Determination of Dependence of Equivalence Ratio on the Air Gap of the Medium Pressure Injection Gas Burner

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Abstract. In this work, a series of calculations of a complete premixing injection gas burner with various air gap widths with ANSYS Fluent software was performed. A natural gas fired injection gas burner is used as a heat source as a part of a thermoelectric generator. Assuming that the gas-air mixture flow is one-dimensional and axisymmetric, the issues were solved in axisymmetric setting, taking into account the gas compressibility. In the performance of a task, a set of assumptions was made: k-epsilon realizable model was picked as turbulence model with scalable wall functions; the flow in the ejector, mixing chamber and diffuser is subsonic; the pressure of the injected air was set to atmospheric pressure; pressure at the inlet to the gas burner is subcritical (≤ 86 kPa for methane). Based on the calculations represented above, the dependence of the equivalence ratio on the air gap width was determined.

1. Introduction

One of the main points that determines the thermoelectric generator features is the choice of the heat source. A brief review of modern approaches to the thermoelectric generator modules development is represented in the [1] paper. In a present-day usage of thermoelectricity for natural gas combustion, gas ejectors became widely used, which also became the basis of gas burners designed with incomplete or complete gas-air premixing. Gas ejectors provide a homogeneous constitution of the gas-air mixture, have the self-regulate ability (the maintaining coefficient of ejection) in a certain range of stress changes, which can be reduced with heating the gas or air, or the availability of backpressure or rarefaction in the combustion chamber, or etc. In this work, the results of a numerical study of the subsonic axisymmetric methane-air ejector were obtained with the software complex ANSYS Fluent [2] and the Response Surface tool use. There are a lot of works on this subject. The ejectors theory is developed in monographs and study books [3], [4]. An air-air subsonic ejector at several modes and with different coefficients of ejection was studied in work [5]. The initial and main mixing areas of the ejector with a constant cross-sectional area of the mixing chamber are noted. It is concluded that the main disadvantage of the mixing chamber with a constant cross-section is that the ejected flow is slowed down in the initial mixing area and only in the prime mixing area the ejected stream is accelerated, where the static pressure also increases. In [6] work, the air-gas mixing system for a burner with premixing with computational gas dynamics (CFD) was optimized. A significant improvement in the mixture homogeneity at the outlet with the use of an air-supply system and several
ejectors has been experimentally proven. The author of [7] represents a high-compression ejector with a tangential gas injection into the mixing chamber calculating method. In [8] work, conditions for optimal combinations of the ejector and diffuser are found for small compression ratios. It is shown that for large coefficients of ejection (> 3) and corresponding to them small compression ratios, the optimal ejector and diffuser system is several times more economical than the usual optimal isolated ejector with the same diffuser.

2. Model and methods

The target of the research in this work was an ejector whose geometrical dimensions were obtained using the method described in [9]. As a turbulence model, according to [10], a k-epsilon realizable model with scalable wall functions was chosen, which is most suitable for these issues. The gravity forces influence was not taken into account. The perfect gas equation with taking into account compressibility was used. It was assumed that the air-gas mixture flow is stationary, axisymmetric, air is fed to the ejector with constant discharge. The wall surfaces roughness was set to zero. The input parameter for the Design of Experiments tool is the air gap width specified in Figure 1. The output parameter is the equivalence ratio, calculated as the average over the output boundary of the diffuser.

![Figure 1. Dependence of the excess air ratio (equivalence ratio) on the size of the air gap.](image)

The software complex ANSYS Fluent performs a numerical solution of the systems of equations using the control volumes approach. The basic equations of mathematical model (continuity equations, balance of momentum equations, energy equations) describing the behavior of the primary and ejected gas flow (1) – (8) have the form:

\[
\frac{\partial}{\partial x_i}(\rho u_i) = 0, \quad (1)
\]

\[
\frac{\partial}{\partial x_i}(\rho u_i u_j) = \frac{\partial P}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j}, \quad (2)
\]

\[
\frac{\partial}{\partial x_i}(u_i (\rho E + P)) = \nabla \left( \alpha_{eff} \frac{\partial T}{\partial x_i} \right) + \nabla \left( u_i (\tau_{ij}) \right), \quad (3)
\]

\[
\tau_{ij} = \mu_{eff} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \frac{2}{3} \mu_{eff} \frac{\partial u_k}{\partial x_k} \delta_{ij}, \quad (4)
\]
where $\tau_{ij}$ is the viscous stress tensor. Transport equations for k-epsilon realizable turbulence model are represented as:

$$\frac{\partial}{\partial x_j}(\rho u_j) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma} \right) \frac{\partial k}{\partial x_j} \right] + G_k - \rho \varepsilon,$$

(5)

$$\frac{\partial}{\partial x_j}(\rho \varepsilon u_j) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + \rho \varepsilon C_{\mu} S_k - C_{\varepsilon} \frac{\varepsilon^2}{k + \sqrt{\varepsilon}},$$

(6)

where $G_k = \mu_t S^2$ is the turbulent kinetic energy, which is formed from average velocity gradients, according to Boussinesq hypothesis.

$$C_1 = \max \left[ 0.43, \frac{\eta}{\eta + 5} \right], \eta = \frac{k}{\varepsilon}$$

(7)

$$S = \sqrt{2S_\eta S_\eta},$$

(8)

where $S_{ij} = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)$ - is the deformation tensor.

The constants of the turbulence model are set by default $C_1 = 1.9, \sigma_k = 1, \sigma_\varepsilon = 1.2$. Turbulent viscosity $\mu_t = \rho C_{\mu} \frac{k^2}{\varepsilon}$. At the gas nozzle input boundary, a boundary condition for mass flow was set. The air and gas temperatures were set to equal 300$^\circ$K.

3. Results and discussions

As a result of computer simulation, the dependence of the equivalence ratio on the air gap width was obtained (Fig. 2). The complete premixing gas ejection burner device normally work with the equivalence ratio close to unit ($\alpha = 1.05$) [11]. Proceeding from the obtained dependence, the optimal air gap width for this ejector operating mode will be 1.25 mm. It should be noted that the equivalence ratio will increase with ambient temperature decrease. Also, in the future, it is necessary to take into account the operation features of a gas burner based on a gas ejector, such as backpressure or rarefaction in the combustion chamber, which affect the equivalence ratio.

![Figure 2. Dependence of the equivalence ratio on the air gap width.](image-url)
The velocity distribution is plot along an ejector axis. The calculated rate with using the empirical Saint-Venant formula for determining the subcritical velocity of gas outflow from the convergent nozzle deviates by less than 4% relative to the results of computer simulation (figure 3, 4).

\[
w = \sqrt{\frac{2k}{k-1} \frac{P_1}{\rho} \left[1 - \left(\frac{P_2}{P_1}\right)^{\frac{k-1}{k}}\right]} = 310.47 \frac{M}{c}
\] (9)

Subsonic flow, the maximum Mach number in the gas nozzle is 0.66. In figure 5, 6, concentration distributions of methane and oxygen along the output diffuser diameter are constructed. It can be seen from the graph that the gas-air mixture prepared by the gas ejector is enough homogeneous.

![Figure 3. velocity distribution in gas ejector.](image)

![Figure 4. The velocity distribution along an ejector axis.](image)
4. Conclusion
In the course of the work using computer modeling with the ANSYS Fluent software package and the Response Surface tool, the dependence of the equivalence ratio on the air gap width of the gas ejector was determined, on the basis of which complete premixing gas burners are developed. The optimum air gap width, corresponding to $\alpha=1.05$, is determined as 1.25 mm. Factors to be considered in further studies, such as ambient air temperature changes, backpressure or rarefaction in the combustion chamber, are noted.

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