Algorithm of Distillation Plant Parameters Selection Based on “Mass Flow Rate- Enthalpy” Diagram

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Abstract. The problem of fresh water lack can be solved by desalination of the seawater. Desalination of the seawater can be accomplished by several methods. Distillation of the seawater is one of the most promising among them. This article deals with algorithm of distillation plant parameters selection based on “mass flow rate- enthalpy” diagram. This diagram allows to estimate operation of the plant by several criteria such as energy efficiency, real distillation plant output, steam compressor and evaporator efficiency. Criterion of optimal coordination of Steam Compressor (SC) and Evaporator-Condenser (EC) characteristics is minimal distance between point which is characteristics of SC and line – characteristics of EC. Diagram shows an example of coordination of two SC with different productivity with characteristics of one EC. Location of these SC characteristics as a points 2a and 2b on the line which is characteristics of EC means perfect example of coordination when potentials of SC and EC productivities are fully utilized. Diagram confirms linear increase of the total energy cost and quadratic increase of the required power of SC if productivity is necessary to increase at constant EC heat exchange area. Besides, considering bended characteristics of EC, it is possible to note higher energy efficiency of distillation plant at higher temperatures 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
Generation of drinkable water became on the main problems of humanity. Growing lack of the drinkable water can be compensated by desalination of saline water (with salt concentration higher than 10 g/liter) and brine water (with salt concentration equal to 2-10 g/liter) which are stored in oceans, seas and underground springs. The water reserve in these sources is estimated as 98% of all water on Earth.

Possible solutions of drinkable water reproduction as river courses change and iceberg moving are quite limited. In the same time, there are sources of mineralized, waste and sea water along all territory which can solve the problem of water shortage.

Solution of the drinkable water shortage problem is possible if there are efficient technological schemes which allow to obtain drinkable water which cost and quality will be comparable with the cost of natural water [1].
One of the most popular methods for water desalination is reverse osmosis [2], which have the lowest specific energy consumption for every desalination plant. Current research shows that modern reverse osmosis plants exergetic efficiency can reach the values of about 20% [3]. Another popular method is electrodialysis, which is suitable for desalination of sea and brackish water with low salinity. Calculation shows that its specific energy consumption is almost directly related with plant capacity [4]. Finally, most suitable method for waste heat utilization in purpose of drinkable water generation is distillation. Current distillation plants usually consists of large number of stages. They can use steam or mechanical compressor as a heat source [5]. Investigation of their energy efficiency shows that plants with compressor (MVC) have a exergetic efficiency about 8-10% which is lower in comparison with reverse osmosis plant but such plants are more convenient for long exploitation [6]. Another modern technologies include shock-wave generation of salts crystalline hydrates [7,8]. This article consider distillation plant as most universal type of desalination plants and suggest a new method for its parameter designing.

2. “Flow-rate – specific enthalpy” diagram utilization
Scheme of the described plant is presented on figure 1.

![Diagram of the desalination plant](image)

Figure 1. Design scheme of the desalination plant

Designed plant represents MVC type of distillation plants where steam with higher temperature is received from last stage by its compression in compressor. Design scheme of the plant is presented on figure 1.

Preliminary prepared water from water gathering device is pumped in two ducts with given relation of flow rates between them to a heaters. Duct of the first flow passes through distillate heat exchanger and the second flow passes the brine heat exchanger. After heaters two flows of seawater are mixed in one flow which enters every stage of the plant in given relations.
Brine circulation in every stage is provided by recirculating pump. This circulation provides water pumping in a shell side of the evaporator in such way that water flows down along the rubes as a thin film.

Steam, generated in shell side of the first stage enters the tube space of the second stage passing the drops separator and then it start to condense creating distillate and transferring heat through tube inner surfaces to its external surfaces. Brine is flowing along external surfaces of the tubes so part of it evaporates and another part flows down to an airproof pallet of corresponding stage. This steam is combined with the steam which is generated from evaporation of brine which flows from the previous stage. Uncondensed steam and steam generated from partial evaporation of distillate coming from the previous stage enters the tube shell of the second stage where it start to condensing creating distillate.

Thus, distillate is received because of steam condensation in the tube shell of the second stage and heating steam for a third stage is received by brine evaporation in shell side. The same processes occur in all stages.

The only difference in working process is that in last stage generated steam enters mechanical compressor, which increases steam pressure and temperature by adding external work. Obtained steam is overheated so it is mixed with distillate from the first stage to make it wet.

Distillate obtained in the stage is pumped to a next one. From the fifth stage it is pumped to a water-distillate heat exchanger. The same process occur with the brine. Vacuum pressure in plant is kept by steam-water ejector.

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 $P_3$ – steam pressure at the entrance and exit of steam compressor;
- $T_{\text{sat1}}$ and $T_{\text{sat2}}$ – 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);
- $(T_{\text{sat1}} - T_{\text{sat2}} - T_{\text{TD}})$ – EC temperature difference.

Considering coherence between the values of saturation temperatures and corresponding values of absolute pressure and specific enthalpy, analysis of their energy efficiency and productivity of such distillation plant. In described case it is suggested to perform by coordination of SC and EV parameters which are represented by plots in “Mass flow rate- Enthalpy” coordinates, where $h_{\text{sat2}}$ – specific enthalpy of saturated steam at its temperature $T_{\text{sat2}}$.

For EC plot represented the curve of its maximal distillate output dependency $m_0$ on specific enthalpy of secondary saturated steam $h_{\text{sat2}}$ at given value of specific enthalpy of primary steam $h_{\text{sat1}}$ on the entrance to EC and is determined on the base of expression for heat flux through EC heat exchange surface by dividing this vale on evaporation heat value $r$ at steam saturation temperature. Obtained expression is:

$$m_0 = \alpha \cdot S_{\text{surf}} \cdot \left( T_{\text{sat1}} - T_{\text{sat2}} - T_{\text{TD}} \right) / r$$  \hspace{1cm} (1)

This expression is used during plotting by transfer from saturation temperature to corresponding values of specific enthalpy. Corresponding values of specific enthalpies are plotted at X axis instead of temperature $T_{\text{sat2}}$. Plot visually has a form of direct line, however, in real curve is slightly bended upward which is caused by steam specific enthalpy increase during saturation temperature decrease as well as heat transfer ratio decrease during output increase at constant heat transfer area of EC. This
fact confirms the concept that operation at higher saturation temperature is more preferable. However, for the purpose of developed method, specified difference of enthalpy values is not significant and can be neglected. Plot crosses X axis at point with specific enthalpy $h_0$ corresponding evaporation temperature equal to $(T_{sat1} - T_{TD})$.

SC in distillation plant as a rule operates in regime of maintaining certain pressure $p_1$ at the entrance to EC which correspond to evaporation heat $r$. That’s why in selected coordinates $\langle m_0 - h_{sat2} \rangle$ characteristics of its working process is a point, corresponding to saturated steam temperature on the entrance to SC and its steam flow rate. SC as a rule has an opportunity to vary operation regimes. To consider all options of SC setting during diagram plotting it is possible to represent its characteristics as a line. However, during final selection of SC working parameters, point is its characteristics in $\langle m_0 - h_{sat2} \rangle$ coordinates.

3. Diagram utilization of characteristics coordination analysis
Possibility of analysis and coordination of EC and SC characteristics is suitable to consider at the exapmle of one-stage distillation plant, although main theses of suggested algorithm are also applicable for multistage distillation plant.

Neglecting inequality of primary and secondary mass of steam which is compensated in distillation plants by special measures, required diagram is received by coordination point, representing operation of SC, with EC characteristics. It is necessary to note that location of such point above the triangle limited by EC characteristics is unacceptable. It is caused by the fact that EC cannot generated enough steam for SC to operation on its corresponding regime. As result of this, condition of steam temperature constancy at the entrance will be violated and EC characteristics will change.

Analysis of obtained diagram (figure 1) is performed by next criteria:
- importance of the thermal depression losses which is characterized by difference of specific enthalpies $h_j - h_0$;
- energy efficiency which is characterized by specific steam compression work equal to specific enthalpies difference $h_j - h_2$;
- real distillation plant output $m_2$, which cannot surpass SC output;
- SC potential realization as a relation of SC consumed power to minimal power required to provide real output by rectangles areas $h_j-h_2a-2a-1a$ and $h_2a-2a-1a$;
- degree of EC surface potential realization as a relation of heat fluxes power at real and maximal possible temperature difference by rectangles areas $h_j-h_2a-2a-1a$ and $h_j-h_2b-2b-1b$.

Figure 2. Common case of SC and EC characteristics coordination
In common case of the diagram, point which is a characteristic of SC, lies inside aforementioned triangle, for example, point 2 at figure 2, which means:
- real distillation plant output, equal to \( m_2 \), is determined by SC productivity and productivity potential of the EC heat exchange surface \( m_{b2} \) is unachievable because SC cannot provide necessary flow rate of primary steam \( m_{b2} \) and able to generate flow rate no more than \( m_2 \);
- SC potential by compression ratio and temperature difference, characterized by the length of \((h_1-h_2)\) line, is not used fully because EC provide real distillation plant output equal to \( m_2 \) at lesser temperature difference and correspondingly lesser difference of specific enthalpies \((h_1-h_{2a})\).

Thus, variant of EC and SC characteristics coordination, corresponding to point 2 is not optimal by energy efficiency criterion which is confirmed by:
- relation of the lengths \((h_1-h_2)\) and \((h_1-h_{2a})\) as analogue of real and minimal specific energy consumption for generation of 1 kg of distillate;
- relation of rectangles \( h_2-2a-h_1 \) and \( h_{2a}-2a-1a-h_1 \) areas as analogues of real and minimally required values of power consumed by SC for achievement of given productivity at certain heat exchange surface area and certain values of saturation temperatures.

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 3.** 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 3 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 \( m_1 \) 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 \( m_2 \) – 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 \( m_3 \) 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
Criterion of optimal coordination of SC and EC characteristics is minimal distance between point which is characteristics of SC and line – characteristics of EC. Diagram (figure 1) shows an example of coordination of two SC with different productivity with characteristics of one EC. Location of these SC characteristics as a points 2a and 2b on the line which is characteristics of EC means perfect example of coordination when potentials of SC and EC productivities are fully utilized. Diagram confirms linear increase of the total energy cost and quadratic increase of the required power of SC if productivity is necessary to increase at constant EC heat exchange area. Besides, considering bended characteristics of EC, it is possible to note higher energy efficiency of distillation plant at higher temperatures.

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