Application of the “flow-rate – specific enthalpy” diagrams for designing and energy efficiency estimation of the distillation plant

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Abstract. This article deals with application of the “flow-rate – specific enthalpy” diagrams for designing and energy efficiency estimation of the distillation plant. Analysis shows that distillation plant with consecutive evaporation of initial water provides optimal value of specific work spent for compression and consecutive connection of stages by steam have the worst value of work spent for compression.

1. Introduction
Lack of the fresh water became a problem in recent years. According to researches, in 2025 about half of the states will suffer fresh water deficit [1]. Thus, generation of the fresh water is one of the main tasks which must be solved to ensure ecological safety of the Earth population. There are several ways of fresh water generation. One of the most promising is seawater desalination or waste water treatment. There are several ways to desalinate seawater. They include reverse osmosis (RO) [2], electrodialysis (ED) [3], freezing [4] and distillation [5–7]. RO plants have a higher efficiency, however, they require often change of the membranes. ED plants are applicable on the water with relatively small salinity. Freezing plants are currently under development but in future they will allow using cold energy of liquid natural gas for desalination purposes. MVC plants have satisfactory energy consumption but they require careful design of the steam compressor which operation is crucial for plant.

Distillation or thermal desalination is most distributed way to obtain freshwater from seawater. As it is known, seawater is a solution which consists of water which is volatile solvent and salts – non-volatile solid material which is solved in water. Distillation is seawater evaporation with its vapour further condensation.

Distillation plants in turn can be divided on Multi-effect distillation plants (MED) [8], multi-stage flash distillation plants (MSF) [9], multi-effect distillation plants with thermal vapour compression (MED-TVC) [10] and plants with mechanical vapour compression (MVC) [11]. Every type of desalination plant has its own advantages and disadvantages. For example, MED plants can utilize waste heat of thermal power station, however, their efficiency is lower in comparison with RO plants.

2. “Flow-rate – specific enthalpy” diagram plotting
Designing of the distillation plant with heat regeneration has one of the main tasks which is coordination of its main elements characteristics. Evaporator-condenser (EC), suited for condensation of high-
enthalpy initial steam, must be related with distillate out and corresponding heat generation which causes low-enthalpy steam generation from initial water.

Steam compressor (SC), suited for secondary low-enthalpy steam compression, must be related to steam cooler for steam conversion to high-enthalpy steam from initial water.

Next working process parameters became initial data for this case:
– \( m_0 \) – distillate output of plant itself or its part;
– \( \alpha \) – heat transfer coefficient for EC,
– \( S_{\text{surf}} \) – EC heat transfer area,
– \( P_1 \) and \( P_2 \) – steam pressure at the entrance and exit of steam compressor;
– \( T_{\text{sat}1} \) and \( T_{\text{sat}2} \) – saturation temperatures corresponding to a given values of steam at the entrance and exit of steam compressor;
– \( T_{\text{TD}} \) – temperature depression in EC (decrease of the steam saturated temperature in relation to initial water evaporation temperature at accepted evaporation rate in EC);
– \( (T_{\text{sat}1} – T_{\text{sat}2} – T_{\text{TD}}) \) – EC temperature difference.

Most suitable method for such coordination is plotting “flow-rate – specific enthalpy” diagram which is both EC and SC characteristics on one plot. EC characteristics as a dependency of its maximal distillate output on specific enthalpy of secondary steam \( h_{\text{sat}2} \) at given value of specific enthalpy of saturated \( h_{\text{sat}1} \) at entrance to EC is determined on the base of equation for EC distillate output:

\[
m_0 = \alpha \cdot S_{\text{surf}} \cdot (T_{\text{sat}1} – T_{\text{sat}2} – T_{\text{TD}}) / h_{\text{sat}1}
\]

Expression (1) is used during plotting by means of transfer from evaporation temperature to corresponding values of specific enthalpy. Instead of \( T_{\text{sat}2} \), corresponding values of specific enthalpy of saturated steam are plotted at X axis.

Characteristics of steam compressor which maintain pressure \( P_1 \), corresponding to specific enthalpy \( h_{\text{sat}1} \), at the entrance to EC is a point corresponding to specific enthalpy \( h_{\text{sat}2} \) of saturated steam on the entrance to ST and its steam flow rate.

Plotting of the characteristics for EC or its separate stage with \( i \) number starts from determination and plotting specific enthalpy values on X axis. These values correspond to:
– \( h_{1i} \) – temperature \( T_{\text{sat}1} \) of initial steam at the entrance to \( i \) stage of EC;
– \( h_{0i} \) – evaporation temperature \( (T_{\text{sat}1} – T_{\text{TD}}) \);
– \( h_{2i} \) – temperature \( T_{\text{sat}2} \) of the secondary steam on the exit from \( i \) stage.

Then, points \( m_i \) are plotted which correspond to maximal EC stage output according to aforementioned expression, and connected with points \( h_{0i} \). If SC is selected correctly, their characteristics are correspond to points \( m_i \) for last stages of EC.

Diagram for multistage distillation unit with consequent connection of stages by steam where total temperature difference created by SC is distributed along the stages is plotted similarly for every stage separately considering temperatures of the saturated steam at entrance and exit. In this case SC characteristics is plotted independently from number of stages. Feature of the consequent stage connection is displayed at diagram as corresponding number of plots, every one of which is plotted for a given range of steam temperature at entrance and exit of stages and thermal depression in every of them. Stages output is summarized for determination of total output of distillation plant. This means that if every stage is set in optimal way because values of every element output will be decreased if at least one of them is set not in optimal way. Diagram has visually undetectable difference at plots difference of stage output due to specific enthalpy difference, utilization distillate and brine bypass, heat losses through external surface etc. These differences are not significant for the purpose of developed method.

3. Diagram application
Practical interest has been shown in option of stage parallel connection when all stages operate on the same values of evaporation temperatures \( T_{\text{sat}1} \) and \( T_{\text{sat}2} \), however, initial seawater is pumped only in the first stage. In rest stages, brine is pumped consequently. In this case separated SC can be used for every
stage or one common for all stages. In this case, evaporation degree and value of thermal depression will not be equal. Example of such distribution is presented in table 1.

**Table 1.** Distribution of the evaporation degree and thermal depression along the stages if EC stages are connected in parallel manner

| Number of stages | Stage 1 | Stage 2 | Stage 3 | Stage 4 | Stage 5 |
|------------------|---------|---------|---------|---------|---------|
| Evaporation degree | 10%     | 20%     | 30%     | 40%     | 50%     |
| Seawater concentration in Brine, % | 1.1  | 1.25 | 1.43 | 1.67 | 2 |
| Thermal depression, °C | 0.264 | 0.3 | 0.343 | 0.401 | 0.48 |
| Stage temperature difference, °C | 1.736 | 1.7 | 1.657 | 1.6 | 1.52 |
| Increase of the maximal stage output | 14% | 12% | 9% | 5% | 0 |

The main feature of the diagram for multistage distillation plant with consequent brine evaporation is parallel location of plots of maximal output. In case of using of one common SC in all stages saturation temperature in the entrance of EC is the same for all stages. If individual SC are used for every stages, real temperature will differ even if all SC are the same. At different output they will provide different saturation temperatures at the entrance of EC. For more accurate diagram plotting it is necessary to have SC head characteristics.

**Figure 1.** Options for SC and EC characteristics coordination for distillation plant

Line 1 – for initial EC, line 2 – for EC, line 3 – for EC with doubled heat transfer area in comparison with initial EC, 4 – for EC, which received concentrated brine instead of initial water $m_1$, $m_2$, $m_3$, $m_4$ – characteristics of the perfectly corresponding SC.

Figure 1 shows diagrams of EC and SC characteristics for 4 options, three of which are options of distillate output increase in comparison with initial option by increase of the heat transfer area:

– line 1 – EC characteristics of initial option of distillation plant, point m1 lying on it is perfectly coordinated characteristics of SC of this distillation plant;
– sum of lines 1 and 2 – characteristics of two-stage EC where secondary steam of the first stage (line 1) is used as heating steam for second stage (line 2). Point m2 – SC characteristics which compressed secondary steam of second stage and converting it to heating steam of first stage;
– line 3 – EC characteristics with doubled heat transfer area in comparison with initial EC, point m3 is coordinated characteristics of SC;
sum of lines 1 and 4 – characteristics of two-stage distillation plant with the same EC, where second
stage (line 4) instead of initial water utilized preliminary evaporated in first EC brine (line 1), points m1
and m4 are perfectly coordinated SC characteristics separately for every of stage.

4. Conclusions
Analysis of the plotted diagram allows to make conclusions:

– increase of the EC heat transfer area of the distillation plant is a way to decrease required power of
SC by both increase of the output at the same pressure range at SC for distillation plant with constant
number of stages and increase of the decrease of the SC pressure range at the same flow rate;

– distillation plant with consequent evaporation of initial water provide best average value of specific
compression work, calculated by the length of the lines (h14 - h24) < (h11 - h21);

– distillation plant with consequent connection of stage by steam provides worst value of specific
compression work, calculated according to lines (h11 - h21) < (h12 - h22).

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