Evaporation studied on a duplicated vessel, pilot scale evaporator equipped with a heat pump

1. Theory

In a steam-heated concentrator temperature changes with the location in the vessel because of the heat-currents from various directions. The hydrostatical pressure changes vertically, which causes the change of the boiling point temperature. Upon concentrating the solution, the increase in its boiling point needs to be taken into account, so, the distribution of the temperature in the vessel can be influenced by the distribution of the concentration as well. In the practice, the evaporation of pure water is studied, so, no composition based alteration in the boiling point temperature can occur. The boiling water in the evaporation vessel reaches only a few *cm*-s of height, thus the increase in the boiling point based on the hydrostatical pressure is negligible as well.

The temperature of the liquid in the vessel can be determined by the pressure of the vapor space using the vapor pressure curve of the solvent, or, in the case of water, the steam table. In our case, boiling only a few *cm*-s of pure water, the temperature is the actual measured value. In the case of an increase in the boiling point, the quantities are just virtual, therefore we define a virtual liquid-side boiling point (T_{virt}), a virtual temperature difference and a virtual heat transfer coefficient (k_{virt}).

$$\dot{Q} = k_{virt} \cdot A \cdot (T_{1,F} - T_{virt}) \qquad (1)$$

$\dot{Q}$ Heat current crossing the heating surface of the concentrator $[W]$

k_{virt} Virtual heat transfer coefficient $\left[\frac{W}{m^2 \cdot K}\right]$

A Surface area used for heat transfer $[m^2]$

$T_{1,F}$ Temperature of the operating fluid of the heat pump $[°C]$

T_{virt} Virtual temperature, here meaning the temperature of the vapor space $[°C]$

To determine the heat transfer coefficient, the heat current through the wall of the vessel needs to be measured. In an evaporator, mainly heat needs to be dissipated to form vapor. The measurement of the quantity of the vapor condensate is based on a very accurate mass measurement. Heat transferred through the heated surfaces can differ to that calculated from the quantity of the vapor. Two factors need to be taken into account:

a) Heat loss: If evaporation is carried out at a temperature significantly higher than environmental temperature, mainly in the case of an equipment operated by high pressure steam heating, we need to calculate with a large amount of heat dissipated towards the environment. In our case, evaporation is carried out at approximately room temperature, so heat loss is negligible.

b) Self-evaporation: If a liquid is fed into a low-pressure vessel, so that it's boiling point at the pressure of the vessel is lower than its temperature, it evaporates. In this case, some of the vapor condensate is the result of self evaporation.

The effects of the mentioned to phenomenon: heat loss is resulting in vapor condensing on the un-insulated wall, while the vapor formed by self-evaporation can be a couple per cents compared to the vapor quantity calculated from the total heat current. These two effects compensate each other when $T_0 > T_1$ and $T_1 > T_{1,environmental}$.

The equation constructed (4) knowing the complete mass balance (2a), the heat balance constructed with the negligation of the heat loss (3a) affords the calculation of the quantity of vapor forming by heat ransfer and self-evaporation.

$$L_0 = W + L_1 \qquad (2a)$$

Where $W = W_{1,self} + W_{HT}$ (2b)

$$L_0 \cdot i'_0 + \dot{Q} = W \cdot i"_{p1} + L_1 \cdot i'_1 \qquad (3a)$$

$$\dot{Q} = W \cdot i"_{p1} + L_1 \cdot i'_1 - L_0 \cdot i'_0 \qquad (3b)$$

$$W = \frac{\dot{Q}}{i"_{p1} - i'_1} + L_0 \cdot \frac{(i'_0 - i'_1)}{(i"_{p1} - i'_1)} \qquad (4)$$

L_0 The rate of the feed $\left[\frac{kg}{s}\right]$

W The quantity of the vapor condensate $\left[\frac{kg}{s}\right]$

L_1 The quantity of the residue $\left[\frac{kg}{s}\right]$

W_{HT} Vapor formed by heat transfer $\left[\frac{kg}{s}\right]$

$W_{1,self}$ Vapor formed by self-evaporation $\left[\frac{kg}{s}\right]$

i'_0 Specific enthalpy of the feed $\left[\frac{kJ}{kg}\right]$

$i"_{p1}$ Specific enthalpy of a vapor of the pressure of the vapor space $\left[\frac{kJ}{kg}\right]$

i'_1 Specific enthalpy of a liquid at the pressure of the vapor space $\left[\frac{kJ}{kg}\right]$

The vapor formed by heat transfer equals:

$$\frac{\dot{Q}}{i"_{p1} - i'_1} = W_{HT}$$

The vapor formed by self-evaporation equals:

$$\frac{L_0 \cdot (i'_0 - i'_1)}{i"_{p1} - i'_1} = W_{1,self}$$

The self-evaporation coefficient:

$$\frac{(i'_0 - i'_1)}{i"_{p1} - i'_1} = \beta$$

Knowing the temperatures and the enthalpies, the quantity of the vapor formed by self-evaporation can be calculated.

Regarding a heat-pump evaporator, neglecting the heat loss, the sum heat current transferred through the wall of the evaporator and the heat delivered by self-evaporation equals the heat dissipated upon vapor condensation.

$$\dot{Q}_{cond} = W \cdot \left(i"_{p1} - i'_1\right) \qquad (5)$$

$\dot{Q}_{cond}$ Heat driven off in the condenser $[W]$

$\left(i"_{p1} - i'_1\right)$ The enthalpy difference between the vapor and the condensate of the solvent $\left[\frac{J}{kg}\right]$

Performing total condensation, the mass flowrate of the vapor equals the mass flowrate of its condensate, therefore it is sufficient to measure the latter.

Heat current transferred through the wall can be calculated (6) knowing the heat dissipated in the condenser and self-evaporation.

$$\dot{Q} = \dot{Q}_{cond} - L_0 \cdot \beta \cdot (i"_{p1} - i'_1) \qquad (6)$$

Electrical energy consumed by the equipment (P_0) consists of the consumptions of the stirring motor, the ventilator, the compressor and the centrifugal evacuator, because the heat flow transferred through the wall is supplied by the condensation of the vapor.

The evaporator studied during the laboratory practice is mainly used in the cleaning of some oily emulsions, sewage of cleaning, degreasing bathes, with the forming vapor condensate fed back into the technology. Considering economy, it is a crucial question, how much useful material can be formed using a given amount of energy. Different types of evaporators are compared based on the energy needed to recover a unit amount of water. A heat-pump evaporator only needs electricity. Its consumers: the compressor, the centrifugal evacuator, the ventilator, and the stirring motor.

The energy value for 1 dm^3 of vapor condensate is:

$$\frac{\bar{P}_0 \cdot t}{V_p} \qquad (7)$$

t Time of the measurement

$\bar{P}_0$ The average of the electrical energies showed by the consumption counter $[kW]$

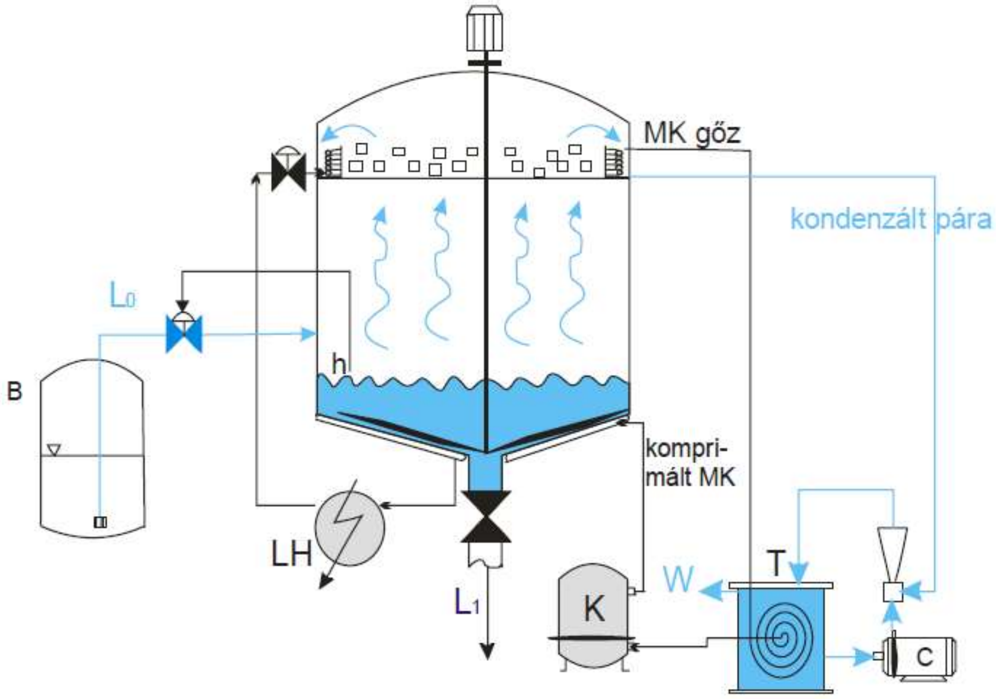
V_p The volume of the collected vapor condensate during the measurement time $[dm^3]$

2. Description of the equipment

The studied equipment is a R 150 v03 type, operating fluid heat pump evaporator, that is capable of producing $150 \frac{kg}{day}$ of vapor condensate in case of an operation with tap water. It uses a Freon gas R407C as an operating fluid. The evaporator itself is a duplicated, acid-resistant vessel, equipped with a stirrer. It is a raised vessel with the surface area of $0{,}29\ m^2$.

On starting the equipment, the building vacuum draws 16 liters of the fluid to be evaporated L_0 into the evaporator, from the feed tank 'B'. In the vessel, the fluid starts to boil as a result of the heating and the vacuum. Vapor forming travels through a spray catcher containing Raschig rings, then condensates on the surface of a pipe coil. The condensate proceeds to the tank 'T', and exits through overflow. The tank 'T' functions also as a secondary evaporator thet ensures that the operating fluid of the heat pump enters the compressor in gas state. A centrifugal evacuator is attached to the bottom of the tank, which circulates the condensate through a Venturi-pipe. Vacuum formed by ejector extracts the non-condensable gases from the evaporator.

The level transducer placed in the evaporator regulates the membrane valve of the inlet tubing, so, the quantity of the material in the evaporator vessel is constant. After reaching a steady state, the flowrate of the vapor needs to be the same as the feed flowrate. The residue (L_1) can be removed from the vessel at the end of the measurement, after stopping the vacuum.



1. Figure – Schematic depiction of the evaporator R 150 v03

The evaporator has a duplicated vessel and operates using a heat pump with an operating fluid. The operating fluid is a Freon-gas (R407C) that evaporates at a low pressure (and at the corresponding low temperature) in the pipe coil at the top of the evaporator and dissipates the gained heat at high pressure (and thus high temperature) in the duplicated bottom of the evaporator during condensation. The pressure of the operating fluid is raised to a sufficient level by the compressor. Heat released during the condensation boils water in the evaporator. Condensation of the operating fluid is completed by the air cooler 'LH'. It is then fed into the pipe coil at the top of the evaporator through an expansion valve. The pressure-enthalpy diagram of R407C can be found next to the equipment.

To begin the experiment, please follow the steps below:

1. Check the level of the vessel containing vapor condensate. It should be at maximum.
2. Fill the feed tank with at least 40 liters of water and measure its temperature.
3. Check if the filter at the end of the feeding pipe is clean.
4. If the window of the equipment is open, clean the sealing and mount the glass.
5. Close the valve used to release the residue.
6. Place the filling tube of the antifoam agent under water (to evade feeding air).
7. Place a vessel under the pipe of the vapor condensate, to collect water coming out at the beginning.
8. Acknowledge any error messages.

3. The aim of the measurement

Studying evaporation on a pilot scale, heat pump evaporator. Calculation of the virtual heat transfer coefficient and the electrical energy used for the production of a unitary amount of condensate.

4. The measurement process

The evaporator operates by an electrical current of 220 V. The energy consumed during the measurement is measured by an electrical counter that gives information about the consumed value in W, and the measurement time. The counter shows a total operational time, it needs to be noted at the beginning of the measurement (when pressing the START/STOP button). It also shows the totel consumed amount of electrical energy, that also needs to be noted at the beginning.

Upon setting the ON/OFF lever into 'ON' position, the evaporator is switched on and stirring starts. The experiment begins with switching the START/STOP button into its left hand position. The time of the experiment is measured from this point. Upon starting, a small amount of vapor condensate (1-2 liter) exits, it needs to be measured as it influences the mass balance.

Approximately 30 minutes are needed to reach the final vacuum. In a steady state, the average of the vapor condensate flowrate and the feed flowrate on a specific interval of time should be the same, as the level controller keeps the quantity of water in the evaporator constant. During the experiment, the vacuum in the evaporator, the pressure of the operating fluid on the high pressure end of the compressor, the temperature of the operating fluid must be noted from the display of the evaporator. The actual value the electrical performance and the vapor flowrate in the steady state needs to be measured as well.

5. Finishing the measurement

The experiment ends by switching the START/STOP switch to its right hand standing. The residue can be let out from the equipment through the valve under the window, after reaching atmospheric pressure.

- After collecting the residue, the stopwatch needs to be stopped and the ON/OFF lever needs to be turned onto OFF.
- The total time and used energy from the electrical counter needs to be noted.
- Discarding the vapor condensate and the residue after measuring their quantities and temperature.
- Filling the feed tank with 40 liters of water.

6. Measurement table

Atmospheric pressure: ……………………………Hgmm

Values of the electrical counter:…………………..(time)   at the end: ……………….

…………………...kWh   at the end: ……………….

Level of feed tank: …………………….dm^3

Feed temperature: ……………………..°C

Quantity of condensate collected at the beginning: …………………cm^3

Quantity of residue:…………………………………...dm^3

Temperature of vapor condensate: …………………….°C

Temperature of residue: ……………………………….°C

		1	2	3	4	5	Avg.
	Time						
Evaporator	Vacuum [Hgmm]						
Heating gas	Compressor pressure [Mpa]						
	Compressor temperature [°C]						
Vapor	Quantity [dm^3]						
	Time needed to collect a specific amount						
Feed	Level of feed tank [dm^3]						
	Time needed to feed a specific amount						
Electrical consumption	Value of counter [W]						

7. Results

Error of mass balance $\frac{L_0-(W+L_1)}{L_0}\cdot 100$		%
$\dot{Q}_{cond}$		W
β		-
$\frac{L_0\cdot\beta\cdot(i"_{p1}-i'_1)}{\dot{Q}_{cond}}$		%
$\dot{Q}$		W
k_{virt}		$\frac{W}{m^2\cdot K}$
$\frac{\bar{P}_0\cdot t}{V_p}$		$\frac{kWh}{dm^3\ of\ vapor\ condensate}$

Report:

Measurement table

Detailed calculation with data and units

Table of the results

Discussion, remarks