Thermodynamic Losses in Multi-effect Distillation Process

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Abstract. The multi-effect distillation (MED) is one of desalination technologies. It is also applied in chemical engineering and other industries for evaporation, distillation, crystallization, etc. In a large multi-effect distillation plant, some tiny thermodynamic losses might have a great influence to the performance and design parameters. For the detailed analysis and design of a MED desalination plant, a series of experiments were carried out. The thermodynamic losses in a MED desalination plant is analyzed as an example to show its effect on the performance and structure parameters. The thermodynamics losses have a cumulative effect. With the increase of effect number and the concentration ratio, the thermodynamic losses shall be a dominant factor for the operation performance of a MED plant.

1. Introduction
Desalination is becoming one of the important measures for fresh water supplement in offshore area. It developed very fast in the past decades. The global desalination production is $7.48 \times 10^7 \text{m}^3 \cdot \text{d}^{-1}$ now, and it will reach $10^8 \text{m}^3 \cdot \text{d}^{-1}$ in 2015[1]. China is one of the countries in the world facing severe water shortage. Up to now the desalination capacity in China is $7 \times 10^5 \text{m}^3 \cdot \text{d}^{-1}$ and it will be increased to $2.6 \times 10^6 \text{m}^3 \cdot \text{d}^{-1}$[2]. Nowadays the dominant commercial techniques of desalination are multiple stage flash (MSF), reverse osmosis (RO) and multiple effect evaporation (MEE) [3-5]. In the history the development of MEE desalination technique was restrained by the problems of scaling and capital cost. With the design of low temperature multiple effect evaporation technology, the application of thermal vapor compressor (TVC) and the cheap materials in the plant, it gets a fast development [6]. It seems that the market of MSF desalination technique is partially displaced by the MEE desalination technique. Compared with the RO sea water desalination technique, the MEE desalination shows advantages for high salinity, sea water with pollution and low sea water temperature [7]. The low temperature multiple effect evaporation technique has the characteristics of low scaling and corrosion, simplicity of sea water pretreatment, high quality

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of distilled water, possible use of low temperature exhaust heat and suitable for low temperature sea water, etc. Its capacity reached 8% of the global desalination market [8].

MEE desalination device belongs to heat equipment. Different from the normal heat transfer process in common heat exchange equipment, when we analyze and design MEE desalination device, it is crucial to accurately understand the thermodynamic losses. There are some analyses on thermodynamic losses in MEE desalination system, but little attention and special discussion is given on this. The methods to treat the thermodynamic losses are different. For example, Darwish [9,10] and Kamal [11,12] built the simplified model of systematic analysis, where the boiling point elevation of seawater (BPE) is set to be a fixed value, and other resistance losses are ignored; El-Dessouky’s [13,14] model is classic and comprehensive including thermodynamic losses caused by the BPE, flow resistance of demister, flow resistance in tubes and the condensation resistance in tubes, but the loss caused by pressure drop when steam flowing through heat transfer tube bundle. Not all the correlative formulas are from the experiments in the running conditions of MEE.

The apparent heat transfer temperature difference of LT-MEE desalination device is only between 2°C and 4°C and the device is running in the vacuum condition, when the saturation temperature is sensitive to pressure difference, so the effect of thermodynamic loss on the system performance should not be ignored. The concentration shortage of thermodynamic loss is the main reason of engineering calculation deviation. In this paper, the correlative formula between the LT-MEE desalination device resistance and the physical property are derived from the experimental results. The thermodynamic loss in the desalination device and their distribution are accurately calculated. The impacts of evaporator/condenser effects on the various thermodynamic losses in the system are analyzed. The theory on the operation characteristics of the LEE desalination system is concluded.

2. Desalination processes and analysis on thermodynamic losses

LT-MEE desalination device consists of horizontal tube falling film evaporator and condenser, the rear condenser, flash tank and non-condensable gas drawn out system, etc., as shown in figure 1.
The intake seawater is divided into two parts after coming out of the rear condenser, where it is used to cool the steam. One part is fed into the evaporators as feed water, and the other part is rejected back into the sea as rejected seawater. The feed water flows through a distributor and is equably distributed on the top row tube in the evaporators. Then under the action of gravity, it flows downward along the tube bundle in the form of horizontal tube falling film. The seawater is heated by the steam in the tube and some turns into steam, which is called secondary steam and flows into the steam tank in the evaporator. Then it flows through a demister, where the seawater droplets carried by the steam are gotten rid of, and goes into the tubes of next effect evaporator as the heating steam. The rest of the concentrated brine flows into the brine space of next effect evaporator, where some strong brine flashes because of the pressure change. The strong brine is finally flow into the last effect evaporator, where it is discharged out of the system.

The heating steam, provided by external heat source, flows into the steam-inlet tube header of first effect evaporator, and releases heat and condenses inside the horizontal tubes to heat the seawater outside of the tubes. The condensed water flows into the fresh water tube chamber, then either returns to the boiler feed water system or into the flash tank according to the different quality of heating steam. The secondary steam produced in the first effect flows into the tubes of the second effect evaporator, releasing heat and condensing. The condensed water goes into the flash tank, where some flash into steam because of the reduced pressure. The flashed steam flows into the steam-inlet tube header of next effect evaporator, and the condensed water flows into the fresh water tube chamber of next effect evaporator. By that analogy, the steam produced in the last effect evaporator condenses into water in the rear condenser. All of the condensed water is discharged out of the unit as product water.

The average apparent temperature difference is the ratio of total temperature difference, which is the temperature difference between the temperature of heating steam in the first effect evaporator and the saturation temperature of secondary steam produced in the last effect evaporator, to the number of effect. Compared with fresh water system under the same pressure, in desalination system the condensing temperature of the steam in the tubes decreases because of boiling point elevation of the seawater and the flow resistance of the steam. That leads to an obvious reduction of the effective heat transfer temperature difference in evaporators. The difference between the apparent heat transfer temperature difference and effective heat transfer temperature difference is known as thermodynamic loss of the heat transfer process.

In multi-effect evaporation desalination process, the flow direction of the steam produced in evaporators is shown by the arrows in figure 2. When the steam flows through the tube bundle 5 to steam collection chamber, the shadow part in the right figure in figure 2, there exists the pressure drop $\Delta p_t$, so the saturation temperature of steam close to the steam collection chamber will be lower than the evaporation temperature in center of tube bundle. The steam flows through the demister 6 and passes by the steam channel 3 and goes into the steam-inlet tube header of next effect evaporator. In the process, another pressure drops $\Delta p_d$, $\Delta p_f$, $\Delta p_b$ form and pressure drops down further. The corresponding saturation temperature also further reduces. The steam flow in the tubes of next effect evaporator will produce pressure drops $\Delta p_c$. Therefore, along the tube, the saturation temperature of steam condensation in the tube will gradually reduce. All of the temperatures reductions lead to
condensation temperature falling, which makes the heat transfer temperature difference in the evaporator reduce. This is the thermodynamic loss caused by the steam flow resistance in the device.

**Figure 2.** Schematic of resistance loss in LT-MEE desalination system

In addition, the boiling point of the falling film evaporation seawater outside the tubes is higher than fresh water under the same pressure, which means that the heat transfer temperature difference further reduces. While the steam evaporated from the seawater is superheated corresponding to the pressure inside the evaporator, and its condensation temperature will reduce a little. That is the heat loss caused by seawater properties. The seawater boiling point elevation (BPE) and temperature loss ($\Delta t_p$) caused by steam flow resistance can be reflected qualitatively in figure 3.

**Figure 3.** Tephigram for adjacent effects of LT-MEE desalination system

3. **Mathematical model of thermodynamic loss**
The thermodynamic mathematical model of LT-MEE desalination system is similar to that in literature\(^{[15]}\), the formulas to calculate the thermodynamic losses are as follows.
The formula to calculate seawater boiling point is given in literature [16]:

$$BPE = AX + BX^2 + CX^3$$  \hspace{1cm} (1)

Where,

\begin{align*}
A &= (8.325 \times 10^{-2} + 1.883 \times 10^{-4} T + 4.02 \times 10^{-6} T^2) \\
B &= (-7.625 \times 10^{-4} + 9.02 \times 10^{-5} T - 5.2 \times 10^{-7} T^2) \\
C &= (1.522 \times 10^{-4} - 3' \times 10^{-6} T - 3' \times 10^{-8} T^2)
\end{align*}

Where, \( X \) is salinity, g/kg. \( T \) is water temperature, °C.

The flow resistance through the mesh demister is expressed as [17],

$$
\Delta \rho_d = 3.88178 \left( \rho_d \right)^{0.375798} \left( \frac{v}{d_w} \right)^{0.81317} \left( \frac{d_w}{L_d} \right)^{-1.5611417} L_d
$$ \hspace{1cm} (2)

where, \( \rho_d \) is the density of the mesh, kg/m³. \( v \) is the velocity of vapor phase, m/s. \( d_w \) is the diameter of the metal mesh wire, mm. \( L_d \) is the thickness of the mesh, m.

The flow resistance in the steam channel, that is the pressure drop when the steam flow after the mesh demister and go into the steam tube inlet, including local resistance \( \Delta \rho_\alpha \) and flow resistance along the passage \( \Delta \rho_\beta \), could be calculated from [18]:

$$\Delta \rho_\alpha = \rho \alpha \left( \frac{v^2}{2} \right)$$ \hspace{1cm} (3)

$$\Delta \rho_\beta = \frac{1.306 \times 10^{-4} M^2 L (1 + 3.6/\delta)}{\rho \delta^3}$$ \hspace{1cm} (4)

where, \( M \) is the steam flow through the passage, kg/s. \( v \) is the flow velocity when the saturated steam flows through the minimum cross section in the tube bundle, m/s. \( R \) is the radius of the bend, m. \( \beta \) is the bend angle, °. \( L \) is the length of the steam passage, m. \( \rho \) is the density of the steam in the passage, kg/m³. \( \delta \) is the equivalent diameter of the passage, m. \( \alpha \) is the local loss coefficient, calculated by:

$$\alpha = \frac{0.00146 + 0.00181 \times \left( \frac{\delta}{R} \right)^{3.5}}{0.00181} \cdot \beta$$ \hspace{1cm} (5)

The flow resistance through the tube bundle could be calculated from the formula in the literature [19], which is obtained from the experimental results that steam sweeps across the horizontal falling film tube bundle.

$$\Delta \rho_\gamma = \frac{NG^2}{2 \rho}$$ \hspace{1cm} (6)

where, \( N \) is the number of columns. \( G \) is the steam mass flux per unit cross section area, kg/(m²·s). \( f \) is the resistance correction coefficient. When the equilateral triangle arrangement of tubes is adopted, the outer diameter of the pipe is 25.4mm, is the spray density, kg/(m·s). \( D \) is the outer diameter of the tube, m. \( \mu \) is the dynamic viscosity of saturated spray seawater, Pa·s. \( \eta \) is the kinematic viscosity of saturated steam, m²/s.

The flow resistance in the tube condensation could be calculated according to the literature[20]:

$$\Delta \rho_c = L_c \cdot c \rho \nu^2 Re_c^{\frac{1}{x}}$$ \hspace{1cm} (8)
where, \( L \) is the length of the pipe, m. \( c, a \) and \( b \) are empirical constants. \( v \) is the steam inlet velocity, m/s. \( \bar{x} \) is the integral average dryness of steam. The inner diameter of the pipe is 24mm, \( Re<3000 \), \( a=-0.234 \), \( b=5/3 \), \( c=4.6 \).

4. Analysis of examples

Based on above models, through the calculation and analysis on the examples, we obtain the thermodynamic loss in large LT-MEE desalination device and the distribution in every evaporator. It is shown that the total heat transfer difference loss, caused by the resistance loss and seawater boiling point elevation, changing with the effect number of evaporators. The calculation parameters and the configuration parameters of evaporator/condenser in LT-MEE desalination plants with various effects are listed in table 1 and table 2 respectively.

**Table 1. Parameter range for calculation**

| Parameter                              | Value  | Parameter                              | Value  |
|----------------------------------------|--------|----------------------------------------|--------|
| Distillate production/(t·d⁻¹)          | 15000  | Concentration ratio                    | 1.5    |
| Heating steam temperature/°C           | 68     | Salinity/%                             | 32.0   |
| Evaporating temperature in the last    | 46     | Feed seawater temperature/°C           | 41     |
| effect/°C                              |        | Diameter of steam channel/m            | 3      |
| Length of steam channel/m              | 2      |                                        |        |

**Table 2. Evaporator/condenser configuration parameters of desalination plants with various effects**

| Parameter                              | Value  |
|----------------------------------------|--------|
| Arrangement mode of tube bundle        | Regular triangle |
| Tube spacing-outer diameter ratio      | 1.3    |
| Row-column ratio of tube bundle        | 2.2    |
| Outer diameter of tube/mm              | 25.4   |
| Thickness of tube/mm                   | 0.7    |
| Length of tube/m                       | 7      |
| Wire diameter of demister/mm           | 0.3    |
| Packing density of demister/kg·m⁻³     | 150    |
| Pad thickness of demister/m            | 0.05   |
| Number of evaporators/condensers \( n \) | 6  8   10  12  14 |
| Area of demister/m²                    | 7.6    5.8  4.8  4.2  3.7 |
| Heat transfer area of each evaporator/m² | 7828  8115 8504 9087 9799 |
| Column number of tube bundle            | 80     81    83    86    89 |
| Row number of tube bundle               | 177    179   184   190   197 |

Take the example of 6 effects LT-MEE desalination plant for example. Proportions of various resistance losses are shown in figure 4. It can be seen that the thermodynamic loss caused by flow resistance occupy 10.8%, where the proportion of thermodynamic loss caused by the steam passage flow resistance is minimal, only 0.1%, that can be neglected.
The Variation of thermodynamic loss, due to the demister flow resistance, the tube bundle flow resistance and the condensation flow resistance in the tubes, with the number of effects are shown in figure 5 to figure 7 respectively. With the fixed value of effect number, the thermodynamic losses caused by all the flow resistances increase accelerating with the rise of the effect number. With the rise of the effect number, the evaporation temperature reduces gradually, and the latent heat of vaporization increases, while the amount of condensing water and the concentrated seawater gathered effect by effect increase, and the flash steam from the condensing water and the concentrated seawater in each evaporator \( m_{df}, m_{bf} \) increases effect by effect. Both these factors lead to the amount of the steam vapor decreases first then increases in each of evaporators, as shown in figure 8. The density of saturated vapor in the evaporators decreases gradually, it would affect the steam velocity together with the amount of the steam, and then further affect various flowing resistance. According to steam characters, the lower of evaporating temperature, the more saturated temperature reduction caused by unit pressure drop, so the heat loss in low temperature evaporator is more obvious.

**Figure 4.** Proportions of various resistance losses

**Figure 5.** Variation of thermodynamic loss due to the demister with the number of effects

**Figure 6.** Variation of thermodynamic loss due to the tube bundle with the number of effects
Figure 7. Variation of thermodynamic loss due to the condensation process with the number of effects

Figure 8. Variation of mass flow rate of the generated vapor with the number of effects

The thermodynamic loss caused by various resistances in the same sequence evaporator decreases with rise of evaporator number. Because of the fixed total amount of fresh water, with the increase of the evaporator number, the load of every effect decreases. At the same time, the saturated temperature in the same sequence evaporator increases and the latent heat of vaporization decreases, which makes the steam in the evaporator slowly decline, as shown in figure 8. When the saturation temperature increases, saturated steam density increases, skimmer flowing resistance in the same sequence evaporator and tube condensing flow resistance decrease with increasing number of evaporator. Keep the steam velocity through the demister in the first effect evaporator fixed, then the demister area is determined. So with the rise of evaporator number, the flowing resistance of the first effect skimmer keeps unchangeable. The tube bundle flowing resistance are not only affected by the above factors, but also affected by the falling film flow spray density. Calculation example in this paper is based on the condition of consistent total amount of feed water, with the increase of evaporator number, the seawater spray density in the same sequence evaporator decreases, as well as the vapor production decreases. The co-action of steam flow, steam density and the water spray density makes the tube flow resistance in same sequence evaporator decreasing with the increasing of evaporator number. Meanwhile, with the increase of the evaporating temperature, the saturation temperature reduction caused by the unit pressure drop turns smaller. Therefore, various thermodynamic losses in the same sequence evaporator decreasing with the increasing number of evaporator/condenser.

Table 9 shows the proportion of the thermodynamic loss caused by each resistance and the total thermodynamic loss caused by all the resistances changing with evaporator effect numbers. It is shown that with the increase of evaporator number, the total heat loss caused by flow resistance decreases. The proportion of thermodynamic loss caused by skimmer flow resistance continuously increases. When the effect number increases from 6 to 14, the proportion increases from 16.8% to 49.9%, and the proportion of tube bundle flow resistance and tube condensation flow resistance decrease from 41.4% and 41.7% to 26% and 24% respectively.

In this paper the total resistance ranges from 1260Pa to 1830Pa, so the average flow resistance per effect ranges from 90Pa-305Pa, and the maximum flow resistance in single evaporator is about 395Pa. Therefore, the characteristic of “low flow resistance” could be concluded in low temperature multi-effect evaporation desalination device. The apparent heat transfer temperature difference is only between 2°C and 4°C, which shows typical “little temperature difference” heat transfer. And the heat transfer process is operated under the vacuum and “in saturation state”. The pressure has a close relation to temperature. The change of saturation temperature can affect the effective heat transfer temperature difference, and it is “highly sensitive” to pressure change. Take the evaporating temperature of 60°C for example, resistance loss 395Pa corresponds to 0.43°C, which make the effective heat transfer temperature difference decrease by 10.7%-21.5%. It is seen that if the low flow resistance that less than 400Pa, is not considered carefully, it is enough to make the disruptive results
of water desalination device performance. The structure design of the desalination device should reduce the vapor flow resistance as possible, as well as be forecast accurately in thermodynamic calculation and consider the thermodynamic loss caused by flow resistance, and the “low flow resistance” is required in the device performance calculation and design.

We have discussed thermodynamic losses caused by the flow resistance device, seawater boiling point elevation further exacerbates the loss. Because seawater boiling point is higher than that of fresh water, on the premise of fixing the pressure inside and outside of the evaporator tubes, that makes heat transfer temperature difference reduced between the inside and outside, which could be calculated from formula (1). The loss of total heat transfer temperature difference for the device caused by the flow resistance loss and seawater boiling point elevation loss is shown in Figure 10. With rise of evaporator effect number, the total thermodynamic loss increases, where the proportion of the loss caused by seawater boiling point elevation increases significantly. When the effect number is 6-14, the loss caused by seawater boiling point elevation accounts for 56.3%-81.4%.

As shown in formula (1), BPE is the function of salinity and temperature, and the salinity affects BPE more greatly. Therefore, when the other parameters are unchanged, BPE in every effect evaporator does not change a lot. In fact, it is the increased evaporator number makes rise of the total temperature drop. With the evaporator number increasing, temperature drop caused by the resistance loss decreases, while that caused by BPE increases, under the co-action of both the factors, the total thermodynamic losses rises.
Figure 11 shows the apparent and effective temperature difference in each effect changing with the effect numbers. It is shown that when the effect number is 6, the apparent temperature difference in each effect is 3.5-3.9 °C, and the effective temperature difference is 2.6-3.2 °C. The proportion of the corresponding thermodynamic loss is 15.8% - 28.2%. When the effect number is 14, the apparent temperature difference in each effect is 1.4-2 °C, the effective temperature difference 0.8-1.3 °C. The proportion of the corresponding thermodynamic loss reaches up to 35% - 43.8%. Obviously desalination plant is “high sensitive” to various types of losses.

![Figure 12. Effect of thermodynamic loss on performance of LT-MEE desalination plant](image)

The performances of LT-MEE desalination plant, including the gained output ratio (GOR) and the specific heat transfer area (SHTA), are compared in figure 12 when the thermodynamic losses are considered and ignored and only resistance loss is ignored. It can be seen that when the thermodynamic losses are considered the values of GOR are same for the same effect number plants, but there is bigger difference in SHTA. That is the heat transfer area of the evaporator need to be increased, and with the increase of effect number, the difference is becoming more and more obvious. Within the scope of this paper, the relative deviation of SHTA reaches 39.4% if the thermodynamic losses are ignored compared with when the losses are considered, the relative deviation of SHTA also could reach 10% when only resistance loss is ignored. Therefore, a large design error will occur if the thermodynamic losses are ignored.

Increasing the number of evaporator can improve GOR and decrease the resistance loss, but intensify the thermodynamic loss caused by seawater boiling point and increase the total thermodynamic loss, and then increase the heat transfer area. Therefore, the two factors should be weighed when analyzing the economy to determine the optimal effect number.

The theory of “small temperature difference, low flow resistance, saturated state, high sensitive” on the operation characteristics of LT-MEE desalination plant is obtained according to the analysis on the thermodynamic losses in the plant. It is the basis to scientifically understand the theory on characteristics and fully analyze every thermodynamic loss in the plant for building integrated theory and method to design LT-MEE desalination plant.

5. Conclusion

According to the operation characteristics of large LT-MEE desalination plant, calculation and analysis on the distribution of thermodynamic losses caused by various factors in each evaporator are carried on. And the influences of effect number on every thermodynamic loss is investigated as well. In the scope of calculation in this paper, the following conclusions can be obtained:

1) The theory of “small temperature difference, low flow resistance, saturated state, high sensitive” on the operation characteristics of LT-MEE desalination plant is obtained according to the analysis on the thermodynamic losses in the plant.
When the effect number is fixed, the thermodynamic losses caused by demister flow resistance, tube bundle flow resistance and condensation flow resistance in the tube increase with the increase of evaporator sequence, and the increase rate gradually becomes larger.

With the increase of the effect number, the thermodynamic loss caused by steam flow resistance in the same effect sequence evaporator slowly declines. The gross thermodynamic losses decreases caused by flow resistance. The proportion of thermodynamic loss caused by demister flow resistance rises. The tube bundle flow resistance and condensation flow resistance in the tube decrease. The thermodynamic loss caused by seawater boiling point elevation increases, and its proportion increases significantly.

The total thermodynamic losses increases with the increase of the effect number, and the proportion is fairly considerable. It must be paid full attention in designing the plant.

6. References
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