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INDUSTRIAL EVAPORATION

Venting in Multiple-Effect Evaporators

Effects on Capacity and Energy Efficiency

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1. Introduction

The performance of a multiple-effect evaporator depends on its thermal design, process configuration, and operating conditions.

Venting removes noncondensable gases, yet the venting system does not always receive sufficient attention during equipment design, operation, and maintenance.

Although it often consists of small-diameter piping and simple orifice plates, an improperly sized venting system can substantially reduce the plant’s evaporation capacity and energy efficiency.

2. Sources of noncondensable gases

Noncondensable gases in industrial evaporators come from three main sources:

- Gases in the heating steam;
- Gases dissolved or entrained in the product being processed;
- Air leakage into the system.

In the author’s field experience, air leakage is often the main source of noncondensable gases, particularly in older or poorly maintained equipment.

Manways, gaskets, flanged connections, and centrifugal pump mechanical seals are potential points of air ingress in areas under vacuum.

Air ingress tends to increase as the installation ages and seals deteriorate, especially where preventive maintenance is inadequate.

3. How noncondensable gases affect heat transfer

Noncondensable gases on the steam side impair heat transfer through several mechanisms.

At a given total pressure, these gases reduce the partial pressure of steam and its saturation temperature. They also impose additional resistance to steam transport toward the condensing surfaces.

In more severe cases, gases can accumulate locally and form pockets that restrict steam access to heat-transfer surfaces.

As a result, part of the installed heat-transfer area is underused, reducing evaporator performance.

Under Dalton's law, the total pressure of the mixture is the sum of the partial pressures of steam and noncondensable gases (NCG) [3] [5].

$$P_{total} = P_{steam} + P_{NCG}$$

The heat transfer rate can be expressed as [4]:

$$Q = U \cdot A \cdot \Delta T$$

Here, Q is the heat transfer rate, U is the overall heat transfer coefficient, A is the heat-transfer area, and ΔT is the representative temperature difference. A lower saturation temperature reduces ΔT, and the additional resistance to steam transport reduces the effective overall coefficient [1] [3].

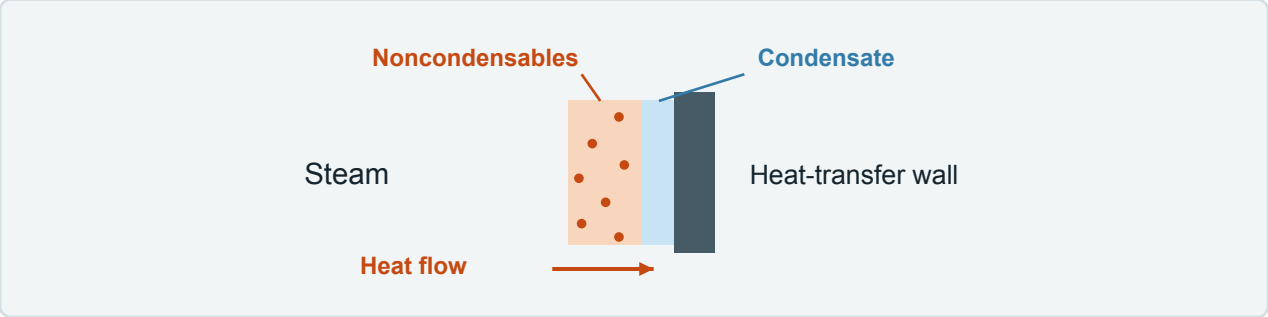

Figure 1 — Effect of noncondensable gases. Gases accumulate near the condensing surface and add resistance to heat and mass transfer.

4. Insufficient versus excessive venting

Ideally, a venting system would remove only noncondensable gases without losing any steam.

In practice, this condition is extremely difficult to achieve.

The aim is to establish a vent flow sufficient to remove noncondensable gases while allowing a small, controlled steam loss.

Insufficient venting

An insufficient vent flow allows noncondensable gases to accumulate inside the equipment, impairing heat transfer and reducing effective use of the installed area.

This can reduce evaporation capacity and alter the temperature profile across the plant.

Excessive venting

An excessive vent flow causes unnecessary steam losses and penalizes energy performance at both ends of the plant:

- At the inlet, it wastes steam that should contribute to product evaporation;
- At the outlet, it increases the heat load on the condenser and cooling-water system.

Some of the energy supplied to the evaporator reaches the condensing system without contributing to product concentration.

Finding the balance

The challenge is to establish a vent flow that removes noncondensable gases while minimizing steam loss.

In practice, accepting a small additional steam loss is preferable to letting residual noncondensable gases impair thermal performance.

Determining this flow is one of the challenges in sizing the venting system.

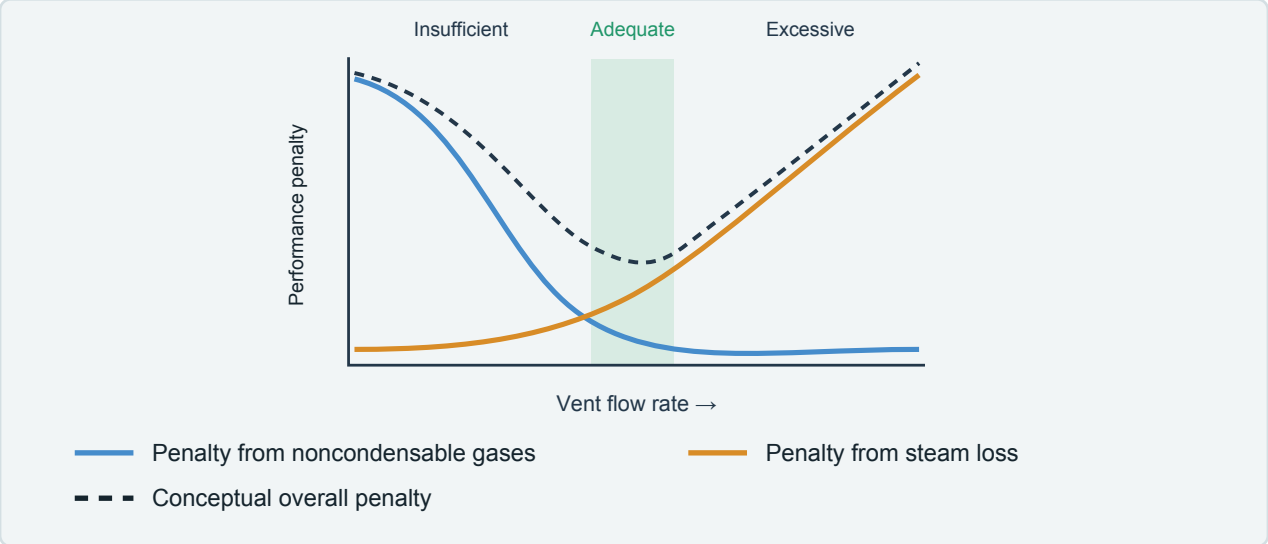

Figure 2 — Balancing vent flow. Qualitative plot without a numerical scale or experimental data.

5. Venting system configuration

All equipment in an evaporation plant that uses condensing steam for heating must have suitable means to remove noncondensable gases.

This includes tubular calandrias, plate evaporators, pasteurizers, and preheaters.

Two configurations can be considered for routing noncondensable gases.

Cascade system

In a cascade system, the gases extracted from one effect are routed to the next, continuing in sequence until they reach the condensing system.

This arrangement recovers some of the steam in the vent stream, but it transfers noncondensable gases between effects.

Common-header system

The author favors an arrangement that independently extracts noncondensable gases from each unit and sends them directly to the condensing system through a common header.

When properly sized and operated, this arrangement prevents successive transfer of noncondensable gases between evaporator bodies.

Each vent point has its own flow restriction sized for the operating conditions of the corresponding unit.

The choice of configuration should reflect the characteristics of the plant and the balance among thermal performance, energy recovery, and effective removal of noncondensable gases.

In *Perry's Chemical Engineers' Handbook*, Standiford describes cascade venting as a way to recover some of the vent steam in the next effect and identifies direct venting to the condenser for plants with a high noncondensable gas load [1]. Minton recommends routing the vents from multiple-effect evaporators directly to the condenser and generally advises against venting from one effect to another [2].

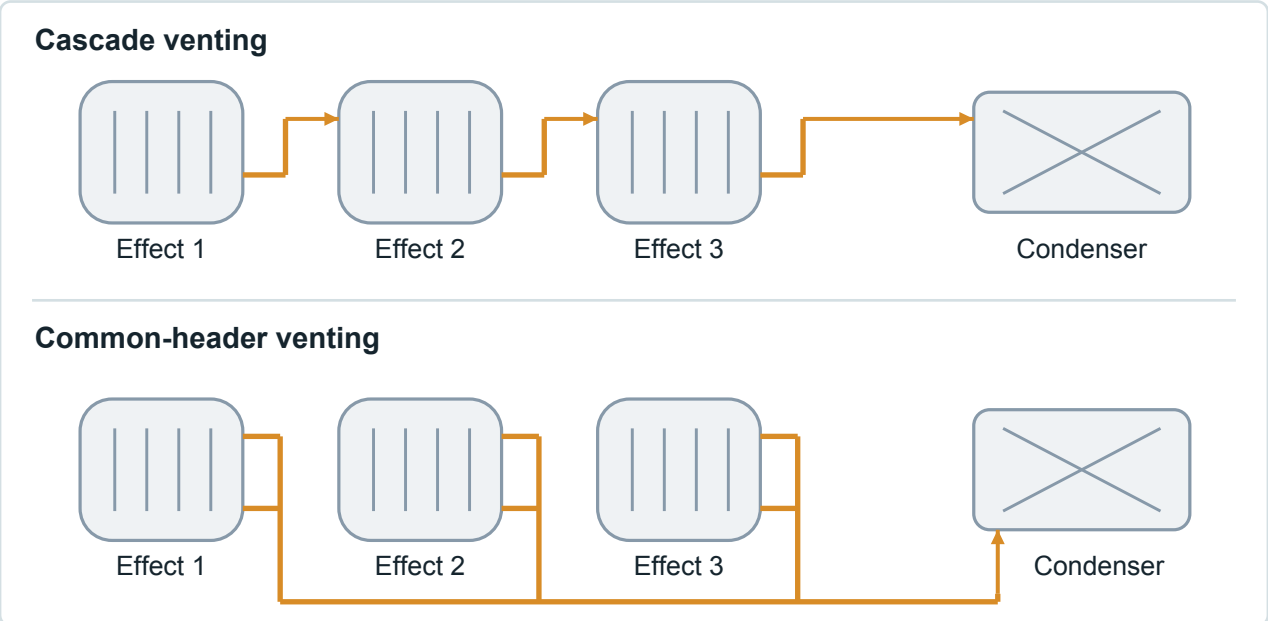

Figure 3 — Comparison of venting configurations. Only vent lines are shown. The main steam, product, and condensate lines are omitted.

6. Location of vent points

The location of vent points is an important design consideration.

Air is denser than water vapor at the same pressure and temperature, but density difference alone does not determine gas distribution inside a calandria.

Equipment geometry, steam flow direction, condensation, and stagnant regions also influence gas distribution.

As a general recommendation for tubular calandrias, locating vent points in both the upper and lower regions of the vessel is advantageous.

The arrangement must nevertheless suit the construction of each unit. The steam flow path and the location of gas accumulation zones should guide vent point selection [2] [3].

7. Sizing orifice plates

In many industrial installations, orifice plates in the vent lines determine the vent flow.

Initial sizing can be based on the estimated heating steam flow to each unit, using a fraction of that flow as the basis for venting.

The percentage depends on the plant characteristics, process conditions, and the experience of the engineer responsible for sizing.

The estimated flow and the upstream and downstream pressure and temperature conditions are used to determine the orifice diameter, accounting for compressible flow.

The initial sizing should then be validated by evaluating the evaporator’s operating performance.

8. Troubleshooting existing installations

In industrial practice, a technical investigation is rarely requested specifically to assess the venting system.

Commonly reported symptoms include:

- Evaporation capacity below the rated value;
- Difficulty reaching the target concentration;
- Difficulty establishing or maintaining vacuum;
- Operating temperatures above design values;
- An unsuitable temperature profile across the effects.

A problem in the venting system is often identified by elimination after a systematic review of other operating conditions.

The first step is to retrieve the original equipment design conditions.

For example, consider a milk evaporator designed for the following conditions:

Parameter	Design condition
Feed flow rate	10,000 kg/h
Feed solids content	12%
Concentrate solids content	50%
Concentrate flow rate	2,400 kg/h
Evaporation capacity	7,600 kg/h
First-effect shell temperature	76 °C
Final-effect separator temperature	49 °C

Once the design baseline has been established, the actual equipment performance is evaluated.

Items to check include steam supply conditions, cooling-water availability, and condenser cleanliness.

If the problems persist after the other potential causes have been investigated, the venting system must be evaluated.

Missing orifice plates are a particularly critical issue encountered in industry.

During maintenance or plant modifications, these components may be removed and left out.

As their presence generally cannot be confirmed by external visual inspection, the evaporator may run for years in this condition, with significant losses in energy efficiency.

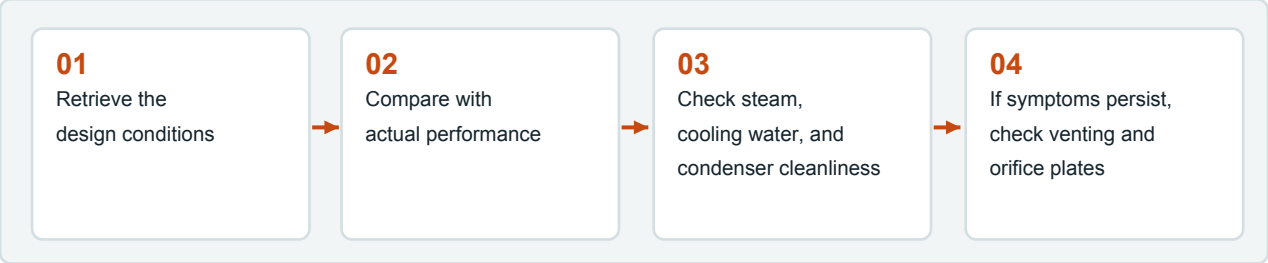

Figure 4 — Troubleshooting sequence. Sequence based on the author's field experience. Investigate venting after evaluating the other potential causes.

9. Field validation of sizing

Venting system sizing can be validated indirectly by evaluating overall evaporator performance.

After the correctly sized orifice plates have been installed, the equipment is returned to service and its operating conditions are reassessed.

Restoring the original design conditions is an important indicator that the system is adequate.

Where possible, the evaluation should also include specific steam consumption and the heat load on the condensing system.

$$SSC = \dot{m}_{\text{live steam}} / \dot{m}_{\text{water evaporated}}$$

Specific steam consumption is expressed in kg of live steam per kg of water evaporated.

$$Q_{cond} = \dot{m}_{water} \cdot C_p \cdot \Delta T$$

Q_{cond} is the rate of heat absorbed by the cooling water, $\dot{m}_{water}$ is its mass flow rate, C_p is its mean specific heat, and ΔT is the increase in water temperature from the condenser inlet to its outlet. With the flow rate in kg/s and C_p in kJ/(kg·K), the result is in kW.

Recovering rated capacity alone does not establish that the plant is operating at its best attainable energy efficiency.

However, pursuing the absolute minimum steam loss is not always technically or economically justified.

A small, controlled steam loss should be accepted as part of proper venting system operation.

10. Leak tightness, inspection, and maintenance

When air ingress increases, the priority should always be to restore the plant’s leak tightness.

Resizing the venting system should not be used to compensate for maintenance deficiencies.

Once properly sized and validated, the system should require no recalibration while process conditions and plant characteristics remain as designed.

Periodic inspection should focus on checking:

- The presence of the orifice plates;
- Installation at the specified locations;
- Conformance of the orifice diameters;
- The absence of deposits and obstructions;
- The integrity of the vent piping.

Significant changes to process conditions or production capacity may nevertheless justify reviewing the original sizing.

In preventive maintenance, periodic inspection confirms that the components conform to their specifications. Restore leak tightness before any sizing review prompted by increased air ingress.

11. Identification and technical documentation

Flow restrictions in industrial venting systems are often left unidentified.

All orifice plates should be physically identified with clearly visible tags that can withstand industrial conditions.

The tags should correspond to the plant's technical documentation.

Up-to-date process flow diagrams and data sheets should identify the components, their locations, and their specifications.

Sound technical documentation is essential to preserving the equipment's original design characteristics throughout its service life.

12. Conclusion

Despite its apparent simplicity, the venting system plays a fundamental role in multiple-effect evaporator operation.

Insufficient venting reduces heat transfer and evaporation capacity. Excessive venting wastes steam and increases the energy demand of the cooling system.

Proper sizing, together with leak tightness, preventive inspection, and technical documentation, directly supports the plant's sustained performance and energy efficiency.

The venting system should be sized to meet process conditions. Maintenance deficiencies should be corrected at their source.

The importance of the venting system lies in its effect on overall evaporator performance, regardless of the size of its piping or the simplicity of its components.

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