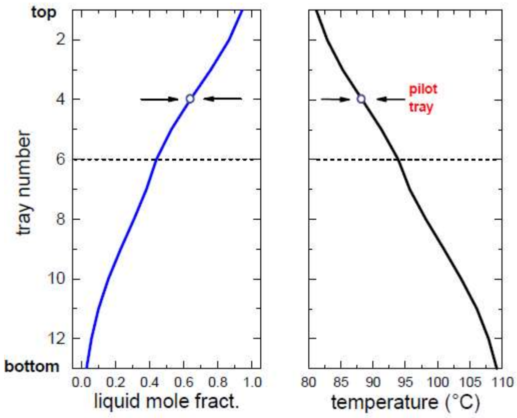
COMPOSITION CONTROL

- Assigned pressure and feed



- At steady state, the product composition is univocally linked to the internal composition profile
  - If a controller can keep a given composition on **one** tray, then also the internal composition profile remains almost fixed, as well as the compositions **of both products**
- One usually prefers assigning the internal temperature rather than the composition
  - **Cost** of sensor
  - Measurement speed and reliability
  - Anticipated disturbance detection

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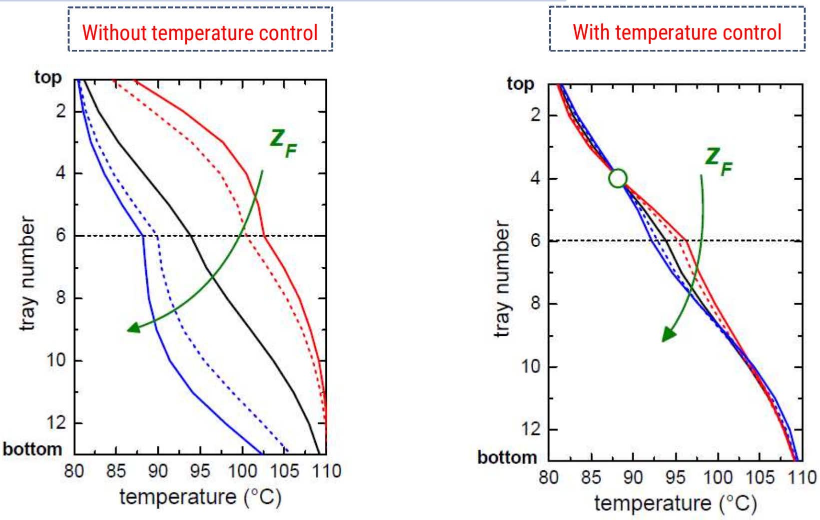
EXAMPLE: DISTURBANCE IN z_F



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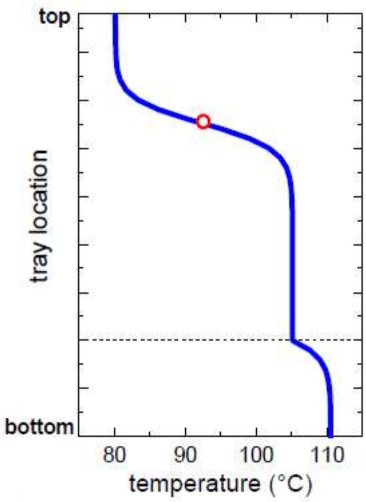
WHERE TO LOCATE THE PILOT TRAY

- In the section the **most valuable** product is withdrawn from
- Close to the **disturbance** inlet
  - Hence, not too far from the feed tray
- **Close to the product** withdrawal point
  - Hence, not too far from the column ends
- On a tray where **temperature changes a lot** with composition
  - Hence, far from the column ends
- On a tray that **fractionates a lot**
  - The speed at which the composition profile on a tray can be changed (by the controller) is ~ proportional to the fractionation that tray carries out
- Far from the top and bottom **accumulation** points
  - To have a small lag in the response



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TEMPERATURE CONTROL

- If the changes in z_F are not too large, and if the energy expenditure is enough, a single temperature controller is sufficient to mantain the purity of both products
  - In practice, the process interactions are exploited
    - More generally, only the composition of the product **closer to the TC** can be controlled satisfactorily
- Hence, to achieve composition control, one of the two FCs (independent variables) is replaced by a TC
- Therefore, the **controllers usually employed** in a column are:
  - FC → to set the degree of separation
  - TC (with possibly a FC cascaded to it) → to set the separation distribution
  - Top LC → for inventory control
  - Bottom LC → for inventory control
  - PC (not indicated in the schemes that follow) → for inventory control

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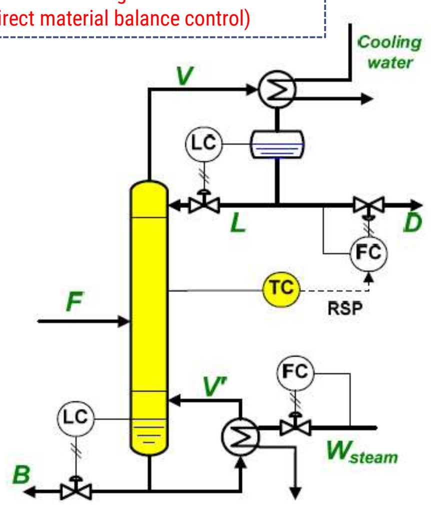
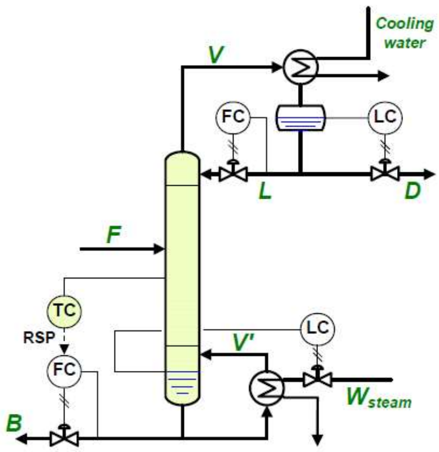
MAIN CONFIGURATIONS

DV configuration
(direct material balance control)



LB configuration
(direct material balance control)



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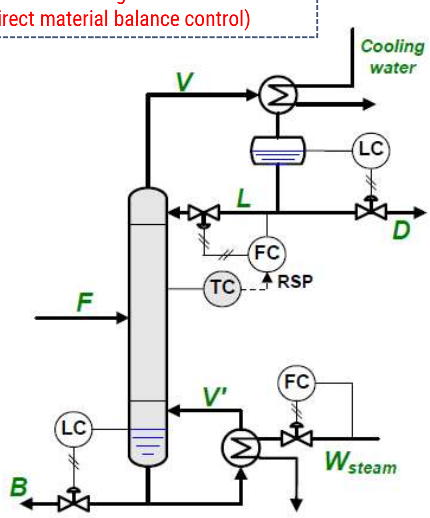
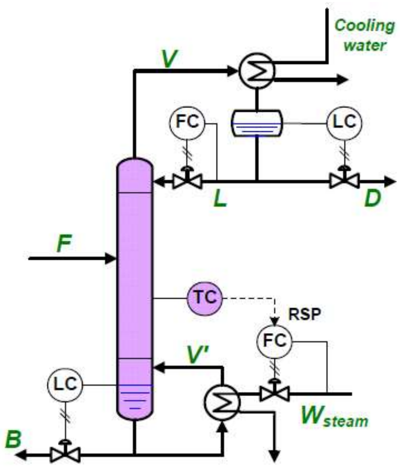
MAIN CONFIGURATIONS /cont'd

LV-1 configuration
(indirect material balance control)



LV-2 configuration
(indirect material balance control)



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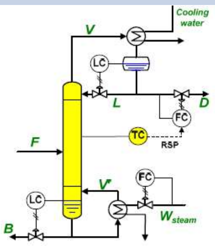
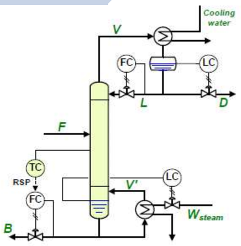
MAIN CONFIGURATIONS /cont'd

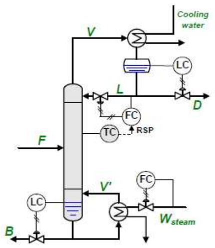
DV



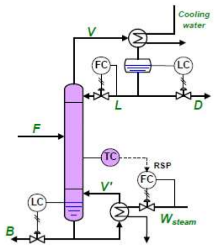
LB



LV-1



LV-2



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FEATURES OF COMMON SCHEMES

DV
- Particularly suitable for D<<L (difficult separations or light-poor feeds) and for D<<B («unbalanced» separations)
- Allows larger throughput than LV-2
- Allows more stable D flow than LV-2
- The top LC tuning interacts with the column speed of response («nested» control loop)

LB
- Particularly suitable for B<<D
- Possible inverse response of the bottom level
- Results in large residence times in the sump (large bottom holdup to prevent inverse response)
- The response is not very prompt («nested» control loop)

LV-1
- Particularly suitable for L<<D
- Prompter control than DV and less prompt than LV-2
- Allows larger througput than LV-2
- Allows reducing the bottom holdup (minimum residence time in the sump)
- Particularly suitable if the pilot tray is not far from the top

LV-2
- Particularly suitable for V'<<B
- Very prompt control
- May result in inverse response of the controlled T
- Particularly suitable for variable feed rates