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Adaptive air distribution in an ejector burner for the utilisation of methanol-mixed fuels

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ABSTRACT

Numerous studies have focused on the utilisation of alcohol fuels because of the energy crisis. However, the combustion efficiency and stability of alcohol fuels are unacceptable. This study proposed an ejecting combustion method for utilising methanol-mixed fuels and numerically investigated the characteristics of adaptive air distribution in an ejector burner. The geometrical parameters of the ejector burner were optimised and validated by an experiment. Results show that the suction effect of negative pressure in the mixing chamber and the entrainment effect of fuel jet flow both play important roles for an ejector burner to draw air. The positions of ejector nozzle exit locating at the suction chamber axis and low operating pressure are beneficial for obtaining a stable air distribution. Molar entrainment ratio (MER) rapidly increases with an increase in parameter α, which is defined as the ratio of throat diameter to nozzle exit diameter, but declines with increasing ejector back pressure. In the experiment, the changing rate of MER is less than 6.4%, and combustion efficiency is higher than 99.2% in the load range of 20–120%, which is highly consistent with that of the simulation. The optimised burner could automatically distribute air supply and facilitate stable combustion.

1. Introduction

Energy utilisation has recently become a public concern because of the shortage in fossil fuels, the increase in oil price and the severity of environmental pollution. A number of clean and renewable energies are under development [1–4]. Methanol-mixed fuel, which mainly consists of methanol, propane and a small amount of additives, is a potential substitute for gasoline because of their similarities in physical property. However, with only half of the low calorific value of gasoline, methanol-mixed fuel has a high latent heat of vaporisation, which is more than thrice that of the former fuel. Aside from the difficulties in ignition and combustion stability, combustion efficiency would thus be low if methanol-mixed fuels are utilised by using traditional methods. This study thus presents a novel ejecting combustion method [5] for the utilisation of methanol-mixed fuels. This method is characterised by the vaporisation of liquid methanol-mixed fuels and the automatic adjustment of air supply using an ejector. The adaptive air distribution and combustion performance of an ejector burner must be studied, because the efficiency in the automatic adjustment of air supply is poor when the ejector burner load changes in a large scope.

Ejector is widely used in industrial sectors, such as water desalination, geothermal power and chemical plants, particularly in refrigeration systems [6,7]. Yang et al. [8] analysed the influence of different geometrical structures of ejector nozzles on drawing quality, and circular nozzle exit was found to have the best performance. Varga et al. [9], Ruangtrakoon et al. [10] and Yan et al. [11] indicated that the ratio of ejector throat area to nozzle exit area significantly affects the drawing quality of ejector. Nozzle position also affects entrainment efficiency. Pounds et al. [12] and some other investigators [13–15] studied the influence of nozzle position on entrainment performance, and found an optimal nozzle position could produce a maximal coefficient of performance. Pianthong et al. [16] and some investigators [17–19] studied the effects of mixing chamber length, suction chamber angle and diffuser chamber length on entrainment performance. In addition, Chunnanond and Aphornratana [20], Yan et al. [21] and Chong et al. [22] investigated the static pressure along the ejector axis at different operating conditions. Opgenorth et al. [23] investigated the effect of back pressure on entrainment ratio to improve the efficiency of ejectors in refrigeration systems. Sriveerakul et al. [24,25] and other researchers [26,27] discussed the mixing process of fuel flow and air in mixing chamber. However, most of the aforementioned

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Nomenclature

Q_v	volume flow of liquid fuel ($m^3\,s^{-1}$)
Q_h	volume flow of mixing gas ($m^3\,s^{-1}$)
N_h	molar flow rate of mixing gas ($mol\,s^{-1}$)
N_f	molar flow rate of fuel ($mol\,s^{-1}$)
M_k	molar mass of air ($kg\,mol^{-1}$)
M_f	molar mass of fuel corrected by mass fraction ($kg\,mol^{-1}$)
P_h	absolute pressure of mixing gas (Pa)
T_h	temperature of mixing gas (K)
P_{dy}	total pressure of mixing gas (Pa)
P_{jy}	static pressure of mixing gas (Pa)
R	gas constant, $R = 8.314$ ($J\,k^{-1}\,mol^{-1}$)
S	ejector throat area (m^2)
P_O	operating pressure (Pa)
P_b	back pressure (Pa)
ρ_f	liquid fuel density corrected by mass fraction ($kg\,m^{-3}$)
ρ_h	density of mixing gas ($kg\,m^{-3}$)
v	flow velocity of mixing gas ($m\,s^{-1}$)
L	length (mm)
D	diameter (mm)
Greek	
α	ratio of throat diameter to nozzle exit diameter
η	combustion efficiency
β	fuel mass fraction
Subscripts	
f	pure fuel
k	air
h	mixing gas of air and fuel
m	mass
i	inlet
o	outlet
Abbreviations	
MER	molar entrainment ratio
NEL	nozzle exit location

studies have focused on ejectors used in refrigeration systems, and to our knowledge, no work has been reported on the adaptive air distribution characteristics of ejector burners.

In this work, a CFD simulation method was used in this study to investigate the adaptive air distribution characteristics of an ejector burner with varying geometrical parameters. As the air distribution characteristics are determined by its geometrical parameters and operating parameters, the effects of four key parameters on MER were studied, including the fuel nozzle exit location (NEL), the ratio α of the ejector throat diameter to the fuel nozzle exit diameter, the operating pressure and the ejector back pressure. The structure of the ejector burner was optimised to realize automatic adjustment of air supply when the burner load changes in the range of 20–120%. Finally, an experimental investigation was conducted to validate simulation results and the performance of the optimised ejector burner. This work could contribute to the design of ejector burners with adaptive air distribution and promote the practical application of methanol-mixed fuels.

2. Research methods

2.1. Physical structure

The ejector burner was designed on the basis of ejecting combustion technology. A small amount of heat coming from the combustion chamber vaporises the liquid methanol-mixed fuels in the spiral vaporiser. The gaseous fuel is then fed to the fuel nozzle from the fuel outlet and jetted into the suction chamber with a high speed. Owing to the entrainment effect, a large amount of air could be drawn into the suction chamber and then mixed with the gaseous fuel in the mixing chamber and the diffuser. Finally, combustion occurs after the mixture is sprayed into the combustion chamber. Fig. 1 shows the geometrical structure of the ejector burner studied in this work. The ejector burner was designed to have a maximum load of 100 kW. The preliminary dimensions are listed in Table 1.

2.2. CFD models

2.2.1. Governing equations

In this study, computation was performed using the package of FLUENT 6.3. The governing equations used in the numerical computation are momentum, energy, continuity, mass transport and k–ε equations [28]. The expression of these governing equations in a cylindrical coordinate system is given as follows:

$$\frac{\partial}{\partial x}(\rho u\varphi) + r\frac{\partial}{\partial r}(r\rho v\varphi) + r\frac{\partial}{r\partial\theta}(\rho w\varphi) = \frac{\partial}{\partial x}\left|\Gamma_\varphi\frac{\partial\varphi}{\partial x}\right| + \frac{\partial}{r\partial r}\left|r\Gamma_\varphi\frac{\partial\varphi}{\partial r}\right| + \frac{\partial}{r^2\partial\theta}\left|\Gamma_\varphi\frac{\partial\varphi}{\partial\theta}\right| + s_\varphi \quad (1)$$

where φ denotes different variables, Γ_φ denotes generalised diffusion coefficient and S_φ denotes generalised source. Different values of φ, Γ_φ and S_φ have different expressions [29,30].

2.2.2. Grids

As shown in Fig. 2, the grids of calculation model were divided into two parts by the combustion chamber outlet, namely, the ejector burner domain and the combustion domain. The combustion domain is an axial symmetric cuboid meshed into approximately 0.25 million hexahedral elements. The ejector burner domain was meshed in the same manner (approximately 0.15 million elements). However, the size of grids in the ejector domain is relatively smaller than that in the combustion domain because of the comparatively smaller dimension and faster flow velocity of gaseous fuel. A total of 0.4 million computing elements were used, which was verified by a grid with a total of 0.76 million elements. For two grids, the difference of static pressure at mixing chamber exit is less than 0.05%, which illustrates that the grid with 0.4 million elements has a satisfying computational accuracy.

2.2.3. Solution methods

Based on practical operating conditions, fuel entrance and air entrance were set as pressure inlet boundary condition, and combustion domain exit was set as pressure outlet boundary condition in the computational model. The pressure in air entrance and combustion domain exit was 0 Pa (gauge pressure). The adiabatic boundary condition was used for the walls. According to fuel composition, the mass fractions of methanol and propane at the fuel entrance were set as 0.96 and 0.03, respectively. Nitrogen was used to replace the nonreactive additive, and the mass fraction was 0.01 at the fuel entrance. The mass fraction of oxygen was set as 0.23 in the air entrance. The initial temperature was 450 K at the fuel entrance.

The standard k–ε turbulence model was adopted in this work, and the constants used in this model were $C_{1\varepsilon} = 1.44$, $C_{2\varepsilon} = 1.9$, $\sigma_k = 1.0$ and $\sigma_\varepsilon = 1.2$ [29,30]. Segregated solver was used in the