



Three-dimensional CFD modeling and simulation on the performance of steam ejector heat pump for dryer section of the paper machine

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ABSTRACT

A three-dimensional model of the steam ejector heat pump for the dryer section of the paper machine was developed by applying the Computational Fluid Dynamics (CFD) technique, which provided the pressure and velocity distributions of fluid flow in heat pump. The results indicated that the fluid velocity field in heat pump has an incomplete axially symmetrical distribution. The entrainment ratio of the heat pump initially increases rapidly with the increase of the ejected steam inlet pressure and then decreases after the inlet pressure exceeds one certain value. There exists a critical value for the mixed fluid pressure under the given operating conditions. The optimal ratio of the diameter of constant area mixing section to the steam nozzle throat diameter is about 3.4 and the optimal ratio of length to diameter of constant area mixing section L/D_m is 6. An optimal divergence angle of diffuser was observed under different diffuser length. There is an optimized steam nozzle position under the given operating condition where the maximum of entrainment ratio was observed. The CFD technique is found to be an efficient alternative to predict the ejector performance and the conclusions of the research can provide a beneficial reference for structural optimization design of ejector.

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1. Introduction

The dryer section of paper machine is one of the main sections for the steam consumption of paper making process, in order to save gasoline consumption and resolve poor drainage of dryer, the steam ejector heat pump is often used as the heat supply system. The steam ejector heat pump is a kind of energy saving equipment which has no moving parts, simple structure, no direct consumption of mechanical (electrical) energy and can improve the parameters for the low pressure steam [1–8]. The fluid flow process of the steam ejector heat pump is very complicated, including the interaction of shock wave, the boundary layer and the shear layer, and so far the mechanism of fluid flow has not been completely clear. This resulted in adopting the semi-theoretical and semi-

empirical method to design equipment, and the problems of instability, poor dynamic regulation performance and the inconsistency of the design performance and the actual performance were often occurred in engineering practice.

In order to overcome these aforementioned shortcomings, there are many researchers concentrating on analyzing the steam injection process of fluid flow in the pump and the influence of ejector operating conditions and geometrical parameters on the entrainment performance of steam ejectors by using experimental investigations and numerical simulation [9–28]. Such as Nakagawa et al. [29] experimentally analyzed the effect of mixing length on the ejector system performance. The mixing length significantly affected the entrainment ratio and the magnitude and profile of the pressure recovery. Liu et al. [30] investigated a variable geometries two-phase flow ejector to show that the motive nozzle efficiency decreases as the ejector throat area decreases. Kawamura and Nakagawa [31] analyzed the characteristics of the two-phase flow oblique shock waves in the supersonic carbon dioxide two-phase flow. Li Hai-jun [32] with the help of PHOENICS software analyzed the complex flow inside the steam ejector heat pump by solving the two-dimensional N–S equations; C. Li and Y.Z. Li [33]

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adopted the method of numerical simulation for investigating the entrainment behavior and the effects of different operating conditions, thermal and structural parameters, different working fluids on the performance of steam ejector heat pump. Xiao-Dong Wang [34] analyzed the flow distribution of steam jet vacuum pump at different operating conditions to find out pressure ratio (K) is a dominant position in affecting the pump's performances. J. Fan et al. [35] use an analytical approach to build an initial jet-pump and global optimization were made to increase the pump efficiency and reduce the energy requirements of the pump. Ruangtrakoon et al. [36] use CFD technique to investigate the effect of the primary nozzle geometries on the performance of an ejector used in the steam refrigeration cycle and obtained that moving the nozzle into the mixing chamber reduces the ejector performance. Kavous Ariafar et al. [37] in his study adopt a numerical investigation of flow in the primary nozzle of a steam ejector to further explore the differences between ideal gas and wet steam. Hongqiang Wu [38] employed the CFD technique to analyze the flow characteristics of the steam ejector and the effects of the length and convergence angle of the mixing chamber on the entrainment ratio of the ejector. More recently, Fanshi Kong [39] utilized numerical approach to detect the performance of single-stage ejector-diffuser system and two-stage ejector-diffuser, and the primary results of the two-stage ejector-diffuser system showed favorable capacity of collecting the extra momentum and increasing the entrainment effects of the system. All the previous work done in the published literature prove that configuration optimization is an effective way to enhance the entrainment performance of steam ejector heat pump and CFD technique is a reliable tool to perform such research with low cost if sufficiently validated through comparison with experimental data.

We all know that the entrainment performance of steam ejector heat pump depends on a number of factors, such as geometric arrangement or structural parameters, thermal parameters, various operating conditions, material properties of working fluids and some other related factors. The dynamic characteristics of steam ejector heat pump were known to be extremely complicated and to have strong flow unsteadiness and high turbulent mixing, thus it is not easy to obtain the best operation conditions and geometrical parameters of steam ejector heat pump through simple experimental investigations. Therefore, considering the complexity and difficulty on the experimental researching, how to enhance the performance of steam ejector heat pump in a reliable and accurate way became a significant task. Meanwhile, it is the understanding of the effects of different operation conditions and geometrical parameters on the mixing process and entrainment ratio, that will allow a more reliable and accurate steam ejector design. Hence, the optimal work for steam ejector heat pump is strongly suggested to be carried out. A thorough understanding of the relationship between these critical factors and ejector entrainment ratio is essential to design high performance ejectors. A way for achieving all the aforementioned goals at a reasonable cost is adapting the three dimensional technique and numerical software. Computational Fluid Dynamics (CFD) is a powerful prediction method and has been widely used in various industrial fields. At present, the CFD method has been the quantitative design tool for engineering device optimization and amplification, it can not only give an approximate flow field within the equipment, and can also provide some information that experiment can not or difficult to measure [40]. But most of the previous studies on the entrainment performance of ejectors mentioned above are based on the assumption of "simplified ejection fluid inlet for circumferential", simplified the complex three-dimensional fluid flow of the steam jet pump into a two-dimensional fluid flow problem in order to reduce the computational expenses and time when they adopted the CFD

techniques to analyze this problem. Thus, the aim of this study is to provide a theoretical foundation for the equipment design of steam ejector heat pump used in dryer section of the paper machine by applying CFD method to develop a three dimensional model of the steam ejector heat pump that could provide the pressure and velocity distributions of fluid flow in heat pump. Furthermore, the numerical method is also adopted to investigate the effects of operation conditions and geometrical parameters on ejector performance. All the work will benefit the structural optimization design and further industrial applications of steam ejector heat pump.

2. Experimental equipment and working principle

An steam ejector experimental system is setup to investigate the global and local performance of steam ejector heat pump, the sketch of experimental setup was schematically illustrated in Fig. 1. The main elements of the stand are listed in the figure caption. It consists of a steam boiler, steam ejector heat pump, data acquisition systems, a computer, water tanks, pressure transmitters and gauges, thermocouples and other associated equipment for flow control and measurement (flowmeters and valves). The steam produced by steam boiler entered the ejector through the valve V1, used as the working steam. After the compression of steam by steam ejector heat pump, the compressed steam discharged into water tank through the valve V3, the water used as entrained fluid to enter the receiving chamber of heat pump was obtained through the valve V2. During the experiment, valves V1, V2 and V3 were used to adjust the pressure of working steam, entrained fluid, and mixed fluid respectively. The measurement of pressure was relatively easy to obtain which can just be measured through precision pressure gauges with an accuracy of 0.4% over the operating range, two data acquisition systems were used in the experiment, one for measuring the static pressure and the other for measuring temperature at eight different locations along the length of the steam ejector heat pump. Connecting the two acquisition systems to a personal computer, and then all readings of the measured data were recorded automatically and monitored by the computer. During the experiment, the mass flow rates were measured by YFA11 type vortex flowmeters, and the temperature was measured by copper-kang steel thermocouples with a diameter of 0.3 mm. Generally speaking, due to the existence of shock wave, the interaction of boundary layer and shear layer, the fluid flow velocity distribution inside the steam ejector heat pump is rather complicated, which are extremely difficult to measured through simple experimental apparatus within a reasonable cost and a accurate measurement. Considering the complexity, accuracy, economical efficiency and difficulty on the experimental researching about the internal velocity distribution in steam ejector heat pump and the main purpose of the researching work for analyzing the effects of influential factors on the entrainment ratio, in order to validate the hypotheses and predictions, the experimental measurement were successfully conducted to measure the entrainment ratio for comparison with calculating one. Experiments were carried out under steady state operating conditions. Measurements in the experiment were repeated three times at each operation conditions to ensure repeatability and reliability of data. The average values of the measured experimental data were calculated and were used in the evaluation of the performance of the steam ejector heat pump and for the comparison with simulated results. The details for the comparison between the measured data and simulated results were described carefully in the experimental validation section.

The steam ejector heat pump is always classified into two categories, one type with mixing chamber just consists of a constant area mixing section, and another type with mixing chamber

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