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Performance improvement of steam ejectors under designed parameters with auxiliary entrainment and structure optimization for high energy efficiency

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ABSTRACT

Steam ejectors are regarded as a promising energy-saving technology, which have been widely used in many industries. The aim of this paper is to optimize the geometrical parameters of the auxiliary entraining entrance that has a significant influence on the entrainment performance. In this study, the developed auxiliary entrainment and structure optimization make good use of the low-pressure potential inside the throat for performance improvement. Moreover, the influence of auxiliary entraining entrance geometric parameters on internal flow fields and mass flow rate have been obtained numerically and analyzed carefully, and the special internal flow characteristics are also presented and discussed in detail to emphasize the role of auxiliary entraining entrance geometric parameters in determining entrainment performance. The results reveal that the major influence factors of entrainment performance are the effective suction pressure area, the near-wall mixed steam velocity and the negative affect on main entraining entrance. And there are an optimum geometrical parameters combination of the auxiliary entraining entrance, whose opening center position is 119mm, opening width is 5 mm and opening angle is 90° for the given ejector and operation parameters, with a maximum entrainment ratio improvement of 3.80% comparing with that of the conventional designed steam ejector. Furthermore, the auxiliary entraining entrance can be designed in an appropriate range.

1. Introduction

As the rapid development of global industrialized economy, energy source has increasingly become a bottleneck for sustainable development of our modern society, which plays a determining role in national economic strength and the living standard of people. However, excessive consumption and unreasonable waste of energy for meeting the short-term economic development have not only aggravated this bottleneck effect further, but also caused serious energy shortage and environment pollution problems, even energy war. Therefore, energy conservation and high energy efficiency is of crucial importance for developing low-carbon economy and becoming the common aspiration world-wide [1]. For meeting this aspiration, some research works focus on the optimization of the traditional heat transfer process, such as the optimization framework of designing multi-stream compact heat exchangers [2] and the optimization design of plate-fin heat exchangers with multi-objective cuckoo search algorithm [3]. The heat transfers do achieve higher efficiency and lower energy consumption, but the converted energy of that is often of lower quality and may not be used in some industrial processes. Steam ejector is a simple fluid entrainment and circulation machinery, which can use the Venturi effect to draw low-grade heat energy and improve its quality to be reused without consuming mechanical work [4]. Because of simple structure, low maintenance cost and high energy efficiency as compared with the conventional steam ejectors that had been considered as the most promising energy-saving heat pump. Moreover, this low-grade heat energy is available in various industrial processes and has been being wasted directly without reasonable management or efficient utilization. Fortunately, the application of ejectors is beneficial to recover a great part of the waste heat of the entrained steam and thus obtain high energy efficiency. Therefore, steam ejectors have been finding increasingly applications in various energy equipment and industrial processes. For example, the multi-effect distillation (MED) systems equipped with steam ejector can reduce system heating power and cooling water mass flow as the effective utilization of low-pressure vapor energy in the seawater desalination [5]. The proton exchange membrane fuel cell (PEMFC) systems installed with ejector have achieved higher energy efficiency and lower emission because of the

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Nomenclature

p	pressure, kPa
m	mass flow rate
Δm	mass flow rate increment, g/s
μ	entrainment ratio
x	axial coordinate, mm
ε_μ	entrainment ratio improvement, %
X	auxiliary entraining entrance opening center position, mm
d	auxiliary entraining entrance opening width, mm
θ	auxiliary entraining entrance opening angle, °
S	effective suction pressure area, kPa. mm^2
A	circulation area, mm^2
x_0	lowest-pressure position, mm
x_f	fully-developed point, mm
X_{cr}	critical X value of producing negative effect, mm

Subscripts

P	primary steam
H	entrained steam
h	auxiliary entrained steam
C	outlet mixed steam

Abbreviations

COP	coefficient of performance
PEMFC	proton exchange membrane fuel cell
NXP	nozzle exit position
BOG	boil-off gas
MED	multi-effect distillation

anode/hydrogen recirculation [67]. The vapor-compression refrigeration cycle with supercooling using an ejector can improve the cooling capacity and coefficient of performance (COP) compared to the single-stage one [8], and so on.

Actually, the structural design method of ejectors is far from satisfactory, thus the designed ejector capacity is usually far smaller than its theoretical value, only 20–50% of that, if not anything smaller, which results in the poor performance and limits its wider and more efficient use. As important as ejectors can be, therefore, their structural design and optimization has never stopped, and speeds up instead due to the strong voice of energy saving and emission reduction. Many studies have focused on the optimization of ejector operation parameters and geometric parameters for acquiring the maximum entrainment ratio, which are closely related with ejector performance and thermodynamic irreversibility. The numerical results of Wang et al. [9] and experimental results of Huang et al. [10] have disclosed the same phenomenon that the back pressure has a critical value under which the ejector performance can achieve its best. This phenomenon is called as double chocking state; once the back pressure exceeds this critical value, the ejector capacity will degenerate sharply. Tang et al. [11] found that the entrainment ratio of steam ejector can achieve its peak value if the primary steam pressure remains at its optimum value, and decreases monotonously with the decrease of entrained steam pressure. Sriveerakul et al. [12] comprehensively analyzed the influence of operation parameters on ejector performance, and revealed that the entrainment ratio and critical back pressure cannot increase simultaneously as the primary steam pressure increase, but the entrained steam pressure does so. Unfortunately, this achievement is a result of sacrifice of energy quality. Chen et al. [13] developed a new 1-D theoretical model with a wide range of operation parameters and provided a good reference for designing high-performance steam ejectors. Besides the operation parameters, more attention has also been paid to the optimization of geometrical parameters. The nozzle plays an important role in inducing low-pressure regions by Venturi effect to draw entrained steam, which determines the entrainment potential directly. Pianthong et al. [14] investigated the ejector performance as a function of NXP (the primary nozzle exit position) numerically, they found that the entrainment ratio raised slowly as NXP gradually away from the inlet section. However, Chen et al. [15] revealed that the ejector performance can reach its best with an optimum NXP. Fu et al. [16] disclosed that there is an optimum diameter ratio range, that is defined as the ratio of the outlet diameter to the throat, and a much broader range of divergent section length of nozzle, at which the given steam ejector can perform the best entrainment performance. The simulation results of Hou et al. [17] shown that the primary fluid flow rate increases with the primary nozzle diameter, but the entrainment ratio decreases significantly. Mixing chamber contained the complex mixing process of primary fluid and entrained fluid, where accompanied severe flow field variation and thermodynamic irreversibility that closely related to the ejector performance. Wu, et al. [18] disclosed that there is an optimum length range and an optimum value of convergence angle of mixing chamber at which the steam ejector can achieve the most desired entrainment performance. Chen, et al. [15] drew similar conclusions to Wu at al. [18], the only difference is that they think it is the specific optimum length instead of an optimum range, and this length decreases as the primary fluid pressure increases. MyoungKuk, et al. [19] and Zhu et al. [20] also proved the existence of the optimum convergence angle, moreover, that is very sensitive to ejector performance. Although the ejector throat is at the end of the mixing process, it has crucial effect on the ejector performance. Sriveerakul et al. [12] found that the critical backpressure can be raised with a longer throat section but that has no influence on the entrainment ratio. Liu, et al. [21] revealed that the entrainment ratio improvement is about 20% by adjusting the area ratio from 18.23 to 30.25 as the effective cross-area increases with the throat diameter.

Steam ejector performance has been improved greatly after the optimization of operation parameters and geometric parameters. However, there is still a great distance from that of the theoretical value, which is impossible to avoid because of the inherent defects of the existing design theory of conventional ejector. In order to solve this problem, efforts have been made to change the conventional ejector structure slightly. Xing et al. [22] proposed a double ejector system to boost COP (coefficient of performance) and volumetric heating capacity of a two-stage trans-critical CO_2 heat pump cycle. Tan et al. [23] used the same way to draw more fuel BOG (boil-off gas) into compression system for reducing energy loss. Opgenorth et al. [24] developed a lobed nozzle of supersonic ejector for maximizing pressure recovery and thus performance improvement. Zhu et al. [25] proved that the ejector equipped with an annular bypass of nozzle wall can effectively reduce the primary flow rate thus improve entrainment performance. The above efforts have really improved the design of steam ejectors and the optimization is obvious. However, this effectiveness is based on steam ejectors whose operation and/or geometric parameters are not optimized, that is to say, those novel structure ejectors mentioned above may be shrunk even failed if the operation and/or geometric parameters have been optimized perfectly of corresponding convention ejector.

To overcome these difficulties, in our previous paper [11], the auxiliary entrainment was proposed to take full use of the potential pressure energy of ejector throat low-pressure area to draw extra entrained steam into the steam ejector, and our numerical simulations proved its effectiveness in improving the entrainment performance of steam ejectors. In this paper, the main contribution is structure optimization of geometrical parameters of auxiliary entraining entrance.