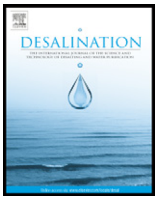
Desalination 353 (2014) 15–20

Contents lists available at ScienceDirect

Desalination

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



Numerical investigation of the influences of mixing chamber geometries on steam ejector performance

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HIGHLIGHTS

- CFD simulations were carried out to investigate the performance of the ejector.
- There exists an optimum mixing chamber length range.
- There is a fixed optimum mixing chamber convergence angle.

ARTICLE INFO

Article history:
Received 9 May 2014
Received in revised form 12 August 2014
Accepted 2 September 2014
Available online 19 September 2014

Keywords:
Numerical investigation
Steam ejector
Chamber length
Convergence angle

ABSTRACT

In this study, computational fluid dynamics (CFD) method is employed to investigate the effects of the mixing chamber geometries on the performance of steam ejectors used for multi-effect distillation systems. The internal flow characteristics of the steam ejector and the effects of the length and convergence angle of the mixing chamber were obtained. It is found that there is an optimum range of the mixing chamber length at which the ejector will acquire its largest entrainment ratio and the mixing chamber also has an optimum convergence angle at which the steam ejector performance is the best.

1. Introduction

Multi-effect distillation (MED), which can greatly reduce the energy consumption of seawater desalination systems, especially if it is combined with thermal vapor compression (TVC), is one of the most important and widely-used large-scale desalination methods. The thermal vapor compression is accomplished by steam ejector. The performance of the steam ejector is one of the limiting factors for improving the energy efficiency of MED-TVC desalination systems. The structure of steam ejectors is very simple and without any moving parts. It compresses a low-pressure vapor (entrained steam) by a high-pressure vapor (primary steam) through a series of energy and momentum exchanges into a mid pressure vapor. However, due to the fact that it involves strong irreversible mixing and other effects, its thermodynamic efficiency is usually very low. Entrainment ratio that is defined as the ratio of entrained low-pressure steam flow rate to high-pressure primary vapor flow rate is the main performance indicator of the steam ejectors. Increasing the entrainment ratio is of great importance for practical applications by optimizing the steam ejector structure and design.

Because of the practical importance, the wide potential applications and the complexity of the phenomena taking place inside the ejector, a lot of work has been carried out to improve the performance of the ejectors. Actually, as early as in 1950, Keenan *et al.* [1] developed a theory for designing and analyzing of the ejectors based on one-dimensional gas dynamic theory. However, this theory could be only used to predict the overall performance of the after-design ejectors without taking the effects of the ejector geometrical parameters into account. The flow pattern and other possible physical phenomena such as shock wave, choking and even phase transition inside the ejectors may well influence their performance. Therefore, improving the ejector performance of an ejector system needs understanding the physical phenomena that takes place inside the ejectors. Many researchers have engaged in researching the shock wave and choking of the ejectors with experimental and numerical methods. The results disclosed that the effect of the fluid parameters on the ejectors performance is important and direct [2–5]. The experimental results and theoretical predictions both proved that there exists a critical value for the ejector outlet pressure under the given primary and entrained vapor pressure conditions. Exceeding this critical pressure will result in fast degeneration of the ejector performance [2,3]. Riffat and Omer [4] used a commercial CFD package to predict the performance of a methanol driven ejector.

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http://dx.doi.org/10.1016/j.desal.2014.09.002
0011-9164/

Wang [5] simulated the flow through a steam ejector, whose results were validated against the experimental data by Sriveerakul *et al.* [6]. The numerical results are in good agreement with the experimental results [4,5]. There are also numerous studies of the geometrical parameters and structure because of their crucial effects on the performance of the ejectors [7–9]. Zhu *et al.* [7] tried to find the optimum nozzle outlet position (NXP) and the mixing chamber convergent angle by numerical simulations. From 210 testing results, it is found that the optimum NXP is not only proportional to the mixing section throat diameter, but also increases as the primary flow pressure rises. And the ejector performance is very sensitive to convergence angle θ, especially near the optimum working point. The entrainment ratio can vary as much as 26.6% by changing θ. A relatively bigger θ is required to better maximize the ejector performance when the primary flow pressure rises. Ji [8] numerically studied the influence of the convergence angle of the mixing chamber. The mixing chamber convergence angle in the study was varied as 0°, 0.5°, 1.0°, 2°, 3.5° and 4.5°. The ejector with a mixing-chamber convergence angle of 1.0° has the best performance. Natthawut *et al.* [9] investigated experimentally the effect of the primary nozzle geometries on the ejector entrainment. In their study, the experimental steam jet refrigerator was tested with 8 different primary nozzle's geometries. For one particular primary nozzle, operated at a fixed entrained pressure, the nozzle exit Mach number is remained unchanged with the primary pressure. And the entrainment ratio is essentially constant and independent from the area ratio of the primary nozzles.

There are many structural factors that influence the ejector performance. The primary nozzle geometries are crucial to the primary steam. The mass flow rate and the nozzle exit velocity of the primary steam are decided by the primary nozzle throat diameter and diverging ratio, respectively. Ejector throat length is commonly believed to have little influences on the entrainment ratio, but the critical back pressure increased with the throat length and thus allowed to operate the ejector in double chocking mode in a wider range of operating conditions. And a proper ejector throat diameter is necessary for designing of the ejectors. Furthermore, as has been pointed out above, the ejector performance is very sensitive to the convergence angle of mixing chamber especially near its optimum value, and a slight variation in it may produce a great influence on the ejector performance. Although there are many studies on the ejector geometries, there are little investigations concerned with the mixing chamber length of the steam ejector, which is crucial to the performance of the ejectors. In this work, the effects of both the convergence angle and the length of the ejector mixing chamber on the flow characteristics and the entrainment ratio are numerically investigated.

2. CFD model and validation

2.1. Geometrical and mathematical models

A schematic view of a typical supersonic ejector is shown in Fig. 1. A steam ejector usually consists of four key parts: primary nozzle, mixing chamber, ejector throat and subsonic diffuser. The fluid with the highest total energy is referred to as the primary stream and introduced into the primary nozzle in which its flow state is changed from subsonic to supersonic, creating a low pressure region at the nozzle outlet and in the mixing chamber. The entrained stream is drawn into the flow and accelerated by the pressure difference between the entrained steam and the mixing chamber that is created by the primary stream. The entrained stream is then mixed with the primary steam and recompressed in the mixing chamber and very complex interactions with the mixing layer and wave shocks in the ejector throat may take place. The mixed steam is further compressed as it flows through the diffuser.

Steam ejectors are classified into two categories, the constant-area mixing ejector and the constant-pressure mixing ejector according the geometrical parameters of the mixing chamber. It is well known that the constant-pressure ejector shows a better performance than the constant-area ejector and is widely used [10]. Therefore, in this paper, only the constant-pressure mixing ejectors are studied aiming at a better understanding of the effects of the mixing chamber geometrical parameters on the ejector performance. The main geometrical parameters of the ejector used for this study are listed in Table 1.

The commercial software Gambit 2.2 and FLUENT 6.3 were used as the grid generator and the CFD solver, respectively. An axisymmetric two-dimensional model is used as suggested by Pianthong *et al.* [11]. The mathematical model of the flow includes the Reynolds time-averaged Navier–Stokes, continuity and energy equations with the assumption of the steady and compressible flow of constant physical properties. Unsteady-state mathematical models are used to solve the problem for better convergence; the steady-state results are obtained by setting the time step to a large value after several time steps. The near wall condition was treated using the "standard wall function" and the convective terms were discretized by the second-order upwinding scheme. The realizable k–ε turbulence model was used, which was reported to predict accurately the spreading rate of jet flows and provides better performance for separation and recirculation flows [12]. Boundary conditions at the primary nozzle inlet and the entrained steam inlet of the ejector were set as "pressure inlet" condition. Meanwhile, the "pressure outlet" condition was applied on the ejector outlet of the mixing steam. Water vapor of the working fluid was assumed to be an ideal gas considering the fact that the absolute pressure inside the mixing chamber is relatively low. And the vapors that enter the ejector are all assumed to be saturated.

With the above assumptions, the governing equations can be written as follows:

The continuity equation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = 0 \tag{1}$$

The momentum equation:

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}\left(\rho u_i u_j\right) = -\frac{\partial P}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} \tag{2}$$

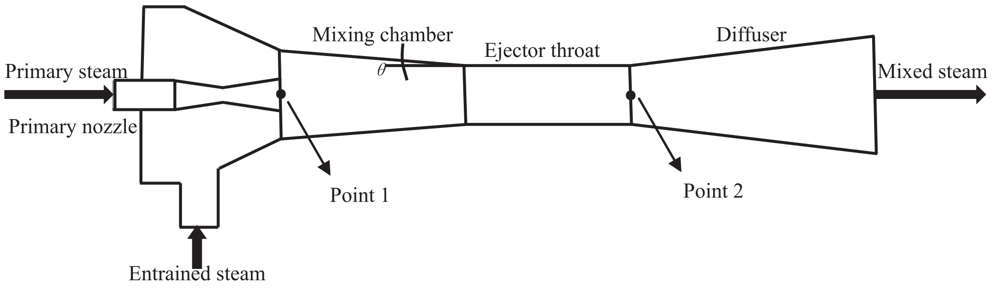

Fig. 1. Typical ejector geometry.