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Numerical optimization on the geometrical factors of natural gas ejectors

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A B S T R A C T

Increasing production and recovery from mature oil and gas fields often requires a boosting system. Introducing natural gas ejectors can be considered to be a cost-effective way for boosting the production of low-pressure natural gas wells. The CFD technique was employed to investigate the effects of the geometrical factors of natural gas ejectors, the optimal geometrical factors were obtained by numerical simulation to maximize entrainment ratio. Numerical results show that the optimal inclination angle of the mixing chamber was 14°, the optimal diameter ratio of the mixing tube to primary nozzle throat was 1.7, the optimal length to diameter ratio of the mixing tube was 5.0 and the optimal inclination angle of the diffuser was 1.43°. In order to validate the numerical results, a field experiment was carried out. The entrainment ratios obtained by the numerical simulation agreed well with the field data, giving a maximum entrainment ratio up to 93%, proving the optimized geometrical factors of a natural gas ejector. This study may provide a beneficial reference for the design of supersonic ejectors and be helpful for the further applications in boosting natural gas production.

1. Introduction

Ejectors, also known as jet pumps or injectors, are not new for compressible fluids and can be dated back to 1852 in England. Subsequently, many applications have been found in engineering industries. In the aerospace area, ejectors were used to augment the thrust of aircraft propulsion systems [1,2]. In the district-heating applications, the design and application of steam-driven jet injectors were investigated by Ref. [3]. The most relevant application was the enhancement of the coefficient of performance (COP) of refrigeration systems [4].

As an energy-efficient and environment-friendly technique, ejectors have become the focus of renewed interest in many scientific areas. Adequate ejector design and accurate performance prediction are critically important and require a deep understanding of the entire process. Conventional methods of obtaining such information are usually based on theoretical or experimental studies. Although theoretical ejector performance and analysis can determine the influence of certain ejector geometries, the flow physics and the effects of other important geometrical factors, such as the inclination angle of the mixing chamber, the length of the mixing tube, are usually neglected. Experimentation is the best way of obtaining useful data, but the cost in both time and money of constructing an experimental system may limit the wide application of this method. Numerical simulation based on physics principles provides an effective alternative for studying ejector performance and identifying the best technical options of geometry, operational conditions, real fluid behavior, etc.

Over the years, several mathematical models, commonly based on the 1D fluid dynamics theory and assuming that the radial velocities of both the primary and secondary flows are uniform distributed, have been proposed. Keenan and Neumann [5] used a 1D model to analyze ejectors without a diffuser. This model was based on ideal gas dynamics with the principles of conservation of mass, momentum and energy. The model was later modified by Keenan et al. [6] who introduced the concept of constant-pressure mixing, but the heat and friction losses were still ignored. Munday and Bagster [7] proposed the concept of a fictive throat named (effective area) to explain some ejector phenomena. Based on the assumption of constant-pressure mixing, Huang et al. [8] set up a model to predict the ejector performance when the ejector was in critical mode operation. These theoretical models were helpful in obtaining ejector performance under different operation conditions, and the results agreed well with the experimental data. However, the effects of other important geometrical factors such as the convergence angle of the mixing section, the length of the mixing tube and the length of the diffuser are not reflected in those theoretical models due to the limitation of the 1D flow simplification.

Experimental methods have been used to analyze the effects of the geometrical factors on supersonic ejector performance.

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Nomenclature

d	diameter (m)
G	natural gas volume flow rate under standard condition ($m^3 \times 10^4$ per day)
L	length (m)
m	natural gas mass flow rate (kg/s)
P	pressure (MPa)
S	generalized source
t	time (s)
u	entrainment ratio (%)
Pi	axial pressure (MPa)

Greek symbols

ϕ	generalized variable
κ	isentropic index
θ	inclination (deg)
ρ	density (kg/m^3)
Γ	generalized diffusion coefficient
ν	specific volume (m^3/kg)

Subscripts

c	throat of primary nozzle
d	diffuser
H	high/motive pressure
L	low/induced pressure
mc	mixing chamber
mt	mixing tube

Experimental data obtained by Keenan et al. [5,6], and Huang and Chen [9], showed that the entrainment ratio decreased as the primary nozzle moved away from the mixing tube. In contrast, Aphornratana and Eames [10] reported that the entrainment ratio increased as the primary nozzle moved away from the mixing tube. Both works however suggest that there is an optimal location for the primary nozzle for obtaining the best performance. ESDU [11] recommended that the best design for the convergence angle of the mixing chamber is about 10°, while ASHRAE [12] proposed that the optimal value is in the range of 7–10°. In addition, optimal inclination angle of diffuser is in the range of 4–8° according to ESDU, whereas ASHRAE recommended 5–7°. Many recent studies based predominantly on the CFD approach [13–15], were expected to provide a reasonable cost and a good understanding of local phenomena. In the present work, the CFD modeling technique has been used to investigate the geometrical factors of natural gas ejectors.

1.1. Natural gas ejector

Our primary interest in this paper is the use of supersonic ejectors in boosting the production of low-pressure natural gas. Generally, with the extended production life of gas wells, their pressure gradually decreases leading to reduced production or, what is more serious, abandonment of the field. Obtaining the maximum total recovery from all gas wells and maintaining their production are highly desirable in the industry. Thus an important issue is to solve the problem of raising gas pressure when it is lower than pipeline pressure in order to transport it to the processing system. To maintain production of low-pressure wells, the conventional method is to use natural gas compressors, but the operation and maintenance of compressors is of high cost. Compared to this method, ejectors have several advantages, no moving parts, relatively low capital cost, simplicity of operation, reliability and low maintenance cost. The most important benefit is that ejectors can be powered by the energy of high-pressure gas wells usually wasted through choke valves, to boost the natural gas production, ejectors can therefore achieve the same results as compressors.

Despite the ejectors having so many advantages in boosting low-pressure natural gas, few investigations have been performed on their use. In 1987, the CALTEC group designed an ejector system and carried out trials at Hewett Field in the North Sea. Sarshar et al. [16–18] indicated that jet pumps were a cost-effective way in boosting production and recovery from low-pressure gas and oil wells. They concentrated their analysis on the feasibility and reliability of the system. The performance of their system in the North Sea and other fields, was investigated experimentally, showing that the entrainment ratio reached to 78% when the high pressure, low pressure and discharged pressure were 5.5 MPa, 1.6 MPa and 2.0 MPa, respectively. Melancon and Nunn [19] and Andreussi et al. [20] also investigated its operation mechanism and economics. Recently, Chong et al. [21] carried out geometrical optimization throughout experimental work. However, their geometrical optimization was done for the maximum pressure ratio, and the effect of the diffuser was neglected.

In the studies mentioned above, little has been reported about the influence of the geometrical factors on natural gas ejector performance under constant back pressure (i.e. the transportation pipeline back pressure). In the present work, the geometrical factors of natural gas ejectors were optimized numerically for the maximum entrainment ratio. These results were then validated by field experiment. The work will be beneficial for the design of supersonic ejectors and contribute to potentially widen their applications in natural gas fields in the future.

1.2. Principle of natural gas ejector

Supersonic ejectors of natural gas are simple and reliable devices to boost the production of low-pressure gas wells. Fig. 1 shows the natural gas ejector's five main components: primary nozzle (A), secondary nozzle (B), mixing chamber (C), mixing tube (D) and diffuser (E). Supersonic natural gas ejectors employ a natural gas with high pressure as the motive or primary stream and a low-pressure gas as induced or secondary stream, The motive gas passes through a convergent/divergent primary nozzle to achieve supersonic velocity, creating a low-pressure environment at its exit in order to draw the induced gas into the mixing chamber. As the two streams travel through the mixing chamber and mixing tube, complex interactions between the mixing layer and shock-waves take place. The mechanical energy transferred from the high to the low-pressure level, results in a pressure between the motive and the induced pressure. Consequently, the supersonic ejector enables low-pressure natural gas to be extracted at a lower pressure than the back pressure imposed by the pipeline. As described above, the natural gas ejector consists of five main parts. For the sake of simplicity, it has been assumed that the flow in the primary and secondary nozzles is isentropic flow, and the primary and the secondary nozzles can be designed using empirical correlations. Many researchers have attempted to resolve the mechanism of