Energy 66 (2014) 860–867

Contents lists available at ScienceDirect

Energy

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

Reducing energy consumption of a steam ejector through experimental optimization of the nozzle geometry

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ARTICLE INFO

Article history:
Received 17 July 2013
Received in revised form
10 January 2014
Accepted 16 January 2014
Available online 11 February 2014

Keywords:
Energy consumption
Steam ejector
Experimental optimization
CFD simulation
Supersonic nozzle

ABSTRACT

Steam ejectors use pressurized vapor as the motive flow for running in steam cycles. The major parameter that affects the thermal energy consumption is the pressure of motive flow used in this device. In the current study, a malfunctioning experimental ejector is studied numerically to reveal the source of low evacuation rate from a suction chamber. This ejector was designed to operate under a motive pressure of 6 bar. However, the required vacuum in the suction vessel was not attained unless the pressure of motive steam was increased to 8 bar. The fastest and the most inexpensive way of improving the device performance was considered as replacing just the primary nozzle, with no further changes in ejector's body because, the ejector was connected to other unit facilities and hence the ejector replacement was very costly. The optimization procedure was performed through using numerical CFD (Computational Fluid Dynamics) simulations. The shape of internal supersonic nozzle was changed in many CFD analyses and the most optimized nozzle was selected for manufacturing. After installing the designed nozzle, an improved entrainment capability under the nominal pressure of 6 bar was observed and the desired vacuum level was attained.

1. Introduction

MED (multi-effect distillation) is one of desalination methods in which a series of condensation–evaporation processes is taking place in a nearly vacuum condition. The objective of this process is to provide a low-pressure condition inside evaporators to be able to evaporate water at considerably low temperatures [1]. It not only promotes the efficiency of the desalination process, but also prevents the formation of salinity on tube bundles leading to unchanging values for heat transfer coefficients. At such conditions, the total energy required to evaporate seawater will be substantially decreased [2].

Apart from using the mechanical driven pumps, there is an alternate way to evacuate the air from the system interior. The alternative that is frequently used in desalination systems is to use ejectors. The principle of this method is to entrain the internal air via a supersonic jet flow. Ejectors that are used in desalination facilities are particularly designed to produce higher vacuum levels. These types of ejectors might be driven by air or steam. Recently, some process enhancement by integrating optimal steam ejectors were developed which allows a 10–25% reduction in the amount of valuable steam [3].

Fig. 1 shows a schematic diagram of the steam cycle in a conventional desalination unit. A package of serial evaporators, a condenser, an ejector, and a thermo-compressor are used to recycle the steam to the system. As seawater vaporizes in the system, dissolved air and non-condensable gases are evolved. These gases should be vented to prevent over-pressurizing of the system. The ejector draws the mixture of non-condensable gases from the condenser as the secondary flow. This process causes the seawater to evaporate at lower pressure conditions in the system and thus, less thermal energy is required. The discharge flow of the ejector (i.e. the mixture of primary and secondary flows) is exhausted into the atmosphere.

The remainder non-condensable vapors in the condenser are recycled to the first stage evaporator via a thermal vapor compressor. Although large-scale ejectors i.e. thermo-compressors play a significant role in such systems, they are not investigated herein.

Since the performance of ejectors is controlled by the thermodynamic states of entrained and motive flows, the pressure of motive steam affects the ejector performance significantly.

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0360-5442/$ – see front matter © 2014 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.energy.2014.01.055

Nomenclature

English letters

A	section area (m^2)
D	diameter (m)
E	total energy (J)
g	gravitational acceleration (m^2/s)
k	thermal conductivity (W/m K)
L	length (m)
$\dot{m}$	mass flow rate (kg/s)
M	Mach number (Dimensionless)
P	static pressure (Pa)
r	radial coordinate (m)
T	static temperature (K)
u	velocity components (m/s)
x	independent variable (–)
y	dependent variable (–)
z	axial coordinate (m)
CR	compression ratio (Dimensionless)
ER	entrainment ratio (Dimensionless)

Greek letters

α	converging angle (deg)
κ	turbulence kinetic energy (m^2/s^2)
ε	turbulence dissipation rate (m^2/s^3)
ρ	density (kg/m^3)
θ	tangential coordinate (deg)
τ	stress tensor (Pa)
μ	dynamic viscosity (Pa s)

Subscripts

d	diffuser flow (–)
p	primary flow (–)
s	secondary flow (–)

Therefore, steam consumption and interior vacuum level are strongly related to a proper ejector design. This paper will primarily focus on the effect of nozzle geometry on ejector's performance.

The productive studies based on classical one-dimensional theory for ejectors have been continuously carried out since 1950 [4]. Nowadays, flow visualization methods are frequently used for determining the complicated flow pattern inside ejectors. Though the well-known internal phenomena have been revealed by CFD (Computational Fluid Dynamics) methods to estimate the real flow properties in steam ejectors, the deep-concealed mixing mechanisms within these devices are still ambiguous and need more efforts to investigate. The works done by Riffat et al. [5,6] could be mentioned as the first CFD studies performed on ejectors. Some numerical studies in supersonic ejectors were supported with appropriate experimental data [7,8]. The results of such numerical methods were used to optimize the mechanical design of ejectors [9–11]. CFD studies concerned about turbulence modeling revealed that the two-equation turbulence theories (such as k–ε and k–ω models) may be best suited to represent the mixing and compressing phenomena in ejectors [12].

Rusly et al. [13] performed several simulations on ejectors using finite volume techniques to resolve the flow dynamics in the ejectors. During their validation steps, it was found that predicted entrainment ratios from CFD data had a greater accuracy on definite area ratios of the device. Although, they were recorded no shock wave in their ejector.

Kouhikamali et al. [14] presented a numerical method for large size ejectors used in desalination systems called thermo-compressor. They could experimentally modify the entrainment ratio of a malfunctioning thermo-compressor through using some CFD simulations which were performed to visualize the flow streamlines and vortices in the mixing zone.

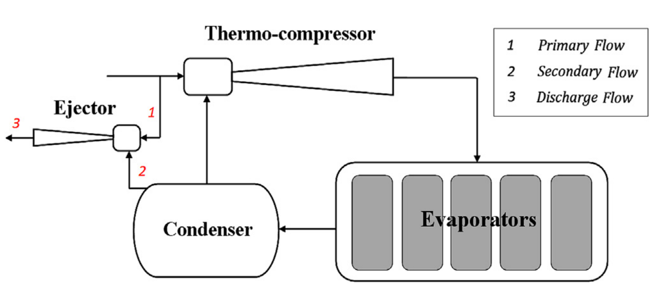

Fig. 1. Schematic of flow diagram in a thermal distillation system equipped with a steam ejector.

Some valuable numerical attempts made to produce applicable design curves for estimating the converging angle of mixing zone of ejectors [15]. These graphs were used to optimize the casing geometry of conventional ejectors.

Some parametric studies were conducted by Yari et al. [16] to optimize the performance of novel ejector-expansion cascade refrigeration cycles under various operating conditions. The proposed cycles exhibited a reasonable value of coefficient of performance with a much less value of discharge temperature, compared to the conventional cycles.

A recent study [17,18] on comparing different CFD approaches (i.e. 2D and 3D numerical modeling) was performed on the actual shape of ejectors, in order to consider non-symmetrical effects of flow bending inside the suction pathway. The results showed a considerable difference and were outlined in applicable design methodologies for optimizing the geometry of vapor compressors which could deliver a high amount of suction steam at the discharge boundary.

Ji et al. [19] focused on the effects of operating pressure and ejector geometry on the flow structure and the performance of a steam ejector. The converging angle of the duct considered the geometrical parameter in their study and was varied from 0.5 to 4.5 deg. After validating their numerical simulations with available experimental test case, they found that the ejector with a converging duct angle of 1 deg. had the best performance.

The reasons of obtaining the numerical results outside the experimental data in some ranges of operating conditions of ejectors were discussed thoroughly in Ref. [20]. Since the behavior of steam flow in the supersonic nozzle used in the main body of ejectors is doubtful to be a single-phase phenomenon, a novel two-phase simulation was performed according to recent development in wet-steam theory [21]. It was found that the entrainment ratio of a vapor compressor is significantly increased according to occurrence of condensation shock in the motive steam. This resultant could be used for further energy analysis in order to reduce the required motive energy for running a high-performance ejector.

In the current study, an existing in-site ejector is adjusted through modifying its nozzle geometry such that an elevated rate of suction flow is attained under ejector's nominal operating condition.