Applied Thermal Engineering 71 (2014) 410–418

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Optimization of geometric parameters for design a high-performance ejector in the proton exchange membrane fuel cell system using artificial neural network and genetic algorithm

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HIGHLIGHTS

- Effects of the ejector geometry parameters on entrainment ratio are investigated.
- The optimal design is discussed to achieve a high entrainment ratio.
- The importance of L_m/D_m is the most in optimization of ejector performance.
- The optimum NXP is proportional to the mixing section throat diameter D_m.

ARTICLE INFO

Article history:
Received 1 December 2013
Accepted 30 June 2014
Available online 17 July 2014

Keywords:
Ejector
PEM fuel cell
Geometric parameters
Entrainment ratio
Optimization

ABSTRACT

In this study, a CFD model is adopted for investigating the effects of the four important ejector geometry parameters: the primary nozzle exit position (NXP), the mixing tube length (L_m), the diffuser length (L_d), and the diffuser divergence angle (θ) on its performance in the PEM fuel cell system. This model is developed and calibrated by actual experimental data, and is then applied to create 141 different ejector geometries which are tested under different working conditions. It is found that the optimum NXP not only is proportional to the mixing section throat diameter, but also increases as the primary flow pressure rises. The ejector performance is very sensitive to the mixing tube length while the entrainment ratio can vary up to 27% by change in the mixing tube length. The influence of θ and L_d on the entrainment ratio is evident and there is a maximal deviation of the entrainment ratio of 14% when θ and L_d vary from 2° to 8° and $6D_m$ to $24D_m$, respectively. To make sure the correlation of all geometric parameters on the ejector performance, the artificial neural network and genetic algorithm are applied in obtaining the best geometric.

1. Introduction

In the PEM fuel cell system, the stored hydrogen is commonly under pressure; therefore the supply of hydrogen to a PEM fuel cell needs a pressure regulator in order to reduce pressure to the fuel cell operating pressure. The simplest way to supply hydrogen is in the dead-end mode, where the power consumption of the auxiliary devices is minimized and the fuel utilization is as high as possible, hence, higher system efficiency. The long-term operation in the dead-end mode is possible only with extremely pure hydrogen use. Any impurity in hydrogen and water vapor that may remain in the anode side will eventually accumulate in the fuel cell. To eliminate this accumulation of impurities, purging of the hydrogen compartment may be required. If purging of hydrogen is not possible or is preferred due to safety and system efficiency problems, the hydrogen should be supplied in excess of stoichiometrically required ($S > 1$). In this system, the unused hydrogen that is returned to the inlet, either by a passive (ejector) or an active (pump or compressor) device has to carry the product water from the cell. In systems with mechanical pumps, the main drawback is that they consume electrical power, generate vibration and noise and make the sealing of the system difficult. These systems consist of mechanical components that are not desirable in terms of reliability and simplicity. The convergent nozzle ejectors can

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http://dx.doi.org/10.1016/j.applthermaleng.2014.06.067
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recirculate the unreacted hydrogen without using any moving parts. The objective of ejector is to pump fluids from a low pressure region to a high pressure region. Ejector in PEM fuel cell system uses the high-pressure hydrogen as the primary fluid to suck the anodic exhaust as the secondary flow. Since the ejector needs no parasitic power and has very simple mechanical structure, the fuel utilization efficiency and total efficiency of the system is increased [1–3]. Moreover, the usage of the convergent nozzle ejector is to decrease the water vapor condensation inside the ejector due to the low temperature of the primary and secondary flows in the PEM fuel cell system [4,5]. The ejector performance under varying operating conditions is often analyzed through theoretical studies. The conventional ejector models are usually based on the 1-D fluid dynamics theory assuming that the primary and the secondary flows have uniform distributed velocities in the radial direction [6–10]. These models can determine the effects of some of the geometry parameters on the ejector performance, like the primary nozzle throat and the mixing chamber diameter. Studying the effects of other important parameters like the primary nozzle exit position (NXP), the mixing tube length (L_m), diffuser length (L_d), and the diffuser divergence angle (θ), is not possible, due to the limitation of the 1-D flow simplification of these models. In the recent years, a number of two-dimensional models have been introduced for the ejector simulation in the PEM fuel cell system [4,5]. In these models, different velocity profiles are assumed at each stage of the mixing process in order to solve the mass and momentum equations. A number of experimental [11–17] and numerical [18–21] studies are conducted on optimal ejector geometry in various application fields. Yang et al. [22] investigated and compered the effects of five different nozzle structures of ejector on the performance of a steam ejector by the CFD technique. They found that the elliptical and rectangular nozzles decreased the steam ejector performance while the cross-shaped and square nozzles improved the entrainment ratio of the ejector. Keenan and Neumann [23] reported that an optimum ejector mixing tube length is about 7 times the mixing tube diameter. The CFD studies of Kandakure et al. [24] indicate that at low value of throat to nozzle area ratio, the annular area available for air flow reduces. In addition, they claim that there is an optimum area ratio for the maximum air entrainment rate. Zhu et al. [21] investigated the effects of the primary nozzle exit position and the mixing section converging angle, θ, on the ejector performance by the CFD technique. Here, they revealed that the optimum NXP is proportional to the mixing section throat diameter. The ejector performance is very sensitive to θ, especially near the optimum working point. Henzler [25] through experimental data suggested that the optimum relative position is in 0.4–0.9 range. Due to the complex nature of the flow in the ejector, there is no fixed optimum nozzle position or the mixing tube length (L_m) that could meet all operating conditions.

The inlet of the primary fluid and the inlet of the secondary fluid or the ratio of these two parameters are the important components of an ejector. The diameter of throat to the diameter of the nozzle ratio (D_m/D_t), the mixing tube length to the mixing tube diameter ratio (L_m/D_m), diffuser length (L_d), diffuser divergence angle (θ) and the distance between nozzle tip and entry to the mixing tube (NXP) are the geometry parameters that could be expressed in the ejector. The contents that are discussed in this section of the convergent – divergent nozzle are applied for the ejector. Unlike the previous studies that have investigated the effects of one or two geometry parameters of the above mentioned parameters on the characteristic and the entrainment ratio of the ejector, here, the effects of the ejector geometry parameters consist of the nozzle exit position, the mixing tube length, diffuser length, and the diffuser divergence angle on the flow characteristic and the entrainment ratio are investigated simultaneously, based on the CFD modeling technique for the convergent nozzle ejector in the PEM fuel cell system. The model is calibrated by comparing the simulation data to the available experimental results obtained from an ejector [21]. Based on the CFD model, 141 different ejector geometries are developed in order to investigate the effects of the above mentioned parameters on the performance of the ejectors. Due to the complexity of the simultaneous application of these parameters on the ejector performance, by applying the artificial neural networks, the relation between these parameters and ejector performance is obtained. Here, as well, the best value for any of these parameters is obtained through genetic algorithm (and Bees algorithm (BA)), in order to achieve the highest performance of the ejector.

2. Mathematical modeling

The closed loop hydrogen supply system with ejector and a schematic diagram of the ejector which consists of the primary nozzle, the suction chamber, the constant pressure and constant-area mixing sections and the diffuser with its characteristics dimension are show in Fig. 1a and b respectively. During PEM fuel cell operation, the hydrogen is released from the storage tank and its pressure is reduced in the pressure regulator, the primary flow, which is accelerated to high speed as it passes through the convergent–divergent nozzle inside the ejector, generating a low pressure region in the suction chamber that is capable of entraining unused hydrogen in the PEM fuel sell stack, the secondary flow. The primary and secondary flows mix in the constant area chamber and this mixture is then expanded to a higher pressure in the diffuser before entering the fuel cell stack.

2.1. Governing equations

The axisymmetric condition, steady-state flow and ideal gas mixtures are assumed in this model. In addition, the effect of gravity and the phase change of vapor to liquid water are neglected. The conservation equations (the mass, momentum, energy and species) for the physical phenomena in the ejector are employed in the axisymmetric compressible form. For variable density flows, the favre averaged Navier–Stokes equations are the most proper ones for this study. The total energy equation, including viscous dissipation is applied here and is coupled to the set with real gas state equation. The governing equations with the above mentioned assumptions can be written in their compact Cartesian form as follows:

Mass conservation:

$$\frac{\partial}{\partial x_i}(\rho u_i) = 0 \tag{1}$$

where, u_i and ρ are the velocity in the ith direction and density, respectively.

Momentum conservation:

$$\frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial P}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} \tag{2}$$

where, P and τ_{ij} are the pressure and stress tensor.

Energy conservation:

$$\frac{\partial}{\partial x_i}(u_i(\rho E + P)) = \vec{\nabla} \cdot \left(K_{\text{eff}} \frac{\partial T}{\partial x_i} + u_i(\tau_{ij}) \right) \tag{3}$$

$$\rho = \frac{P}{RT} \tag{4}$$