Energy 140 (2017) 673–681

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Design and numerical investigation of an adaptive nozzle exit position ejector in multi-effect distillation desalination system

Chen Wang [a], Lei Wang [a, *], Xinli Wang [a], Hongxia Zhao [b]

[a] School of Control Science and Engineering, Shandong University, Jinan, PR China
[b] School of Energy and Power Engineering, Shandong University, Jinan, PR China

ARTICLE INFO

Article history:
Received 14 December 2016
Received in revised form
28 June 2017
Accepted 26 August 2017
Available online 28 August 2017

Keywords:
MED-TVC desalination
Ejector
Entrainment ratio
NXP
CFD simulation

ABSTRACT

Few investigations have been conducted on an ejector that has an auto-tuning capability to regulate the performance of a multi-effect distillation-thermal vapour compression (MED-TVC) desalination system with the variation of operating conditions. In this study, an adaptive nozzle exit position (ANXP) ejector was first proposed to enhance ejector performance by self-adjusting the position of the primary nozzle with the change of primary pressure. A computational fluid dynamics (CFD) model was established and validated using experimental data. Simulation results indicate that there is an optimum NXP range of 43 mm–70 mm for an ejector to achieve its highest performance. The maximum increase of the entrainment ratio is 35.8% compared to that at an NXP of −30 mm. The secondary flow rate first increases and then decreases while the primary flow rate remains unchanged with the increase of the NXP in fixed working conditions. Furthermore, a correlation between optimum NXP and primary pressure was developed to provide designing parameters for the ANXP ejector.

1. Introduction

With the advantages of saving energy, protecting the environment and simple structures, ejectors driven by low-grade energy are widely used in many applications, such as multi-effect distillation (MED) desalination systems [1,2], carbon capture [3] and air-conditioning systems [4,5]. The ejector was first invented by Sir Charles Parsons around 1901 [6]. Since then, many research studies have been carried out to improve the performance of the ejector, which can be evaluated by the entrainment ratio (*Er*), the ratio between the secondary and primary mass flow rates. The 1D model of the ejector was first made in 1950 to predict the performance of the ejector in critical mode [7]. To develop the model, Munday et al. [8] formulated an effective area concept, assuming that secondary flow is effectively choked when it reaches sonic velocity in the mixing chamber. This model has been widely used by many researchers as guidance for ejector design. Recently, a shock circle model at the critical mode operation was formulated by Zhu et al. [9] via the introduction of a “shock circle” at the entrance of the ejector throat. Chen et al. [10] proposed the use of a new 1D model to predict the performance of an ejector in both critical mode and sub-critical mode with the consideration of *Er* and back pressure under different primary pressures. Although all the aforementioned models are relatively accurate in terms of the prediction of ejector performance, their applications are limited by the fact that they cannot describe the effects of some important geometric parameters, such as NXP, AR (the area ratio between the ejector throat and primary nozzle throat) and θ (the converging angle of the mixing chamber) on the performance of ejector. As a result, by using a CFD technique, Yan et al. [11–13] evaluated the effects of six key geometric parameters on an ejector cooling system and found that NXP and AR are the most sensitive geometries to the ejector performance. Zhu et al. [14] found that ejector performance is very sensitive to θ when it works near the optimum working point.

The utilisation of ejectors in MED desalination systems, called MED-TVC desalination systems, has been regarded as a major development over the last few decades. A new design parameter of the primary flow swirl intensity was adopted by Park et al. [15] to achieve the high performance and effective operational stability of ejectors in MED-TVC desalination systems. By preheating entrained vapour before entering the ejector, Han et al. [16] conducted a new method to alleviate the condensation phenomenon inside the ejector for the improvement of ejector performance. Wu et al. [17] researched the effects of the mixing chamber geometries on the

* Corresponding author.
E-mail address: leiwang@sdu.edu.cn (L. Wang).

http://dx.doi.org/10.1016/j.energy.2017.08.104
0360-5442/

performance of ejectors in MED-TVC desalination systems. The simulation data illustrated that the use of different mixing chamber geometries produce significant differences in ejector performance. Similarly, Fu et al. [18] indicated that there is an optimum range for the primary nozzle outlet diameter for the best possible ejector performance. Moreover, the influence of some important shape factors on ejectors was tested by Sharifi et al. [19–21] to obtain a new ejector model that is used in MED-TVC desalination systems. In the investigation of the influence of ejector suction position on system performance, Kouhikamali et al. [22] summarised that changing the ejector suction location from the last effect to the middle effects reduces MED-TVC desalination system energy consumption.

Although massive investigations have been conducted on ejectors, little work has been done to alleviate the effects of heat source instability on ejector performance, which causes huge decreases in system efficiency. By applying a movable spindle at the primary nozzle inlet, Varga et al. [23,24] analysed the effects of AR on ejector performance. Experimental data showed that the mass flow rate of the primary flow can be successfully adjusted by the spindle to strengthen ejector performance. This kind of ejector is called a variable area ratio (VAR) ejector. Lin et al. [25], Li et al. [26] and He et al. [27] conducted similar work. The main drawback of the VAR ejector is that the position of the spindle is controlled by a step motor, which increases space requirements and economic demand. To tackle this problem, in this paper, the concept of ANXP ejector was first proposed by adding a bellows with a primary nozzle. The ejector can self-adjust the primary nozzle position with the variation of primary pressure. Experimental data reported in the literature was used to validate the ejector simulation model. The results of CFD modelling were used to identify the correlation between primary pressure and optimum NXP to provide designing parameters for the ANXP ejector.

2. Experimental rig

2.1. ANXP ejector

As demonstrated in Fig. 1, the designed ANXP ejector consists of six main parts: (1) a bellows; (2) a primary nozzle; (3) a suction chamber; (4) a mixing chamber; (5) a throat; and (6) a diffuser. The working principle of the ejector is as follows. The primary flow with high pressure and low velocity flow is converted into a supersonic flow with low pressure by the primary nozzle, which creates a relatively low pressure region in the suction chamber. As a result, the secondary flow is entrained into the mixing chamber, and the two flows begin to mix in a very complex way via energy and momentum exchanges, after which a normal shockwave occurs in the ejector throat. Finally, the sufficiently mixed flow is discharged by the diffuser and compressed to a high pressure. Compared to a conventional ejector, an ANXP ejector has an added bellows with a primary nozzle that can automatically adjust the primary nozzle position according to the variation of primary pressure, which has the capability of enhancing both the efficiency and stability of the ejector. The correlation between NXP and primary pressure, which is essential for the designing of an ANXP ejector, is described in a later section.

As can be seen from Fig. 2, a bellows is a convoluted shell consisting of a series of toroidal shells. When pressure is supplied to the bellows, the angle of the shells in the bellows changes [28]. It is true that the force generated by the compressed vapour is on the surface area of bellows, which enables the bellows has radial displacement and axial displacement. However, the right side of the bellows in this paper is fixed with ejector, therefore, the radial displacement is constrained and bellows can only move along the axis direction. This makes the bellows behave in a strong elastic mechanism. By using this deformation, the horizontal movement of the primary nozzle can be accomplished.

The force needed for the displacement of the bellows is:

$$F = Kx \tag{1}$$

where x is the displacement of the bellows, and K is stiffness coefficient, which is calculated using Eq. (2).

$$K = \frac{1.7 D_m E_b^t t_p^3}{w^3 C_f} \tag{2}$$

where D_m is the equivalent radius of the bellows, E_b is the elasticity

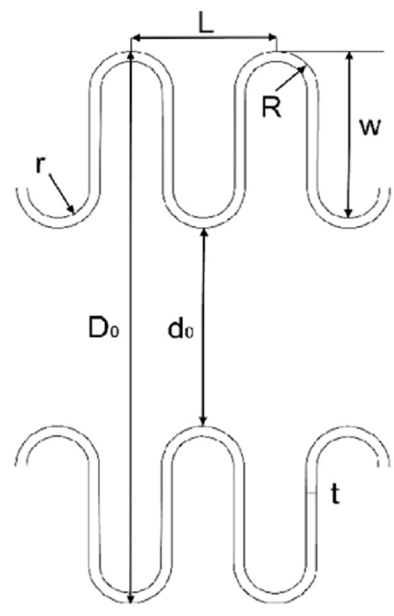

Fig. 2. Schematic diagram of a typical bellows.

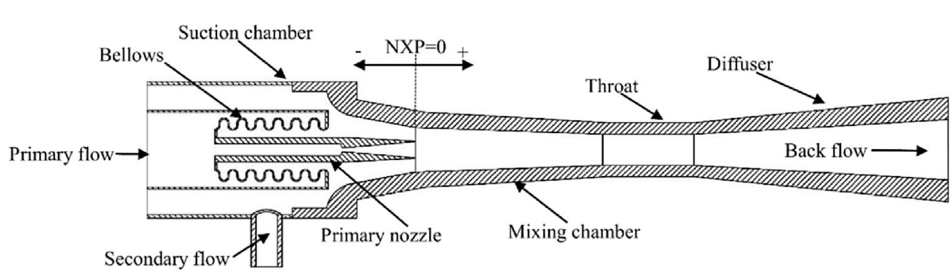

Fig. 1. Schematic diagram of an ANXP ejector.