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Combined auxiliary entrainment and structure optimization for performance improvement of steam ejector with consideration of back pressure variation

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ABSTRACT

It is crucial to enhance the entrainment performance of steam ejectors which operate under double-critical conditions to widen their application in industries. In this paper, combined auxiliary entrainment technical approach is proposed and corresponding geometric structure optimization has implemented systematically, for a better use of the inside low-pressure potential thus greatly improving the entrainment performance of the steam ejector under double-critical conditions. Moreover, a comprehensive analysis and discussion of the influence of the geometrical parameters on the auxiliary entrainment performance has been obtained from mass flow rate, pressure field and special internal flow characteristics. The results reveal that the combined auxiliary entrainment is the best choice for the given steam ejector operating under the double-critical conditions, and the optimum geometrical parameters of throat auxiliary entraining entrance are same as the designed condition and remain unchanged. For the diffuser auxiliary entraining entrance, the opening starting position X_s could be set at the entrance of the diffuser identically, the opening angle could be chosen as a common range R_θ from 75° to 105°. However, the optimum opening width d increases with the decrease of back pressure p_C. In general, there is an optimum geometrical parameters combination that the entrainment performance can achieve its maximum value for each p_C. The smaller the p_C, the bigger the entrainment ratio improvement, as large as 34.8% for p_C of 32 kPa.

1. Introduction

In the past few decades, severe energy wasting and environmental destruction, caused by the high-energy consumption industries and extensive mode of economic growth, have gone far beyond the tolerance capacity of our ecosystem. This seriously restricts the development of economy and society and threatens our healthy life. Therefore, advocating ecological civilization construction and energy sustainable development are of crucial importance for getting rid of this bottleneck, and have become the common aspiration of the world [1]. Steam ejector regarded as one of the most promising energy-saving machineries that may make a significant contribution to energy sustainable development, not only because of its ability to recover low-grade energy, but also the simple structure and high reliability. It can use a certain amount of high-pressure primary steam to suck the fluids of low-grade energy and boost its quality for reutilization without consuming any mechanical work [2]. Most important of all, this low-grade energy is available in many industrial processes and solar collectors, etc. [3] that being wasted directly/mostly without reasonable management or efficient utilization. Therefore, steam ejector can be applied in various industrial processes to recover and reuse a good part of the low-grade energy, such as fuel cell systems [4,5], multi-effect distillation (MED) desalination systems [6,7], refrigeration and/or cooling systems [8,9], and so on.

As important as it can be, the theoretical research and structural design optimization of the steam ejector has been a hot topic long and is speeding up in the strong voice of energy saving and emission reduction. Generally, there are two different theoretical mixing models used in the design and research of steam ejectors proposed by Keenan et al. One is the constant-pressure mixing model, which assumes that the primary fluid and entrained fluid are mixed at the same pressure starting from a certain location of mixing chamber [10]. Another is the constant-area mixing model, which assumes that the mixing process of these two fluids occurs at the mixing chamber of the same cross-area [11]. After comprehensive comparisons and discussions, it is concluded that the constant-pressure design model can achieve higher entrainment performance, and thus get wide application. Based on this, many researchers have tried to set up corresponding theoretical model to evaluate the working performance of ejectors. Among of these models that have been proposed so far, the 1-D theoretical model proposed by

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Nomenclature

p	pressure, kPa
Δm	mass flow rate increment, g/s
x	axial coordinate, mm
μ	entrainment ratio
ε_μ	entrainment ratio improvement, %
X	diffuser auxiliary entraining entrance center position, mm
d	diffuser auxiliary entraining entrance opening width, mm
θ	diffuser auxiliary entraining entrance opening angle, °
L	effective suction region length, mm
X_s	diffuser auxiliary entraining entrance starting position, mm
d_p	the optimum opening width, mm
R_θ	optimum opening angle range, °
p_s	suction pressure of auxiliary entraining entrance, kPa
p_{cr}	the pressure value of critical state point, kPa
p_b	the pressure value of backflow point, kPa
A	effective cross-sectional area, mm^2
S	effective suction pressure area, kPa mm^2
x_0	lowest-pressure location, mm

Subscripts

P	primary steam
H	entrained steam
$h1$	throat auxiliary entrained steam
$h2$	diffuser auxiliary entrained steam
C	outlet mixed steam

Abbreviations

COP	coefficient of performance
CSPF	cooling seasonal performance factor
MED	multi-effect distillation
NXP	nozzle exit position

Huang et al. [12] has obtained wide recognition and regarded as a basic model for being capable of predicting the ejector performance accurately. Chen et al. [13] extended the capacity of this 1D model to the sub-critical state. Although the theoretical model has been improved greatly, it is still based on many ideal assumptions. Thus, it is inevitable that some special internal flow conditions and complex irreversibility during the actual operation process have been ignored, all which might be sensitive for ejector performance. Therefore, the structural design methods based on the theoretical model are far from satisfactory, they usually lead to poor performance and this certainly limits the ejectors' wider and more efficient application. To improve the working performance, many researchers concentrated themselves on the optimization of the original designed structure of steam ejectors. The conventional ejectors mainly include three sections, the main nozzle, the mixing chamber and the ejector throat, which all play an important role in determining the entrainment performance. As for the main nozzle, the obtained results showed that there is a best value of nozzle exit position (NXP) [14,15] and throat diameter [16], an optimum range of diameter ratio and a much broader range of divergent section length [17], for the given ejector achieving the best working performance. As for the mixing chamber, Jeon et al. [18,19] has optimized the mixing-section diameter based on the cooling seasonal performance factor (CSPF) and the climatic conditions, and then obtained one optimum value in the covered operating conditions. Wu et al. [20] and Chen et al. [21] found that there is an optimum value of convergence angle of mixing chamber and an optimum length range (Wu)/optimum length (Chen) at which the steam ejector can reach the most desired entrainment performance. As for the ejector throat, the obtained results of Sriveerakul et al. [22] showed that increasing the throat length can boost the critical back pressure and has no effect on the entrainment ratio. Liu et al. [23] revealed that the entrainment ratio could be improved of 20% by adjusting the area ratio.

Because of the inherent defects of the existing design theories, although the structure optimization can improve the steam ejector performance greatly, there is still a great gap from the theoretical value. Thus, many efforts have been made to change the conventional ejector structure locally for improving the working performance further. Such as introducing double ejector system [24] and petal nozzle ejector [25] to boost COP (coefficient of performance), adapting lobed nozzle ejector to realize maximizing pressure recovery [26], deploying annular bypass of nozzle wall to reduce the primary flow rate [27], and so on. The above-mentioned efforts have really improved the working performance of the original designed steam ejector, but all the structure optimizations and changes were based on the design operation condition. That is to say, the optimization scheme may be shrunk even fail if the operating conditions change or are different from the design conditions. In fact, the operating conditions can never be maintained unchanged and fluctuation is always the case because of the uncontrollable changes in external environment, such as the seasonal/climatic performance factor of the cooling systems, and the response time and accuracy of the control system, etc. There is no doubt that the departure from the design condition will inevitably result in the deterioration of the ejector performance. In order to make the steam ejector have better entrainment performance under the fluctuating operation condition, Chen et al. [28] proposed a novel ejector with a bypass that could make full use of the superfluous low pressure and increase the entrainment ratio under the given fluctuation conditions. Yang et al. [29] proposed an adjustable ejector that could automatically adjust the main nozzle diameter by a needle, and achieve the maximum performance in the trans-critical CO_2 refrigeration cycle. However, one of the shortcomings of those technical proposals is that the operation and geometric parameters of the original ejector were anything but optimized.

In order to improve the entrainment performance of steam ejector comprehensively, our team has carried out a series of systematic structure optimization of an original conventional steam ejector, which designed for the low-temperature MED desalination systems [6] and is used as a start point for this study. The completed structure optimization includes several primary sections that mainly determined the entrainment performance, that is, the divergent section length and diameter ratio of the main nozzle [17], the convergence angle and length of the mixing chamber [20], and the length and diameter of ejector throat. Moreover, the operation parameters have also be optimized further [30]. After that, a well-designed conventional steam ejector has been obtained with a great entrainment ratio improvement, as much as 30% greater than the original. However, there still have several low-pressure regions, in which the pressure is lower than the entrained steam. Thus, auxiliary entrainment schemes were proposed tying to utilize this potential pressure energy, and our simulations proved that both the throat and diffuser auxiliary entrainment are effective for entrainment performance improvement of steam ejector [30]. Then, the scheme selection and structural optimization of the auxiliary entrainment under the design condition have be investigated comprehensively [31].

In this paper, for the better use of the low-pressure potential inside the steam ejector that operates under the double-critical conditions, the combined auxiliary entrainment approach is proposed and its feasibility verified. After the optimum geometrical parameters combination of the throat auxiliary entraining entrance has been determined, more attention is paid to the systematic geometrical parameters optimization of