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Experimental study on a new method for improving the performance of thermal vapor compressors for multi-effect distillation desalination systems

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HIGHLIGHTS

- A method for improving TVC performance is proposed by preheating TVC entrained vapor.
- Effectiveness of the method has been experimentally verified.
- TVC entrainment ratio is found to increase with the entrained vapor superheat.

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ABSTRACT

A new method is proposed in this study to improve the entrainment performance of thermal vapor compressors (TVCs) that are widely used in multi-effect distillation (MED) desalination systems by preheating entrained vapor. In order to confirm its effectiveness and study the influences of the entrained vapor superheat on the TVC entrainment ratio, a four-effect-parallel-flow MED-TVC experimental system was set up. Hot water from a solar heating system and steam from an electric boiler were used as heat source of the entrained vapor preheating, respectively. The preliminary experimental results show that the entrained vapor preheating could greatly increase the TVC entrainment ratio and the TVC entrainment ratio increases with the entrained vapor superheat. Due to the poor performance of the TVC used in this study, further verification experiments of the proposed method need to be conducted in future work.

1. Introduction

Many countries are beset by freshwater shortage and thus seawater desalination is playing a more and more important role in providing freshwater. There are many types of seawater desalination methods, such as multi-stage flash (MSF) desalination, reverse osmosis (RO) and multi-effect distillation (MED). Among these seawater desalination methods, the MED is most widely used due to its advantages of simple pretreatment, high thermal efficiency and flexible operation mode. The MED systems could be operated independently, or integrated with other auxiliary technologies such as thermal vapor compression and mechanical vapor compression. Comparing with standalone MED systems, systems with vapor compression (VC) have a higher performance ratio because of the effective utilization of low pressure vapor energy. Thermal vapor compressor (TVC), a key auxiliary unit for thermal vapor compression aided multi-effect distillation (MED) desalination systems, governs the overall performance of the system. The motive steam that has to be applied to drive TVC consists of the main energy consumption of the MED-TVC systems [1]. Therefore increasing the TVC entrainment ratio and reducing the motive steam consumption are of great importance for improving the energy performance of the MED-TVC systems.

Many studies were conducted on design and analysis of TVC geometrical parameters to improve the TVC entrainment capacity. Both numerical methods and validation experiments were used in these studies. Based on one dimensional gas dynamics theory, Dutton [2], Christensen [3] and Huang [4] proposed a numerical design and analytical model for TVC which could give the main structure and geometrical parameters such as mixing tube diameter and primary nozzle diameter. Numerical simulation method was used by Riffat et al. [5,6] to conduct a parametric study on TVC to determine the optimum axial position of the primary nozzle. Park et al. [7] and Ji et al. [8] took flow physics including compressibility and turbulence into account to examine the effects of operation pressure and geometry parameters on the TVC performance.

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They also compared the numerical results with the experimental data obtained from a MED plant. Sharifi and Boroomand [9] applied both axisymmetric and three-dimensional models to simulate TVC performance and compared the numerical results with experimental data.

Although the huge efforts have been made, the TVC performance has not been improved significantly due to the complicated physics that takes place inside the TVCs, especially those used for the MED systems. To ensure the TVC entrainment performance, the motive steam and the entrained vapor should be both speeded up to supersonic or sonic states first. With the flow state sharp change from the subsonic to the supersonic, phase change may well take place. The phase change of the motive steam and the entrained vapor may significantly deteriorate the TVC performance. However, as far as the present authors could know, no effective methods have been proposed to remove this difficulty. Based on this consideration, preheating the entrained vapor before it enters the TVC is proposed to improve the TVC entrainment performance [10]. The purpose of the present study is to confirm its effectiveness and study the influences of the entrained vapor superheat on the TVC entrainment ratio.

2. TVC with entrained vapor preheating

Thermal vapor compressor, which is simply a steam ejector using high pressure steam to entrain low pressure steam, is widely used in water desalination, refrigeration and aviation [11]. The TVC performance is measured by its entrainment ratio that is defined as the ratio of the mass flow rate of the entrained vapor to the mass flow rate of the motive steam. There are many factors that have an effect on TVC entrainment ratio which mainly include the thermodynamic parameters of the steam, the fluid flow states and the geometrical parameters of the TVC.

For a given TVC, the flow state of steam inside the TVC is a determining factor for its entrainment ratio. Steam that enters TVC will experience a flow state change from the subsonic to the supersonic and then to the subsonic flow. The flow inside the TVC presents a strong compressibility. As the steam expands rapidly, the pressure and temperature fall sharply and high super-saturation can be achieved. Non-equilibrium condensation occurs when steam arrives at Wilson point. The release of condensation latent heat results in a sudden deceleration of velocity and an abrupt rise in pressure, which is known as condensation shock. This kind of sudden deceleration of velocity and abrupt rise in pressure has a negative effect on fluid flow and TVC performance [12–15].

To counteract this problem caused by the condensation phenomenon that is almost inevitable for most of the TVCs used in MED systems, a MED-TVC desalination system with the entrained vapor preheating is proposed by the present authors. The basic idea is to preheat the entrained vapor that is usually at its saturated state with the external heat sources before it is entrained into the TVC. Preheating the entrained vapor will change the vapor from the saturated state to the superheated state. With the superheated vapor entrained into the TVC, as one could understand, the super-saturation of both the entrained and the compressed vapor will be reduced and thus the condensation phenomenon may well be inhibited. Due to this effect, the TVC entrainment ratio may be greatly increased.

Refer to Fig. 1, from the TVC energy balance, one could easily obtain the following expression for the theoretical entrainment ratio ω_{th},

$$\omega_{th} = \frac{m_s}{m_p} = \frac{h_{v,p} - h_{v,c}}{h_{v,c} - h_{v,s}} \tag{1}$$

where m_s and m_p are the mass flow rates of the entrained vapor and the motive steam, respectively; $h_{v,s}$, $h_{v,p}$ and $h_{v,c}$ are the specific enthalpies of the entrained vapor, the motive steam and the compressed vapor, respectively. As one may expect, ω_{th} is the theoretical maximum value of the entrainment ratio with the assumptions of being fully reversible and of ideal structure design. The real value of the entrainment ratio is usually much smaller due to the irreversibility and dynamic loss. The real entrainment ratio may therefore be written as follows,

$$\omega = \eta_t \omega_{th} = \eta_t \frac{h_{v,p} - h_{v,c}}{h_{v,c} - h_{v,s}} \tag{2}$$

where η_t is called as TVC reversible entrainment ratio efficiency [16]. It takes various influence factors such as geometry parameters, machining accuracy, and of course, the irreversibility and the dynamic loss of the TVC. Comparison shows that η_t could be very small even for a well-designed and well-manufactured TVC. Its value is usually within the range of 0.2 to 0.5, sometimes, even smaller than 0.1. Increasing the reversible entrainment ratio efficiency is thus one of the most effective ways for improving the TVC performance.

However, one may argue that, since the entrained vapor is heated to the superheated steam, the theoretical entrainment ratio ω_{th} may be reduced. One reason is that as the temperature increases, the specific volume of the entrained vapor also increases, so for the same volume flow rate, the mass flow rate may be reduced. Another reason is related to the practical application of the TVC. In order to ensure the compressed vapor to be sent back to the system, which is a basic requirement, the outlet pressure of the TVC is fixed and thus as the entrained vapor is superheated, the specific enthalpy of both the entrained vapor and the

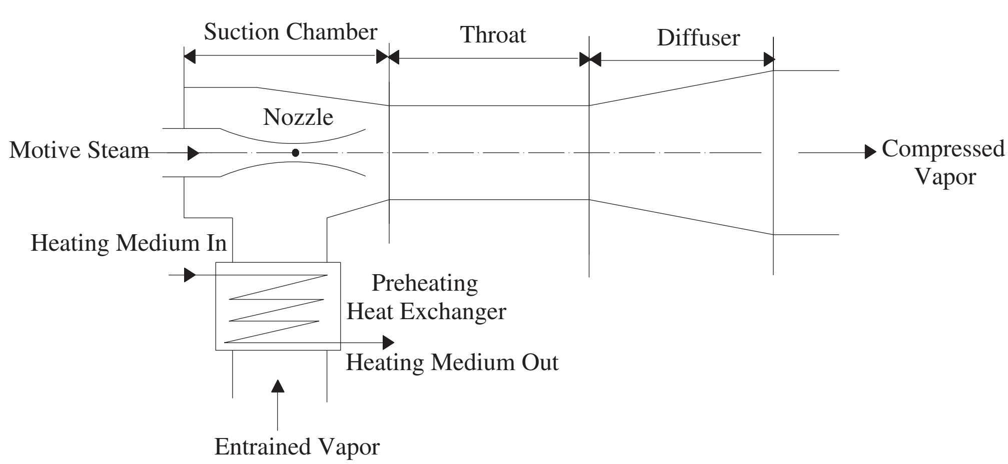

Fig. 1. Schematic diagram of TVC with entrained vapor preheating.