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Numerical study for the influences of primary steam nozzle distance and mixing chamber throat diameter on steam ejector performance

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ABSTRACT

The geometry and operation parameters have important influences on the performance of steam ejectors. An axisymmetric two-dimensional mathematical model for transonic compressible flow inside a steam ejector has been established in this paper to investigate the flow characteristics inside steam ejectors aiming at optimizing primary steam nozzle exit section distance and mixing chamber throat diameter simultaneously. The results show that there are an optimum value for the primary steam nozzle distance ratio and an optimum diameter ratio of mixing chamber throat to primary nozzle throat at which the steam ejector acquires its best entrainment performance under the given design conditions. With the optimized primary steam nozzle distance, the optimization of the diameter ratio of the mixing chamber throat to primary nozzle throat is significant. In our case, the improvement of the entrainment ratio is as large as 25%. Deviation from its optimized value may result in a serious degeneration in the ejector performance. Therefore, to ensure the steam ejector performance, the primary steam nozzle distance should be designed at its optimum value and the diameter ratio of the mixing chamber throat to primary nozzle throat be within a narrow vicinity of its optimum value.

1. Introduction

Energy shortage and environmental pollution have become the bottleneck for sustainable economy and society development. Energy saving and emission reduction have thus received increasing attention from all over the world. Steam ejector is a kind of fluid machinery that uses high-pressure steam to pump low-pressure steam [1]. It has been widely used in thermal evaporation system [2,3], vacuum [4,5] and refrigeration [6,7], due to its convenient operation, simple structure and obvious energy saving effect. With the rapid development of CFD software, many scholars [8–11] have studied the ejector numerically.

Adiabatic acceleration flow and expansion of the primary steam inside Laval nozzle (the primary steam nozzle) leads to the formation of supersonic and low-pressure region at the nozzle outlet section, and a pressure difference between this low-pressure region and the entrained steam is thus established and pushes the low-pressure entrained steam into the ejector. As one could well understand, the geometry of the primary steam nozzle has great influences on flow pattern and thus the ejectors' performance. Installing swirl vanes at the nozzle outlet section could improve the ejector entrainment performance and reduce the frictional loss [12]. Compared with circular, elliptical, rectangular nozzle ejector, the performance of cross nozzle ejector was the best [13]. Fu et al. [14] studied the influences of primary steam nozzle outlet diameter on the flow characteristics and entrainment ratio of a steam ejector. Their results showed that the supersonic jet in the over-expanded wave state flowed more smoothly after leaving the nozzle, and therefore, the energy loss was relatively small and the ejector achieved a good performance. The primary steam nozzle position is also an important structural parameter for steam ejectors. The critical entrainment ratio of an ejector at different nozzle positions were experimentally studied by Chen et al. [15]. Their results showed that the entrainment ratio increased with the nozzle outlet position at first and then remained unchanged within the range covered, which meant that there was an optimum nozzle-exit position (NXP) at which the entrainment ratio would acquire its maximum value. It was found that the entrainment ratio was fully decided by the so-called double choking phenomenon that appeared in the converging section, *i.e.*, only when both the primary and the entrained steam were at their critical state (maximum mass flowrate state) simultaneously, could the ejector obtain its largest entrainment ratio. It should be pointed out however, their experimental result was somewhat based on the assumption that the entrained flow velocity in the converging cone and the mixing flow velocity in the constant area section were both smaller than the sound velocity. Sag and Ersoy [16] studied the influence of the primary steam nozzle on the performance of a steam ejector used for refrigeration and they found experimentally that the ejector system that used the

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optimum primary steam nozzle throat diameter exhibited a higher COP than the classic system. Sun [17] established a thermodynamic model for ejector refrigeration systems and they found that using variable geometry (including NXP) ejector would enhance the performance of ejector refrigeration system. Dong et al. [18] set up a prototype steam-ejector refrigeration system and the effects of nozzle exit position (NXP) and the diameter of the constant area section on the working performance of steam ejector were investigated. Chunnanond and Aphornratana [19] constructed an experimental steam ejector refrigerator and the experiments were carried out to examine the influences of the operating conditions and the geometry including NXP on the system performance. They found that using smaller primary nozzle or retracing the nozzle out of mixing chamber could both increase the COP and the cooling capacity of the system. Riffat and Omer [20] carried out an experimental and numerical study of an ejector refrigeration system using methanol as the working fluid. 4 different NXPs were chosen to investigate the effect of the relative position of the primary nozzle exit within the mixing chamber on the performance of the ejector and the numerical results were used for optimizing ejector geometry. Their results showed that positioning the nozzle exit at least 0.21 length of the mixing chamber throat's diameter upstream of the entrance of the mixing chamber gave better performance than pushing it into the mixing chamber. Varga et al. [21] numerically studied the influences of area ratio between the nozzle and constant area section, nozzle exit position (NXP) and constant area section length on the ejector performance. Their results indicated that for ejectors obtaining optimum performance, all these three geometrical parameters should be optimized. Zhu et al. [22] optimized numerically of primary nozzle exit position and converging angle of mixing section. They found that these two geometry parameters both had very strong influence on ejector performance. The optimum NXP was obtained and was found to be 1.7–3.4 length of the mixing section throat diameter upstream of the start of the mixing section.

One may understand that changing the primary steam nozzle structure and its relative position will change the vortex structure formed in the downstream of the primary steam nozzle as it has been reported in literature, therefore, there should be an optimum structure and position to ensure the ejector to obtain its best performance. Most researches used ideal gas model and the assumption of constant physical property. Wet steam models were also established by some researchers to study the flow inside ejectors. Ding et al. [23] studied non-equilibrium condensation process of water vapor in moist air expanding through a sonic nozzle by numerical simulation. They found that the flow rate of the sonic nozzle was affected by both homogeneous and heterogeneous nucleation. Abadi et al. [24] studied the unsteady supersonic flow of wet steam through a high-pressure thermo-compressor (steam ejector) with consideration of non-equilibrium homogeneous condensation numerically. Two-fluid multiphase flow formulations were used and their results were validated against the industrial data, which proved the effectiveness of the model for modeling steam condensing flows within high-pressure steam ejectors. However, due to the obvious difficulties and the less reliability of the physical, mathematical and numerical model in taking condensation process into consideration, most of the numerical optimization work reported in the literature concerning steam ejectors simply used ideal gas model.

The performance of a steam ejector depends largely on the interactions between the high-pressure and the low-pressure steam. Therefore, during this process, very complex physical phenomena may occur, including transonic flow, shockwaves, mixing, phase change (condensation and evaporation), boundary separation and so on. The exploration of the mixing process inside an air steam ejector was carried out by Bouhanguel et al. [25] experimentally. The flow pattern, shock wave position and turbulence structure were observed visually and the analyses of the observed phenomena were presented. Ariafar et al. [26] studied the fluid mixing and the pressure driving effects on the entrainment ratio of steam ejectors under various operation conditions. The effects of mixing chamber length and convergence angle on the performance of steam ejectors were investigated by Wu et al. [27], the shock wave and vortex inside the steam ejector under different conditions were discussed. Yang et al. [28] studied the influences of the nozzle structure on fluid streamline distribution and vortex structure inside the mixing chamber.

Although many efforts have been made so far concerning the structure optimization of steam ejectors, however, little systematic research work has been reported in the literature for optimizing the primary steam nozzle position and the mixing chamber throat diameter simultaneously. As we have discussed earlier, these two structural parameters have direct and very strong influences on the ejector performance and may affect each other's optimum value, *i.e.* the change in one parameter may result in significant change in the optimum value of another. In this paper, an axisymmetric two-dimensional mathematical model for transonic compressible flow inside a steam ejector has been established to explore and analyze the influences of primary steam nozzle distance and mixing chamber throat diameter on the ejector performance.

2. Physical and mathematical model

The mathematical descriptions for the flow onside the steam ejector including the governing equations and boundary conditions used were exactly same as that given by Fu et al. [14]. The detailed CFD model, the validation of the grid independence, the physical and mathematical and the CFD model were all discussed in full details in Ref. [14] and are simply omitted here for conciseness.

A schematic view of a typical supersonic ejector is shown in Fig. 1. Based on the assumption of one-dimensional steady state flow and constant-pressure mixing, the entrainment ratio and the main structural dimensions were calculated under the operation conditions (the primary steam pressure $p_p = 600$ kPa, the entrained steam pressure $p_s = 15$ kPa, and the mixed steam pressure $p_c = 40$ kPa, which are something for the so-called low-temperature MEE desalination systems) and listed in Table 1. The main designed geometrical parameters of the ejector are listed in Table 2.

Comparing with the supersonic jet of the nozzle exit, the initial velocity at the nozzle inlet may well be neglected. The lateral inlet of the entrained steam is simplified as a uniformly-distributed axial circular-inlet and thus the axisymmetric two-dimensional transonic compressible flow model could be used, as shown in Fig. 2. According to the shape of flow channel, the map-style block partition mesh is adopted to divide the flow domain structure of the ejector into 8 quadrilateral subdomains that are same as that in Ref. [14]. Second-order up-winding formulation is used to discretize convection terms and second-order central differencing for diffusion terms.

To further ensure that the mathematical and numerical model can produce a reliable prediction of the performance of ejector, just like that in Ref. [14], a simulation was carried out to investigate the influence of mixing steam pressure p_c on the performance of the steam ejector. Fig. 3 presents the simulated entrainment ratio ω as a function of the outlet mixing steam pressure p_c under the given operation conditions ($p_p = 600$ kPa, $p_s = 15$ kPa). As one can see from this figure, the

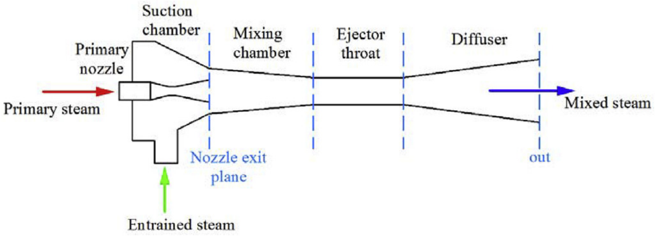

Fig. 1. Schematic diagram of steam ejector.